POSITIVE ENERGY DISTRICTS: TRANSFORMING URBAN AREAS INTO HIGH EFFICIENCY DISTRICTS WITH LOCAL RENEWABLE GENERATION AND STORAGE

EDITED BY: Ursula Eicker, Matthias Haase, Francesco Guarino and Genku Kayo

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Topic Editors:
Ursula Eicker, Concordia University, Canada
Matthias Haase, Zurich University of Applied Sciences, Switzerland
Francesco Guarino, University of Palermo, Italy
Genku Kayo, Tokyo City University, Japan

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EDITORIAL
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Editorial: Positive Energy Districts: Transforming Urban Areas Into High Efficiency Districts With Local Renewable Generation and Storage

*Ursula Eicker**

Canada Excellence Research Chair in Smart, Sustainable and Resilient Cities, Department of Building, Civil and Environmental Engineering, Concordia University, Montreal, QC, Canada

Keywords: positive energy districts, urban densification, renewables, storage, social inclusion

Editorial on the Research Topic

Positive Energy Districts: Transforming Urban Areas Into High Efficiency Districts With Local Renewable Generation and Storage

Positive energy districts have emerged as a new paradigm of next generation city building, where energy is fully supplied from renewable sources (Brozovsky et al., 2021). Different definitions of the spatial boundaries are still in discussion: an autonomous positive energy district supplies 100% or more of its own energy demand and any excess energy is exported to the grid (Lindholm et al., 2021). This concept works in low density districts with large available surface areas for renewable, mostly solar photovoltaic generation, and low demand. In a dynamic positive energy district, energy can be imported and exported from the grid, but the on-site renewable generation must still be higher than the demand. Again, if the urban density is high and the areas for power generation on roofs and façade limited, this concept has its limits. The most flexible definition is a virtual positive energy district, where renewable energy can be freely imported and exported, but does not have to be produced on site. Here questions of renewable ownership and power purchase agreements arise to make sure that new renewables are built to satisfy the demand of a district (Pan and Pan, 2021). Some further differentiations are available with regards to the metric of the balances: overall carbon neutrality is indicated as a priority in some formulations of the positive energy district definition (i.e., in the EU Setplan) in addition to the focus on surplus renewable energy generation (Derkenbaeva et al., 2022).

Positive energy districts thus have to consider both the demand side and the supply and storage options: only if demand is low by retrofitting existing buildings to high energy standards, can local renewables make significant contributions. In today's urban discussion, densification and a resulting demand increase is very much on the agenda, as only dense urban areas can provide public and active transportation and thus overall low greenhouse gas emissions.

The ongoing transformation of the transportation sector to electric vehicles adds local electrical loads to the low voltage distribution network, which can only be reduced by higher public transportation shares. Together with the electrification of heating systems, urban electricity demand is on the rise and its evolution needs to be carefully analyzed to find supply solutions that can cover changing demand (Yuan et al., 2021).

Different options of renewable supply then need to be studied to determine the best energy mix between solar, wind, or waste to energy and to optimize the required storage volume. Options range from short to seasonal storage and strongly depend on the spatial boundaries discussed above: for an autonomous positive energy district, storage units need to increase in size, as the local demand

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Edited and reviewed by:
Stefan Bouzarovski, The University of Manchester, United Kingdom

***Correspondence:**
Ursula Eicker
ursula.eicker@concordia.ca

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must be supplied at all times. This increases the overall cost of the installation, but also the local resilience in cases of power outages (Petkov et al., 2021).

To support the decision making around demand reduction and renewable supply and storage in a complex district scale setting, new simulation and optimisation tools are needed. Digital twins of the built environment are increasingly used to provide geometry information for building demand modeling, but also to manage data sets of construction and usage. Automated workflows need to be developed to facilitate both demand and supply modeling and the optimisation tasks for planning and operation of such renewable systems (Abolhassani et al., 2022).

But the implementation of positive energy districts does not only encounter technical and financial challenges, but needs new frameworks to also offer a socially inclusive and affordable perspective for the residents, so that gentrification is avoided and the districts are mixed and vibrant (Hearn et al., 2021). Furthermore, all stakeholders' needs should be taken in consideration in an integrated social perspective, in addition to pursuing environmental sustainability and circularity practices and exploring new and innovative business models tailored to the aforementioned issues.

Case studies on a neighborhood scale still play an important role to assess performance, economics and engagement of the community. If the success of such case studies in different regions, climates, and social conditions can be shown across the world, positive energy districts will become a major driver of urban decarbonisation.

Lastly, actions to reduce the carbon, environmental and resource footprints of PEDs are due in several domains and by different actors.

The current Research Topic addresses the multiple perspectives discussed above and contributes to a better understanding of potentials and barriers of positive energy districts, with a specific focus on energy modeling, innovative assessment methodologies, case-studies definitions, and implementation.

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REFERENCES

Abolhassani, S. S., Amayri, M., Bouguila, N., and Eicker, U. (2022). A new workflow for detailed urban scale building energy modeling using spatial joining of attributes for archetype selection. *J. Build. Eng.* 46:103661. doi: 10.1016/j.jobe.2021.103661

Brozovsky, J., Gustavsen, A., and Gaitani, N. (2021). Zero emission neighbourhoods and positive energy districts – a state-of-the-art review. *Sustain. Cit. Soc.* 72:103013. doi: 10.1016/j.scs.2021.103013

Derkenbaeva, E., Vega, S. H., Hofstede, G. J., and van Leeuwen, E. (2022). Positive energy districts: mainstreaming energy transition in urban areas. *Renew. Sustain. Energy Rev.* 153:111782. doi: 10.1016/j.rser.2021.111782

Hearn, A. X., Sohre, A., and Burger, P. (2021). Innovative but unjust? Analysing the opportunities and justice issues within positive energy districts in Europe. *Energy Res. Soc. Sci.* 78:102127. doi: 10.1016/j.erss.2021.102127

Lindholm, O., Rehman, H., and Reda, F. (2021). Positioning positive energy districts in European Cities. *Buildings* 11:19. doi: 10.3390/buildings11010019

Pan, W., and Pan, M. (2021). Drivers, barriers and strategies for zero carbon buildings in high-rise high-density cities. *Energy Build.* 242:110970. doi: 10.1016/j.enbuild.2021.110970

Petkov, I., Gabrielli, P., and Spokaite, M. (2021). The impact of urban district composition on storage technology reliance: trade-offs between thermal storage, batteries, and power-to-hydrogen. *Energy* 224:120102. doi: 10.1016/j.energy.2021.120102

Yuan, M., Thellufsen, J. Z., Lund, H., and Liang, Y. (2021). The electrification of transportation in energy transition. *Energy* 236:121564. doi: 10.1016/j.energy.2021.121564

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Residential Densification for Positive Energy Districts

James Bambara[1]*, Andreas K. Athienitis[2] and Ursula Eicker[3]

[1] Centre for Zero Energy Building Studies and CERC Next-Generation Cities, Concordia University, Montreal, QC, Canada, [2] Centre for Zero Energy Building Studies, Concordia University, Montreal, QC, Canada, [3] CERC Next-Generation Cities, Concordia University, Montreal, QC, Canada

The energy footprint of houses can be reduced by replacing the aging stock with higher density and more energy efficient homes equipped with on-site renewable energy production. In this study, a "double density" simulation scenario is considered where each existing detached house in a community is replaced with two houses of equal living area on the same land lot. The new houses were assumed to be equipped with several energy efficiency measures (envelope, HVAC, and domestic hot water) and a building-integrated photovoltaic (BIPV) roof. The TRNSYS software was used to simulate the annual energy performance of the buildings in Montreal, Québec, Canada (45.5°N). It was found that the two new houses, which can accommodate twice the number of people on the same land lot, consumed 30% less energy than the existing house. Individually, each of the new houses required 65% less electricity than the existing house (reduced from 22,560 to 7,850 kWh yr^{-1}). In addition, the BIPV roof installed on the two new houses could generate nearly three times more electricity (44,000 kWh yr^{-1}) than they consumed (15,700 kWh yr^{-1}). Annually, nearly half (44%) of the house's electricity can be directly supplied by the BIPV system. A significant portion of the annual solar electricity generation (84%), which cannot be directly utilized by the houses, can be stored on-site for later use to increase self-consumption (e.g., power-to-thermal energy or charging electric vehicles) or could be exported to the grid to support decarbonization elsewhere (e.g., production of hydrogen fuel for transportation). The combined effect of energy efficient construction and on-site renewable energy production would enable occupants to shift from consuming 5,640 kWh yr^{-1} to producing 3,540 kWh yr^{-1}. Residential densification can significantly contribute toward retrofitting existing communities into resilient positive energy districts.

Keywords: residential redevelopment, densification, energy efficiency, building-integrated photovoltaics, positive energy building, energy flexibility, resilience, decarbonization

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Edgar Liu, University of New South Wales, Australia

Reviewed by:
Riccardo Paolini, University of New South Wales, Australia
Jiying Liu, Shandong Jianzhu University, China

***Correspondence:**
James Bambara
j_bamba@encs.concordia.ca

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INTRODUCTION

As more and more people move to cities, there will be a need for either densification or urban expansion. Densification is a possible way to achieve more compact cities, combat sprawl, and improve urban sustainability. Meanwhile, aging buildings that need to be renovated or replaced create an opportunity for modern designs that can reduce overall energy use while improving quality of life. In Canada, 54% of the buildings were built before 1979, many of which will need to be upgraded in the near future (Natural Resources Canada, 2020). This aging building stock can either undergo a deep retrofit (i.e., same footprint, structure is kept), a deep retrofit combined with extensions (adding floors or footprint area) or be demolished/recycled and rebuilt. Rebuilds and deep retrofits with extensions offer the advantages of densification, whereby more occupants can inhabit the same land area. This can lead to energy savings for building operation and transportation (reduced travel distances and associated congestion/pollution) (O'Brien et al., 2009).

Both retrofits and rebuilds lower energy consumption (and the associated environmental pollution) due to the improved performance of a modern building envelope and HVAC system, amongst others. Several empirical and numerical studies have been performed to quantify the energy and economic potential for improved designs such as thermal insulation (Mohamed, 2020), windows (Aste et al., 2018) and their shading system (Kunwar, 2018), use of heat pump for heating and cooling (Alshehri et al., 2019; Liu et al., 2019) and domestic hot water heating (Minetto et al., 2016), energy recovery ventilation (Psimopoulos et al., 2019), high efficiency lighting and appliances (Fantozzi et al., 2017; Heidari and Patel, 2020) and low flow faucets (Englart and Jedlikowski, 2019). Numerical studies may employ custom models and often commercially available energy modeling software (e.g., TRNSYS, eQUEST, EnergyPlus) to predict the energy consumption of buildings (Crawley et al., 2008; Han et al., 2014). A simulation study in Sweden showed that step-by-step renovations on their aging houses can reduce energy use by up to 75% (Ekström and Blomsterberg, 2016). Other studies have focused on optimizing the geometry and orientation of buildings to reduce their energy consumption (Capozzoli et al., 2009; Granadeiro et al., 2013; Touloupaki and Theodosiou, 2017).

The production of renewable energy on-site using photovoltaics (PV) can further reduce energy use and even lead to net-zero or positive energy buildings (produce more energy than they consume on an annual basis), particularly for detached houses which have a relatively large well-exposed surface area for solar energy capture compared to their energy use (Mohajeri et al., 2016). Dramatic cost reductions of PV technology combined with incentives such as feed-in-tariffs have helped to accelerate their deployment. Meanwhile, their efficiency has been increasing and commercially available monocrystalline PV modules can now convert up to 21% of the incident solar energy into electricity (Jinko Solar, 2020). Energy generation depends mainly on the geometry and orientation of the PV system and to a lesser degree the panel's surface temperature. Hachem et al. (2011) presented a methodology for investigating the impact of design parameters for two-story houses in different neighborhood layouts, on solar energy utilization potential. As demonstrated through the construction of the "Ecoterra" near net zero energy demonstration house in Canada, building-integration of PV technology can further reduce costs by substituting the need for conventional building materials (Bucking et al., 2010). The electrical efficiency and durability can be improved by cooling the PV panels (PV/thermal system), where the heat that would otherwise be wasted can be recovered for use within the building (Athienitis et al., 2011).

In contrast to the number of studies on energy use and solar potential, there are few studies focusing on the relationship between the density and building energy performance (Steemers, 2003; Holden and Norland, 2005; Brown and Logan, 2008; Kontokosta, 2012; Quan, 2016). O'Brien et al. (2009) performed a numerical simulation to compare the energy performance of three housing types in Toronto (detached homes, townhouses, and multi-story residential). The study found higher density in terms of dwelling unit area has both lower building energy use per occupant and per floor area. The study also reports that the solar potential decreases as the density increases, and that there is possibly an optimal density in terms of solar potential. Another study examining Toronto neighborhoods also concluded that higher density in terms of dwelling unit per unit area has lower building energy use per occupant, but slightly higher building energy use per floor area (Norman et al., 2006).

From an extensive literature review, there are a lack of studies that evaluate the impact of different housing densities on energy performance at the land lot scale. Densification of detached homes may consist of replacing aging homes with two new homes (and possible more depending on the land lot size) capable of housing more occupants on the same land lot. These residential rebuilds can offer similar characteristics as their aging counterparts (e.g., similar living area and private outdoor space) while reducing the energy use per occupant. The goal of this study is to compare the energy performance of a typical aging home that was built in the 1970s with a densification scenario where two energy efficient homes of equal living area and equipped with a building-integrated PV (BIPV) roof are built on the same land lot located in the suburbs of Montreal, Québec, Canada (45.5°N, mid-latitude, 4,457 heating degree-days).

ENERGY ANALYSIS

The purpose of this study is to compare the energy performance (consumption and generation) of an existing house with that of two energy efficient homes equipped with BIPV that are built on the same land lot. An energy model will be created for each of the houses and annual energy simulations will be performed to quantify their energy performance.

House Characteristics

The geometry of the existing house reflects typical construction of the 1970s in a Montreal suburb (**Figure 1A**). **Figure 1B** depicts a possible geometry for the case where two new houses are built on the same land lot that previously had one house.

A major objective of this study is to quantify the energy savings potential that can be achieved by replacing aging detached homes with two homes of similar living area. This "double density" scenario would house twice the number of people on the same land area. The new houses are assumed to be built to the highest standards of energy efficiency and will consume significantly less energy than the aging stock. In addition, the new houses will be equipped with a BIPV roof to produce electricity on-site and offset some or all their electricity use.

The existing single-story house is comprised of a basement and a main living floor above it, with a slab on grade garage connected to it (**Figure 2A**). The new houses are designed to have the same living area (typically excludes basement and garage)

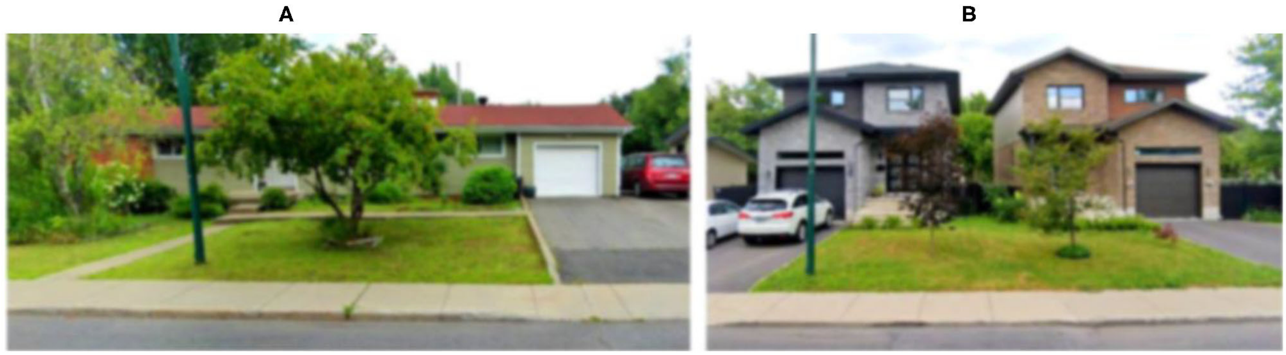

FIGURE 1 | Photos depicting two houses: **(A)** single story existing house; **(B)** two two-story houses built on the same land lot (google maps).

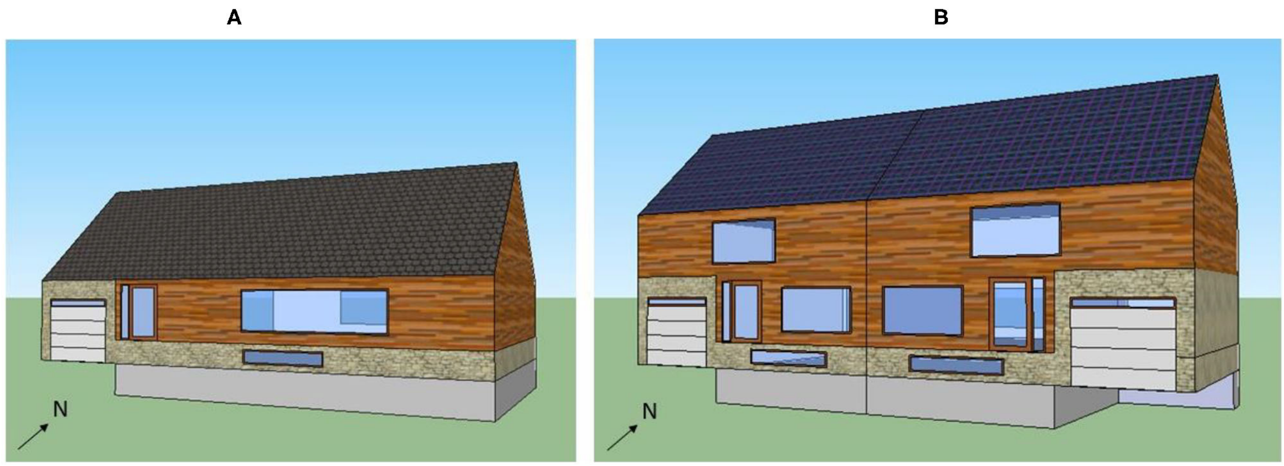

FIGURE 2 | Schematic showing the two modeled houses: **(A)** single story existing house; **(B)** two two-story houses built on the same land lot (they can be semi-detached or spaced with a small distance as shown in **Figure 1**).

as their existing counterparts. In order to build two houses on the same land lot (~850 m^2) while maximizing available outdoor space, the new homes will have two stories. Similarly, the new houses will have an attached garage and a basement. Due to practical geometrical constraints and the required smaller footprint of the new houses, the basement area was reduced by 40% compared to the existing house. This study considers the case where the two new homes are attached to reduce both the amount of construction materials/labor and operation energy consumption (**Figure 2B**). The total footprint of the existing house is 166.8 m^2 and building two houses required 32% more land area (the footprint of each of the new houses is 34% less than existing house). **Table 1** provides the geometry details of the existing and new houses.

Table 2 provides an overview of the energy efficiency measures that were considered in the study. They are related to the space and domestic hot water (DHW) heating, space cooling, building envelope, and ventilation. Due to improved construction, the new house is more airtight than the existing house and so ventilation is required to supply enough fresh air to the occupants. Energy recovery ventilation is used to recover thermal energy from the exhausted ventilation air. It is assumed that the plug loads are the same for the existing and new houses because it is desired to focus on efficiency gains that can be achieved from an improved envelope, HVAC, and DHW design. The most common energy efficiency measures for homes that operate using electricity were selected for this study. An economic study such as life cycle cost analysis would be needed to evaluate whether the selected energy efficiency measures and potentially others satisfy the developer's investment decision criteria. In addition, the roof of the new houses is equipped a BIPV system to generate energy on-site.

Energy Modeling and Simulation

The TRNSYS 17.2 software was selected for the transient simulation of the house climate (Klein et al., 2014). Type 56 multizone building model was used to create the building energy model (TRNSYS 17, 2005). Annual energy simulations of the model are performed to obtain the energy performance (consumption and generation) of the existing and the new

TABLE 1 | Details of the house geometry.

	Existing	New
Garage (m^2)	26.8	26.8
Basement (m^2)	140	83.4
First floor (m^2)	140	56.6
Second floor (m^2)	-	83.4
Total living area (m^2)	140	140
Garage height (m)	3.2	3.2
Basement height (m)	2.1	2.1
Basement height above ground	1.2	1.2
First and second floor height (m)	2.3	2.3
Basement window area (south and north) (m^2)	1.5	1.5
First floor window area (south and north) (m^2)	8	4
Second floor window area (south and north) (m^2)	-	4
Front door area (south) (m^2)	3.5	3.5
Garage door area (south) (m^2)	6.7	6.7
Sliding door area (north) (m^2)	3.7	3.7

TABLE 2 | Energy efficiency measures considered for the modeled houses.

	Existing	New
Space heating	Electric resistance	Electric reversible heat pump
Space cooling	AC unit	Electric reversible heat pump
DHW heating	Electric resistance	Electric CO_2 heat pump
DHW consumption	Standard faucets	Low flow faucets
Thermal insulation	Standard (1970's)	50% higher than existing (Novoclimat standards)
Windows	Double glazed air	Double glazed argon low-e, 50% higher frame insulation
Movable shades	No	Yes
Infiltration rate	Loose construction	Airtight construction
Ventilation	None	Energy recovery ventilation

houses. Each house model consists of four-to-five thermal zones: garage, basement, living floor (one zone for the existing house and one zone for each story of the new houses), and a ventilated attic. Due to the geometry, there are more than one thermal zones for the basement and two floors of the new house.

Energy Modeling Key Assumptions

The details, parameter values and assumptions for the building modeling are presented below and given in **Table 3**.

Weather Data

A typical meteorological year (TMY) weather file for Montreal, Québec, Canada (45.5°N) was used to run the simulations and obtain the energy performance over a one-year period. Type 15 calculates the sky temperature for longwave radiation calculations (TRNSYS 17, 2014). The ground surface temperature is assumed to be the same as the exterior air temperature. The diffuse solar radiation component is calculated using the anisotropic diffuse model by Perez et al. (1988). A simulation timestep (Δt) of 1 h was selected. The energy model was simulated for 455 days, with the first 3 months of results ignored to eliminate the initial transient effects associated with the soil.

Conduction

Type 56 uses the ASHRAE transfer function method to solve the transient conduction heat transfer through opaque envelope components (Stephenson and Mitalas, 1971; Mitalas and Arseneault, 1972). Thermal energy storage is neglected for heat conduction through windows, doors, and the movable shades.

Convection

Type 56 provides internal calculation of natural convective heat transfer coefficients (CHTC) using turbulent natural CHTC correlations developed by McAdams (1959). The exterior CHTC is mainly a function of wind speed and an empirical correlation by McAdams (1959) was selected in the model. Moreover, the model assumes that the air is well-mixed inside each thermal zone.

Shortwave Radiation

Type 56 enables detailed computations for radiation distribution, including multi-reflection and solar radiation leaving the zone through the windows, whereby beam and diffuse components are considered separately. A detailed calculation for distributing the primary solar direct radiation entering the zone is achieved using geometric distribution (TRNSYS 17, 2005). For a detailed treatment of shortwave diffuse radiation, the TRNSYS radiation model applies Gebhart factors (Gebhart, 1961, 1971).

Longwave Radiation

Type 56 enables detailed computations for longwave radiation heat transfer between inside surfaces and from exterior surfaces to the ground and sky.

Ventilation

The existing house does not have mechanical ventilation as sufficient fresh air is provided by natural air infiltration. For the new houses, mechanical ventilation with sensible energy recovery is provided according to ASHRAE (2019) for a three-bedroom house. It is assumed that 60% of the ventilation air is provided to the first floor and the rest to the second floor. The electricity consumed to operate the energy recovery ventilation (ERV) system is included in the plug loads. No ventilation is provided in the basement and garage. Air exchange was neglected between the thermal zones of the basement and two floors of the new house. Ventilation air is assumed to be provided to the largest thermal zone on each floor.

Internal Gains

The internal gains are applied to the house's living area and specified by NRCC (National Research Council of Canada) (2015) and given in **Table 4**. For the two-story houses, the total gains for a house are split with $2/3^{rd}$ to the main floor and

TABLE 3 | Parameter values of different materials/components used in the house model (values for the new house are in parenthesis).

Material/component	Parameter	Value	References
Thermal resistance (m^2 K W^{-1})	Garage floor	0.86 (1.32)	Novoclimat, 2003
	Basement floor	0.57 (0.88)	
	Basement walls	1.94 (2.99)	
	Exterior walls	2.8 (4.31)	
	Roof ceiling	4.69 (7.22)	
	Wall between garage and house	2.29 (3.52)	
	Floor between basement and house	2.29 (3.52)	
	Wall between both houses	N/A (2.2)	
	Opaque portion of garage and doors	0.57 (1.15)	
	Window frames	0.57 (1.14)	
	Windows, front, garage and patio door	0.34 (0.7)	
Movable shades	Solar transmittance	0.3	Assumed
	Solar reflectance on both sides (ρ_{sh})	0.8	
	Absorbed radiation convected to airnode (F_{conv_sh})	50%	
	Additional thermal resistance	0.162 m^2 K W^{-1}	Athienitis, 1998
	Incident irradiance above which shades closes	100 W m^{-2}	Assumed
	Outside air temperature above which can close	15°C	
Window properties	Normal transmittance of window glazing	0.727 (0.544)	DOE, 2015
	Normal reflectance of window glazing	0.129 (0.22)	
	Frame fraction of windows and patio door	15%	Assumed
	Frame fraction of garage door	70%	
	Frame fraction of front door	40%	
	SHGC of windows and patio door	0.777 (0.596)	DOE, 2015
	SHGC of garage and front door	0.785 (0.595)	
Heating	Setpoint temperature for living area	21°C	Assumed
	Setpoint temperature for basement and garage	12°C	
Cooling	Setpoint temperature (living area only)	25°C	
Heat pump (space)	Min. outdoor air operating temperature (wet bulb)	−15°C	Mitsubishi, 2014
Heat pump (DHW)	Min. outdoor air operating temperature (dry bulb)	−25°C	Miles et al., 2017
	DHW heating setpoint temperature (T_{DHW_sp})	60°C	Assumed
Ventilation	Ventilation rate	35 L s^{-1}	ASHRAE, 2019
	Heat recovery ventilation efficiency	60%	Novoclimat, 2003
Infiltration rate	Existing house	0.3 hr^{-1}	Veitch, 2008
	New house	0.1 hr^{-1}	Novoclimat, 2003
	Attic	10 hr^{-1}	Assumed
PV system	PV module electrical efficiency at STC (η_{STC})	21.16%	Jinko Solar, 2020
	Temperature coefficient (β_{PV})	0.35% K^{-1}	
	Wiring losses	2%	Dobos, 2014
	Inverter efficiency	96%	
	PV cell temperature at STC (T_{STC})	25°C	International Electrotechnical Commission (IEC), 2011
Layer thickness	Floor plywood	0.025 m	Assumed
	Ceiling gypsum	0.013 m	
	Foundation wall thickness	0.2 m	
	Slab thickness (garage and basement)	0.1 m	
	Roof plywood	0.019 m	
Surface reflectances	Walls and ceiling (inside and outside)	0.5	
	Living area floors	0.2	
	Concrete floors	0.2	
	Ground floor	0.2	
	PV module	0.95	Nemet, 2009

(Continued)

TABLE 3 | Continued

Material/component	Parameter	Value	References
	Roof shingles	0.95	Assumed
	Window frame	0.3	
Emissivities	All surfaces (except those listed below)	0.9	
	Low emissivity coating	0.1	
	Glass	0.84	TRNSYS 17, 2005
Expanded polystyrene insulation	Specific heat	1.25 kJ kg^{-1} K^{-1}	
	Density	25 kg m^{-3}	
	Thermal conductivity	0.035 W m^{-1} K^{-1}	
Concrete	Specific heat	1 kJ kg^{-1} K^{-1}	
	Density	2000 kg m^{-3}	
	Thermal conductivity	1.3 W m^{-1} K^{-1}	
Plywood	Specific heat	1.2 kJ kg^{-1} K^{-1}	
	Density	800 kg m^{-3}	
	Thermal conductivity	0.15 W m^{-1} K^{-1}	
Gypsum	Specific heat	1 kJ kg^{-1} K^{-1}	
	Density	1200 kg m^{-3}	
	Thermal conductivity	0.58 W m^{-1} K^{-1}	
Soil and ground surface	Depth of ground zone and far-field distances	10 m	Assumed
	Smallest control volume size	0.1 m	
	Specific heat	1 kJ kg^{-1} K^{-1}	Hamdhan and Clarke, 2010
	Density	1800 kg m^{-3}	
	Thermal conductivity	0.6 W m^{-1} K^{-1}	
	Deep earth temperature	6.1°C	RETScreen, 2013
	Amplitude of surface temperature	15.2°C	
	Day of year of minimum surface temperature	60 d	Assumed
Roof slope	North facing roof slope of existing house garage	60°	
	All other roofs	40°	
Constants	Airnode capacitance multiplier	10	
	Density of air	1.204 kg m^{-3}	
	Specific heat of air at constant pressure	1.012 kJ kg^{-1} K^{-1}	
	Density of water (ρw)	1000 kg m^{-3}	
	Specific heat of water at constant pressure (cp_w)	4.2 kJ kg^{-1} K^{-1}	

1/3rd to the second floor. The garage, basement and attic are assumed to not have internal loads. All internal gains are assumed to be convected to the airnode. Only sensible internal gains are considered and latent effects such as occupant transpiration are ignored.

Plug Loads

A fraction of internal gains are plug loads. It was assumed that 50% of the internal gains are plug loads which translates to 4,088 kWh yr^{-1} and in agreement with values provided in the literature (George, 2016). **Table 4** provides the plug load schedule.

Ground Heat Transfer

Type 1244 was selected because it enables detailed heat transfer calculations (using 3D finite difference) between the Type 56 multi-zone building model and the ground surface by creating a geometrical "map" (Personnel communications with TESS Technical Support Team, 2017). A user defined volume of soil is considered for ground heat transfer and divided into control volumes that are assumed to be cubic in shape so there are six unique heat transfers to analyze per control volume. The dimensions of the control volumes were multiplied by a factor of two as they expanded away from the perimeter of the house airnodes. The boundary conditions are specified as adiabatic.

Solar Electricity Generation

The roof of the new house is equipped with BIPV system comprised of monocrystalline PV modules (Jinko Solar, 2020) and an inverter. Two cases will be considered for assessing solar energy capture potential: PV on the south (facing the street) and north facing roof, and PV on the east and west facing roof when the house orientation is rotated by 90° counterclockwise. To calculate temperature-dependent PV electricity generation, a simplified method was used to estimate the PV surface temperature. The BIPV was modeled as a layer of plywood (which separates the exterior air and ventilated attic) with solar absorptance and emittance values corresponding to a typical PV

TABLE 4 | Internal gains, plug loads, and DHW consumption schedules.

Hour of the day	Internal gains (W)	Plug loads (W)	DHW use (L hr^{-1})
0	786.1	393.1	0
1	551.9	276.0	0
2	548.9	274.4	0
3	523.1	261.5	0
4	521.1	260.6	0
5	546.9	273.5	0
6	633.9	316.9	0
7	726.1	363.1	3.1
8	846.9	423.5	12.4
9	880.0	440.0	18.7
10	906.1	453.1	34.2
11	986.1	493.1	17.1
12	991.9	496.0	4.7
13	933.9	466.9	1.6
14	898.1	449.0	3.1
15	911.1	455.6	7.8
16	923.9	461.9	14
17	1088.9	544.4	9.3
18	1410.0	705.0	9.3
19	1588.1	794.0	3.1
20	1568.1	784.0	1.6
21	1483.1	741.5	0
22	1193.9	596.9	0
23	951.9	476.0	0

surface. The energy produced by the PV is taken into account for the surface energy balance.

The rate of electricity generation from the BIPV roof (E_{pv} in W) is estimated using (Skoplaki and Palyvos, 2009):

$$E_{pv} = I_{pv\_so} \cdot A \cdot \eta_{STC} \cdot \left(1 - \beta_{pv} \cdot \left[T_{pv\_so} - T_{STC}\right]\right) \cdot (1 - L_w) \cdot \eta_{inv} \quad (1)$$

where

I_{pv_so} is solar radiation incident on the outside PV surface (W m^{-2})
A is the PV area on the roof (m^2)
η_{STC} is the electrical efficiency of the PV module at STC (%)
β_{PV} is the PV module temperature coefficient (% K^{-1})
T_{pv_so} is the temperature of outside surface temperature of the PV cells (°C)
T_{STC} is the PV cells temperature at STC (°C)
L_w is the wiring losses (%)
η_{inv} is the DC/AC inverter efficiency (%).

The effect of solar incidence angle on electricity generation is not considered. The annual electric energy generated by the STPV cladding (E_{pv_yr}in kWh yr^{-1}) is determined from:

$$E_{pv\_yr} = \sum_{\Delta t=0}^{\frac{365 \cdot 24}{\Delta t}} \left[\frac{\Delta t \cdot \left(E_{pv}\right)}{10^3} \right] \quad (2)$$

where the factor 10^3 serves to convert units W to kW.

Envelope Construction

The level of thermal insulation for the new houses is based on Novoclimat (2003), an advanced standard for energy efficient construction in Canada. A reduction factor was applied to estimate the thermal insulation level in the existing house (see section Model Plausibility Check). The details for the envelope design are presented below:

Walls

All the walls are modeled as a single layer of expanded polystyrene (EPS).

Basement Walls

The foundation walls of the new house consist of concrete with exterior EPS insulation. The foundation walls of new house are made of insulated concrete form comprised of concrete with EPS insulation on each side.

Floor and Ceiling

Inter-stories are modeled as a floor made of plywood and a ceiling finished with gypsum. The garage and basement floor consist of a slab on grade with EPS insulation beneath.

Wall Separating New Houses

The wall that separates the two new houses is assumed to insulated using EPS. If the houses are separated by a small distance as shown in **Figure 1**, this is not expected to significantly affect heating load.

Roof

The roof slope is identical except for the north facing slope of the existing house's garage. The exterior finish is modeled as a layer of plywood with an absorptance and emittance that represents dark shingles or PV panels.

Windows

The windows and doors consist of a glazed portion and a frame portion. The glazed fraction on each facade orientation is the same for the existing and new houses. The glazing types for the existing house are double glazed air filled (for the windows and patio door: 2.5 mm glass, 12.7 mm airspace, 2.5 mm glass; for the custom windows: 3 mm glass, 12.7 mm airspace, 3 mm) and for the new houses double-glazed argon filled with a low emissivity coating (for the windows and patio door: 3 mm glass, 12.7 mm airspace, 2.5 mm glass; for the custom windows: 3 mm glass, 12.7 mm airspace, 3 mm). Custom windows were created for the main door and the garage because their frame area is large compared to the glazed portion. Window 7.3 was used to calculate the overall thermal and incidence angle dependent optical properties of the custom windows (DOE, 2015). The edge heat transfer effects and energy storage in glazing materials and framing is neglected.

Movable Shades

A single motorized movable shade (*sh*) is installed on the inside surface of all windows (excludes garage, front, and patio door) to reduce the cooling load. The solar radiation that is absorbed on the shade and convected to an airnode (Q_{sh}in W) is given by:

$$Q_{sh} = I_{sh} \cdot (1 - \rho_{sh}) \cdot F_{conv\_sh} \tag{3}$$

where

I_{sh} is solar radiation incident on the movable shade (W m^{-2})
ρ_{sh} is solar reflectance of the movable shade (%)
F_{conv_sh} is the fraction of absorbed solar radiation convected to the air (%).

Capacitance Multiplier

A thermal capacitance multiplier was specified to account for interior furnishings.

Thermal Energy Consumption

The output of the TRNSYS simulation provides the heating (Q_{heat} in kJ hr^{-1}) and cooling (Q_{cool} in kJ hr^{-1}) power at each timestep that is required to maintain the desired setpoint temperature.

The annual thermal energy consumption for heating (Q_{heat_yr} in kWh yr^{-1}) is expressed as:

$$Q_{heat\_yr} = \sum_{\Delta t=0}^{\frac{365 \cdot 24}{\Delta t}} \left(\frac{Q_{heat} \cdot \Delta t}{3600} \right) \tag{4}$$

where the factor 3600 serves to convert units hr to s.

Similarly, the annual thermal energy consumption for cooling (Q_{cool_yr} in kWh yr^{-1}) is expressed as:

$$Q_{cool\_yr} = \sum_{\Delta t=0}^{\frac{365 \cdot 24}{\Delta t}} \left(\frac{Q_{cool} \cdot \Delta t}{3600} \right) \tag{5}$$

Electricity Use for Heating and Cooling

An electric air conditioner (AC) unit is used to cool in the existing house and an electric reversible heat pump provides heating and cooling in the new houses. It is assumed that the coefficient of performance (*COP*) of the AC unit and heat pump (cooling mode) is the same and estimated by the following equation that is a curve fit to the manufacturer's data (Mitsubishi, 2014):

$$COP_{cool} = -0.1549 \cdot T_o + 11.086 \tag{6}$$

where T_o is outside air dry bulb temperature (°C).

Similarly, the COP of the heat pump in heating mode is estimated by the following equation that is a curve fit to the manufacturer's data (Mitsubishi, 2014):

$$COP_{heat} = 0.0416 \cdot T_{o\_wb} + 4.4108 \tag{7}$$

where T_{o_wb} is outside air wet bulb temperature (°C).

When the outdoor air temperature is below the heat pump's operating range, electric resistance heating is used where the COP equals to one. The annual electricity consumption for cooling (E_{cool_yr} in kWh yr^{-1}) is given by:

$$E_{cool\_yr} = \sum_{\Delta t=0}^{\frac{365 \cdot 24}{\Delta t}} \left(\left[\frac{Q_{cool} \cdot \Delta t}{3600} \right] / COP_{cool} \right) \tag{8}$$

where the factor 3600 serves to convert units hr to s.

The annual electricity consumption for heating (E_{heat_yr} in kWh yr^{-1}) is given by:

$$E_{heat\_yr} = \sum_{\Delta t=0}^{\frac{365 \cdot 24}{\Delta t}} \left(\left[\frac{Q_{heat} \cdot \Delta t}{3600} \right] / COP_{heat} \right) \tag{9}$$

Electricity Consumption for DHW Heating

The existing house uses electric resistance water heating whereas the new house employs an electric CO_2 heat pump. The schedule provided by NRCC (National Research Council of Canada) (2015) for DHW supply in new homes was adopted for this study (hot water consumption of 140 L day^{-1}) and given in **Table 4**. Since the existing house does not employ low flow faucets, the DHW consumption schedule was increased by 25% to be in agreement with typical house DWH energy use. The hourly water use (v_{DHW} in L hr^{-1}) was converted to thermal energy consumption (Q_{DHW_hr} in kJ hr^{-1}) using the water mains temperature provided by TRNSYS (T_{mains}). The hourly energy consumption for DHW is calculated by:

$$Q_{DHW} = v_{DHW} \cdot \rho_w \cdot c_{p\_w} \cdot (T_{DWH} - T_{mains})/3600 \tag{10}$$

where

ρ_w is the density of water (kg m^{-3})
c_{p_w} is specific heat of water at constant pressure (kJ kg^{-1} $°C^{-1}$)
T_{DWH} is the DHW supply temperature (°C)

the factor 3600 serves to convert units hr to s.

The COP of the CO_2 heat pump is estimated by the following equation that is a curve fit to the manufacturer's data (Miles et al., 2017):

$$COP_{CO2\_hp} = -4 \cdot 10^{-5} \cdot {T_o}^3 - 0.0005 \cdot {T_o}^2 + 0.077 \cdot T_o + 3.2676 \tag{11}$$

When the outdoor air temperature is below the heat pump's operating range, electric resistance heating is used where the COP equals to one. The annual electricity consumption for DWH heating (E_{DWH_yr} in kWh yr^{-1}) is given by:

$$E_{DWH\_yr} = \sum_{\Delta t=0}^{\frac{365 \cdot 24}{\Delta t}} \left(\left[\frac{Q_{DWH} \cdot \Delta t}{3600} \right] / COP_{CO2\_hp} \right) \tag{12}$$

RESULTS AND DISCUSSION

Model Plausibility Check

Since the level of thermal insulation for the existing house is not precisely known, the model was calibrated by adjusting the envelope thermal insulation level to obtain a best fit between the model calculations and the annual use of typical detached houses given by Hydro-Québec (2020). It was found that reducing the thermal insulation levels to 35% below the Novoclimat values provided good agreement between the simulated and

TABLE 5 | Comparison of typical and simulated detached house energy consumption.

Electricity end use	Fraction for typical	Electricity use (kWh yr^{-1})	
		Typical house	Modeled
Heating	55%	13,200	14,097
Cooling	3%	720	535
DHW	16%	3,840	3,838
Plug loads	26%	6,240	4,088
Total	100%	24,000	22,557

typical measured electricity consumption for heating and cooling (**Table 5**). The selected thermal insulation values were also sufficiently close to those reported by Parekh (2005) using data gathered from various surveys of housing stock in Canada. The simulated electricity consumption for DWH heating (based on the NRCC water draw schedule) was nearly identical to the typical house values. The plug loads (which includes lighting, appliances, electronics, and others) have been purposely reduced for the modeled house to reflect the use of newer devices and equipment that may have been recently upgraded (George, 2016). This allows for fairer comparison between the existing and new house, with the focus on evaluating the impact of thermal energy performance. Overall, the modeled house consumes 6% less energy than the typical house (22,557 vs. 24,000 kWh yr^{-1}). Most of this difference is associated with the decision to reduce plug loads.

Impact of Energy Efficiency Measures

This section aims to quantify the effect of applying efficiency measures on the existing house ("existing retrofitted" scenario). Efficiency upgrades that lower the space and DWH heating will have the highest impact on total energy consumption because together they represent ∼71% of the house's energy needs (Hydro-Québec, 2020). **Table 6** presents the values and percent change of electricity consumption (divided by end use) that can be achieved compared to the typical base case house. Efficiency measures for the plug loads are not considered. The energy efficiency measures were implemented sequentially and the impact on energy consumption for each one is described below:

- The use of a reversible heat pump provided the highest potential for energy savings and decreased heating electricity consumption by 58% and total electricity consumption by 37%. The heat pump did not affect cooling because the AC unit's COP was assumed to be equal to that of the heat pump.
- Improving thermal insulation to Novoclimat standards decreased heating electricity consumption by another 7% (heating electricity use is now 65% below the base case) and increased cooling electricity consumption by 11% above the base case. This caused the total electricity consumption to decrease by another 4% (total electricity use is now 41% below the base case). Therefore, improving the thermal insulation has opposite effects on heating and cooling electricity use, with the savings for heating (994 kWh yr^{-1}) being superior to the increase from cooling (62 kWh yr^{-1}) for this high latitude location.
- Upgrading the windows to double glazed argon filled with low-e coating decreased heating electricity consumption by another 7% (heating electricity use is now 72% below the base case) and reduced cooling electricity use to 5% below the base case (change of 16% compared to the previous case where an increase in cooling was observed). Improving the windows caused the total electricity use to decrease by another 4% (total electricity use is now 45% below the base case).
- The use of reflective movable blinds did not impact heating energy use because they are only activated in the cooling season. They provided another 15% decrease in cooling electricity consumption (cooling electricity use is now 20% below the base case). Since cooling represents a small fraction of total energy use, the impact on total electricity consumption was only a 1% reduction (total electricity use is now 46% below the base case).
- Improving the building airtightness and adding mechanical ventilation with ERV decreased heating electricity consumption by another 7% (heating electricity use is now 79% below the base case), increased cooling electricity consumption by an additional 2% compared to the previous case because more warm outside air needs to be cooled (cooling electricity use is now 18% below the base case) and reduced total electricity consumption by another 4% (total electricity use is now 50% below the base case).
- The use of low flow faucets reduces DHW consumption, leading to a 20% decrease in electricity consumption for DHW heating compared to the base case or another 3% reduction in total electricity use (total electricity use is now 53% below the base case).
- A CO_2 DHW heat pump decreased the electricity consumed for DHW heating by another 56% (electricity use for DWH heating is now 76% below the base case). This caused the total electricity consumption to decrease by another 10% (total electricity use is now 63% below the base case).
- In total, the combined effect of these energy efficiency measures caused the space heating, space cooling, DWH heating and total electricity consumption to decrease by 79, 18, 76, and 63%, respectively.

Thermal Energy Consumption

To evaluate the impact of densification on energy use, a comparison of thermal energy must be performed without considering the type of HVAC equipment used. **Table 7** provides a comparison of the thermal energy consumption of the existing house (with all the above energy efficiency measures applied) and the new houses. The energy consumption was nearly identical (<0.2%) for each of the new houses. Since the basement is smaller for the new houses, the results are also presented for the case where heating energy for the existing basement is reduced by 40% to provide a fairer comparison (approximate adjustment). The new house consumes 10, 46 (adjusted), and 65% less thermal energy for heating that the existing house for the living area, basement and garage, respectively. The heating

TABLE 6 | Impact of sequential implementation of energy efficiency measures on electricity consumption.

Energy efficiency retrofit	Electricity consumption (kWh yr^{-1})				
	Heating	Cooling	DHW	Plug loads	Total
Existing house	14,113	536	3,838	4,088	22,575
Heat pump for space heating/cooling	5,869	536	3,838	4,088	14,331
% change	−58%	0%	0%	0%	−37%
Improve insulation	4,875	598	3,838	4,088	13,399
% change	−65%	11%	0%	0%	−41%
Improve windows	3,890	510	3,838	4,088	12,325
% change	−72%	−5%	0%	0%	−45%
Movable blinds	3,891	428	3,838	4,088	12,245
% change	−72%	−20%	0%	0%	−46%
Improve airtightness and add ERV	2,995	438	3,838	4,088	11,358
% change	−79%	−18%	0%	0%	−50%
Low flow faucets	2,995	438	3,070	4,088	10,591
% change	−79%	−18%	−20%	0%	−53%
Heat pump water heater	2,995	438	915	4,088	8,435
% change	−79%	−18%	−76%	0%	−63%

TABLE 7 | Thermal energy consumption of the retrofitted existing and new houses.

Operation	Thermal zone	Annual thermal energy consumption (kWh yr^{-1})		% change
		Existing retrofitted	Per new house	
Heating	Living area	4,866	4,372	−10%
	Basement	791 (475)*	258	−67% (−46%)
	Garage	1,004	352	−65%
	Total	6,661 (6,345)	4,982	−25% (−21%)
Cooling	Living area	3,485	4,021	15%
Total heating and cooling		10,146 (9,830)	9,003	−11% (−8%)

**Approximate adjustment values considering that the garage heating energy use is reduced by 40% are in parenthesis.*

energy was reduced by ∼21% (adjusted) for the entire house. This reduction occurs due to a combination of effects related to adopting a more compact design (e.g., two stories instead of one, adjacency to attached house, geometry). The living area of the new house required 15% more cooling that the existing house mainly because it has less external surface area and less area in contact with a relatively cooler basement. Overall, the denser new house consumed 8% less thermal energy (adjusted) because the requirements for heating outweighed the increase in cooling for this geographic location.

Electricity Consumption

Table 8 presents the electricity consumption by end use for the existing and new houses. The new house consumed 83% less electricity for heating (from 14,097 to 2,344 kWh yr^{-1}), 7% less electricity for cooling (from 535 to 499 kWh yr^{-1}), and 76% less electricity for DHW heating (from 3,838 to 915 kWh yr^{-1}). The plug loads were assumed to remain the same. Overall, implementing the new double density design reduced electricity consumption by 65% (from 22,557 to 7,846 kWh yr^{-1}).

TABLE 8 | Electricity consumption by end use for the existing and new houses.

End use	Annual electricity consumption (kWh yr^{-1})		
	Existing house	Per new house	% change
Heating	14,097	2,344	−83%
Cooling	535	499	−7%
DHW	3,838	915	−76%
Plug loads	4,088	4,088	0%
Total	22,557	7,846	−65%

Photovoltaic Electricity Generation

Renewable electricity can be produced on-site by integrating a PV system with the building envelope. **Table 9** provides the performance of such a system where PV modules are applied to the south facing roof of the existing house (building applied PV) and new houses (ideally building-integrated PV to replace the need for conventional cladding). Since the existing house has more than double the roof surface area covered by PV (97.7 m^2)

TABLE 9 | Energy performance of the PV system installed on the south facing roof.

Result	Existing house	Existing retrofitted	Per new house
Electricity consumption (kWh yr^{-1})	22,557	8,435	7,846
Roof area covered by PV (m²)	0	97.7	46.1
PV peak power at STC (kW)	-	20.7	9.8
PV electricity generation (kWh yr^{-1})	-	31,232	14,793
Portion of house electricity directly from PV	-	41%	41%
Portion of PV electricity available for on-site storage or export	-	89%	78%

TABLE 10 | Impact of house orientation on PV electricity generation.

House orientation	PV location	Electricity generation (kWh yr^{-1})
Front of house facing south	South facing roof	14,793
	North facing roof	7,218
	Total	22,011
Front of house facing east	East facing roof	11,280
	West facing roof	11,386
	Total	22,666

than each of the new houses (46.1 m^2), it generated significantly more electricity (31,232 kWh yr^{-1}) than each of the new houses (14,793 kWh yr^{-1}). Overall, the two new houses produced ∼6% less electricity (29,586 kWh yr^{-1}) than the existing house (31,232 kWh yr^{-1}). When it is available, the house can directly consume the generated solar electricity instead of obtaining it from the grid. Annually, it was found that 41% of the existing and new house's electricity consumption can be obtained directly from the PV system (no storage). However, during the day, the electricity generation often exceeds the energy requirements of the house. The portion of excess electricity represented 89 and 78% of the total electricity produced by the PV system for the existing retrofitted and new houses, respectively. Therefore, a significant amount of energy produced by energy efficient solar houses would be available for further valorization.

A comparison of PV electricity generation using both roof surfaces and for two orientations (front of the house faces south and east) for one of the new houses is given in **Table 10**. The total electricity generated is similar for both orientations (3% higher for the east facing orientation). When the house faces south, the south facing roof produces more than twice the amount of energy (14,793 kWh yr^{-1}) than the north facing roof (7,218 kWh yr^{-1}). When the house is rotated by 90° counterclockwise, both roof surfaces produce similar quantities of electricity.

TABLE 11 | Impact of house orientation on energy performance.

End use	Annual electricity consumption (kWh yr^{-1})		% change
	Front of house facing south	Front of house facing east	
Heating	2,344	2,541	8%
Cooling	499	623	25%
DHW	915	915	0%
Plug loads	4,088	4,088	0%
Total	7,347	7,755	6%
PV electricity	22,011	22,666	3%
Net electricity use	−14,664	−14,911	2%

TABLE 12 | Comparison of the energy performance at the land lot level.

	Existing house	Two new houses
Number of occupants on land lot (pers)	4	8
Electricity consumption (kWh yr^{-1})	22,557	15,691
PV electricity generation (kWh yr^{-1})	-	44,022
Portion of house electricity directly from PV	-	44%
Portion of PV electricity available for on-site storage or export	-	84%
Net electricity use (kWh yr^{-1})	22,557	−28,331
Net electricity use per occupant (kWh yr^{-1} $pers^{-1}$)	5,639	−3,541

Table 11 presents the impact of house orientation on energy performance of one of the new houses. Rotating the house by 90° counterclockwise caused the heating, cooling, and total electricity consumption to increase by 8, 25, and 6%, respectively. The large increase in cooling is likely a result of the patio door (that does not have movable shades) which now faces east (previously faced north) causing more solar gains. Meanwhile, electricity generation increased by 3%, counterbalancing a portion of the higher electricity demand caused by the different orientation. The net electricity use is similar for both orientations (2% more when the front of the house faces east) and carries a negative value because the houses produced nearly three times more energy than it consumes on an annual basis (also known as self-sufficiency ratio).

Energy Performance Comparison

Table 12 presents a comparison of the overall energy performance for the existing and new houses. The two new houses can accommodate twice the number of occupants (eight instead of four) on the same land lot while transforming the status quo of inefficient houses to high efficiency energy generating houses. The existing house consumed 22,557 kWh yr^{-1} whereas the new houses together consumed 30% less energy (15,691 kWh yr^{-1}). Meanwhile, when both sides of the roof of the new houses are equipped with BIPV, nearly three times more energy is produced than is consumed. Annually, almost half (44%) of the house's electricity can be directly supplied by the BIPV roof and 84% of the generated solar electricity could be available for utilization on-site (e.g., thermal or electrical energy storage) and/or elsewhere (e.g., fed into the grid). The combined effect of adopting a denser energy efficient design with on-site renewable energy production enables occupants to shift from consuming 5,639 kWh yr^{-1} to producing 3,541 kWh yr^{-1}.

Power Demand Comparison

Utilities design their baseload and peaking power plants to satisfy the fluctuating demand for electricity. The demand for power is usually greatest in winter for high latitude locations that employ electrified heating such as in Québec. In Ontario, where natural gas is typically used for heating, the peak power demand occurs in summer when electric cooling loads are highest. Peak power supply typically carries a higher cost for utilities due to the initial cost of electric power transmission infrastructure and peaking power plants, which are also usually greenhouse gas (GHG) emissions intensive as they often burn fossil fuels and with lower efficiencies than baseload power plants. Therefore, efforts to reduce and shift the peak power demand profile of buildings can contribute toward lowering the cost, resource utilization, and GHG emissions of existing and new power plant infrastructure.

Figure 3A illustrates the power demand profile for the existing and two new houses in addition to the PV power production on a cold sunny winter day (weather for February 9 shown in **Figure 3B**). The power demand for the two new houses is similar to the existing house from midnight until noon and was lower afterwards by up to 3 kW. The PV power production quickly exceeds the house's power demand but only for a relatively short period, thereby creating the need for technology capable of rapidly converting a large amount of fluctuating excess power.

Use of Excess Solar Electricity

This study reports the upper limit of solar electricity that can be produced on a house by using both surfaces of the roof. Additional solar electricity can be generated from the well-exposed façade surfaces of the house or less may be produced for instance by installing BIPV only on the south-facing roof. Economic analysis would be required to determine the most cost-effective investment. By covering the entire roof with BIPV, a significant portion (84%) of the annual solar electricity produced by the new houses cannot be directly consumed to satisfy its instantaneous energy demand and would therefore be available for use elsewhere. The main solutions for the valorization of the excess electricity generated by low energy solar houses are presented below:

Energy export:

- Displace fossil fuel energy use: The excess solar electricity can be used to reduce electricity and thermal energy that is produced from fossil fuels (e.g., displace natural gas consumed by a power plant or boiler).
- Power-to-X: Convert excess electricity to hydrogen via electrolysis. The obtained hydrogen can be injected into the natural gas pipeline, used to produce hydrogen that would otherwise typically be derived from natural gas or to power fuel cell electric vehicles (EV). It may also be converted to liquid fuels (power-to-liquids) or other chemicals (power-to-chemicals).
- Battery EV charging: The excess electricity can be used to charge battery EV, possibly at a discounted price during curtailment periods.
- Export energy to the grid when the grid needs it by utilizing the flexibility in the building demand profile, incentivized by dynamic electric pricing (Athienitis et al., 2020).

On-site energy storage and utilization of the flexibility in the building electricity demand profile:

- Building thermal mass and setpoint modification: This can be achieved by pre-heating/cooling the building's thermal mass (e.g., using radiant concrete slab) to reduce the thermal loads that occur when solar electricity is not being generated and applying predictive control (Athienitis et al., 2020).
- Controlled appliance loads: This consist of powering devices during the periods where excess solar electricity exists (e.g., cloths and dish washing machines).
- Power-to-thermal energy: Heat pumps could operate using excess solar electricity to produce heat, cooling or ice that can be stored (e.g., in water storage tanks) for later use.
- Electrical energy storage: Electrical energy can be stored by electrochemical (e.g., battery, hydrogen, supercapacitor) or mechanical (e.g., flywheel) means.
- EV charging/refueling: A personal battery EV may be charged using the house's excess electricity during the day and may be well-suited for teleworking. Eventually, it may also be possible to produce, store, and refuel a hydrogen EV at home. Moreover, the EVs could provide bi-directional energy flow by supplying backup power to the house.

Long term energy storage:

- Seasonal thermal energy storage: A borehole may be charged with solar thermal heat (mainly during the summer) or free-cooled (during the winter) and used as a resilient form of heating in winter or cooling in summer. The Drake Landing Solar Community (DLSC) in Alberta, Canada uses seasonal storage of solar energy to provide at least 90% of the space heating requirements for the 52 houses that its serves (Sibbitt et al., 2012).
- Seasonal electrical energy storage: The excess solar electricity that is generated in the summer season may be stored as compressed air or hydrogen and converted back into electricity in winter.

Challenges and Opportunities

Although the energy analysis of land lot densification was conducted for a single location, it is expected that other locations would yield similar outcomes of lowering building energy consumption, producing renewable energy on-site and lowering the amount of land required by humans. Net zero

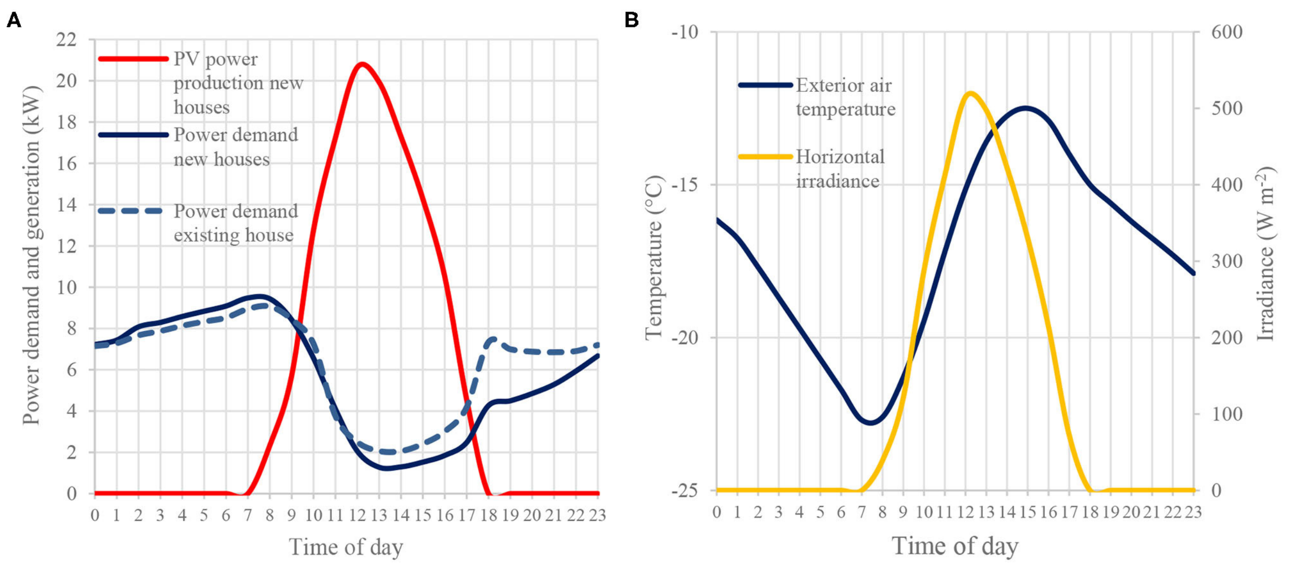

FIGURE 3 | (A) Power demand and solar electricity generation for the existing and two new houses on a cold sunny winter day. **(B)** Exterior air temperature and horizontal irradiance.

energy is more difficult to achieve at higher latitudes (e.g., northern Canada) due to the high heating load compared to solar energy availability whereas positive energy is likely to be possible throughout the U.S.A. Moreover, this study considered only some of the most promising energy efficiency measures and BIPV for on-site generation. A comparison between various options including economic analysis is out of the scope of this paper. For instance, solar water heating could be an alternative to heat pump water heaters. The relative value of the shared roof space for solar thermal and PV mix would need to be assessed for technology selection.

As humans increasingly strive to decouple from polluting sources of energy, it has become apparent that reducing energy consumption through energy efficiency and behavioral changes should be prioritized. This is mainly due to the higher cost, material resource utilization, and pollution associated with renewable energy plus storage solutions. Densified residential rebuilds provides the dual benefit of making more effective use of available land and energy resources. The results of this paper help to quantify potential energy reductions and on-site generation using currently available technologies and could assist governments to develop policy, incentives, and regulations that can expedite this trend. For instance, the zoning laws could be modified to facilitate the conversion of existing homes to densified counterparts, subsidies could help cover the additional cost of the most promising energy efficiency solutions and feed-in-tariffs could improve the economics for installing BIPV.

Utilities will also play an important role in promoting positive energy buildings/districts because they affect the design, operation, and economics of current and future grid infrastructure. For example, large surpluses of solar energy produced from the built environment in the summer could disrupt the economics of existing power plants. A multisector collaborative approach would be useful to effectively transfer excess power and decarbonize elsewhere, such as transportation and industry. Another option includes long term energy storage of summer surplus energy to assist with winter deficits. However, in the short term, this option may only be favorable for remote microgrids such as in Northern Canada due to the high cost of energy storage.

Although redevelopment drastically reduces the consumption of operating and to some extent transportation energy, new construction requires material and human resources that embed significant energy and pollution footprints. Depending on the supplies/materials/equipment selected and countries where they are extracted/processed/manufactured, the time required to recover initial GHG emissions can vary dramatically. For instance, in Québec, building primarily with a low GHG emitting material such as wood and using the excess solar electricity to decarbonize a high GHG emission sector such as transportation would result in a relatively short emissions payback. In contrast, building with carbon intensive materials such as steel or concrete and using the surplus solar electricity to displace relatively clean hydroelectricity would require a much longer period to achieve a payback. Therefore, a life cycle analysis, which considers the environmental impact of the building operation, transportation, and demolition/recycling/construction should be considered when deciding between options. Future work into quantifying the embodied energy and associated pollution of buildings as a function of geographical location would streamline the decision-making process.

CONCLUSION

This paper demonstrated how residential densification can be an effective way to reduce the energy and land required for inhabitants in an urban setting. In this study, the energy performance of a typical aging single family home was compared to a densification scenario where two energy efficient homes of equal living area and equipped with an energy generating BIPV roof are built on the same land lot located in the suburbs of Montreal, Québec, Canada (45.5°N, mid-latitude, 4,457 heating degree-days).

The two new houses can accommodate twice the number of occupants on the same land lot and can transform the status quo of inefficient houses to high efficiency energy generating houses. Of the various energy efficiency measures that were selected, the use of heat pumps for space and water heating achieved the greatest reduction in energy use. When comparing the case where the existing house is retrofitted with the same efficiency measures as the new house, it was found that a denser design decreased the thermal energy required for heating by 21% and increased thermal energy for cooling by 15%, leading to an overall reduction in thermal energy use of ∼8%. Each of the new houses consumed 65% less electricity than the existing house (from 22,560 to 7,850 kWh yr^{-1}) and the two new houses together consumed 30% less energy than its existing counterpart. The BIPV roof produced nearly three times more energy (44,000 kWh yr^{-1}) than consumed by the two new houses (15,700 kWh yr^{-1}). Rotating the houses by 90° counterclockwise was found to have a small impact on the energy consumption (+6%) and generation (+3%). Annually, nearly half (44%) of the house's electricity can be directly supplied by the BIPV roof. A significant portion of the annual solar electricity generation (84%), which cannot be directly utilized by the houses, may be stored on-site to increase self-consumption (e.g., operate heat pumps using excess power to heat/cool/freeze a liquid and store it for later use) and/or used for decarbonization elsewhere (e.g., feed excess electricity into the grid to displace fossil fuel power generation, electrolysis to produce hydrogen fuel for transportation). The peak power demand, which occurs on a cold winter day, was lower for the two new houses than the existing house and could be further reduced by employing power-to-heat plus thermal energy storage strategies together with predictive control. Overall, the combined effect of a denser, energy efficient construction with on-site renewable energy production enables occupants to shift from consuming 5,640 kWh yr^{-1} to producing 3,540 kWh yr^{-1}. The combination of urbanization, a growing population and an aging building stock provides a unique opportunity to retrofit existing communities into positive energy districts. New policy, incentives and regulations regarding the redevelopment of densified net-zero ready homes could be instrumental for this trend to gain momentum.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

AUTHOR CONTRIBUTIONS

JB carried out the work and wrote the paper. UE and AA did proofreading and corrections. All authors contributed to the article and approved the submitted version.

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REFERENCES

Alshehri, F., Beck, S., Ingham, D., Ma, L., and Pourkashanian, M. (2019). Techno-economic analysis of ground and air source heat pumps in hot dry climates. *J. Buil. Eng.* 26:100825. doi: 10.1016/j.jobe.2019.100825

ASHRAE (2019). *Standard 62.2-2019. Ventilation and Acceptable Indoor Air Quality in Residential Buildings*, Atlanta: American National Standards Institute.

Aste, N., Buzzetti, M., Del Pero, C., and Leonforte, F. (2018). Glazing's techno-economic performance: a comparison of window features in office buildings in different climates. *Energy Build.* 159, 123–135. doi: 10.1016/j.enbuild.2017.10.088

Athienitis, A. (1998). *Building Thermal Analysis*. Cambridge, MA: MathSoft Inc.

Athienitis, A. K., Bambara, J., O'Neill, B., and Faille, J. (2011). A prototype photovoltaic/thermal system integrated with transpired collector. *Solar Energy* 85, 139–153. doi: 10.1016/j.solener.2010.10.008

Athienitis, A. K., Dumont, E., Morovat, N., Lavigne, K., and Date, J. (2020). "Development of a dynamic energy flexibility index for buildings and their interaction with smart grids," in *Proceedings of ACEEE Summer Study 2020 Conference on Energy Efficiency in Buildings* (Pacific Grove, CA).

Brown, M. A., and Logan, E. (2008). *The Residential Energy and Carbon Footprints of the 100 Largest US Metropolitan Areas*. Atlanta, GA: Georgia Institute of Technology.

Bucking, S., Athienitis, A., Zmeureanu, R., O'Brien, W., and Doiron, M. (2010). "Design optimization methodology for a near net zero energy demonstration home," in *EuroSun* (Graz).

Capozzoli, A., Mechri, H. E., and Corrado, V. (2009). "Impacts of architectural design choices on building energy performance applications of uncertainty and sensitivity techniques," in *Proceedings of the Eleventh International Building Performance Simulation Association Conference (IBPSA)* (Glasgow).

Crawley, D. B., Hand, J. W., Kummert, M., and Griffith, B. T. (2008). Contrasting the capabilities of building performance simulation programs. *Build. Environ.* 43, 661–673. doi: 10.1016/j.buildenv.2006.10.027

Dobos, A. P. (2014). *PVWatts Version 5 Manual (No. NREL/TP-6A20-62641)*. Golden, CO: National Renewable Energy Laboratory.

DOE (2015). *WINDOW 7.3*. Washington, DC: Department of energy. USA. Available online at: https://windows.lbl.gov/software/window/7/index_7_3_4.html (accessed December 12, 2019).

Ekström, T., and Blomsterberg, Å. (2016). Renovation of Swedish single-family houses to passive house standard–analyses of energy savings potential. *Energy Procedia* 96, 134–145. doi: 10.1016/j.egypro.2016.09.115

Englart, S., and Jedlikowski, A. (2019). The influence of different water efficiency ratings of taps and mixers on energy and water consumption in buildings. *SN Appl. Sci.* 1:525. doi: 10.1007/s42452-019-0539-8

Fantozzi, F., Le Bail, L., Leccese, F., Rocca, M., and Salvadori, G. (2017). General lighting in offices building: techno-economic considerations on the fluorescent tubes replacement with LED tubes. *Int. J. Eng. Technol. Innov.* 7, 143–156.

Gebhart, B. (1961). Surface temperature calculations in radiant surroundings of arbitrary complexity—for gray, diffuse radiation. *Int. J. Heat Mass Transfer* 3, 341–346. doi: 10.1016/0017-9310(61)90048-5

Gebhart, B. (1971). *Heat Transfer, 2nd Edn.* New York, NY: McGraw-Hill.

George, D. (2016). *New profiles of occupancy driven appliance, lighting, plug loads, and hot water use for residential sector energy demand modeling* (master's thesis). Dalhousie University, Halifax, NS, Canada.

Granadeiro, V., Duarte, J. P., Correia, J. R., and Leal, V. M. (2013). Building envelope shape design in early stages of the design process: integrating architectural design systems and energy simulation. *Autom. Constr.* 32, 196–209. doi: 10.1016/j.autcon.2012.12.003

Hachem, C., Athienitis, A., and Fazio, P. (2011). Investigation of solar potential of housing units in different neighborhood designs. *Energy Buil.* 43, 2262–2273. doi: 10.1016/j.enbuild.2011.05.008

Hamdhan, I. N., and Clarke, B. G. (2010). "Determination of thermal conductivity of coarse and fine sand soils," in *Proceedings of World Geothermal Congress* (Bali), 1–7.

Han, Y., Liu, X., and Chang, L. (2014). Comparison of software for building energy simulation. *J. Chem. Pharm. Res.* 6, 467–471.

Heidari, M., and Patel, M. (2020). Stock modelling and cost-effectiveness analysis of energy-efficient household electronic appliances in Switzerland. *Energy Effic.* 13, 571–596. doi: 10.1007/s12053-020-09843-x

Holden, E., and Norland, I. T. (2005). Three challenges for the compact city as a sustainable urban form: household consumption of energy and transport in eight residential areas in the greater Oslo region. *Urban Stud.* 42, 2145–2166. doi: 10.1080/00420980500332064

Hydro-Québec (2020). Available online at: https://www.hydroquebec.com/residential/customer-space/electricity-use/tools/electricity-use.html (accessed March 15, 2020).

International Electrotechnical Commission (IEC) (2011). *Photovoltaic Module Performance Testing and Energy Rating–Part 1: Irradiance and Temperature Performance Measurements and Power Rating IEC 61853-1*. Geneva: International Electrotechnical Commission.

Jinko Solar (2020). *Eagle 78 TR G4 (module JKM475M-7RL3-TV-Q)*. Available online at: https://y19jx2zo8mb2zyqyo1njsh26-wpengine.netdna-ssl.com/wp-content/uploads/2020/07/JKM455-475M-7RL3-V-D2-US.pdf (accessed January 21, 2020).

Klein, S. A., Duffie, J. A., Mitchell, J. C., Kummer, J. P., Thornton, J. W., Bradley, D. E., et al. (2014). *TRNSYS 17. Volume 4. Mathematical Reference*. Madison, WI: Solar Energy Laboratory, University of Wisconsin-Madison.

Kontokosta, C. E. (2012). "Predicting building energy efficiency using New York City benchmarking data," in *Proceedings of the 2012 ACEEE Summer Study on Energy Efficiency in Buildings (American Council for an Energy-Efficient Economy)* (Washington, DC).

Kunwar, N. (2018). *Automated venetian blinds and lighting integrated into office Building Automation Systems: full-scale testing and economic analysis* (master's thesis). Iowa State University, Ames, IA, United States.

Liu, S., Li, Z., Dai, B., Zhong, Z., Li, H., Song, M., et al. (2019). Energetic, economic, and environmental analysis of air source transcritical CO2 heat pump system for residential heating in China. *Appl. Therm. Eng.* 148, 1425–1439. doi: 10.1016/j.applthermaleng.2018.08.061

McAdams, W. H. (1959). *Heat Transmission, 3rd Edn*. New York, NY: McGraw-Hill.

Miles, J., Ito, M., and Hale, D. (2017). *Sanden SANCO$_2$. Heat Pump Water Heater Technical Information*. Plymouth, MI: Sanden International (USA), Inc.

Minetto, S., Cecchinato, L., Brignoli, R., Marinetti, S., and Rossetti, A. (2016). Water-side reversible CO2 heat pump for residential application. *Int. J. Refrig.* 63, 237–250. doi: 10.1016/j.ijrefrig.2015.12.015

Mitalas, G. P., and Arseneault, J. G. (1972). *FORTRAN IV program to calculate z-transfer functions for the calculation of transient heat transfer through walls and roofs*. Ottawa, ON: Division of National Research Council of Canada.

Mitsubishi (2014). *Mitsubishi Electric Corporation. Service Manual. Split-type Air Conditioners. No. OBH684. Revised edition D*. Chiyoda-ku, Mitsubishi Electric Corporation.

Mohajeri, N., Upadhyay, G., Gudmundsson, A., Assouline, D., Kämpf, J., and Scartezzini, J. L. (2016). Effects of urban compactness on solar energy potential. *Ren. Energy* 93, 469–482. doi: 10.1016/j.renene.2016.02.053

Mohamed, M. M. (2020). Optimal thermal insulation thickness in isolated air-conditioned buildings and economic analysis. *J. Electron. Cool. Therm. Control* 9:23. doi: 10.4236/jectc.2020.92002

Natural Resources Canada (2020). *National Energy Use Database*. Available online at: https://oee.nrcan.gc.ca/corporate/statistics/neud/dpa/data_e/databases.cfm (accessed July 11, 2020).

Nemet, G. F. (2009). Net radiative forcing from widespread deployment of photovoltaics. *Environ. Sci. Technol.* 43, 2173–2178. doi: 10.1021/es801747c

Norman, J., MacLean, H. L., and Kennedy, C. A. (2006). Comparing high and low residential density: life-cycle analysis of energy use and greenhouse gas emissions. *J. Urban Plan. Dev.* 132, 10–21. doi: 10.1061/(ASCE)0733-9488(2006)132:1(10)

Novoclimat (2003). *General Technical Requirements*. Quebec: Québec Energy Efficiency Agency.

NRCC (National Research Council of Canada) (2015). *National Building Code of Canada*. Ottawa, ON: National Research Council Canada.

O'Brien, W., Kennedy, C., Athienitis, A., and Kesik, T. (2009). The relationship between personal net energy use and the urban density of solar buildings. *Environ. Plan. B* 37, 1002–1021. doi: 10.1068/b36030

Parekh, A. (2005). "Development of archetypes of building characteristics libraries for simplified energy use evaluation of houses," in *Proceedings of the Ninth International Building Performance Simulation Association Conference (IBPSA)* (Montreal, QC).

Perez, R., Stewart, R., Seals, R., and Guertin, T. (1988). *The Development and Verification of the Perez Diffuse Radiation Model (No. SAND-88-7030)*. Sandia National Labs., Albuquerque, NM; State Univ. of New York, Albany, NY. Atmospheric Sciences Research Center.

Psimopoulos, E., Bee, E., Widén, J., and Bales, C. (2019). Techno-economic analysis of control algorithms for an exhaust air heat pump system for detached houses coupled to a photovoltaic system. *Appl. Energy* 249, 355–367. doi: 10.1016/j.apenergy.2019.04.080

Quan, J. (2016). *Density and energy performance of solar powered buildings in the urban context* (Doctoral dissertation). Georgia Institute of Technology, Atlanta, GA, United States.

RETScreen (2013). *Clean Energy Project Analysis Software. Version 4*. Ottawa, ON: Ministry of Natural Resources.

Sibbitt, B., McClenahan, D., Djebbar, R., Thornton, J., Wong, B., Carriere, J., et al. (2012). The performance of a high solar fraction seasonal storage district heating system–five years of operation. *Energy Procedia* 30, 856–865. doi: 10.1016/j.egypro.2012.11.097

Skoplaki, E., and Palyvos, J. A. (2009). On the temperature dependence of photovoltaic module electrical performance. a review of efficiency/power correlations. *Solar Energy* 83, 614–624. doi: 10.1016/j.solener.2008.10.008

Steemers, K. (2003). Energy and the city: density, buildings, and transport. *Energy Build.* 35, 3–14. doi: 10.1016/S0378-7788(02)00075-0

Stephenson, D. G., and Mitalas, G. P. (1971). "Calculation of heat conduction transfer functions for multi-layer slabs," in *ASHRAE Annual Meeting (August 22–25)* (Washington, DC).

Touloupaki, E., and Theodosiou, T. (2017). Optimization of building form to minimize energy consumption through parametric modelling. *Procedia Environ. Sci.* 38, 509–514. doi: 10.1016/j.proenv.2017.03.114

TRNSYS 17 (2005). *Multizone Building Modeling with Type56 and TRNBuild.* Madison, WI: Solar Energy Laboratory, University of Wisconsin. Available online at: http://sel.me.wisc.edu/trnsys; http://www.trnsys.de (accessed December 12, 2019).

TRNSYS 17 (2014). *Mathematical Reference*. Madison, WI: Solar Energy Laboratory. University of Wisconsin. Available online at: http://sel.me.wisc.edu/trnsys (accessed December 12, 2019).

Veitch, J. A. (2008). "Connecting the building sciences and health sciences in Canada: research gaps,". in *Proceedings of the First Canadian Building and Health Sciences Workshop* (Montreal, QC), 93–105.

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frontiers in Sustainable Cities

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Novel Energy System Design Workflow for Zero-Carbon Energy District Development

*Bahador Samadzadegan†, Soroush Samareh Abolhassani†, Sanam Dabirian, Saeed Ranjbar, Hadise Rasoulian, Azin Sanei and Ursula Eicker**

Canada Excellence Research Chair, Next Generation Cities Institute and Gina Cody School of Engineering and Computer Science, Concordia University, Montréal, QC, Canada

The growing urban population globally leads to higher greenhouse gas (GHG) emissions and stress on the electricity networks for meeting the increasing demand. In the early urban design stages, the optimization of the urban morphology and building physics characteristics can reduce energy demand. Local generation using renewable energy resources is also a viable option to reduce emissions and improve grid reliability. Notwithstanding, energy simulation and environmental impact assessment of urban building design strategies are usually not done until the execution planning stage. To address this research gap, a novel framework for designing energy systems for zero-carbon districts is developed. An urban building energy model is integrated with an urban energy system model in this framework. Dynamic prediction of heating and cooling demand and automatic sizing of different energy system configurations based on the calculated demands are the framework's primary capabilities. The workability of the framework has been tested on a case study for an urban area in Montreal to design and compare two different renewable energy systems comprising photovoltaic panels (PV), air-source, and ground source heat pumps. The case study results show that the urban building energy model could successfully predict the heating and cooling demands in multiple spatiotemporal resolutions, while the urban energy system model provides system solutions for achieving a zero-carbon or positive energy district.

Keywords: urban building energy modeling, urban energy system modeling, PV, heat pump, net zero carbon districts

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Edgar Antonio Barragán,
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Dimitra Papadaki,
National and Kapodistrian University of Athens, Greece

***Correspondence:**
Ursula Eicker
ursula.eicker@concordia.ca

†These authors have contributed equally to this work

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INTRODUCTION

Many cities worldwide have a climate strategy to become carbon neutral by 2050 (Dominković et al., 2016). Currently, 54% of the world's population lives in urban areas, and this figure will rise to 66% by 2050 (Pless and Polly, 2018). Buildings' energy consumption account for about 30% of the world's energy consumption, and 60% of this is due to heating and cooling demand (Lizana et al., 2017). Based on Natural Resources Canada's data, the residential sector accounts for 13% of the end-use consumption in Canada, while this share is 20% in Quebec (Government of Canada, 2020). The successful implementation of net-zero energy buildings has led to applying this concept to a group of buildings and, finally, developing zero-carbon or even ositive energy districts. These zero-carbon or positive energy districts have several advantages, including economies of scale, an opportunity to use waste heat from one building in another, and sharing energy resources (Pless and Polly, 2018).

In the sustainable development of cities toward carbon neutrality, municipalities' role, efficient energy system design, and buildings' energy consumption should be considered (Wiseman, 2018). Municipalities' plans and goals define the scope of changes and enhancements in different sectors. To evaluate different scenarios for municipalities or private developers' decision-making, dynamic energy demand simulation is beneficial to optimally size the urban renewable energy system to achieve a zero-carbon district. Urban Building Energy Modeling (UBEM) is a physics-based approach to analyze and predict a group of buildings' energy consumption considering the indoor and outdoor conditions (Hong et al., 2018). Urban Building Energy Modeling is a novel tool to support and improve sustainable development and energy efficiency measures in districts or cities which considers the thermal load diversity of a group of buildings to design on-site renewable energy systems, estimate CO_2 emission, and predict building energy use (Johari et al., 2020).

An appropriate energy system should be designed and sized to supply those demands after calculating a building or a building cluster's energy demand. Utilizing renewable energy systems is a solution to decarbonize buildings' consumption and reduce the urban ecological footprint. There are several tools under development to ease the process of modeling multiple buildings. City Energy Analyst is a modeling framework to integrate the spatiotemporal analysis of building energy performance, local energy potential assessment, and energy system optimization and analysis in neighborhoods and city districts for urban planning and policymaking (Fonseca et al., 2016). TEASER is a design-driven reduced-order UBEM platform for energy performance analysis on network efficiency and management on different spatial scales (Remmen et al., 2018). Besides, TEASER is integrated with the urban energy systems design to optimize energy systems and networks for both building and urban scales (Ferrando and Causone, 2020).

A reliable and accurate energy system modeling framework can help compare different technical and environmental indicators of the proposed energy system alternatives. Due to the uncertainties, modeling renewable urban energy systems, whether in a standalone configuration or hybrid mode, is a more complex procedure than conventional energy systems. According to Yazdanie and Orehounig (2021), many studies in urban energy system modeling (UESM) suffer from the lack of detailed input data. Therefore, there is a need for a comprehensive and detailed UBEM to provide load input data for UESM. Many detailed UBEM software such as UMI and City Energy Analyst are developed and available, but they do not contain comprehensive UESM, nor are they explicitly designed for such purpose (Fonseca et al., 2016; Reinhart and Cerezo Davila, 2016).

Numerous studies are focusing on integrating different energy sources, including renewable energies, into energy system design. To name a few, Petkov and Gabrielli (2020) developed a framework to design, select, and size a low carbon Multi-Energy System. Their objective was to minimize the annual costs and emissions. They showed that emissions could decrease by 90% if a renewable energy system with short-term storage is used. The same objective functions were used by Tabar et al. (2021) to use waste heat recovery, power to gas, and carbon capture technologies in an energy system framework. In simulation models, the aim is to predict the energy system's performance, such as TRNSYS (Li et al., 2015; Soutullo et al., 2016). Yuan et al. used TRNSYS to design and assess a distributed energy system serving a University campus (Yuan et al., 2020). The proposed system consisted of an internal combustion engine, absorption chiller, thermal energy storage unit, heat pump (HP), and boiler. They realized that integrating thermal storage and distributed energy system leads to higher primary energy efficiency.

Furthermore, Hsieh et al. used quasi-steady state simulation models to study short-term and long-term TES integration with solar collectors in different scales from single buildings to neighborhoods (Hsieh et al., 2017). They reported that using decentral short-term and long-term storage for each building has the best performance, with 48% of the energy being covered by solar energy. Dominković et al. (2016) investigated a methodology in the transition to carbon-free and 100% renewable energy in South-Eastern Europe. Their results show that a single renewable energy source typically has no more than 30% share in an energy system. Usually, a variety of technologies is needed to supply the demand. Pilpola et al. developed a techno-economic model at the national and city-level scale to investigate the possibility of using different renewable energy systems to achieve low and zero-carbon goals in Finland and specifically the town of Helsinki (Pilpola et al., 2019). After coupling multiple technologies, each scenario's cost efficiency is discussed and considered as a variable to compare the proposed scenario's overall efficiency.

Also, there are studies trying to point out the required framework and features of a suitable workflow. Eicker et al. discussed the required concepts of an urban energy modeling platform to model the energy demand and intricate urban renewable energy systems design (Eicker et al., 2020b). The platform will include models of buildings, transportation, energy and distribution systems, food, and water infrastructure to compare different energy system operation scenarios. In another study, Weiler et al. proposed an automated method to calculate central energy generation and supply scenarios using the simulated heating demand based on a CityGML-based model (Weiler et al., 2019). Although several UBEM models have been proposed, they are mostly still in prototype status, and a reliable urban energy simulation model is still a challenge.

For the current study, the role of energy system design and UBEM in the transition to energy-efficient districts are studied. This paper aims to investigate the challenges of a developed integrated UBEM and energy system design workflow. A novel automated framework combining a Python-based UBEM model with a renewable energy system model is developed to calculate and predict new or existing districts' energy demand and then design a renewable energy system. In this work, photovoltaic panels (PV) have been coupled with ground source and air source HPs for covering the heating and cooling demands for a district.

This work uses a detailed UBEM workflow based on 3D urban geometry with different energy-related data from various sources with different formats to calculate the heating and cooling demand. The developed UBEM is highly flexible in providing relevant input data for energy system sizing in any spatiotemporal scale from a thermal zone to a district and hourly to annual results. This allows combining the building demand modeling with international database sources on construction or occupancy, which is often a limitation in urban modeling tools. Furthermore, designing energy systems with considering component-level details has added a higher value to the proposed UESM's flexibility as well as accuracy. Introducing a sufficiently detailed and comprehensive model as a substitute to the high-level energy system design in an urban context increased modeling resolution by capturing the impact of components' performance on other components and the system's efficiency. In addition to the detailed design of a PV system, HPs have been modeled with varying coefficients of performance (COP) to cover the gaps in many previous studies (Rinne and Syri, 2013; Lund et al., 2016), that have considered a fixed monthly or annual value COPs.

METHODOLOGY

The following sections describe the integrated workflow of the UBEM and UESM. **Figure 1** illustrates an overview of the methodology used in this paper.

From Architectural Design to Urban Building Energy Demand Simulation

The importance of a correct pre-design process for a successful design at the building or city scale is undeniable. Overviewing the site's limitations and the client requests cannot be executed without a feasibility study. The feasibility study shows what is possible for the project based on the site, existing conditions, zoning, building codes, local regulations, and other legal restrictions (Green, 2018). The site and climate analysis are also part of the pre-design process. These analyses focus on potentials and conditions around the site (Spreiregen and Beatriz, 2007). The site analysis aims to provide external information about the site, limitations, and assets and connect them to the design's internal needs (Halil et al., 2016). Looking at the neighborhood context, vegetation, climate, historical factors, and many others is part of this process. Spatial design or building massing helps to make a better connection between the site and future buildings. Early-stage building shadow studies, wind flow or radiation analysis, and any other analysis related to urban comfort and façade control, can be executed in this stage. Then the process continues reaching the building design. In this stage, the building's location, orientation, and massing form are defined, so the project reaches to more detailed design like adding façade detail, form detail, or shading properties.

A novel, highly flexible, and dynamic python-based UBEM workflow is developed in the current study. The proposed model can cover all aspects of the building energy modeling in detail and dynamically change all input parameters based on building use-type. Due to the massive amount of input parameters in UBEM models, high computational cost, and considerable uncertainty involved in simulation, it remains a challenge to have a practical and accurate UBEM model. The energy system sizing is highly dependent on building energy demand results and energy demand changes based on building use-type. Thus, all input parameters of the developed UBEM model change based on building use-type to increase the model's accuracy by using more relevant input parameters for each building use-type.

Simulating the urban building energy system requires coupling with an accurate UBEM (Hong et al., 2018). The urban energy system sizing, especially PV system sizing, is highly dependent on the building's roof shape and area (Mohajeri et al., 2018). Most previous studies simplified the building geometry for energy demand calculation which can cause high uncertainty in their building energy demand and energy system sizing calculation (Strzalka et al., 2011). The roof shape and area from the architectural design step are used for energy system sizing

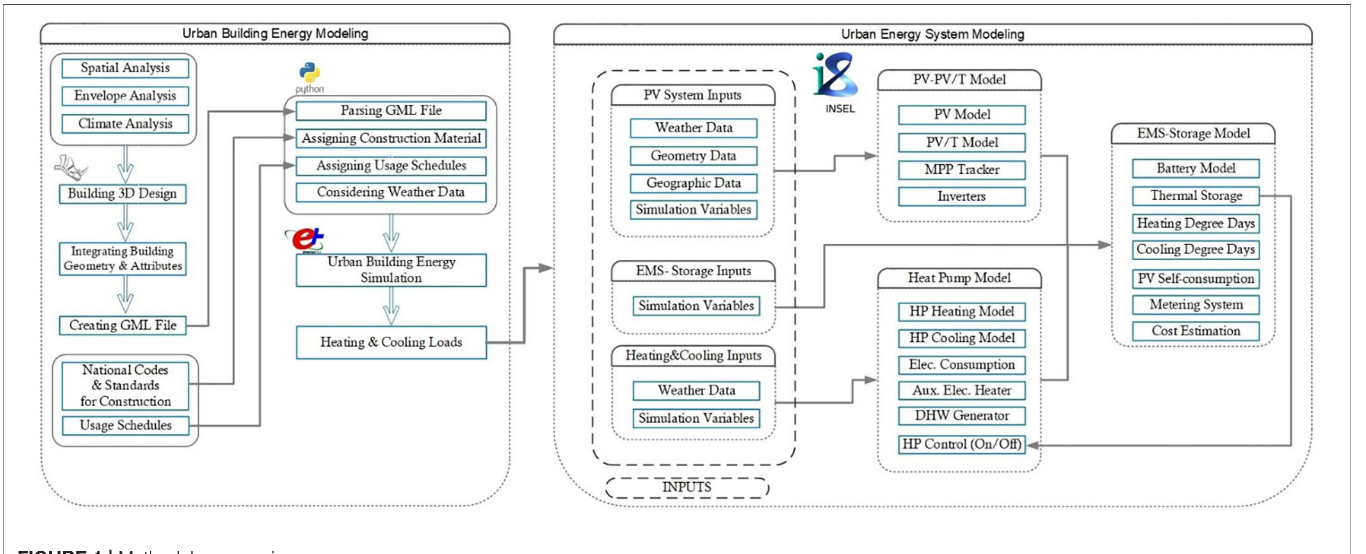

FIGURE 1 | Methodology overview.

in the current study. It is necessary to use the same roof shape in urban building energy demand and energy system sizing calculation to have a compatible and accurate model. In the developed UBEM, buildings and mostly the roofs are modeled in detail and close to reality. The main advantage and contribution of the proposed UBEM model is its compatibility with the energy system sizing. Many downsides of energy system sizing in the previous studies are studied and rectified through the proposed UBEM model.

City Geographic Markup Language (CityGML) (Gröger et al., 2012) was used as an open data model similar to an XML format suitable for storing the geospatial information of the 3D buildings. The CityGML files are parsed, and building coordinates and attributes are extracted using a python code, and the building objects are stored in a python dictionary hierarchically based on the following order:

a) Building ID
b) Building use-type
c) Building coordinates (x,y,z).

Using hierarchical building characteristics in the python dictionary makes it possible to add all the other building information based on the surface type and building use-type. In the next step, the high performance building materials and constructions (standard 189.1-2009) are extracted based on the building use-type from the National Renewable Energy Laboratory (NREL) (NREL, 2018; Building Component Library 2021) and stored in a JSON format called JCM. The JCM file is parsed and embedded in a python dictionary called building construction archetypes (BCA). Each polygon in the building coordinate's part is categorized into the wall surface, roof surface, and ground surface and are stored as a subcategory of building 3D coordinates (**Figure 2**). The construction and material archetypes are assigned to each surface based on its type (roof, ground, or wall) and related building use-type. Consequently, each surface can be added to the building energy simulation software with its construction and material features automatically using python code.

EnergyPlus is used as the building energy simulation program to simulate the energy demand considering the effect of the built environment, the interaction between buildings, and internal gains (Chowdhury et al., 2016; Rao et al., 2018). By iterating through the building characteristics dictionary (BCD), the first item (building IDs) is used for defining building zones. In the next step, the building surface information should be added to EnergyPlus. Hence, the surface coordinates are the successive objects that should be added to EnergyPlus. The coordinates of each building surface are mapped, and the coordinates' connection leads to the creation of the 3D model of buildings and, subsequently, the 3D urban building model in EnergyPlus. Next, the construction and material are assigned to each surface. As each surface is connected to a building use-type in the BCD, a python code is written to search for each surface based on the building use-type related to the surface type in BCD. The information is extracted from the JCM based on surface building-related use-type and surface type obtained from the BCD search in the last step. Finally, each surface construction archetype obtained from the NREL JSON search is assigned to each surface and are added to EnergyPlus.

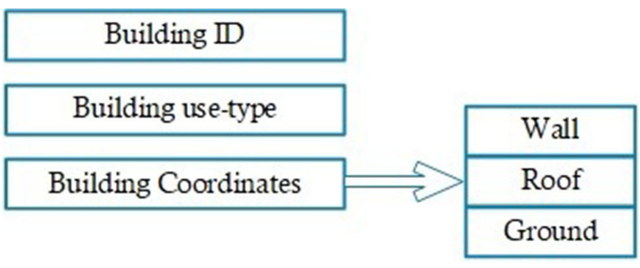

FIGURE 2 | The building characteristics dictionary (BCD).

The urban buildings' geometry enriched with materials and construction features is only part of the urban building energy analysis and energy system sizing. To improve the accuracy of the urban building energy demand calculation, building usage schedules need to be considered as follows:

1) Occupancy schedule
2) Lighting schedule
3) Electrical equipment schedule
4) Ventilation schedule.

These schedules significantly affect energy demand and, consequently, on energy system sizing (Happle et al., 2018); however, most of the time, a fixed schedule for different building use-types is used, which increases the uncertainty of the urban energy demand calculation. Hence, it is necessary to define the schedules based on the building use-type. Usage schedules (e.g., occupancy parameters, lighting, electrical equipment, and ventilation) have been created by the Department of Energy (DOE). They are available for 16 different building use-types on the DOE website (US DOE, 2013). All schedules are extracted from the EnergyPlus IDF files provided on the DOE website for four different building use-types, including large office, secondary school, small office, and midrise apartment.

In this work, a district case study in Montreal, Canada, has been chosen. These Lachine district case study's building use-types are civic center, school, commercial, residential, and office, which are not the same as the DOE building use-types. Therefore, the chosen building use-types for extracting the DOE website schedules are based on their similarities to the real building use-types in the Lachine district. After extracting the schedules, each schedule of occupancy, lighting, electrical equipment, and ventilation is automatically assigned to each building in the district based on the building use-types. All schedules are fed into EnergyPlus along with the 3D urban model and construction archetypes to calculate the heating and cooling demand in the last step. All the other settings of EnergyPlus for the UBEM model are shown in **Table 1**. Occupancy, electrical equipment, lighting, and ventilation are set through comparison with other studies (Kim et al., 2013; Signelković et al., 2016; Sarfraz et al., 2018). The simulated heating and cooling demand are input to the UESM model.

TABLE 1 | EnergyPlus setting parameters for UBEM.

Parameters	Settings	
Window to wall ratio	0.35	
Constant heating set point	22 °C	
Constant cooling set point	25 °C	
HVAC templates	Ideal loads air system	
Solar distribution	Full interior and exterior	
Shading calculation	**Calculation method**	**Average over days in frequency**
	Calculation frequency	Every 20 days
	Maximum figures in shadow overlap calculations	15,000
	Polygon clipping algorithm	SutherlandHodgman
	Sky diffuse modeling algorithm	Simple sky diffuse modeling
	External shading calculation method	Internal calculation
Surface convection algorithm: inside	TARP	
Surface convection algorithm: outside	DOE-2	
Heat balance algorithm	Conduction transfer function	
Sizing period: design day	Winter design day	
	Summer design day	
Solar model indicator	ASHRAE clear sky	
Occupancy	**Number of the people calculation method**	**People/Area**
	People per zone floor area	0.05 people/m^2
Lighting	**Design level calculation method**	**Watts/Area**
	Watts per zone floor area	10 W/m^2
Equipment	**Design level calculation method**	**Watts/Area**
	Watts per zone floor area	6.5 W/m^2
Ventilation	**Design flow rate calculation method**	**Residential: Flow/ExteriorArea and Commercial: Flow/ExteriorWall Area**
	Flow per exterior surface area	Residential: 0.0002 m^3/s-m^2
		Commercial: 0.0005 m^3/s-m^2
HVAC	**Outdoor air method**	**Flow/Area**
	Outdoor airflow rate per zone floor area	0.00043 m^3/s-m^2

UESM

Designing energy systems is of great importance for achieving higher efficiency for a single building, let alone a district or an urban area. Accurate demand forecasting and calculation should be accompanied by an appropriately sized, designed, and installed energy system to have a complete cycle of a sustainable and energy-efficient project. The proposed energy system analysis includes renewable energy sources to reduce carbon and greenhouse gas (GHG) emissions, embodied carbon, and fossil fuel usages. The positive energy concept goes further in utilizing more renewable resources than is consumed while minimizing demand and energy losses and maximizing energy efficiency.

Urban energy system modeling is a block-based simulation model using INSEL 8.2. (Integrated Simulation Environment Language), which comprises many models programmed as independent modular such as meteorological models, PV systems, HPs, battery and thermal storage, controllers, auxiliary electrical heaters, and more. In this study, the general workflow of UESM will be discussed as well as PV, HP, metering, and auxiliary electrical heater sections. Eventually, the results of a case study will be provided and discussed.

UESM Platform and Workflow

Integrated Simulation Environment Language (INSEL) is a graphical programming language using blocks with a focus on renewable energy systems. Its usage domain includes but is not limited to building modeling and meteorology. The graphical environment made it easy for users with limited coding experience to implement their ideas using pre-existing blocks to create system models or even prepare their own user blocks. User-defined blocks can be written in different languages, including Fortran and C, and in the next software versions Python, which adds flexibility to the INSEL block concept (Weiler et al., 2019; Eicker et al., 2020a). Moreover, INSEL comes with a comprehensive library for a few energy system components such as PV panels and inverters, which saves the time required for gathering data from manufacturers.

The UESM workflow starts with acquiring hourly demand (heating, cooling, hot water, and plug load) from the UBEM section as input and calculating solar energy parameters, PV panels potential, HP performance, HP energy output, and energy metering. The high-level connection between different sections is illustrated in **Figure 3**. Internal connections and links between

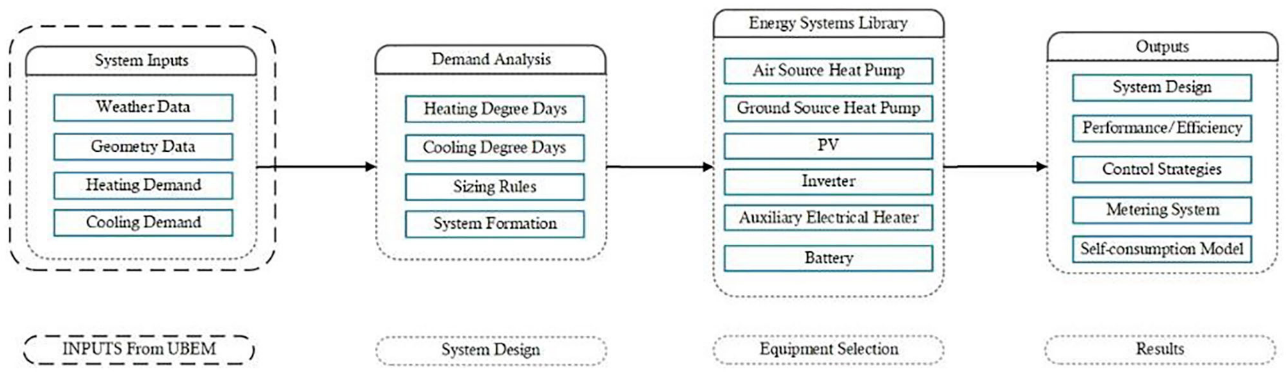

FIGURE 3 | Modified UESM flow diagram showing categories of inputs, demand analysis, energy systems, and outputs.

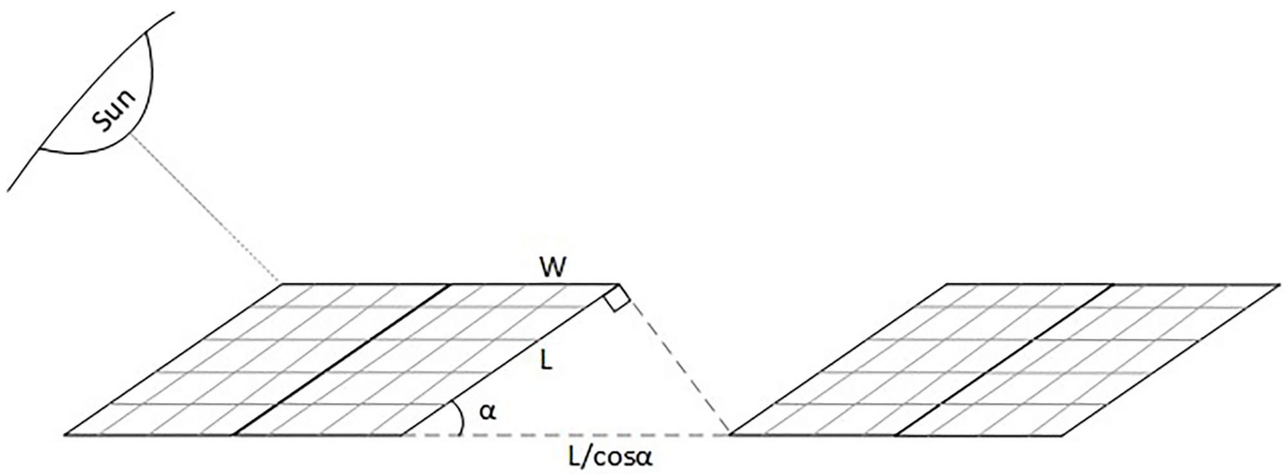

FIGURE 4 | Illustrating the gap between PV rows for minimizing shadows on panels.

models and blocks are not shown for the clearance of the general concept.

PV Systems

By taking the roof surface area information from UBEM, the PV system model can automatically select the PV placement (by width or length) to maximize the PV generation based on the panel dimensions available in the INSEL PV library. To do so, a rectangular surface (a portion of the roof available for PV panels, which we assumed as 65% of the total area) with a given length and width is considered. PV panels will be placed by both the short and long sides, and the formation with the highest number of PV panels will be selected. The gap between PV rows is determined with the highest strictness to minimize PVs' shadowing effect (**Figure 4**).

The PV block simulates the selected PV panel's hourly current-voltage curve using a module-specific parameter set from the INSEL library, with meteorological data inputs, including temperature, global radiation, wind speed, and the user inputs like tilt angle and azimuth for each project. It is worth mentioning that a maximum power point tracker block is integrated into the system to get maximum power at each time step. A selected inverter (appropriately sized for the project) converts the PV-generated DC power to AC and provides the PV system output to the energy metering section of UESM. The characteristics of the used PV panel and PV system design parameters are shown in **Table 2**. The remaining parameters will be determined in each time step and will be fed to the PV block.

HP System

Electrification of heating systems using HPs and electric boilers has been suggested in recent years to reduce GHG emissions of the heating sector (Thomaßen et al., 2021). Integrating HPs with PV or PV/T panels could enhance renewable energy utilization in urban areas. Aguilar et al. conducted a techno-economic assessment of a PV-HP system supplying an office building's heat demand in Spain (Aguilar et al., 2019). This system reduced the primary non-renewable energy consumption and CO_2 emissions by 74%.

TABLE 2 | Selected PV panel and PV system design parameters for the Montreal case study.

Tilt angle (degrees)	31
Azimuth angle	180
Ground reflectance	0.2
Latitude	45.5
Longitude	73.62
Nominal power (W)	300
MPP voltage (V)	53.76
MPP current (A)	5.54
Efficiency (%)	17.24
Width (mm)	1,072
Height (mm)	1,623

Heat pumps are included in many projects aiming for energy efficiency and decarbonizing due to their high COP, the capability of integrating into heat recovery systems (process heat or waste heat), their flexibility in using different energy sources, including renewables, and the availability in varying capacities and features. The COP is a unitless HP performance indicator. The COP is highly dependent on different parameters. It cannot be referred to as the best and only equipment selection criteria. The COP is determined by dividing useful energy generated (transferred) by the HP's electricity consumption and varies mainly due to source and sink temperatures, resulting in different values in different working conditions.

Researchers have made numerous attempts to determine a correlation between each project's unique properties (heat sink and source temperatures, demand values) and HP's performance to reach an acceptable range of matching results between simulation and real-world experimental data (HPTCJ, 2010; Arpagaus et al., 2018; Jesper et al., 2021). The availability of various technologies and different technical specifications and details for HPs does not allow for a single parameter set to model all HPs.

In the current study, a previously implemented procedure (Weiler et al., 2019) has been used as an accurate HP system model in different conditions. This model uses HP manufacturers' published performance data and interpolation to specify a correlation between COP, HP's heat output, and electricity consumption in different conditions, including additional heat source and heat sink temperatures and heat demand levels. It is worth mentioning that the third parameter can be derived easily in the presence of the two parameters mentioned above. Moreover, instead of COP, which is only accurate in a single condition, seasonal COP (SCOP) has been used, which can be calculated as follows where Q and E are HP heat output (kWh) and electricity consumption (kWh) and E, and H subscripts relate to the heating and cooling cycles.

$$SCOP_H = \frac{\sum_{i=1} Q_H}{\sum_{i=1} E_H} \tag{1}$$

$$SCOP_C = \frac{\sum_{i=1} Q_C}{\sum_{i=1} E_C} \tag{2}$$

Low-temperature heating is crucial for lowering energy loss and improving systems energy and exergy efficiencies. Heating supply temperatures as low as 30 and 35°C are shown to be feasible for surface heating and fan coil systems (Hesaraki et al., 2015). Furthermore, many studies have shown that a supply temperature of 40°C is sufficient for meeting the domestic hot water demand. At the same time, the risk of Legionella can be eliminated via supplementary heating or point of use heating (Lund et al., 2014; Lee, 2018). By reviewing literature regarding the low-temperature heating concept, supply temperatures of 40 and 11–12°C are selected for heating and cooling, respectively (Nordman et al., 2012; Huang et al., 2019).

In each time step, the HP model will take heating and cooling demand (kW) from the input file provided by UBEM. With respect to the outdoor temperature, the model interpolates values for HP's electricity consumption, its COP, and the HP output energy. Then the model divides demand by HP output and rounds the quotient up to the closest integer to obtain the number HPs required to meet the demand in each time step. The HP system's electricity consumption will be scaled up accordingly. Besides, electricity balance, PV self-consumption, energy exported and imported from the grid, and SCOPs are calculated in each iteration. The highest value will be reported as the number of HPs required in heating and cooling cycles.

APPLICATION OF THE WORKFLOW TO A CASE STUDY

As the second-largest municipality in Canada, Montreal has provided an action plan that includes goals, challenges, and requirements needed to become more sustainable. In the pathway toward sustainability and carbon mitigation goals, the city has three main sustainable development challenges, which are (Montr, 2020):

- Reduction of GHG emissions by 80% (3,003-kilo tons of CO_2 equivalents) by the year 2050 compared to the year 1990 baseline.
- Enhancing access to services and facilities among different city neighborhoods and the ethical distribution of resources for every dwelling.
- To become an exemplary model for other cities by integrating sustainability plans into all aspects of the city.

The developed workflow was applied to a district development called Dominion Bridge in Montreal's Lachine East borough. Lachine-East is a former industrial hub bordered by the Lachine Canal on its southern part, 6th Avenue to the west, Victoria Street to the north, and the east's Canadian Pacific Railway line. This project's area is 63.8 hectares and includes two heritage buildings that are going to be preserved.

Location is one of the main factors in this project, considered in all design stages. The urban plan should respect the site's identity as the former Dominion Bridge steel bridge company represents Canadian industry's golden age. On the other hand, since an urban farm will be located on the south of the site, the entire building roof area can be considered for PV panels installation, as the green spaces requirements of the municipally are already met. The 3D building geometry of the case study is generated in the Rhinoceros 3D software with a total floor area of 277,000 sqm. The model consists of six building blocks with different heights and floor areas. **Table 3** indicates the buildings' geometrical characteristics. **Figure 5** shows the location of each building in the area and the generated 3D model of the buildings.

The buildings are mixed-use with residential, commercial, civic center, and school use-types. In this massing model, 90% of the total area is considered for residential buildings and 10% for the rest of the buildings. The offices and retails are considered on the buildings' ground floor to make this design respond to eco-district policies. The area of the office and retails are around 9,500 sqm.

New zoning is proposed for the Lachine-Est area in which buildings with distinct shapes, sizes, and orientations and, therefore, different demand profiles are designed. Moreover, two options are considered for the energy systems: air source heat pump (ASHP) and ground source heat pump (GSHP). As a renewable source, an identical PV system, including a maximum power point tracker and inverter, will provide electricity in both cases. For each building, two energy systems will be selected separately regarding its demand profile to understand better and compare GSHP and ASHP performances.

The construction and architectural features and other thermal properties are assigned based on the building use-type. The definition of the building use-types in this model is not precisely the same as DOE building use-types. Therefore, the closest similarities between the DOE building use-types and real building use-types in the Lachine district are shown in **Table 4**.

RESULTS AND DISCUSSION

The developed UBEM model was used to simulate the energy consumption of the Lachine East project based on the assumptions listed in **Table 1**. The monthly heating and cooling demand were estimated at the building and district levels. The specific energy demand is shown in **Figure 6**. According to **Figure 6A**, the different cooling and heating demand for each building is influenced by the surface area to volume ratio of buildings, which changes solar gain and ventilation. The solar gain through the glazing and wall surface and ventilation have a different effect on building energy demand. Increasing the solar gain increases the cooling demand while increasing the ventilation can prevent heat trapped in the buildings and

TABLE 3 | Case study buildings' geometrical characteristics.

Building ID	Floor area (sqm)	No. of floors	Total floor area	Total surface area
Building A	13,637	9	122,737	25,673
Building B	5,174	6	31,044	7,434
Building C	5,469	9	49,224	12,033
Building D	7,882	6	47,292	7,266
Building E	5,890	2	11,782	2,702
Building F	1,690	9	15,210	5,166

TABLE 4 | Matching building use-types in DOE with the case study buildings' use-types.

Lachine building use types	DOE building use-types
Civic center	Large office
School	Secondary school
Commercial	Large office
Residential	Midrise apartment
Office	Small office

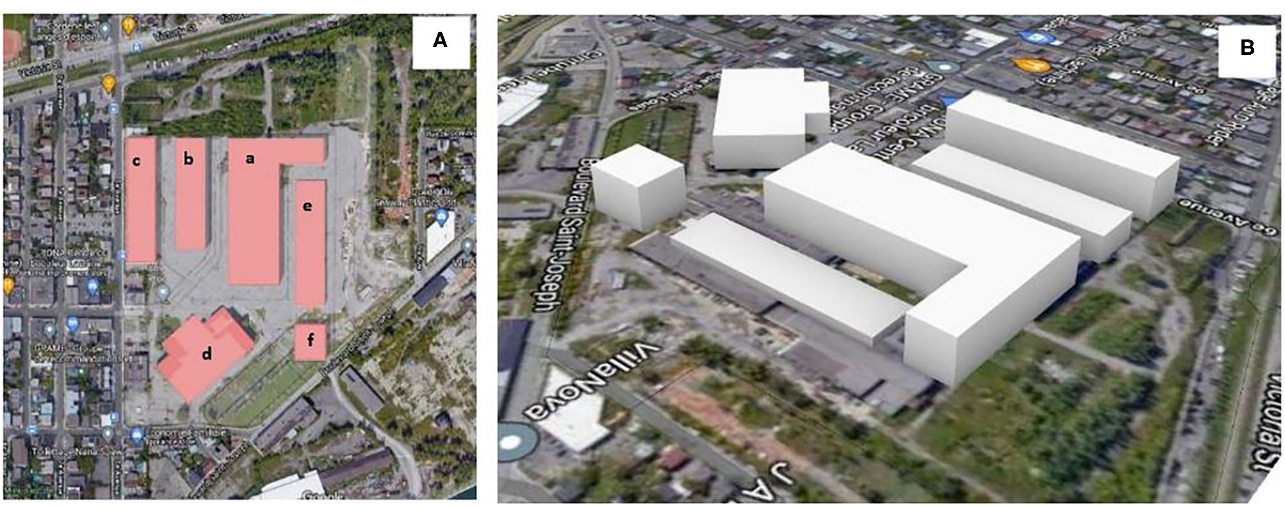

FIGURE 5 | (A) Master plan of the Lachine East project. **(B)** 3D model of the case study.

consequently decrease the cooling demand. **Figure 6A** shows that building A has the highest specific cooling demand. **Figure 6B** indicates that the building D and F have the highest specific heating demand, respectively.

Figure 7 shows the simulated monthly cooling and heating demand of the buildings. The figure reveals that the cooling load peak is mainly in July, while the heating load peak is between December and January. Building C and D's heating load, and building B, E, and F follow a similar trend, with a slight difference. Building A shows the highest monthly cooling and heating load in a whole year.

The annual district heating and cooling demands are 20 and 7 GWh, respectively. The district's predicted heating and cooling loads are used to calculate the energy system performance using UESM.

Urban energy system modeling results for both energy system scenarios are summarized in **Table 5**. As mentioned before, energy systems are selected to be compatible with low-temperature heating systems with high efficiency. In each scenario, two types of HPs (ASHP and GSHP) were considered to provide heating and cooling demands. Heat pump sizes were selected regarding two criteria, SCOPs and demand, and to have a reasonable comparison between two HP types, a 70-ton (245 kW) HP model is selected for each HP type. Heat pumps are modeled using thorough performance documentation provided by manufacturers (Trane, 2015; Maritime Geothermal, 2018). Performance data of the chosen ASHP and GSHPs are shown in **Tables 6**, **7**. This data is used to simulate the HP performance in each time step and condition precisely.

In the present study, due to the sizeable conditioned floor area of the buildings and limited space for PV panels as the only local renewable power generation system, not reaching energy positivity is a foreseeable outcome. The UESM result backed the claim above that low roof area to total floor area ratio plays a vital role in getting closer to energy-positive districts. **Figure 8** shows that except for Building E, which has the smallest total floor area among all buildings, the AC electricity generated by PV is insufficient for covering HP's electricity demand. The higher the floor number in a building, the smaller the relative contribution of roof PV generation to the buildings' energy consumption.

For the HP system, in most time steps the number of operating HPs, consequently, the HPs heat generated is greater than the demand values, as it was designed for maximum load conditions. Thus, the system is not optimized regarding cost or energy efficiency on the system level, as the paper's focus is on introducing an automatized simulation workflow merely.

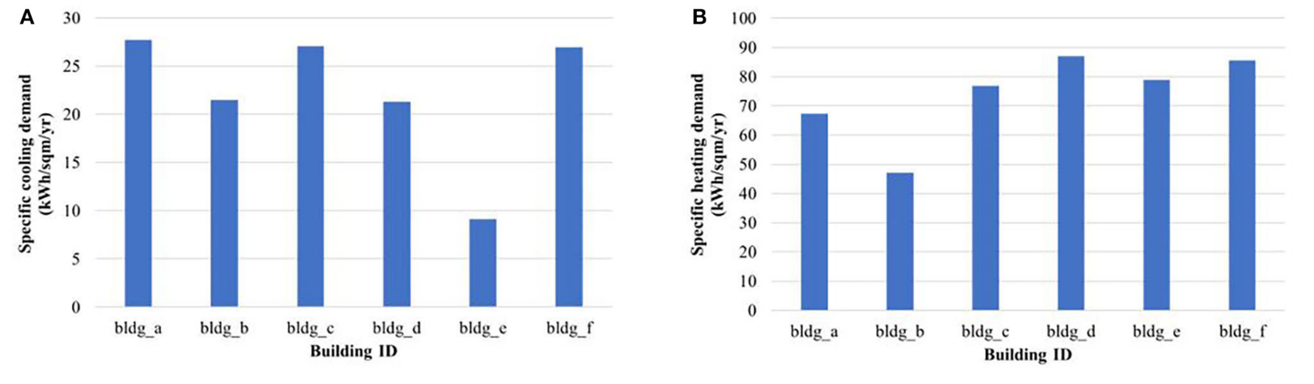

FIGURE 6 | (A) Specific cooling demand (kWh/sqm/year). **(B)** Specific heating demand (kWh/sqm/year).

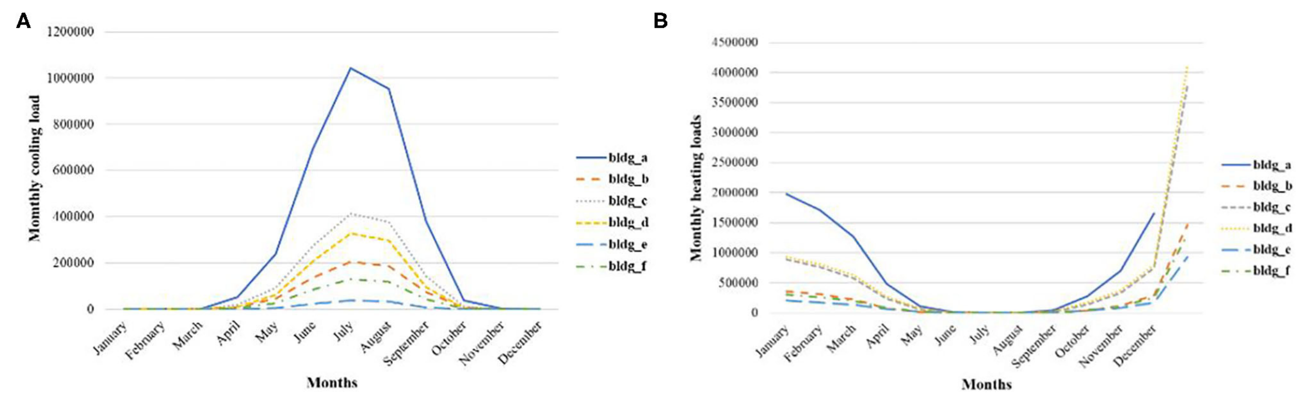

FIGURE 7 | (A) Monthly cooling loads (kWh). **(B)** Monthly heating loads (kWh).

TABLE 5 | UESM results summary.

6 Large scale buildings	Building A		Building B		Building C		Building D		Building E		Building F	
HP type	**GS**	**AS**	**GS**	**AS**	**GS**	**AS**	**GS**	**AS**	**GS**	**AS**	**GS**	**AS**
Heating SCOP	3.28	3.12	3.28	3.13	3.32	3.21	3.30	3.15	3.40	3.39	3.43	3.44
Cooling SCOP	5.63	5.05	5.66	5.04	5.64	5.05	5.63	5.05	5.59	5.05	5.68	5.05
Elec. demand (kWh/yr)	3,452	3,783	780	899	1,711	1,903	1,686	1,867	542	637	803	931
PV generation (MWh/yr)	1,836		673		724		899		752		205	
PV self-consumption ratio	0.50	0.53	0.38	0.42	0.60	0.63	0.48	0.51	0.26	0.30	0.83	0.88
Number of panels	4,347		1,593		1,716		2,130		1,782		486	
Number of HPs (heating)	30	25	6	5	14	11	14	12	3	3	5	4
Number of HPs (cooling)	20	16	5	4	9	7	8	6	2	2	3	3
Cooling temp (C)	12	11	12	11	12	11	12	11	12	11	12	11
Heating temp (C)	40	40	40	40	40	40	40	40	40	40	40	40
PV gen./elec. demand	0.53	0.49	0.86	0.75	0.42	0.38	0.53	0.48	1.39	1.18	0.26	0.22

Air source and ground source HPs, energy metering, and PV system output for each building.

TABLE 6 | W900 GSHP heating performance (Maritime Geothermal, 2018).

Supply temp (°C)	Source temp (borehole) (°C)	Electrical consumption (kW)	COP
40	−3.9	56.63	3.04
40	−1.1	57.28	3.36
40	1.7	57.98	3.66
40	4.4	58.64	3.95
40	7.2	59.14	4.22
40	10	59.47	4.51
40	12.8	60.18	4.74
40	15.6	59.95	5.03

TABLE 7 | CMAA 070 ASHP heating performance (Trane, 2015).

Supply temp (°C)	Source temp (outdoor air) (°C)	Electrical consumption (kW)	COP
40	−30	100.2	2.00
40	−25	97.4	2.05
40	−5	70.2	3.01
40	0	70.1	3.43
40	7	69.9	4.09
40	10	69.8	4.42
40	15	69.8	5.01
40	25	69	4.64

Although the result of case studies are not necessarily comparable or interchangeably usable for result validation, the study by Xu et al. (2020), due to the similarity of context, is interesting. They studied a 108-ton air source HP system in China's severe cold region (similar weather to Montreal) with a supply temperature of 36°C. They calculated HP's COP and electricity demand to be 3.2 and 10.65 kWh/m^{2}yr, respectively, compared to 3.24 and 22.12 kWh/m^{2}yr in this study. It should be noted that the difference in HP annual electricity demand is entirely compatible with the difference in the heating energy demand of both studies (34.10 and 72 kWh/m^2).

Energy-related parameters should be investigated carefully to identify any possible barriers to achieving higher energy efficiency. Parameters such as heating and cooling SCOPs, HPs electricity demand, electricity to/ from grid, and PV self-consumption ratios are considered key performance indicators to UESM. Moreover, in some cases, there might be a restriction that can affect the whole design concept. For instance, having an upper limit for electricity exporting to the grid can be interpreted as a definite need for adding battery storage.

There are some pros and cons associated with each choice in a more focused comparison between two types of HPs. Since the GSHPs heat is mostly provided by boreholes, wells, lakes, or underground water, a GSHP typically has higher source temperature levels than ASHPs. The latter depend on outdoor air temperature, which can be as harsh as −30°C under Canadian conditions. As a result, ASHP needs a significantly higher compression ratio to transfer heat from the outdoor air to the condenser, especially in cold climates such as the case study location, leading to higher electricity consumption and lower COP than GSHPs. The technology improvements and innovations should not be taken for granted as a few years ago, ASHPs could only work down to −8°C, and using ASHPs in cold climates was not a standard option.

Air source heat pumps are generally more sophisticated equipment, with more power and costlier. On the other hand, there are costs associated with GSHPs such as drilling, piping, heat exchanger, or pumps, which might change the balance of cost between two systems. The number of ASHPs and GSHPs required in different buildings shows that the lower number of equipment can be counted toward ASHP systems' advantage.

CHALLENGES

Developing an integrated UBEM and UESM is a challenge due to the difference in their spatial and temporal input, output, and calculation process resolution. The developed UBEM model was

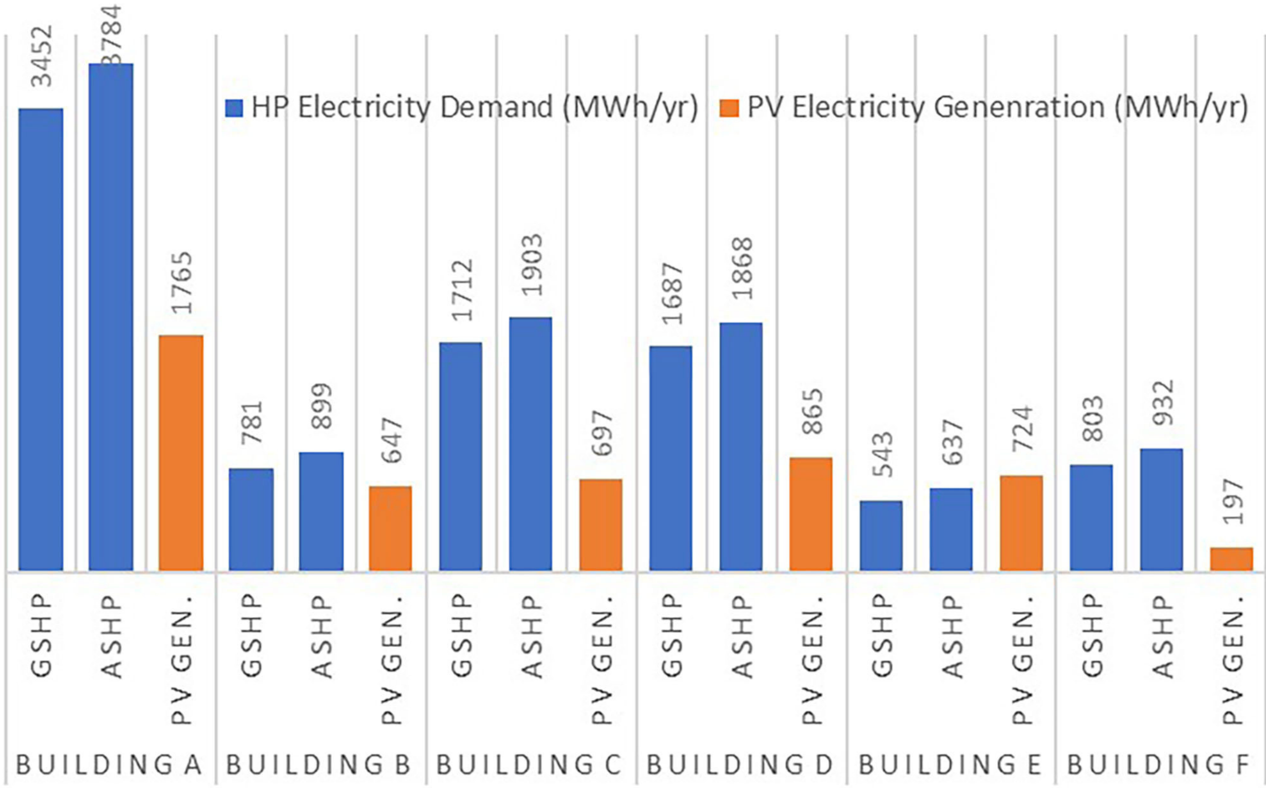

FIGURE 8 | HP total electricity demand vs. AC electricity generated by on-site PV system.

designed to be highly flexible in terms of its temporal and spatial input and output resolution. This flexibility gives the capability to the UBEM to provide suitable input in any temporal and spatial resolution for UESM. As the proposed UESM requires hourly heating and cooling demand for each thermal zone and the whole district, the UBEM can correctly provide these inputs. The resolution of the UBEM heating and cooling demand results can spatially alter the fine-grained resolution, such as in thermal zones scale, to the low resolution of an entire building or a whole district. The temporal resolution can change between yearly to sub-hourly resolution. Although the proposed UBEM uses archetypes for some input parameters, analyzing the heating and cooling demand of UBEM was correlated to the real geometry, building total floor area, and building use-type of the district Lachine. On the other hand, using highly accurate and the same building geometry resolution for renewable potential calculations, the combined UBEM and UESM can calculate the heating and cooling demand and size of different energy systems in any spatial and temporal resolution.

In the current case study, compact, rectangular-shaped buildings with high thermal insulation levels are an excellent start, but not enough toward having a positive energy district. Even though there are always site limits that constrain architects and urban planners' abilities, changing some buildings' orientation so that the longer side faces south could have a significant impact on decreasing the heating demands. Also, in projects with large areas, it can be good practice for implementing innovative ideas like dedicating areas to small urban farms on the site, which reduces food-related transportation energy demands. The residue could be used as an input for biofuel production.

From the energy efficiency point of view and considering the proposed geometry's size and scale, reaching the zero-energy goal with local photovoltaics sounds unattainable, let alone positive energy. Using 65% of the roof area for PV installation and using HPs with high-efficiency ratings are the only measures put into the design process. Although this paper's focus differs from optimization or defining a more detailed energy system design process, a number of improvements out of many are discussed. For instance, adding thermal storage could be beneficial for the system due to the excessive heat generated in each time step (referring to HP section), which lowers the number of HPs required for meeting demands in subsequent hours and, consequently, the HPs electricity demand. Moreover, properly sized battery storage improves the PV self-consumption ratios. It helps the system to meet the upper limit for electricity export to the grid, if there are any. A cost-benefit analysis of the system would be essential for the system, knowing the high cost of batteries and thermal storage systems.

Regarding the energy systems design, using lower heating temperature for heating (40°C) instead of conventional values of up to 60°C or higher is a smart choice that not only can meet the expectations but also increases both energy and exergy efficiencies and lowers heat losses. Adding heat-recovery equipment in the ventilation process could be a significant improvement for lowering heating and cooling demands and associated electricity consumption. The other point that could not go unnoticed is the HP system sizing that needs improvement. Other than sizing based on the maximum demand, a lower percentile like 98% could be a smarter choice. It means that the system is currently sized for 100% of a year's hours and results in the system oversizing for 8,585 h of a year. By designing for lower percentiles, which can be done in either the demand calculation step (UBEM) or limiting the number of HPs (UESM), considerable savings can be achieved.

CONCLUSION

Decarbonization of the urban area acquires the maximum renewable energy and considers the energy demand reduction measures. This work described a novel workflow integrating an urban building energy simulation module accompanied by an urban energy system simulation model. Combining the UBEM and UESM models allows this opportunity to dynamically predict the district energy demand, calculate the renewable energy systems capacity, and sizing energy systems. To have a compatible UBEM and UESM, the UBEM is designed to be highly flexible capable of calculating the heating and cooling demand in any spatial and temporal resolution. The developed model was tested on a case study, a future district in Montreal, Canada. The heating and cooling demand were simulated at the building and district levels and used as input to the UESM model to size the energy systems. It was shown that reaching the zero-carbon goals requires applying stricter constraints on design parameters. Moreover, owners, planners, and designers ought to illustrate realistic goals for each project. For instance, in the Lachine-East case study, considering the buildings' size and scale made reaching carbon neutrality on a local scale almost impossible given the available renewable resources. Nevertheless, implementing some green and sustainable design strategies could mitigate climate impact and GHG emissions. It is of great importance to distinguish between the PV self-consumption ratio and the net value of HPs' electricity demand covered by local PV production. **Table 5** and **Figure 8** show that in small buildings like Building E, local PV produces 75–100% of the HP electricity demand, while this value for larger buildings like Building C can be as low as 38%. The proposed integrated workflow promotes advantages including, but not limited to, accurate demand calculations in complex geometries from building scale to urban areas, autonomous PV system sizing and PV potential calculation, HPs system sizing, and energy metering. However, adding a feedback loop in the sense that makes the workflow dynamically update and optimize the demand calculation parameters will bring a much more efficient and sustainable tool to the table.

DATA AVAILABILITY STATEMENT

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

AUTHOR CONTRIBUTIONS

SR, HR, and SD: introduction. BS, SD, AS, and SS: methodology. SS, BS, and SD: formal analysis. AS: geometry. SD, BS, HR, SR, and SS: writing—original draft preparation. UE: writing—review and editing and supervision. All authors contributed to the article and approved the submitted version.

REFERENCES

Aguilar, F., Crespí-Llorens, D., and Quiles, P. V. (2019). Techno-economic analysis of an air conditioning heat pump powered by photovoltaic panels and the grid. *Sol. Energy* 180, 169–179. doi: 10.1016/j.solener.2019.01.005

Arpagaus, C., Bless, F., Uhlmann, M., Schiffmann, J., and Bertsch, S. S. (2018). High temperature heat pumps: market overview, state of the art, research status, refrigerants, and application potentials. *Energy* 152, 985–1010. doi: 10.1016/j.energy.2018.03.166

Chowdhury, A. A., Rasul, M. G., and Khan, M. M. K. (2016). "Parametric analysis of thermal comfort and energy efficiency in building in subtropical climate," in *Thermofluid Modeling for Energy Efficiency Applications*, eds M. M. K. Khan and N. M.S. Hassan (Cambridge, MA: Academic Press), 149–168. doi: 10.1016/B978-0-12-802397-6.00007-5

Dominković, D. F., Bačeković, I., Cosić, B., Krajačić, G., Pukšec, T., Duić, N., et al. (2016). Zero carbon energy system of South East Europe in 2050. *Appl. Energy* 184, 1517–1528. doi: 10.1016/j.apenergy.2016.03.046

Eicker, U., Schumacher, J., Brennenstuhl, M., and Weiler, V. (2020a). "SWC 2019 renewable energy supply concepts for next generation cities using the integrated urban modeling platform INSEL 4D," in *Proceedings of the ISES Solar World Congress 2019 and IEA SHC International Conference on Solar Heating and Cooling for Buildings and Industry* 2019 (Santiago), 2479–2487. doi: 10.18086/swc.2019.51.02

Eicker, U., Weiler, V., Schumacher, J., and Braun, R. (2020b). On the design of an urban data and modeling platform and its application to urban district analyses. *Energy Build.* 217:109954. doi: 10.1016/j.enbuild.2020.109954

Ferrando, M., and Causone, F. (2020). "An overview of urban building energy modelling (UBEM) tools," in *Proceedings of Building stimulation 2019: 16th IBPSA International Conference and Exhibition* (Rome), 3452–3459. doi: 10.26868/25222708.2019.210632

Fonseca, J. A., Nguyen, T. A., Schlueter, A., and Marechal, F. (2016). City Energy Analyst (CEA): integrated framework for analysis and optimization of building energy systems in neighborhoods and city districts. *Energy Build.* 113, 202–226. doi: 10.1016/j.enbuild.2015.11.055

Government of Canada (2020). *CER – Canada's Energy Future 2020*. Available online at: https://www.cer-rec.gc.ca/en/data-analysis/canada-energy-future/2020/index.html (accessed March 9, 2021).

Green, A. (2018). *Why a Feasibility Study is Your First Step Towards a Successful Building Project*. New York, NY: Amy Green Design.

Gröger, G., Kolbe, T., Nagel, C., and Häfele, K.-H. (2012). "OGC City Geography Markup Language (CityGML) en-coding standard," in *Ogc*, 1–344. Available online at: http://www.opengeospatial.org/legal/ (accessed January 25, 2021).

Halil, F. M., Nasir, N. M., Hassan, A. A., and Shukur, A. S. (2016). Feasibility study and economic assessment in green building projects. *Proc. Soc. Behav. Sci.* 222, 56–64. doi: 10.1016/j.sbspro.2016.05.176

Happle, G., Fonseca, J. A., and Schlueter, A. (2018). A review on occupant behavior in urban building energy models. *Energy Build.* 174, 276–292. doi: 10.1016/j.enbuild.2018.06.030

Hesaraki, A., Ploskic, A., and Holmberg, S. (2015). Integrating low-temperature heating systems into energy efficient buildings. *Energy Proc.* 78, 3043–3048. doi: 10.1016/j.egypro.2015.11.720

Hong, T., Langevin, J., and Sun, K. (2018). Building simulation: ten challenges. *Build. Simul.* 11, 871–898. doi: 10.1007/s12273-018-0444-x

HPTCJ (2010). *Survey of Availability of Heat Pumps in the Food and Beverage Sector*. Available online at: http://www.hptcj.or.jp/e/publication/tabid/360/Default.aspx (accessed January 10, 2021).

Hsieh, S., Omu, A., and Orehounig, K. (2017). Comparison of solar thermal systems with storage: from building to neighbourhood scale. *Energy Build.* 152, 359–372. doi: 10.1016/j.enbuild.2017.07.036

Huang, S., Zuo, W., Lu, H., Liang, C., and Zhang, X. (2019). Performance comparison of a heating tower heat pump and an air-source heat pump: a comprehensive modeling and simulation study. *Energy Convers. Manag.* 180, 1039–1054. doi: 10.1016/j.enconman.2018.11.050

Jesper, M., Schlosser, F., Pag, F., Walmsley, T. G., Schmitt, B., and Vajen, K. (2021). Large-scale heat pumps: uptake and performance modelling of market-available devices. *Renew. Sustain. Energy Rev.* 137:110646. doi: 10.1016/j.rser.2020.110646

Johari, F., Peronato, G., Sadeghian, P., Zhao, X., and Widén, J. (2020). Urban building energy modeling: state of the art and future prospects. *Renew. Sustain. Energy Rev.* 128:109902. doi: 10.1016/j.rser.2020.109902

Kim, Y. J., Yoon, S. H., and Park, C. S. (2013). Stochastic comparison between simplified energy calculation and dynamic simulation. *Energy Build.* 64, 332–342. doi: 10.1016/j.enbuild.2013.05.026

Lee, S. (2018). An overview of the european technical guidelines for the prevention, control and investigation of infections caused by Legionella species. *Perspect Public Health* 138, 241–247. doi: 10.1177/1757913918790922

Li, P., Nord, N., Ertesvåg, I. S., Ge, Z., Yang, Z., and Yang, Y. (2015). Integrated multiscale simulation of combined heat and power based district heating system. *Energy Convers. Manag.* 106, 337–354. doi: 10.1016/j.enconman.2015.08.077

Lizana, J., Chacartegui, R., Barrios-Padura, A., and Valverde, J. M. (2017). Advances in thermal energy storage materials and their applications towards zero energy buildings: a critical review. *Appl. Energy* 203, 219–239. doi: 10.1016/j.apenergy.2017.06.008

Lund, H., Werner, S., Wiltshire, R., Svendsen, S., Thorsen, J. E., Hvelplund, F., et al. (2014). 4th Generation District Heating (4GDH). Integrating smart thermal grids into future sustainable energy systems. *Energy* 68, 1–11. doi: 10.1016/j.energy.2014.02.089

Lund, R., Ilic, D. D., and Trygg, L. (2016). Socioeconomic potential for introducing large-scale heat pumps in district heating in Denmark. *J. Clean. Prod.* 139, 219–229. doi: 10.1016/j.jclepro.2016.07.135

Maritime Geothermal (2018). *Commercial W-Series and WH-Series Water to Water Heat Pumps - Installation and Service Manual.*

Mohajeri, N., Assouline, D., Guiboud, B., Bill, A., Gudmundsson, A., and Scartezzini, J. L. (2018). A city-scale roof shape classification using machine learning for solar energy applications. *Renew. Energy* 121, 81–93. doi: 10.1016/j.renene.2017.12.096

Montr, S. (2020). *Sustainable Montréal 2016-2020*. Available online at: https://montreal.ca/en/articles/sustainable-montreal-2016-2020-8944 (accessed March 9, 2021).

Nordman, R., Kleefkens, O., Riviere, P., Nowak, T., Zottl, A., Arzano-Daurelle, C., et al. (2012). *Seasonal Performance Factor and Monitoring for Heat Pump Systems in the Building Sector.* SEPEMO-Final Report.

NREL (2018). *Building Component Library*. Natl. Renew. Energy Lab. Available online at: https://bcl.nrel.gov/ (accessed March 9, 2021).

Petkov, I., and Gabrielli, P. (2020). Power-to-hydrogen as seasonal energy storage: an uncertainty analysis for optimal design of low-carbon multi-energy systems. *Appl. Energy* 274:115197. doi: 10.1016/j.apenergy.2020.115197

Pilpola, S., Arabzadeh, V., Mikkola, J., and Lund, P. D. (2019). Analyzing national and local pathways to carbon-neutrality from technology, emissions, and resilience perspectives—case of Finland. *Energies* 12, 1–22. doi: 10.3390/en12050949

Pless, S., and Polly, B. (2018). *Communities of the Future: Accelerating Zero Energy District Master Planning Preprint*. Available online at: https://www.osti.gov/biblio/1470715 (accessed January 11, 2021).

Rao, S., Conant-Gilles, D., Jia, Y., and Carl, B. (2018). Rapid Modeling of Large and Complex High Performance Buildings Using Energyplus. in *2018 Building Performance Analysis Conference and SimBuild co-organized by ASHRAE and IBPSA-USA* (Chicago, IL), 9–16. Available online at: https://www.ashrae.com/FileLibrary/Conferences/SpecialtyConferences/2018BuildingPerformanceAnalysisConferenceandSimBuild/Papers/C002.pdf (accessed January 25, 2021).

Reinhart, C. F., and Cerezo Davila, C. (2016). Urban building energy modeling - a review of a nascent field. *Build. Environ.* 97, 196–202. doi: 10.1016/j.buildenv.2015.12.001

Remmen, P., Lauster, M., Mans, M., Fuchs, M., Osterhage, T., and Müller, D. (2018). TEASER: an open tool for urban energy modelling of building stocks. *J. Build. Perform. Simul.* 11, 84–98. doi: 10.1080/19401493.2017.1283539

Rinne, S., and Syri, S. (2013). Heat pumps versus combined heat and power production as CO_2 reduction measures in Finland. *Energy* 57, 308–318. doi: 10.1016/j.energy.2013.05.033

Sarfraz, O., Bach, C. K., and Wilkins, C. K. (2018). Plug load design factors. *ASHRAE J.* 60, 14–19.

Signelković, A. S., Mujan, I., and Dakić, S. (2016). Experimental validation of a EnergyPlus model: application of a multi-storey naturally ventilated double skin façade. *Energy Build.* 118, 27–36. doi: 10.1016/j.enbuild.2016.02.045

Soutullo, S., Bujedo, L. A., Samaniego, J., Borge, D., Ferrer, J. A., Carazo, R., et al. (2016). Energy performance assessment of a polygeneration plant in different weather conditions through simulation tools. *Energy Build.* 124, 7–18. doi: 10.1016/j.enbuild.2016.04.031

Spreiregen, P. D., and Beatriz, D. P. (2007). *Pre-Design*. Chicago, IL: Kaplan AEC Education.

Strzalka, A., Bogdahn, J., Coors, V., and Eicker, U. (2011). 3D City modeling for urban scale heating energy demand forecasting. *HVAC R. Res.* 17, 526–539. doi: 10.1080/10789669.2011.582920

Tabar, V. S., Hagh, M. T., and Jirdehi, M. A. (2021). Achieving a nearly zero energy structure by a novel framework including energy recovery and conversion, carbon capture and demand response. *Energy Build.* 230:110563. doi: 10.1016/j.enbuild.2020.110563

Thomaßen, G., Kavvadias, K., and Jiménez Navarro, J. P. (2021). The decarbonisation of the EU heating sector through electrification: a parametric analysis. *Energy Policy* 148:111929. doi: 10.1016/j.enpol.2020.111929

Trane (2015). *Multi-Pipe Units With Scroll Compressors, Model CMAA 012 to 140*.

US DOE (2013). *Commercial Prototype Building Models/Building Energy Codes Program*. U.S. Dep. Energy. Available online at: https://www.energycodes.gov/development/commercial/prototype_models (accessed January 25, 2021).

Weiler, V., Stave, J., and Eicker, U. (2019). Renewable energy generation scenarios using 3D urban modeling tools-methodology for heat pump and co-generation systems with case study application. *Energies*. 12:403. doi: 10.3390/en12030403

Wiseman, J. (2018). The great energy transition of the 21st century: the 2050 zero-carbon world oration. *Energy Res. Soc. Sci.* 35, 227–232. doi: 10.1016/j.erss.2017.10.011

Xu, W., Liu, C., Li, A., Li, J., and Qiao, B. (2020). Feasibility and performance study on hybrid air source heat pump system for ultra-low energy building in severe cold region of China. *Renew. Energy* 146, 2124–2133. doi: 10.1016/j.renene.2019.08.079

Yazdanie, M., and Orehounig, K. (2021). Advancing urban energy system planning and modeling approaches: Gaps and solutions in perspective. *Renew. Sustain. Energy Rev.* 137:110607. doi: 10.1016/j.rser.2020.110607

Yuan, J., Cui, C., Xiao, Z., Zhang, C., and Gang, W. (2020). Performance analysis of thermal energy storage in distributed energy system under different load profiles. *Energy Convers. Manag.* 208:112596. doi: 10.1016/j.enconman.2020.112596

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Supporting the Sustainable Energy Transition in the Canary Islands: Simulation and Optimization of Multiple Energy System Layouts and Economic Scenarios

Giovanni Barone, Annamaria Buonomano, Cesare Forzano, Giovanni Francesco Giuzio and Adolfo Palombo*

Department of Industrial Engineering, University of Naples Federico II, Naples, Italy

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Edited by:
Francesco Guarino,
University of Palermo, Italy

Reviewed by:
Giovanni Tumminia,
Istituto di Tecnologie Avanzate per l'Energia "Nicola Giordano" (ITAE), Italy
Caroline H-Vermette,
University of Calgary, Canada

****Correspondence:***
Giovanni Francesco Giuzio
giovannifrancesco.giuzio@unina.it

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The Canary Islands have great potential for the implementation of sustainable energy systems due to its availability of natural resources. The archipelago is not connected to the mainland electricity grid and the current generation system is mainly based on traditional fossil fuel. Therefore, the islands strongly dependent on fuel importations, with high costs due to logistics. Furthermore, due to the inadequate coverage of residential heating and cooling needs, the per capita energy consumption is far below the Spanish national average. This occurrence has inspired an intense debate on the current development model of the Canary Archipelago, which has led to the implementation of actions and measures aimed at achieving greater energy sustainability in the archipelago. Furthermore, at a local scale, an important investment plan has been carried out by the Spanish grid operator to ensure energy supply, to improve the system security and reliability, and to optimize the integration of renewable energies. Future measures and investments will be crucial to ensure a sustainable growth, both from the economic and the environment point of views. In this framework, this paper aims to discuss and compare the energy solutions, based on renewable energy technologies, identified to boost the sustainable transition of the islands. To this aim, multiple configurations of a wind power plant coupled with reversible hydro power/storage system for the distributed and on-site energy production in the island of Gran Canaria were modeled, simulated, and optimized by a TRNSYS/Matlab algorithm suitably developed. Specifically, along with the proposed system layouts, different scenarios related to diverse annual costs growth rate of fuel were investigated. The proposed analysis covers a time horizon of 20 years, up to 2040, and aims at assessing the impact of the investigated solution on energy demand, energy supply, and population incomes. Depending on the considered fuel cost growth rate, the best system configurations allow a primary energy saving in the range of 58.1–68.1%. Based on the system choice, the enterprise will generate significant revenues to the island population. The net present values are estimated in the range $1.50 \times 10^3 \div 1.84 \times 10^3$ and $0.85 \times 10^3 \div 1.27 \times 10^3$ M€, respectively for the two considered scenarios (annual costs growth rate of fuel 2 and −2%).

The analysis demonstrates the importance of investments targeted at the implementation of renewables. The proposed scenarios indicate that the current energy model has the potential to radical change and to tackle climate change and energy issues while producing substantial economic savings and better life conditions for the population in the next years.

Keywords: sustainable energy transition, renewable technologies, sustainability in Canary Islands, modeling and simulation, multiple scenarios, multi-objective optimization

INTRODUCTION

Most of the islands that are far from the mainland are highly dependent on fuel imports for transports and power generation. This leads to high costs of supply as well as to well-known environmental issues (Lee et al., 2020). The use of local energy sources, such as wind, solar, and tidal energy can mitigate the fossil fuel consumption and reduce the island vulnerability (Alves et al., 2020). Nevertheless, the high intermittence of renewable energy sources (RES) slows the advance of the 100% renewable islands. In this framework, storage systems play a crucial role in the island energy transition, enhancing both the renewable energy penetration and the reliability of the electricity supply (Nastasi et al., 2021).

Several islands experimented with new energy production mix and planned new strategies to increase the implementation of RES at its highest potential. At the same time, some islands already succeeded in fully meeting the demand through renewables, leading the way toward energy transition. The topic of Renewable Energy Island (REI) attracted the attention of many researcher and policy makers since islands, and isolated areas in general, are interesting test fields for such projects (Kapsali and Anagnostopoulos, 2017).

Karl Sperling critically analyses the renovation process of the Danish island of Samsø obtained by upgrading its energy system—mostly based on fossil fuel technologies—to a fully RES-based one (Sperling, 2017). Here, the author investigated the global context in which the project—internationally recognized as a best practice example—was carried out and provided interesting insights to effectively transform island communities. Government support, future vision, and population cooperation have been identified as the main discriminating factors of success.

Other research works addressed the techno-economic feasibility of several technological solutions reducing fuel consumption and carbon dioxide emissions, such as the interconnection with other neighboring islands or mainland, as well as the adoption of energy storage systems (Groppi et al., 2021). However, technological solutions are strongly dependent on the specific island geographical, morphological and political cases.

To give some representatives examples of the current studies on the topic, in Cauz et al. (2020) different plant layouts comprised of photovoltaic panels, lithium-ion batteries, hydrogen based storage and wind turbines was investigated for the Easter Island case study. Authors concluded that the most diversified renewable energy mix is the most viable solution. This resulted from a mixed-integer linear programming (MILP) optimization algorithm, an established optimization method that ensures the global optimum solution (Alberizzi et al., 2020). Authors successfully adopted the MILP algorithm to find-out the configurations with the minimum investment and operation costs. The cost of the system was chosen as the only objective function.

The use of batteries is demonstrated to be an interesting solution as also reported in Lorenzi et al. (2019); in this work two battery technologies—lithium-ion and vanadium ones—are compared. Batteries implementation into the island of Terceira (Azores) allows to increase the renewable energy share up to 46%. The paper focuses on the optimal unit commitment of the hybrid polygeneration system of the island. A suitable optimization algorithm developed in Matlab environment was coupled with the electricity dispatch control model of the system to guarantee the minimum operation cost at each time step. Batteries not only increase the use of renewables but also have positive impact on the profitability of the entire system.

Much attention is now paid to the production and storage of hydrogen. It is widely recognized as a valuable alternative to store the surplus of renewable energy, therefore, many studies focused on the use of this technology in larger isolated energy systems. In Kavadias et al. (2018), an Hydrogen-based Energy Storage system (HES) was studied for a cluster of nine islands in the Aegean Sea. The system behavior was modeled in Matlab and an optimization was carried out to identify the best system in terms of RES exploitation. The optimal solution allowed to use a significant amount of renewable energy (up to 39%), otherwise lost. Authors estimated an overall average process efficiency of 57%. Moreover, the HES system was tested in the transport sector as well, achieving promising results. However, authors did not investigate the enterprise in terms of economic expenditures and did not include cost functions in their optimization procedure.

Further studies focusing on water electrolysis for hydrogen production in islands are reported in Khosravi et al. (2019) and Zhao et al. (2019). This technology coupled with other RES-based systems will certainly play an important role in the energy transition, especially for its storage capacity for a longer time scale compared to chemical batteries. However, the obtained conversion efficiency of the entire process was low and the need for further studies was recommended to make the system more competitive (Cauz et al., 2020).

On a large scale, Pumped Hydro Energy Storage systems (PHES) are particularly effective as they permit large potential energy storage and increase the reliability of the power network

(Pérez-Díaz et al., 2015). PHES is a well-established technology but requires high investments and management costs, as well as careful design.

Despite their high costs, such systems can be economically viable as demonstrated in Nikolaou et al. (2020). With the aim to exploit the highest amount of the in-site produced renewable energy, the construction of a PHES was investigated for the Crete island. The system was simulated on different scenarios by a suitable dynamic simulation model developed in Matlab. Optimal solutions were found from an economic point of view and provided an investment cost of the system around 41 ÷ 42 M€ for each simulated scenarios.

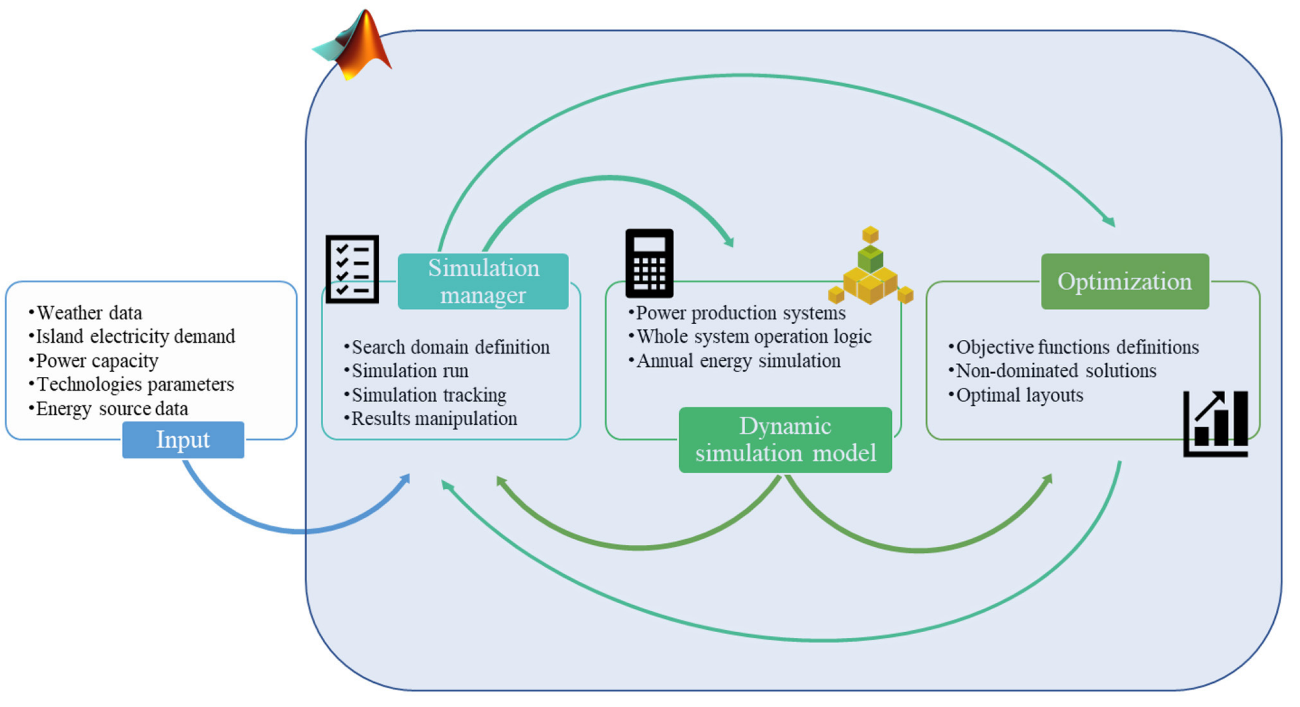

FIGURE 1 | Algorithm architecture.

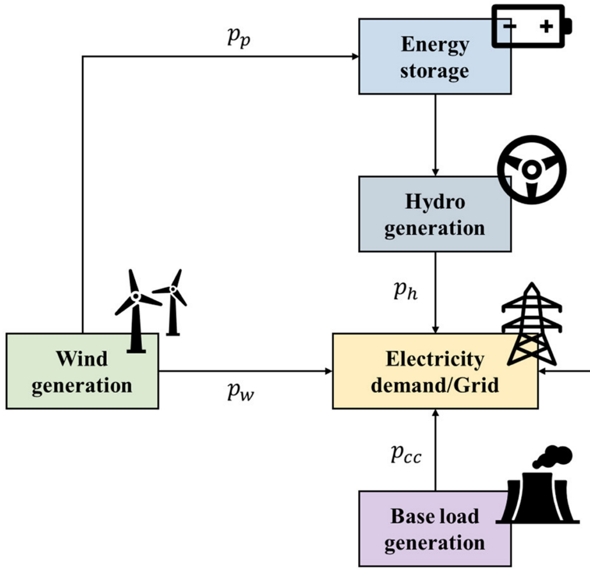

FIGURE 2 | Schematic diagram of the model developed in TRNSYS.

Bueno and Carta (2005a) developed a mathematical model to be used as general tool for sizing PHES systems coupled with wind turbines. Then, their model was applied to find the minimum cost layout of a Wind Pumped Hydro Storage System (WHPPS) on the island of El Hierro, Canary Islands (Bueno and Carta, 2005b). By their studies, authors estimated a maximum renewable energy penetration of circa 69%, and placed the basis for further studies and the construction of a similar system in 2014 (Garcia Latorre et al., 2019), the first of its kind in Canary Islands. It is worth noticing that the design of such energy systems based on the minimum implementation and operation costs does not guarantee the minimum use of primary energy as well. As stated, reducing the fuel importation issues in islands is challenging and needs to be faced in the next future. Therefore, to ensure a sustainable growth, both the economic and energy/environmental aspects deserve more attention. Several methods can be adopted for multi-criterion optimization, such as exhaustive search, random sampling (Monte Carlo methods) or evolutionary algorithm. All of them are based on the non-dominance concept (Ippolito et al., 2014).

A recent work reported in Das et al. (2021) provides an interesting example of such approach. Specifically, a RES-based plant in the Saint Martin's island (Bangladesh) was designed by two different heuristic optimization algorithms: (i) the non-dominated sorting genetic algorithm II, and (ii) the infeasibility driven evolutionary algorithm. Compared to a single-objective approach, the multi-objective provides better environmental benefits with comparable costs.

Similar results are obtained in Giudici et al. (2019), where authors developed a dynamic simulation model to evaluate the water and energy production potential in the island of Ustica, Italy. Then, authors optimized the system (PVs, Wind turbines, Diesel engines, and desalination plants) by a genetic algorithm considering the net present value, the electricity surplus, and the water deficit as conflicting objectives. Evolutionary methods are particularly convenient with high number of decision variables which would lead to high computational costs. They can be successfully adopted in the solution of multi-objective optimization problems of distribution networks or Electrical Energy Storage systems (EES) management to minimize energy losses, as in Ippolito et al. (2014).

Despite the convenience of multi-criterion optimization in the design workflow is largely demonstrated, the current literature shows that such a tool is not widely adopted in the specific case of renewable energy generation systems in off-grid islands involving energy storage devices.

Several studies focusing on the energy transformation of Canarian Islands were published (Cabrera et al., 2018; Meschede et al., 2018; Gonçalves et al., 2020). The construction of the WHPPS in El Hierro represents the first step of a switch in the energy policy of the archipelago government. As discussed in Uche-Soria and Rodríguez-Monroy (2020), the future energy strategies have to rely on renewable energy, self-consumption, energy efficiency, electrification of demand, interconnections and sustainability. In this context, the Spanish grid operator, Red Electrica de Espana, has made important investment to increase the grid reliability, the share of energy produced by RES and the supply security of the archipelago. This will lead to the construction of the Soria-Chira pumped-storage hydropower plant in the island of Gran Canaria (Red Eléctrica de España, 2021).

This article fits in the context of the energy renewal taking place on the island of Gran Canaria with the aim of supporting the design and the construction of the new energy infrastructure and of proposing a case study analysis as a best practice example of how a community can transform its fossil fuel-based energy system into a renewable energy-based one. Specifically, a calculation algorithm is developed

TABLE 1 | Description of the model components.

Technology	Type #	Modeling approach	Comments
Wind energy conversion system	Type 90	The output power is calculated by the power vs. wind speed curve. The wind speed is required as input.	The site elevation has to be entered. The air density is corrected according to the generator height.
Upper/bottom reservoir	Type 39	The water mass is calculated according to the inlet and outlet water mass flow rate which are linked to pumps and hydropower turbine types. The energy stored is evaluated by: $e_s = m_r \cdot g \cdot H_{eff}$ (1)	The working conditions are defined by the overall volume, as well as a maximum and a minimum level. e_s is the energy stored in the reservoirs, m_r is the water mass available in the reservoirs, g is the acceleration due to gravity and H_{eff} is the effective head.
Variable speed pump	Type 745	The corresponding pump fluid flow rate is calculated according to the available power.	–
Hydropower turbines	Custom equation	The power of the hydro turbines is calculated by: $p_h = \frac{\eta_h \cdot \rho_w \cdot g \cdot H_{eff} \cdot \dot{Q}_{turb}}{1000}$ (2) Trnsys does not include types to simulate hydropower turbines.	p_h is the power output of the hydro turbine, η_h is the hydro turbine efficiency, ρ_w is the water density, g is the acceleration due to gravity, H_{eff} is the effective head, and $\dot{Q}_{turb}$ is the hydro turbine flow rate.
Fossil fuel power generators	Custom equation	The power production of both base load and peak load integrations and their fuel expenses are added as equations to balance the total electricity demand.	The related priority logics were considered in the balance.

in Matlab/TRNSYS environments to simulate both the energy and economic performance of multiple WHPPS configurations. The analysis is conducted with the approach of the dynamic simulation to ensure high resolution calculation and detailed simulation outcomes. Furthermore, by considering real electricity load data and the actual generation mix of the islands, the decommissioning of the existing fuel oil-based generators is investigated along with the integration of the WHPPS in the island power grid.

The proposed energy scenarios are modeled in TRNSYS and then, by a Matlab script suitably developed, a co-simulation approach is used to carry-out a multi-objective optimization. The modeling approach based on dynamic calculation of the energy fluxes within the islands and the multi-objective optimization represent the main novel aspects of this work. Dynamic simulation is capable to reliably predict energy system performances and provide a deep understanding of hybrid generation systems behavior, which is fundamental to avoid operation failures. Nevertheless, while small energy systems are largely investigated by this approach, in very few works dynamic simulation is applied to small- or medium-scale energy communities, such as islands. Furthermore, islanded community optimizations based on both energy and financial indices are rare, so this paper aims to fulfill this literature gap.

Moreover, the multi-objective optimization, unlike the published works reported in previously discussed papers (i.e., Bueno and Carta, 2005a,b; Kavadias et al., 2018; Lorenzi et al., 2019; Cauz et al., 2020; Nikolaou et al., 2020), has been conducted by considering two objective functions: the primary energy consumption and the net present value on a time span of 20 years. They are suitably selected according to the need for reducing both the fuel consumption and the electricity production costs which will guarantee a sustainable growth to the island population. The optimization is carried considering two annual fuel cost growth rate.

MODELING AND OPTIMIZATION METHODOLOGY

The mathematical model for the dynamic simulation of the proposed renewables-based energy production system is developed in TRNSYS environment (Klein, 2006). Furthermore, to identify the energy and cost optimal layouts of the investigated systems, a simulation and optimization script has been suitably implemented by means of Matlab which allows the programmatical manipulation of the TRNSYS model and the management of the simulation results.

As depicted in **Figure 1**, the algorithm comprises three main subroutines: the simulation manager, the calculation engine, and the optimization procedure. It allows the user to define the search domain of various model parameters, to sequentially launch and keep track of the TRNSYS simulations and further manipulate the outputs of the other subroutines. However, no detailed description of the simulation manager is provided for sake of brevity, while, the developed power system model and the method adopted to optimize its design are described hereinafter.

System Modeling

To carry out the proposed analyses, an approach based on dynamic simulation is adopted. Specifically, TRNSYS is used to develop a model of the considered energy system and dynamically simulate it. Such tool is conceived to be adapted to small and off-grid islands and their specific needs, in diverse locations, and on multiple scales. The model includes all the energy production and storage devices, as well as their related control strategies.

TRNSYS was chosen as it is powerful and flexible to simulate transient systems. The tool allows for the transient simulation of many plant configurations which can be modeled by its large "Type" library, each representing system components. In addition, a wide database of weather data files is available by the tool.

With respect to the developed dynamic simulation model, the diverse proposed technologies are modeled: the windmills and the hydro power/storage system coupled together forming a wind pumped hydro storage system, WPPHS. This solution successfully fits the needs of islands, namely the high availability of renewable energy sources (strongly intermittent) and the difficulty to dispatch their potential overproduction since there is often no connection to the mainland power grid.

The system allows to store the renewable energy surplus during the peak power production and shift the availability of renewable energy to maximize the RES penetration. When the wind turbines (WTs) produce more electricity than needed, the electricity surplus is stored in form of gravitational potential energy by pumping the water from a lower reservoir to a higher one. Whenever necessary, the stored potential energy is converted again into electricity and delivered into the island grid by means of the hydropower turbines (HTs). A sketch of the described system layout is shown in **Figure 2**, whilst a more detailed methodology description of the adopted TRNSYS components is reported in **Table 1**. Here, the TRNSYS types adopted for the plant elements and the modeling approach are given.

Energy Management Modeling

This section provides information about the control logic of the entire systems. All the following working strategies are implemented by custom equations using suitable TRNSYS types.

The base load is balanced by the combined cycle (p_{cc}) which works more efficiently than other fossil fuel technology, nevertheless it is characterized by high inertia. The plant power production is kept at its highest capacity ($p_{cc,max}$) accordingly with the island power demand (p_d). The logics of the combined cycle power plant is shown in Equation (3). It is regulated to decrease its output power only if the island's electricity demand is lower than its maximum power capacity.

$$p_{cc} = \begin{cases} p_{cc,max} & if\ p_{cc,max} \leq p_d \\ p_d & if\ p_{cc,max} > p_d \end{cases} \tag{3}$$

The rest of the island electricity demand is covered by renewable energy sources, such as wind (p_w) and hydro power (p_h), when

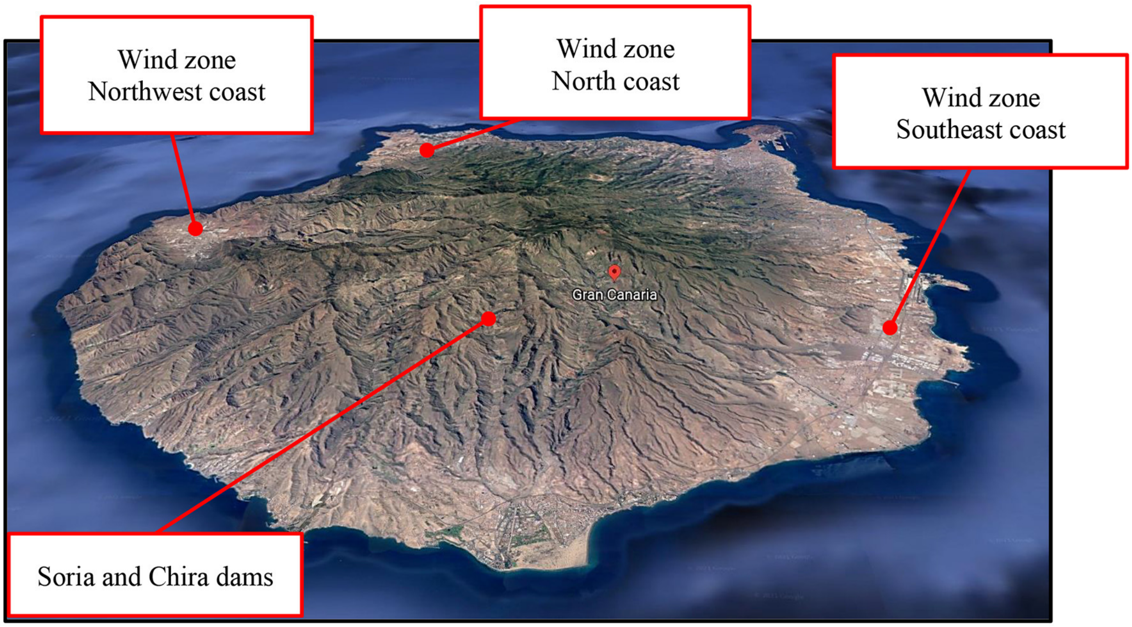

FIGURE 3 | Gran Canaria island and potential locations of the investigated systems.

they are available, or by fossil fuel technologies (p_{gt}) as back-up systems if required. Specifically, the share of wind and hydro power that are exploited is calculated by Equations (4) and (5). They describe the behavior of the WPPHS system. Specifically, when wind power is available $\left(p_{w,a} > 0\right)$, this is primarily used by the electricity network. The hydro turbines are activated to integrate the rest of the power need. Furthermore, in the case of both the wind and hydro power are not sufficient to fully balance the island's needs, the supplementary required power is provided by gas turbines as described by Equation (6).

$$p_w = \begin{cases} p_{w,a} & if\ p_{w,a} \leq p_d - p_{cc} \\ p_d - p_{cc} & if\ p_{w,a} > p_d - p_{cc} \end{cases} \tag{4}$$

$$p_h = \begin{cases} p_d - p_{cc} - p_{w,a} & if\ p_{w,a} \leq p_d - p_{cc} \\ 0 & if\ p_{w,a} > p_d - p_{cc} \\ p_{h,max} & if\ p_d - p_{cc} - p_{w,a} > p_{h,max} \end{cases} \tag{5}$$

$$p_{gt} = \begin{cases} p_d - p_{cc} - p_w - p_h & if\ p_d - p_{cc} - p_w - p_h > 0 \\ 0 & if\ \ p_d - p_{cc} - p_w - p_h \leq 0 \end{cases} \tag{6}$$

The available wind power not dispatched to the grid is stored by pumping $\left(p_p\right)$ the water from the bottom to the upper reservoir according to Equation (7).

$$p_p = \begin{cases} 0 & if\ p_{w,a} \leq p_d - p_{cc} \\ p_{w,a} - p_d - p_{cc} & if\ p_d - p_{cc} < p_{w,a} \leq p_{p,max} \\ p_{p,max} & if\ p_{w,a} \geq p_{p,max} \end{cases} \tag{7}$$

It should be emphasized that the swirling and pumping cannot take place simultaneously as it is not allowed by the hydro power technology considered. Its operation is also dictated from the actual state of charge of the upper and bottom reservoirs. No water pumping occurs if the upper tank is full and no power integration takes place if it is empty. The reverse is true for the lower basin. Any surplus power which cannot be directly dispatched or stored is calculated according to Equation (8).

$$p_{surplus} = \begin{cases} 0 & if\ p_{w,a} \leq p_{p,max} \\ p_{w,a} - p_{p,max} - p_d - p_{cc} & if\ p_{w,a} > p_{p,max} \end{cases} \tag{8}$$

Energy and Economic Assessment

In order to assess both the energy performance and the potential economic savings of the analyzed system, several indexes widely adopted in the literature are introduced. Each considered system layout is compared to a reference one to evaluate its convenience.

The annual primary energy consumption ($e_{p,annual}$) is calculated according to Equation (9) by considering only the technologies based on fossil fuel combustion. $p_{ff,t}$ and $\eta_{ff,t}$ are respectively the power production and the conversion efficiency of the *ff-th* technology at the time *t*, whilst *T* is the number of the simulation time step (Δt) in an annual calculation.

$$e_{p,annual} = \sum_{t=i}^{T} \sum_{ff} \frac{p_{ff,t} \cdot \Delta t}{\eta_{ff,t}} \tag{9}$$

The primary energy saving is calculated by Equation (10) where the annual primary energy consumptions of the reference (*ref*) and proposed (*prop*) scenarios are compared.

$$PES = 1 - \frac{e_{p,annual,prop}}{e_{p,annual,ref}} \tag{10}$$

The economic profitability of the implementation of the considered system layout is estimated by means of a detailed economic model included in the simulation/optimization subroutine mentioned in the previous sections. The model accounts for all the costs related to initial investments for design, purchasing and construction (I_n), replacements ($c_{r,n}$), operation and maintenance ($c_{O\&M}$), and fuel costs (c_{fuel}). The total annual cost (c_{annual}) is assessed for every year (n) of the analyzed time horizon (N) by Equations (11) and (12). The latter involves the unitary cost of the various fuels ($c_{kWh,ff}$) and their related combustion low heat value (LHV_{ff}). The annual fuel cost growth rate *fcgr* is also considered.

$$c_{annual,n} = I_n + c_{r,n} + c_{O\&M} + c_{fuel} \cdot \left(1 + fcgr\right)^n \quad (11)$$

$$c_{fuel} = \sum_{t=i}^{T} \sum_{ff} c_{kWh,ff} \cdot \frac{p_{ff,t} \cdot \Delta t}{\eta_{ff,t} \cdot LHV_{ff}} \quad (12)$$

Thus, the economic savings (R_n) are calculated by Equation (13) and then the net present value (NPV) by Equation (14), calculated by taking into account the annual discount rate a.

$$R_n = c_{annual,ref,n} - c_{annual,prop,n} \quad (13)$$

$$NPV = \sum_{n=0}^{N} R_n \cdot (1 + a)^{-n} \quad (14)$$

A further considered economic index is the discounted pay back, DPB, which is evaluated as:

$$DPB\,(0, N) \;:\; NPV = 0 \quad (15)$$

To carry-out the system optimization, two objective function are selected: the primary energy consumption ($OF_1 = e_{p,annual,prop}$) and the net present cost ($OF_2 = NPC = -NPV$). Several system layouts are simulated, and the set of the non-dominated solution is identified. Then, the optimal system layout, x, is selected by Equation (16).

$$x \;:\; [OF_1\,(x)\,,\, OF_2\,(x)] = \min\,(\|[OF_1\,(x) - \min\,(OF_1\,(x))\,, OF_2\,(x) - \min\,(OF_1\,(x))]\|) \quad (16)$$

CASE STUDY

The capability of the proposed methodology—use of dynamic simulation and optimization for the early design of hybrid renewable systems of large islands—and the feasibility of the proposed renewable based system are investigated through a suitable case study analysis referred to the island of Gran Canaria. The system implementation in the island power network is analyzed by modeling and simulating its energy and economic performance, optimized by maximizing the use of the available renewable power sources and the related incomes for the island community. The energy system of Gran Canaria currently strongly relies on the use of fossil fuel, therefore, the implementation of smart power and storage energy systems is essential to radically change the growth scheme of the island. In this framework, the current policy of the government of Gran Canaria, and the Canarian Archipelago in general (see **Figure 3**), is strongly oriented to the exploitation of the in-site energy sources and the reduction of imported primary energy. For such a reason, the Gran Canaria government has planned the construction of a reversible hydro power plant between the existing water reservoir of Chira and Sorio, two of the several surface water that presently guarantee the potable water supply for irrigation to the island population. The two basins will be connected by a high pressure circuit, a low pressure circuit, an energy evacuation system and a plant with high pressure and low pressure distributors. The Chira and Sorio dams are 2 km distant and have respectively a water storage capacity of 5.6×10^6 and 32.2×10^6 m^3. They will guarantee an effective head of 293 m (901 m, Chira; 608 m, Soria) to the reversible hydropower turbine. A high voltage power line (220 kV) will ensure the energy transfer. Furthermore, a 20 km underground circuit will also supply desalinated water to the reservoirs (Red Eléctrica de España, 2021). As discussed above, significant benefits are expected in terms of harmful gas emission and energy security, even more by exploiting two existing reservoirs. However, the project also implies some potential environmental externalities. The concerns about the impact that the project will have on the selected area are reported by the authors of Jaime Sadhwani and Sagaseta de Ilurdoz (2019). The construction of the infrastructure will alter the island's hydrology which could affect the related flora and fauna in unpredictable ways.

As stated in the EECan25 document (Estrategia Energetica de Canarias 2015–2025) (Gobierno de Canarias, 2017), wind power is a pillar of the Canary Island energy transition. Indeed, an increase in the on-shore and off-shore wind power capacity is set, respectively to 1,025 and 310 MW by 2025. Several studies have been conducted to support the development of the wind power implementation in the Canary Islands. According to Martín Mederos et al. (2011), González et al. (2017), and Schallenberg-Rodríguez and García Montesdeoca (2018), the best locations to exploit the off-shore wind source in Gran Canaria are the area between Tenerife and the west-northwest coast and the south and southeast part of the island. As concern the on-shore wind power availability, the major wind zones are located in the northwest and the southeast coasts, an estimated area of 255 km^2 (Cabrera et al., 2018). It should be noted that modern wind power plants can also reach a land use of 0.2 km^2/MW (Paul Denholm et al., 2009), which means that high installed capacity would significantly impact on the natural and landscape heritage of the island.

In **Figure 3**, the location selected for the hydropower construction, as well as the main island's areas suitable for the wind power plant installation are reported.

The averaged and the maximum wind speeds are respectively 6.9 and 20.8 m/s, whereas the maximum frequency of occurrence is recorded in the range $4 \div 7$ m/s, evaluated by the Meteonorm weather file of Las Palmas de Gran Canaria.

As depicted in **Figure 4**, the electricity demand of the island in the 2019 (blue boxes) is quite regular over the year with a maximum and minimum load of about 534 and 261 MW,

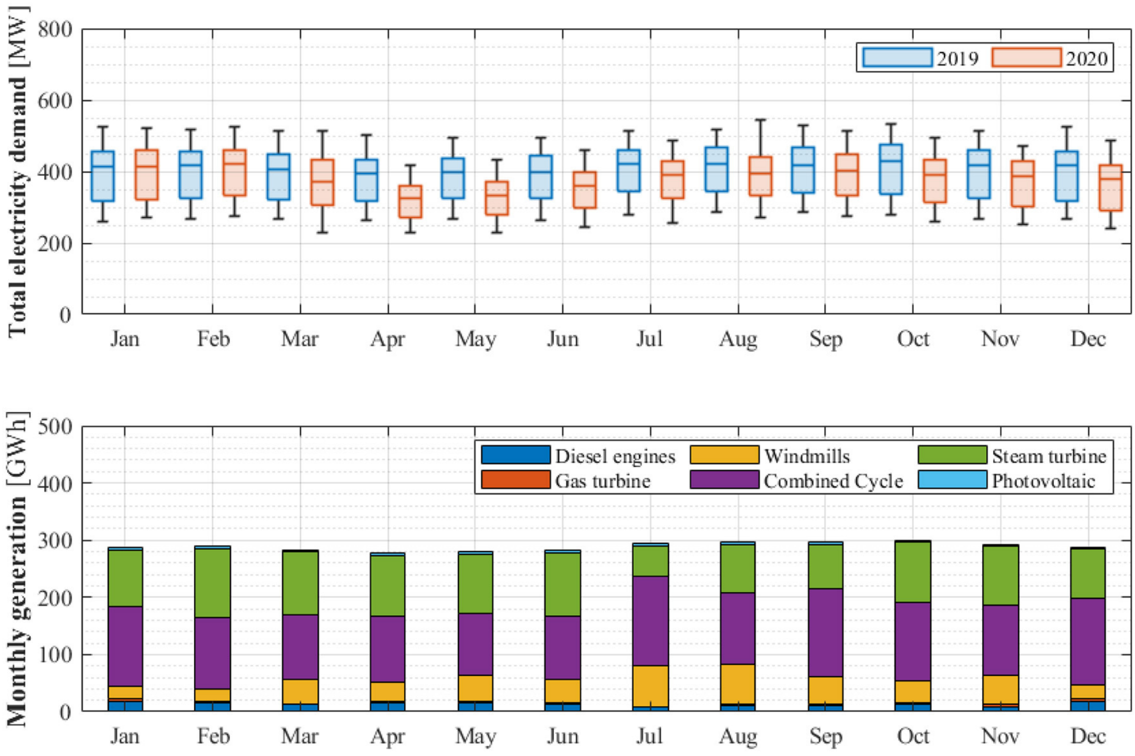

FIGURE 4 | Statistics relative to 2019 and 2020 electricity demand (top) and monthly electricity need coverage (bottom) related to 2019.

TABLE 2 | Proposed case.

Technology	Fuel	Power capacity of reference case (MW)	Power capacity of proposed case (MW)	Considered component capacity (MW)	Storage capacity (GWh)
Steam turbines	Fuel oil	260	0	–	–
Diesel engines	Fuel oil	65	0	–	–
Gas turbines	Gas oil	147	300	–	–
Combined cycle	Gas oil	439	100 ÷ 220	100, 150, 200, 220	–
Wind turbines	–	86	86 + 50 ÷ 400	50, 100, 200, 300, 400	–
Photovoltaic plant	–	40	40	–	–
Hydropower	–		150 ÷ 400	150, 200, 250, 300, 350, 400	–
Storage capacity	–		–	–	4.3

TABLE 3 | Parameters used in the energy and economic analysis.

Technology	Fuel	Useful life (year)	Conversion efficiency $\eta_{ff,t}$ (–)	Investment cost I_n (€/kW)	O&M costs $c_{O\&M}$ (€/kW)	Fuel cost c_{fuel} (€/GJ)	Fuel cost growth rate fcgr (% annual)
Steam turbines	Fuel oil	25–30	0.51	970	25.0	9.7	2.0 and −2.0
Diesel engines	Fuel oil	25–30	0.46	970	25.0	9.7	2.0 and −2.0
Gas turbines	Gas oil	25–30	0.47	1,850	46.0	17.0	2.0 and −2.0
Combined cycle	Gas oil	25-30	0.54	1,850	46.0	17.0	2.0 and −2.0
Wind turbines	–	20–25	–	1,470	19.0	–	–
Hydropower storage	–	25	0.85 and 0.80	1,680	34.0	–	–

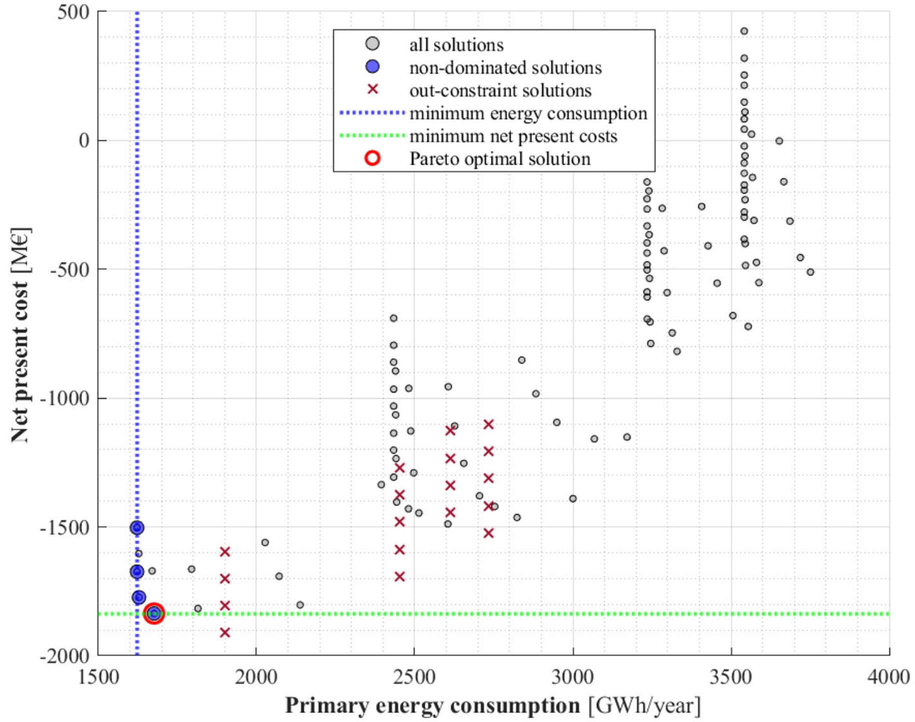

FIGURE 5 | Objective functions of the simulated layouts and Pareto front, 2% of fuel cost growth rate.

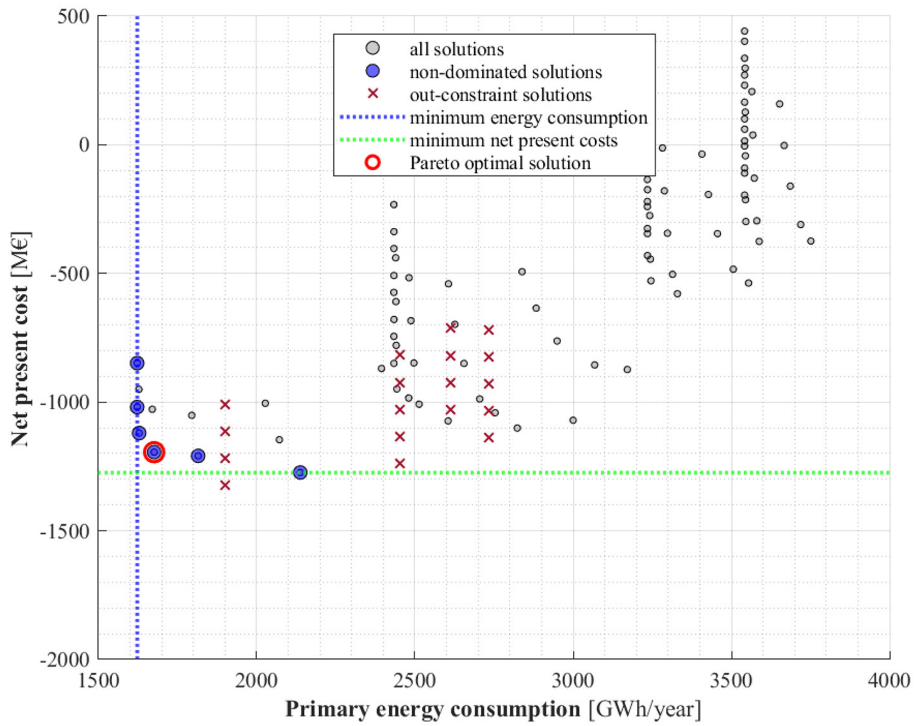

FIGURE 6 | Objective functions of the simulated layouts and Pareto front, −2% of fuel cost growth rate.

TABLE 4 | Layout characteristics of non-dominated solutions: annual fuel cost growth rate of −2%.

Annual fuel cost growth rate	Layout	Combined cycle capacity (MW)	Hydro/pumping capacity (MW)	Wind plant capacity (MW)	Primary energy consumption (TWh)	Net present cost (M€)
2.0%	# 19*	100	300	300	1.68	-1.84×10^3
	# 24	100	350	300	1.63	-1.77×10^3
	# 29	100	400	300	1.62	-1.67×10^3
	# 30	100	400	400	1.62	-1.50×10^3
−2.0%	# 8	100	200	200	2.14	-1.27×10^3
	# 14	100	250	300	1.82	-1.21×10^3
	# 19*	100	300	300	1.68	-1.19×10^3
	# 24	100	350	300	1.63	-1.12×10^3
	# 29	100	400	300	1.62	-1.02×10^3
	# 30	100	400	400	1.62	-0.85×10^3

**Optimal solution according to equation (16).*

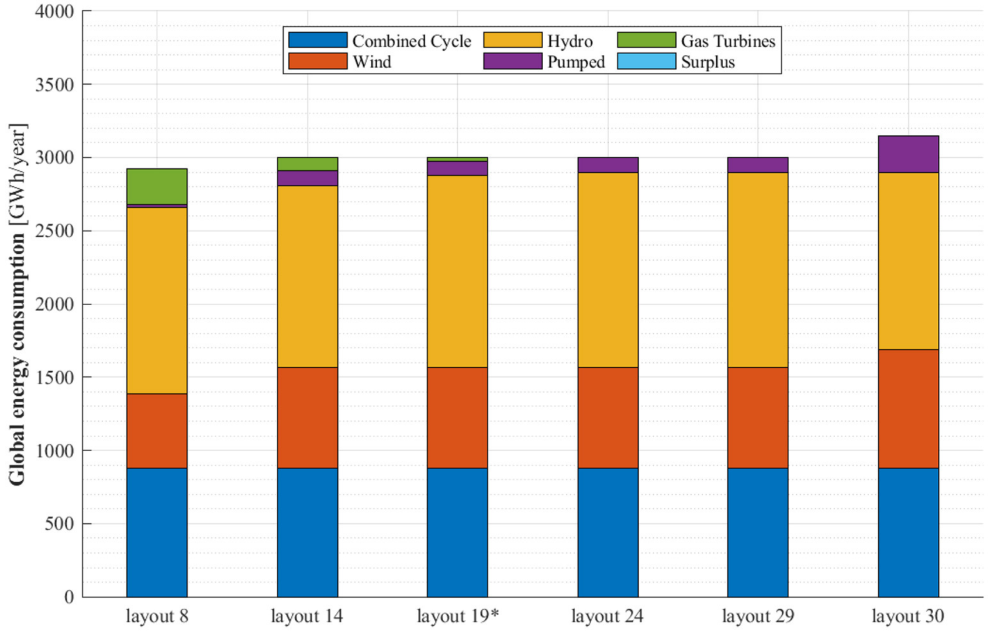

FIGURE 7 | Share of energy consumption by sources for the layouts of the Pareto front in the two considered scenarios.

recorded in October and January, respectively. It also can be seen by the monthly power generation showed in **Figure 4** that only the 16% of the total annual electricity needs is generated by renewables (i.e., from wind power turbines, 86 MW, and photovoltaic fields, 40 MW). The rest of the electricity production is demanded to two large power plants and several generation sub-stations which are fuelled by fuel oil and gas oil. The actual energy generation mix is summarized in **Table 2** with their related power capacities, according to the information provided by Padrón et al. (2011) and Cabrera et al. (2018).

It worth noticing that the data shown in **Figure 4** refer to 2019 and 2020 and are extrapolated from the 10 min measures of the Spanish grid operator.[1] The 2019 electricity demand is considered more representative of the actual island demand than the 2020 one (red boxes), as a significant decrease in demand is recorded since March, probably due to the lockdown period due to Covid-19 pandemic.

The energy system described so far is taken as baseline for the energy and economic analysis of the proposed system which is characterized by the WPPHS system and a new configuration of the existing power plant. The optimization of the system is carried out by also assuming the decommissioning of the fuel oil generators, such as steam turbines (STs) and diesel engines (DEs), and part of the combined cycle plant (CC). The latter is resized considering a new capacity of the plant which is varied in the range 100 ÷ 220 MW. Furthermore, a higher capacity of ∼300 MW is made available by retrofitting the gas turbines (GTs) that are part of the combined cycle. The new hypothesized scenario provides the CC and GTs as base load and peak load system,

[1]Red Eléctrica de España. Available online at: https://www.ree.es/en (accessed February 2021).

respectively, following the behavior described by Equations (3) and (6).

As concern the WPPHS, the power capacities of the renewable energy technologies range for both the wind turbines and the hydro/pumping system. Specifically, the integration in the island grid of a wind farm of 50 ÷ 400 MW and the reversible hydro turbines (HTs) of 100 ÷ 400 MW are simulated. The power capacities of the new energy scenarios are reported in **Table 2**, where the storage capacities (evaluated by Equation 1) of the two water reservoirs—being part of the reversible hydropower system are also reported. Simulations are carried out considering wind turbines with a rated capacity of 2 MW, therefore, the number of turbines can vary in the range 25 ÷ 200 units covering an area of 10 ÷ 80 km^2.

The analysis is also carried out for two different scenarios characterized by an annual fuel cost growth (*fcgr*) rate of 2.0 and −2.0%, respectively, for which the same optimization procedure is implemented.

All the parameters involved in the economic and energy analysis and the system optimization are reported in **Table 3** (Marrero and Ramos-Real, 2010). Note that the economic analysis is conducted on a time horizon of 20 years. Moreover, no investment costs are considered for the existing generators, whereas a replacement of such components is hypostasised after 10 years. Being a public investment and assuming a concessional interest rate for the loan, the discount rate is set equal to 5.0% according to the minimum discount rate suggested in Cigala (2016).

The optimization is carried out only considering the non-renewable loads.

RESULTS AND DISCUSSION

Simulation results of the conducted analysis are discussed in this section. An exhaustive search is conducted among all the system layouts obtained by varying the combined cycle plant and the hydropower capacities, as well as the number of wind turbines. A total number of 120 annual simulations are performed, and for each investigated configuration, the two defined objective functions ($e_{p,annual,prop}$ and *NPC*) are calculated. Simulation results are shown in **Figures 5**, **6** where the net present cost of each simulated system is plotted against the corresponding primary energy consumption for the two simulated scenarios.

By the procedure described in the methodology section, the non-dominated solutions (Pareto front) are identified (blue circle markers) and then the optimal layout (red circle marker) is selected among them by Equation (16). Note that the scatter plot also reports the solutions excluded by the optimization (x markers) since they require a peak load capacity higher than ∼300 MW, which is the maximum power capacity of GTs.

The solutions that comprise the Pareto front are also reported in **Table 4**. It can be noted that the scenario with an annual fuel cost decrease (*fcgr* = −2.0%) is characterized by a higher number of non-dominated solutions and, therefore, a wider range of layouts to choose. However, according to the adopted criteria (Equation 16), layout 19 results to be the best trade-off between the primary energy consumption (1.68 TWh) and the net present cost (−1.84 × 103 and −1.19 × 103 M€) of the system in both the scenarios. Note that a negative NPC corresponds to a positive NPV.

Layout 19 allows for saving 67.1% of primary energy which is lower than the valued obtained for Layout 24, 29, and 30 that account for a primary energy saving of 68.0, 68.1, and 68.1, respectively. In fact, a lower share of renewable energy is involved in the production of electricity due to the greatest use of the GTs due to the lower hydro pumping capacity. However, this solution has a lower global cost over 20 years which leads to more affordable electricity purchasing costs for the island population.

The global energy consumptions and the share of energy production by sources are summarized in **Figure 7** for the layouts reported in **Table 4** (for both scenarios). It can be noted that a very high penetration of renewable energy power generation can be reached by the implementation of the proposed system. Both the wind and the hydro generators significantly contribute to the electricity supply. Furthermore, due to the large storage capacity considered and the reduced availability of energy surplus by WTs, the HTs mainly work as electricity generators, as demonstrated by the reduced amount of energy stored by pumping depicted in **Figure 7**.

It is worth noticing that decision-makers could also be interested in Layout 30 which returns the highest pumped/generated power ratio of HTs leading to a more reliable energy supply. However, this is the most expensive alternative despite certain environmental advantages. Also, Layout 8 is interesting for its maximum NPV in the scenario in which the fuel cost decrease over the year but it has the highest primary energy consumption.

For the same system layouts, the detailed cash flow analysis is shown by **Figures 8**, **9** where the net present value over 20 years is indicated for each layouts of the Pareto front. The costs of the 0th year represent the investment costs of the system, as high as 0.63×10^3, 0.86×10^3, 0.94×10^3, 1.03×10^3, 1.11×10^3, and 1.26×10^3 M€ for the Layout 8, 14, 19, 24, 29, and 30, respectively. The assumptions described in the previous section lead to DPBs of 6.6, 7.2, 7.9, and 9.1 in the first scenario (*fcgr* = 2.0%), while DPBs, respectively of 5.2, 7.1, 7.6, 8.4, 9.1, and 9.4 were calculated in the second scenario (*fcgr* = −2.0%). At the 10th year of the analysis, further incomes related to avoided costs of fossil fuel systems replacement allow the NPVs to rapidly increase. Layout 8, 14, and 19 entail the higher NPVs at the 20th year, although they increased with a lower rate because of the higher fuel consumption and their related costs. It should be also highlighted that the second scenario is characterized by lower NPVs than the first one. It is due to the significant economic savings due to the lower cost of fuel.

In order to complete the analysis, the dynamic profiles of electricity generation are plotted for the optimal system layout (Layout 19) for both a winter and summer sample week in **Figures 10**, **11**, specifically, the 2nd and 30th weeks of the year. Here, it is possible to see the different behavior of the investigated system between the winter and summer seasons. Due to the lower availability of wind energy source, the winter season is characterized by a high use of hydro power (light red area in

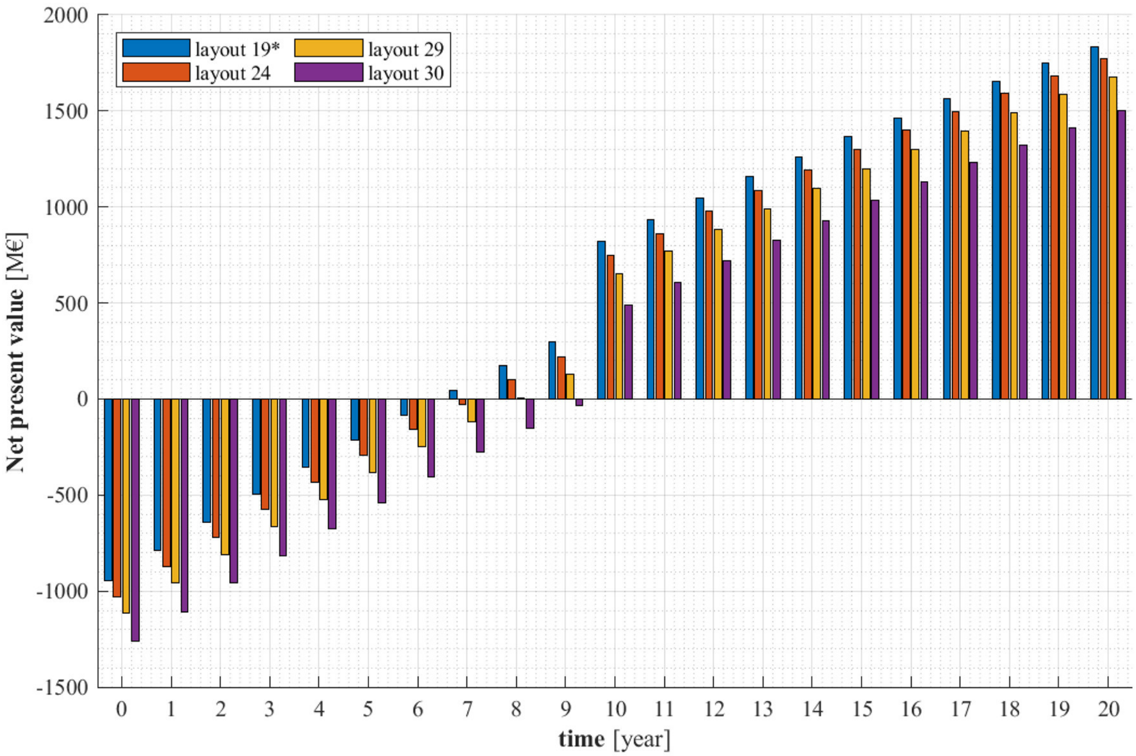

FIGURE 8 | Cash flow analysis: annual fuel cost growth rate of 2%.

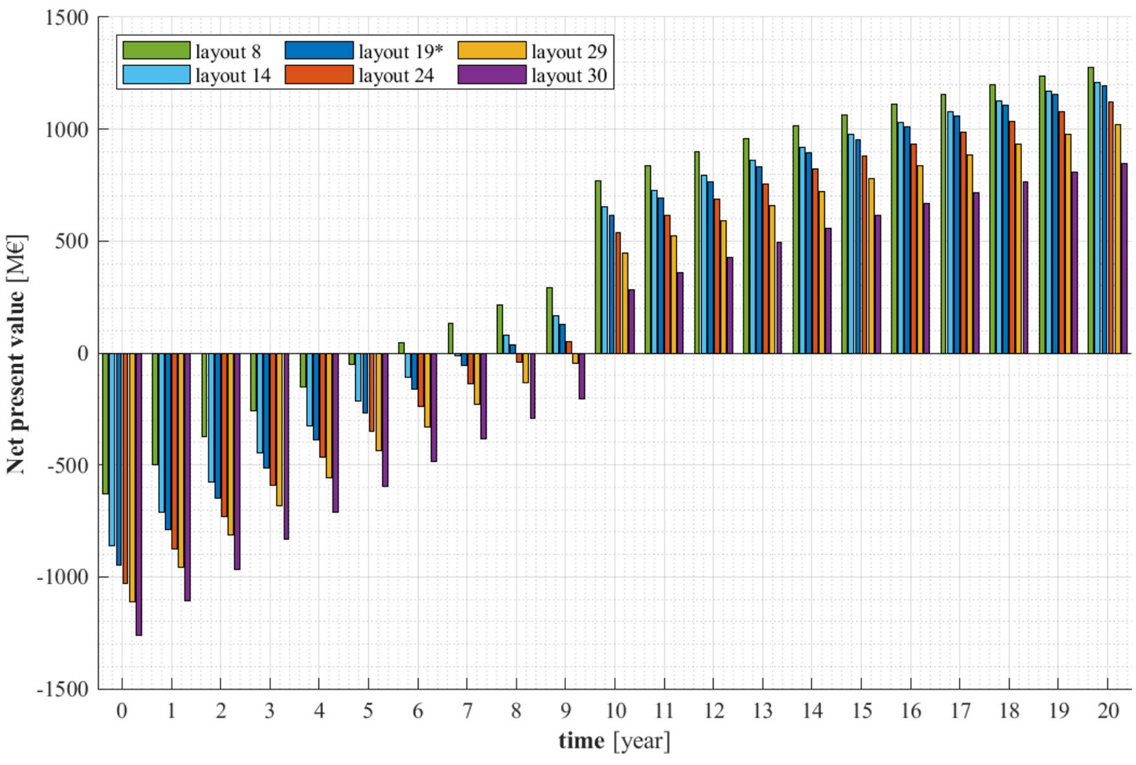

FIGURE 9 | Cash flow analysis: annual fuel cost growth rate of −2%.

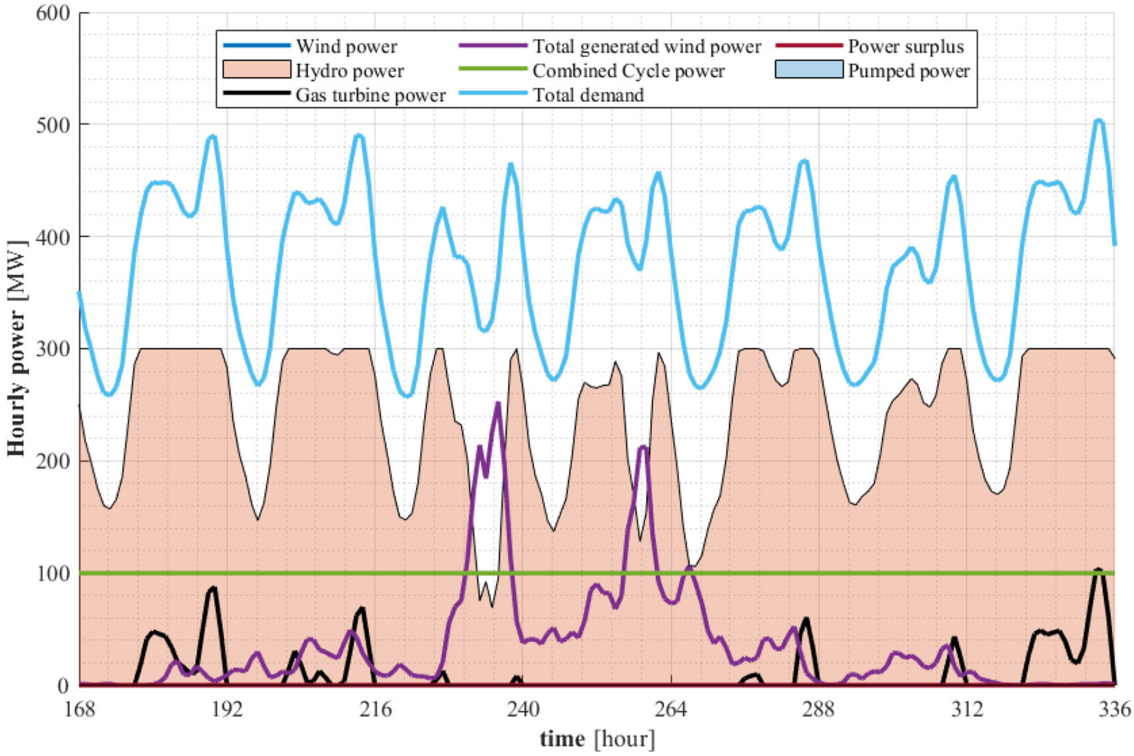

FIGURE 10 | Winter sample week (2nd week of the year).

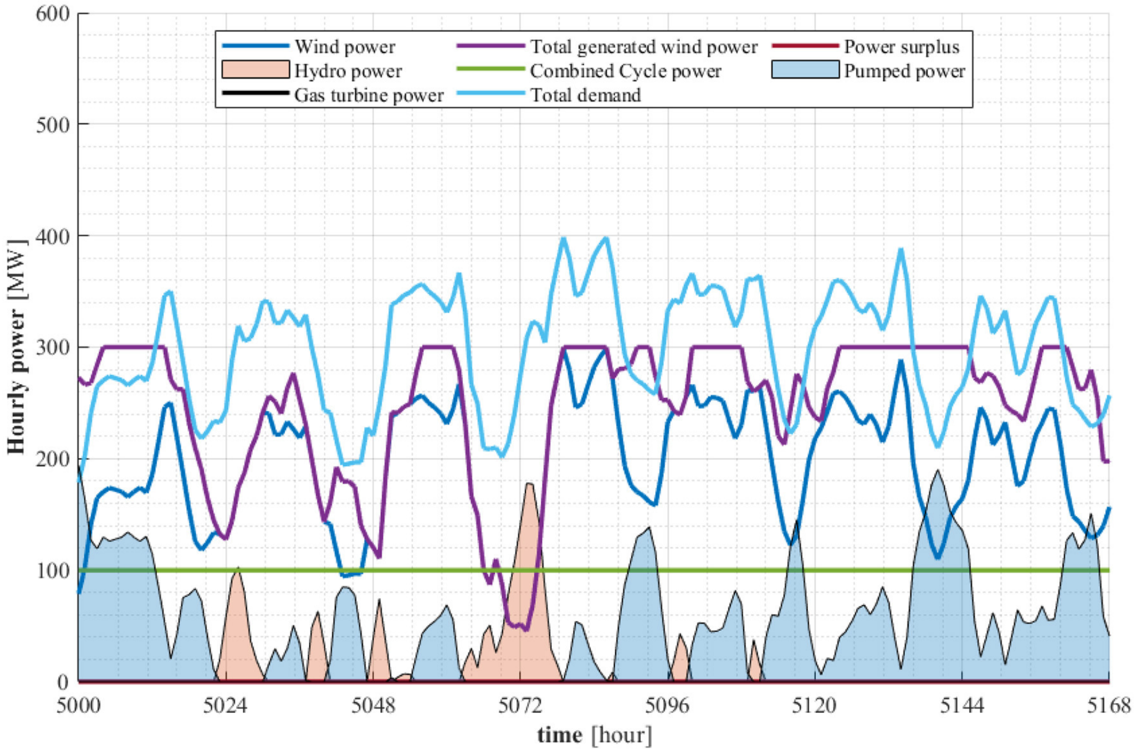

FIGURE 11 | Summer sample week (30th week of the year).

Figure 10). On the contrary, a high overproduction of WTs is recorded in the summer season with a high rate of energy storage (light blue area in **Figure 11**) which implies no use of GTs. It should be pointed out that the load profile depicted in **Figures 10**, **11** as a light blue line is obtained by subtracting the power generated by the wind turbines and photovoltaics that are already present on the island from the total island demand. This resulted in a lower demand for the new system during summer, due to the grater exploitation of renewable energy.

CONCLUSIONS

This manuscript focuses on the use of dynamic simulation and optimization for the early design of renewable based systems for large islands. More specifically, the proposed methodology is applied to the implementation of a Pumped-Storage Hydropower plant coupled with Wind turbines and the partial decommissioning of the existing power generation systems of the island of Gran Canaria, Canary Islands. The selected case study aims at providing insights on how to foster the sustainable transition of island communities. To this aim, a dynamic simulation model of the proposed renewable based system is developed in TRNSYS, whereas a multi-objective optimization based on dynamic simulations of the system is conducted by a suitable algorithm implemented in Matlab/TRNSYS with the aim to maximize both the renewable energy share and the related incomes for the island population. The analysis is conducted by using energy demand data of the island of Gran Canaria provided by the Spanish grid operator and by considering two different scenarios characterized by a positive and a negative annual fuel cost growth rates.

The layout—consisting of 300 MW hydropower/storage system, a 300 MW wind farm, and a 100 MW combined cycle plant—is identified as the best trade-off between energy performance and economic profits for both the simulated scenarios. This system configuration enables for an important reduction of primary energy consumption corresponding to a PES value of 67.1% and a RES penetration of 58%. By the economic point of view, such plant layout has an investment cost of 0.94×10^3 M€ and NPVs, calculated on a time span of 20 years, of 1.84×10^3 and 1.19×10^3 M€ for the first and the second scenarios, respectively. The analysis proved the economic viability of such a system along with the greater renewable energy source exploitation due to the high-capacity storage system integrated in the island isolated power network.

Furthermore, it is possible to generally conclude that the choice of the optimal system configuration can be significantly affected by the financial background of the archipelago. Specifically, the annual fuel cost growth rate has an important role in the economy of the enterprise. As demonstrated, a negative annual fuel cost growth extends the set of the non-dominated solutions and makes more economically viable the exploitation of fossil fuel technologies. On the contrary, an increasing price of oil would encourage the implementation of a high capacity of renewable energy. Decision-makers must carefully evaluate the consequences that this choice will have on the island economy along with the effect of the system layout will have on the stability and security of the energy supply.

Finally, the proposed case study analysis can be considered as an example of mix of innovative technologies for the deployment of renewable energy toward the energy self-sufficiency of islands, whereas the proposed methodology is a valuable tool for islands energy planning. As conceived, the simulation and the optimization model can be applied to other isolated communities on multiple scales and with different energy sources. This flexibility is necessary to effectively contribute to the international goal of the sustainable development.

Further investigations to resolve the limits of this research should include the analysis of grid stability issues and the generalization of obtained results. Concerning the first topic, further research should be dedicated to address grid voltage fluctuations issues due to the presence of intermittent energy sources. Finally, the proposed methodology and scenarios could be applied to different large islands subjected to diverse economic, and weather and natural resources conditions, with the aim to generate diverse case studies. These analyses could extend the obtained findings both qualitatively and quantitatively for the use of stakeholders and decision makers, increasing the knowledge of potentials and limits of islands energy communities and technologies.

DATA AVAILABILITY STATEMENT

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

AUTHOR CONTRIBUTIONS

All authors listed have made a substantial, direct and intellectual contribution to the work, and approved it for publication.

REFERENCES

Alberizzi, J. C., Rossi, M., and Renzi, M. (2020). A MILP algorithm for the optimal sizing of an off-grid hybrid renewable energy system in South Tyrol. *Energy Rep.* 6, 21–26. doi: 10.1016/j.egyr.2019.08.012

Alves, M., Segurado, R., and Costa, M. (2020). On the road to 100% renewable energy systems in isolated islands. *Energy* 198:117321. doi: 10.1016/j.energy.2020.117321

Bueno, C., and Carta, J. A. (2005a). Technical–economic analysis of wind-powered pumped hydrostorage systems. Part I: model development. *Sol. Energy* 78, 382–395. doi: 10.1016/j.solener.2004.08.006

Bueno, C., and Carta, J. A. (2005b). Technical–economic analysis of wind-powered pumped hydrostorage systems. Part II: model application to the island of El Hierro. *Sol. Energy* 78, 396–405. doi: 10.1016/j.solener.2004.08.007

Cabrera, P., Lund, H., and Carta, J. A. (2018). Smart renewable energy penetration strategies on islands: the case of Gran Canaria. *Energy* 162, 421–443. doi: 10.1016/j.energy.2018.08.020

Cauz, M., Bloch, L., Rod, C., Perret, L., Ballif, C., and Wyrsch, N. (2020). Benefits of a diversified energy mix for islanded systems. *Front. Energy Res.* 8:147. doi: 10.3389/fenrg.2020.00147

Cigala, C. (2016). *Sustainable Energy Handbook. Module 6.1: Simplified Financial Models*. Bruxells: Capacity4dev.

Das, B. K., Hassan, R., Tushar, M. S. H. K., Zaman, F., Hasan, M., and Das, P. (2021). Techno-economic and environmental assessment of a hybrid renewable energy system using multi-objective genetic algorithm: a case study for remote Island in Bangladesh. *Energy Convers. Manage.* 230:113823. doi: 10.1016/j.enconman.2020.113823

Garcia Latorre, F. J., Quintana, J. J., and de la Nuez, I. (2019). Technical and economic evaluation of the integration of a wind-hydro system in El Hierro island. *Renew. Energy* 134, 186–193. doi: 10.1016/j.renene.2018.11.047

Giudici, F., Castelletti, A., Garofalo, E., Giuliani, M., and Maier, H. R. (2019). Dynamic, multi-objective optimal design and operation of water-energy systems for small, off-grid islands. *Appl. Energy* 250, 605–616. doi: 10.1016/j.apenergy.2019.05.084

Gobierno de Canarias (2017). *Estrategia Energética de Canarias 2015–2025*. Available online at: www.datosdelanzarote.com/Uploads/doc/Estrategia-Energética-de-Canarias-2015-2025–2018050912053194EECan25_Documento Preliminar_junio2017-(1).pdf

Gonçalves, M., Martinho, P., and Guedes Soares, C. (2020). Wave energy assessment based on a 33-year hindcast for the Canary Islands. *Renew. Energy* 152, 259–269. doi: 10.1016/j.renene.2020.01.011

González, A., Pérez, J. C., Díaz, J. P., and Expósito, F. J. (2017). Future projections of wind resource in a mountainous archipelago, Canary Islands. *Renew. Energy* 104, 120–128. doi: 10.1016/j.renene.2016.12.021

Groppi, D., Pfeifer, A., Garcia, D. A., Krajačić, G., and Duić, N. (2021). A review on energy storage and demand side management solutions in smart energy islands. *Renew. Sustain. Energy Rev.* 135:110183. doi: 10.1016/j.rser.2020.110183

Ippolito, M. G., Di Silvestre, M. L., Riva Sanseverino, E., Zizzo, G., and Graditi, G. (2014). Multi-objective optimized management of electrical energy storage systems in an islanded network with renewable energy sources under different design scenarios. *Energy* 64, 648–662. doi: 10.1016/j.energy.2013.11.065

Jaime Sadhwani, J., and Sagaseta de Ilurdoz, M. (2019). Primary energy consumption in desalination: the case of Gran Canaria. *Desalination* 452, 219–229. doi: 10.1016/j.desal.2018.11.004

Kapsali, M., and Anagnostopoulos, J. S. (2017). Investigating the role of local pumped-hydro energy storage in interconnected island grids with high wind power generation. *Renew. Energy* 114, 614–628. doi: 10.1016/j.renene.2017.07.014

Kavadias, K. A., Apostolou, D., and Kaldellis, J. K. (2018). Modelling and optimisation of a hydrogen-based energy storage system in an autonomous electrical network. *Appl. Energy* 227, 574–586. doi: 10.1016/j.apenergy.2017.08.050

Khosravi, A., Syri, S., Assad, M. E. H., and Malekan, M. (2019). Thermodynamic and economic analysis of a hybrid ocean thermal energy conversion/photovoltaic system with hydrogen-based energy storage system. *Energy* 172, 304–319. doi: 10.1016/j.energy.2019.01.100

Klein, S. A. (2006). *Solar Energy Laboratory, TRNSYS. A Transient System Simulation Program*. Madison, WI: University of Wisconsin, Madison.

Lee, T., Glick, M. B., and Lee, J. H. (2020). Island energy transition: assessing Hawaii's multi-level, policy-driven approach. *Renew. Sustain. Energy Rev.* 118:109500. doi: 10.1016/j.rser.2019.109500

Lorenzi, G., Vieira, R. S., Silva, C. A. S., and Martin, A. (2019). Techno-economic analysis of utility-scale energy storage in island settings. *J. Energy Storage* 21, 691–705. doi: 10.1016/j.est.2018.12.026

Marrero, G. A., and Ramos-Real, F. J. (2010). Electricity generation cost in isolated system: the complementarities of natural gas and renewables in the Canary Islands. *Renew. Sustain. Energy Rev.* 14, 2808–2818. doi: 10.1016/j.rser.2010.06.007

Martín Mederos, A. C., Medina Padrón, J. F., and Feijóo Lorenzo, A. E. (2011). An offshore wind atlas for the Canary Islands. *Renew. Sustain. Energy Rev.* 15, 612–620. doi: 10.1016/j.rser.2010.08.005

Meschede, H., Child, M., and Breyer, C. (2018). Assessment of sustainable energy system configuration for a small Canary island in 2030. *Energy Convers. Manage.* 165, 363–372. doi: 10.1016/j.enconman.2018.03.061

Nastasi, B., Mazzoni, S., Groppi, D., Romagnoli, A., and Garcia, D. A. (2021). Solar power-to-gas application to an island energy system. *Renew. Energy* 164, 1005–1016. doi: 10.1016/j.renene.2020.10.055

Nikolaou, T., Stavrakakis, G. S., and Tsamoudalis, K. (2020). Modeling and optimal dimensioning of a pumped hydro energy storage system for the exploitation of the rejected wind energy in the non-interconnected electrical power system of the Crete Island, Greece. *Energies* 13:2705. doi: 10.3390/en13112705

Padrón, S., Medina, J. F., and Rodríguez, A. (2011). Analysis of a pumped storage system to increase the penetration level of renewable energy in isolated power systems. Gran Canaria: a case study. *Energy* 36, 6753–6762. doi: 10.1016/j.energy.2011.10.029

Paul Denholm, M. H., Jackson, M., and Ong, S. (2009). *Land-Use Requirements of Modern Wind Power Plants in the United States*. National Renewable Energy Laboratory, Golden, CO: U. S. Departement of Energy.

Pérez-Díaz, J. I., Chazarra, M., García-González, J., Cavazzini, G., and Stoppato, A. (2015). Trends and challenges in the operation of pumped-storage hydropower plants. *Renew. Sustain. Energy Rev.* 44, 767–784. doi: 10.1016/j.rser.2015.01.029

Red Eléctrica de España (2021). *Cental Hidroeléctrica Reversible Soria-Chira*. Available online at: https://www.ree.es/es/actividades/proyectos-singulares/central-chira-soria

Schallenberg-Rodríguez, J., and García Montesdeoca, N. (2018). Spatial planning to estimate the offshore wind energy potential in coastal regions and islands. Practical case: the Canary Islands. *Energy* 143, 91–103. doi: 10.1016/j.energy.2017.10.084

Sperling, K. (2017). How does a pioneer community energy project succeed in practice? The case of the Samsø renewable energy island. *Renew. Sustain. Energy Rev.* 71, 884–897. doi: 10.1016/j.rser.2016.12.116

Uche-Soria, M., and Rodríguez-Monroy, C. (2020). Energy planning and its relationship to energy poverty in decision making. A first approach for the Canary Islands. *Energy Policy* 140:111423. doi: 10.1016/j.enpol.2020.111423

Zhao, G., Nielsen, E. R., Troncoso, E., Hyde, K., Romeo, J. S., and Diderich, D. (2019). Life cycle cost analysis: a case study of hydrogen energy application on the Orkney Islands. *Int. J. Hydrogen Energy* 44, 9517–9528. doi: 10.1016/j.ijhydene.2018.08.015

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GLOSSARY

$\dot{Q}_{turb}$	Hydro turbine flow rate, m^3/s
H_{eff}	Effective hydrostatic head, m
$c_{O\&M}$	Total operation and maintenance cost, $M€$
c_{annual}	Total annual cost, $M€/yr$
c_{fuel}	Total fuel cost, $M€$
c_r	Total replacement cost, $M€$
e_p	Primary energy consumption, MWh
e_s	Stored energy, GWh
m_r	Water mass of reservoirs, kg
$p_{h,max}$	Maximum power output of the hydro turbines, MW
p_h	Power output of the hydro turbines, MW
$p_{cc,max}$	Maximum combined cycle plant power output, MW
p_{cc}	Actual combined cycle plant power output, MW
p_d	Power demand, MW
p_{gt}	Gas turbine power output, MW
$p_{p,\text{max}}$	Maximum power capacity, MW
p_p	Actual pumped power, MW
$p_{surplus}$	Power surplus, MW
$p_{w,a}$	Available wind power, MW
p_w	Power output of the wind turbines, MW
η_h	Hydro turbine efficiency, *(-)*
ρ_w	Water density, m^3/kg
CC	Combined Cycle plant
DE	Diesel Engine
GT	Gas Turbine
HES	Hydrogen-based Energy Storage system
HT	Hydropower Turbine
MILP	Mixed-Integer Linear Programming
PHES	Pumped Hydro Energy Storage systems
REI	Renewable Energy Island
RES	Renewable Energy Sources
ST	Steam Turbine
WHPPS	Wind Pumped Hydro Storage System
WT	Wind Turbine
DPB	Discounted Payback period, *yr*
I	Total investment cost, $M€$
NPC	Net Present Cost, $M€$
NPV	Net Present Value, $M€$
OF	Objective function
PES	Primary energy saving, *%*
R	Economic savings, $M€$
a	annual discount rate, *%*
fcgr	fuel cost growth rate, *%*
g	Acceleration due to gravity, m/s^2
Δt	simulation timestep, *h*

frontiers in Sustainable Cities

REVIEW
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Integrating Electric Vehicles to Achieve Sustainable Energy as a Service Business Model in Smart Cities

Bokolo Anthony Jnr.*

Department of Computer Science, Norwegian University of Science and Technology, NTNU, Trondheim, Norway

The digitalization of the power grid to smart grid provides value added services to the prosumers and other stakeholders involved in the energy market, and possibly disrupts existing electricity services in smart cities. The use of Electric Vehicles (EVs) do not only challenge the sustainability of the smart grid but also promote and stimulate its upgrading. Undeniably, EVs can actively promote the development of the smart grid via two-way communications by deploying Vehicle-to-Grid (V2G) and Grid-to-Vehicle (G2V). EVs have environmental benefits as compared to hybrids or even internal combustion engine vehicle as they can help minimize noise levels, pollution, and greenhouse gas emissions. The integration of EVs could bring substantial changes for the society not only in providing transportation services but also shifting economies from petroleum and reducing the carbon dioxide (CO_2) emission from the transportation sector. Therefore, this study employs secondary data from the literature to explore how EVs can achieve sustainable energy as a service business model in smart cities. Findings from this study suggest that EVs are major assets for a sustainable energy future as EV batteries offers an untapped opportunity to store electricity from renewable energy sources. Implications from this study discusses the issues and recommendations for EVs integration in smart cities.

Keywords: energy informatics, sustainable energy, smart grid, business model, smart cities, Electric vehicles integration

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***Correspondence:**
Bokolo Anthony Jnr.
anthony.j.bokolo@ntnu.no

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INTRODUCTION

A smart city is a city where residents can securely gather, manage, and disseminate data that relates to all areas of their daily lives in a sustainable and ubiquitous manner (Heo et al., 2014; Anthony Jnr, 2020a). In smart cities services provided to citizens are facilitated by Information and Communication Technologies (ICT) in a resourceful manner (Zuccalà and Verga, 2017; Jnr et al., 2020a). Smart cities comprise of different sectors such as smart building, mobility, energy systems, water and air quality, climate change, etc. (Zuccalà and Verga, 2017). However, this study is aligned to Electric Vehicles (EVs) in the context of sustainable energy. Sustainable energy systems can lessen harmful emissions and increase resources usage more efficiently. Integrating EVs in smart cities may create such benefits by providing energy storage and creating new revenue streams from EVs batteries (Bedogni et al., 2013; Bohnsack et al., 2014). Presently, the adoption of EVs is increasing with global sales amounting to about 5% by 2020. Likewise, the European Union (EU) is committed to minimize Europe's greenhouse gas emissions to about 80–95% in 2050.

Therefore, the production and use of energy are changing as such electrical and energy systems are important infrastructures utilized in smart cities. The integration of EVs is expected to pave the way to green mobility with zero carbon emissions (Karpenko et al., 2018). Simultaneously, the use of EV are getting significant attention across the world. The emergence of EV introduces new opportunities and threats to existing energy system. Accordingly, findings from the literature reported that by the end of 2016 ∼1.3 million EVs were globally in used (Eider et al., 2017). EVs may range from hybrid electric cars, plug-in electric cars, and hydrogen vehicles, and may utilize one or more traction engines or electric engines for propulsion (Hinz et al., 2015). EV comprises of e-buses, e-bikes, e-cars, e-scooters, and e-railway (Kirpes et al., 2019), that contributes to reduce pollution in cities thereby achieving deep decarbonization in the transportation sector (Sanseverino and Sanseverino, 2018). Evidently, the integration of EV in smart cities can lead to synergies with smart demand-side systems, distributed generation, and renewable energies in improving the usage of energy assets in energy grid. This is because EV can be scheduled to recharge when energy demand is low thus generating cost savings for EV users (Weiller and Neely, 2014). Besides, EVs can serve as energy storage and supply providers if they are used in bulk by an intermediary, generally denoted to as aggregator.

Clearly the profitability of integrating EVs within the energy grid or domestic-based energy services depends on the magnitude and volatility of energy prices in the retail and wholesale energy markets (Weiller and Neely, 2014). Additionally, EVs can be suitable energy sources in the event of blackouts. In areas prone to power disruptions, such as in many emerging economies. An EV battery of about 24 kWh (100-mile range) can provide 2 days of power supply for an individual household (Weiller and Neely, 2014). For example, EVs can offers up to 16 kWh electricity capacity for domestic use (Weiller and Neely, 2014). Accordingly, to utilize clean energy sources EVs can be charged domestically via home generation sources such as solar panels and can further be utilized to arbitrage energy prices through smart charging and discharging, to enter decreased-price contracts with energy suppliers, and to deliver back-up electricity services in the cases of power disruptions (Weiller and Neely, 2014).

While, EVs have the precise attribute to decrease environmental degradation, cities are faced with the challenge of how to deploy business models that comprises of components required to transforms EVs as a source of economic value (Bohnsack et al., 2014). Also, prior studies related to EV usage in smart cities mainly examines the technical solutions without fully exploring the business perspective as regards to the viability or feasibility of large-scale integration of EVs in smart cities (Weiller and Neely, 2014). Grounded in the literature, this study addresses this gap in theory and practice by identifying the EV components and actors involves in achieving a sustainable energy as a service business model in smart cities. The remainder of this study is structured as follows. Section 2 is literature review, and then section 3 is the methodology. Findings is presented in section 4. Section 5 is the discussions and implications, and section 6 is the conclusion.

LITERATURE REVIEW

Over the past years, a research trend toward the adoption of EVs has been observed in smart cities as EVs enable the decrease of urban carbon dioxide (CO_2) reduction schemes. Accordingly, few studies have been carried out in order to improve the mainstream integration of EVs by citizens in a flexible and efficient manner. Among these studies Anthony Jnr (2020b) employed enterprise architecture approach to facilitate digital transformation of EVs for electro mobility toward sustainable mobility. The author aimed to achieve data integration of electric mobility solutions from diverse stakeholders and systems involved in urban mobility services. Another study by da Silva and Santiago (2019) investigated the optimal electricity trading policy for solar powered microgrids using a modeling approach for plug-in hybrid EVs. The study highlighted that battery management is important to promote the extensive integration of microgrid connected EVs.

Additionally, Karpenko et al. (2018) explored how data exchange and interoperability cab be attained in an Internet of Things (IoT) ecosystem for EV charging and smart parking. Their research focused to resolve problem of non-interoperability that hinders seamless communication among different applications used with EVs and charging stations which uses different interoperability standards. Li et al. (2017) investigated how big data analytics can be employed to improve EV integration for green smart cities. Thus, data analytics technique was utilized for handling big data of EVs and smart grid in providing data analytics solutions and needs for EV integration to smart cities. Shuai et al. (2016) conducted a survey on EV charging in the smart city grounded on an economy driven approach. The authors provided an overview of economic approaches by considering the bidirectional energy flows and unidirectional energy flows in the energy grid via EV charging.

Furthermore, Hinz et al. (2015) aimed to improve the adoption of EV by providing complementary mobility services grounded on a two-step approach. The authors attempted to address the substantial gap regarding the use of EVs as a strategy to lessen oil consumption and reduce climate problem added by mobility services. Rodríguez et al. (2015) researched on EV integration within smart grids via interoperability solutions. The authors evaluated interoperability for all level of physical systems including stakeholder connections in providing services in relation to existing regulatory schemes and business models. Weiller and Neely (2014) examined the usage of EVs for providing energy services based on an industry perspective. A conceptual framework was proposed that identifies several services EVs can provide. Also, the factors such as social barriers, technology maturity, and corporate strategies that impacts the adoption of EVs are captured by the researchers.

Based on the reviewed studies that explored EV integration in smart grid or/and smart city. None of the studies explored how to achieve sustainable energy as a service business model in smart cities by considering the actors and components as well as the barriers that impends integration of EV in smart cities and recommendations to improve EV integration within smart cities.

METHODOLOGY

This study adopts a review of secondary sources to explore how EVs can achieve sustainable energy as a service business model in smart cities.

Inclusion and Exclusion Criteria

In the inclusion criteria first, the title and abstract of the retrieved sources were examined. Next, only papers that were related to EV integration in smart city or/and smart grid were included. In addition, for exclusion criteria all articles written in languages other than English language were excluded. Finally, empirical evidence was synthesized and extracted from the included articles. The selected articles were studied in detail.

Search Strategies, Data Sources, and Quality Assessment

To search for related papers an online search from digital libraries (Google Scholar, ScienceDirect, ProQuest, Springer, Wiley, IEEE Xplore, ACM, Emerald, Taylor and Francis, ISI Web of Science, Sage, Inderscience, and Scopus), were employed. These online libraries were employed because they are considered appropriate search engines for review in smart cities and sustainable energy research. To ensure that a comprehensive search was employed search terms or keywords were formulated. The search strings were framed with Boolean operators (AND, OR) to improve searching of relevant studies and to increase the quality of the search process. The main search terms comprise of electric vehicles OR Energy as a Service OR Electric vehicles integration AND business model AND smart grid AND smart cities. Thus, several articles were retrieved from digital libraries and some articles were assessed based on an inclusion and exclusion criteria in relation to the aim of the study (explore how to integrate EVs can achieve sustainable energy as a service business model in smart cities).

Figure 1 shows the Preferred Reporting Items for Systematic Reviews and Meta-Analysis (PRISMA) flowchart which was used for screening of articles as previously utilized by Anthony Jnr (2020d), Anthony Jnr and Abbas Petersen (2020). The final search resulted to 114 articles using the keywords above. No articles were established as duplicates resulting to 114 articles. The articles were checked against the inclusion and exclusion criteria and 55 sources were removed since they were not related to integrating EVs to achieve sustainable energy as a service business model in smart cities resulting to 59 articles. The remaining articles was checked for quality assessment. A check was carried out to verify if the articles were indexed in Scopus or/and ISI Web of Science databases. The findings suggest that more than half of the selected studies meet the inclusion and quality assessment criteria.

Data Analysis

Descriptive analysis was employed similar to prior study (Lin et al., 2013), to quantitatively explain the main features and implications of integrating EVs into the energy grid. Therefore, this study provides descriptive analysis of secondary data sourced from research articles and content analysis is employed as the main method to systematically gain a comprehensive analysis of empirical evidence. Findings from secondary sources used in this study are not statistically represented, but they provide rich understanding toward policy related to EV integration in smart cities.

FINDINGS

This section provides findings from the literature based on descriptive analyses of secondary sources.

Energy Informatic for Sustainable Society

Presently, Information System (IS) researchers are exploring how to counteract increased greenhouse gas emissions (GHG) toward supporting sustainability of energy system termed as energy informatics (Kossahl et al., 2012). Respectively, this current study belongs to the energy informatics domain as specified by Watson et al. (2010), since this study investigates how Information System (IS) components and actors are into a business models for integrating EVs to contribute toward energy sustainability of smart cities. According to Watson et al. (2010), Brandt et al. (2012) energy informatics is concerned with the role of Green Information Technology and Green IS initiatives can contribute to shaping the energy grid of the future.

Energy informatics further entails the analyzes, design, and deployment of sustainable systems to improve the productivity of energy supply and demand systems (Watson et al., 2010; Jnr, 2020; Jnr et al., 2020a,b). Thus, IS components deployed in EVs are envisioned to play a significant role on the quest for cities to attain a decarbonized and sustainable energy system (Kirpes and Becker, 2018). Therefore, to fully achieve a sustainable energy adoption in cities while transitioning to a low carbon energy system, decision makers need to employ renewable energy generation strategies to foster the integration of EVs in smart cities (Zame et al., 2018). Although, the integration of EVs has been highlighted in the literature, energy as a service business model as related to the integration of EVs has not been sufficiently explored.

Background of Smart Cities and Sustainable Mobility

Urban areas are inhabited by about half the world's inhabitants and its expected that in 2050 the population in these urban areas will increase to ∼2.6 billion to 6.3 billion residents (Spickermann et al., 2014). Due to these urban challenges the topic of smart cities is globally gaining prominence (Anthony Jnr et al., 2020). Smart cities can bring future environmental, social, and financial benefits supported by technological innovations and digitalization (Ekman et al., 2019; Anthony Jnr, 2020c). Hence cities are becoming smart by implementing digital innovations in providing smart services that make life easier for citizens (Ekman et al., 2019; Anthony et al., 2020). Besides, a smart city is a social system that integrates business and technology into the society (Ekman et al., 2019).

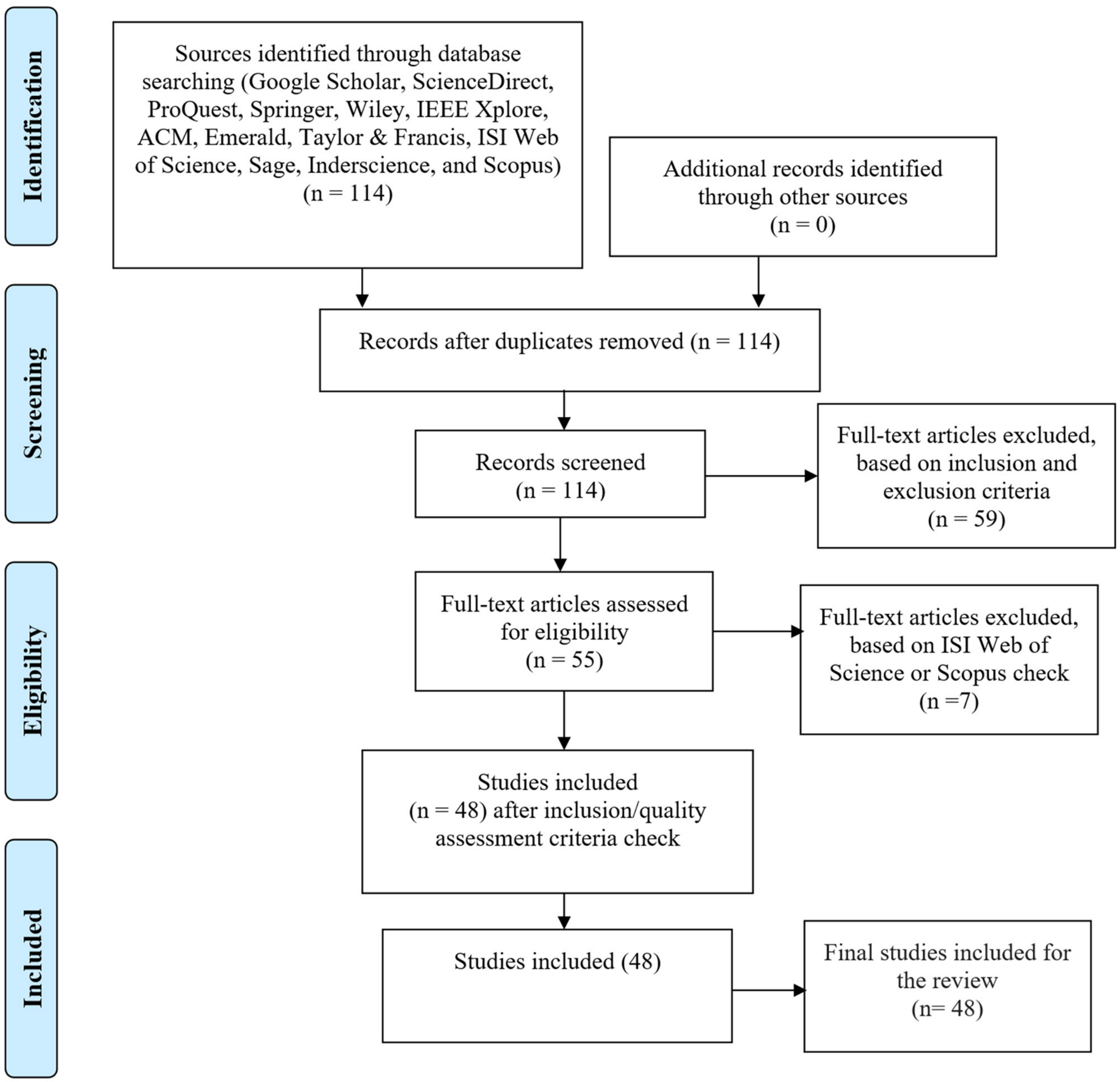

FIGURE 1 | PRISMA flowchart for the selected articles.

Smart city is a digital transformation where new actors arise and old actors may disappear due to the effect of deployment of disruptive technologies and new business models (Ekman et al., 2019; Anthony Jnr, 2020c). The fact that a substantial increase of the urban inhabitants is expected over the coming years leads to the postulation that the transport sector will be impacted within the next decades. As the number of vehicles in cities might significantly increase and pollution issues (Tcholtchev et al., 2012; Anthony and Petersen, 2019). Evidently, urban mobility is one of the main issues faced by cities. Therefore, there is need to improve the current urban mobility infrastructures by resolving the social, economic, and environmental constraints for a sustainable and competitive urban mobility systems (Spickermann et al., 2014). One possible alternative for achieving sustainable mobility in smart cities is the adoption of EVs such as electric bicycles, electric cars, segways, etc. (Tcholtchev et al., 2012).

Role of Smart Grids and Sustainable Energy Systems

Rapid growth and urbanization across the world and the increased need for energy related services necessitates the need to create more innovative business models in smart cities (Sanseverino and Sanseverino, 2018). Energy systems are deployed in smart cities such as smart appliances, energy sensors, smart meters, and smart grid. Smart sensors and meters can record and report energy consumption automatically and are one of the key enablers of sustainable energy transition (Cavoukian et al., 2010). The EU targets to install smart meters in ∼80% of EU households in majority of member states as part of their energy policies aimed at supporting the balancing of electricity supply and demand within the energy grid. Thus, supporting climate change or sustainable energy policies (Zame et al., 2018). An example of a smart meter deployed in smart cities is the Advanced Metering Infrastructure (AMI) which supports bidirectional electricity flows utilizing a two-way communication allowing Energy Service Providers (ESPs) to receive electricity consumption data of residents (Vaidya and Mouftah, 2018). It also supports sending control signals or pricing back to customers in real time (Vaidya and Mouftah, 2018).

One of the energy systems in smart city is the smart grid which provide a transition toward a more sustainable energy system (Bellekom et al., 2016). In general, a smart grid is refers to as an electricity network that can autonomously integrate the actions and behavior of actors (such as producers and consumers), connected to it in order to achieve an economic, sustainable, and secure energy supplies (Rathnayaka et al., 2012). A smart grid deploys ICT with advanced energy infrastructure to achieve a bidirectional flow of information and electricity. It is self-healing as it quickly detects disruptions and rapidly recovers. It is also resistance to cyber-attacks and mitigates and improved energy quality, and facilities the interconnection to achieve plug-and-play (Rathnayaka et al., 2012). A smart grid employs a centralized generation and top-down distribution based on paradigm shift from the present energy network to a new digitalized grid (Giordano and Fulli 2012). A smart grid is envisioned as the next generation energy grid (Mustafa et al., 2014), and plays an important role in smart cities thereby facilitating smart decisions based on information to provide flexibility for energy usage for domestic use or for a city (Heo et al., 2014).

Smart grid aims to achieve energy resource management in a more efficient, resilient, and reliable manner (Cavoukian et al., 2010; Mustafa et al., 2014). The smart grid is different from the traditional energy grid as the traditional grid focused on the connections between the transmission, generators, and distribution (Rathnayaka et al., 2012; Anthony Jnr et al., 2020). Traditional energy grids are unable to manage complex energy scenarios. Thus, in the traditional energy grid users do not actively participate (Heo et al., 2014). The consumer only consumes the energy provided by the utility company and pay the electricity bill. In comparison, in the smart grid the energy consumer (typically called a prosumer), not only utilize energy but also generate and provide electricity back to the grid (Anthony et al., 2019). EVs are recognized as a main contributed in the realization of the smart grid vision since their batteries can possibly be utilized as a flexible electricity storage (Mustafa et al., 2014). Thus, the smart grid can manage EV connection, charging, and incorporating cleaner sources of energy into the energy grid thereby providing consumer control over energy cost and usage (Cavoukian et al., 2010).

Role of EVs in Smart Cities

The need to increase environmental concerns and reduce oil supply has sprung the need for research toward the electrification of the transportation sector, and technological development have advanced the rapid integration of EVs in cities. The term electric vehicle refers to vehicles deploying electric motor(s) for propulsion, comprising both rail and road vehicles, underwater and surface vessels, as well as electric aircrafts (Eider et al., 2017). EV aids electricity management as the batteries can store energy to be used as reserve of energy when the EVs are idle. Thus, EVs can serve as energy storage facilities by providing the needed flexibility to the smart grid operator. By providing energy back to the grid, thereby serving as a distributed energy source. Accordingly, EVs can be leveraged by network operators to enhance renewable energy usage for self-healing or to provide supplementary energy services, so as to lessen the dependency on diesel source generators (Eider et al., 2017). Thus, lessening electricity fluctuations and inefficiencies faced in today's grid. Similarly, for energy suppliers the electrification of vehicles offers off-peak supply and demand, which lessens the burden on the energy grid during peak hours (Dijk et al., 2013).

EVs can support additional services such as power factor regulation, voltage support, renewable energy tracking, active harmonic filtering, peak shaving, and load balancing. Additionally, in case of power outage EV can be utilized as an emergency backup source in residential area (Li et al., 2017). Conversely, EV load within the energy grid can upsurge energy prices up, and change energy generation resulting in an increased CO_2 emission. Additionally, resulting to uncontrolled charging and high penetration which threatens the sustainability of electricity distribution networks (Eider et al., 2017). As highlighted by Dijk et al. (2013) EVs may become the connection between energy and the transportation sectors. Additionally, the integration of EVs in smart cities provides large amounts of data that can be utilized to create new opportunities and business models for enterprises improving their competitive positions and business strategies of companies involved in EV adoption (Dijk et al., 2013).

Electric Vehicles as Flexibilities in Smart Cities

Climate change and the increased need for energy are driving policy makers to explore how to improve the adoption of sustainable services and products (Kotilainen et al., 2017). Transportation and energy both contribute to 49 percent of total greenhouse gases released to the atmosphere. Findings from the literature revealed that EVs has been sustainable adopted using Renewable Energy Sources (RES) and Vehicle to Grid (V2G) deployment (Kotilainen et al., 2017). EVs can offer pervasive services in the form of energy demand response via the EV batteries which store electrical energy. Thus, EVs can be used for driving/mobility purposes as well as for energy services making the batteries as asset (Weiller and Neely, 2014). Evidently, EV can contribute toward the transition to a sustainable energy demand supply system for the energy grid where peak and baseload demand is managed in association with supply sources from renewables. EVs provides the opportunities to provide a Vehicle-to-Grid (V2G) or Grid-to-Vehicle (G2V) capabilities.

G2V involves the flow of electric energy from the energy grid to the EV (Anthony Jnr et al., 2020) or simply the charging of the EV battery from the energy grid (Brandt et al., 2012), whereas V2G involves the return of energy from the EV battery into the energy grid. This helps to achieve a synergy between the electricity system and EV fleets (Hinz et al., 2015). V2G allow the EV to be able to function as energy storage that could be charged at night and can displace consumer's load during daytime when the vehicle is not in use (Brown et al., 2010). EV owners can charge their EV battery when energy cost is low and feed in the energy grid when there is high prices and high demand (Hinz et al., 2015). However, V2G entails two-way transmission of energy between the EV and the charging station, a feature which only exists in some manufactured EVs such as the Mitsubishi i-MiEV but may not be available for other standard EVs (Weiller and Neely, 2014). As EVs can charge at a rate of about 50 kW and discharges via V2G technologies at a rate restricted to about 3.7 kW on a standard European energy grid or intermediate charging of about 20 kW (Weiller and Neely, 2014).

Besides, the integration of V2G involves deployed EV to be equipped with a link to the energy grid for flow of electrical energy, deployment of communication control by the grid operator, and lastly vehicle on-board control and metering systems (Rathnayaka et al., 2012; Vaidya and Mouftah, 2018). The on-board metering sensors will facilitate tracking of energy flows from and to the EV. This will help for better energy resources management and provides opportunity for arbitrage (Eider et al., 2017), for EV owners and EV fleet owners, or EV charging stations to get money by trading energy power to the grid (Brown et al., 2010; da Silva and Santiago, 2019). This also helps to mitigate peak demand shocks within smart cities and offers the grid operator with a cost-effective medium to balance supply and demand, relying on EV batteries as energy buffers or storage facilities (Eider et al., 2017).

As pointed out by Eider et al. (2017) EVs are often faced with electricity transmission and/or DC/AC conversion losses. Thus, electricity losses should be considered when EVs receives and provide energy services through V2G. Additionally, the integration of EVs for V2G capabilities enabling the possibility that stored energy could be feed back to the energy grid, requires that EV chargers are potential sources for power quality disturbances and harmonics (Brown et al., 2010). Moreover, there may be associated risks involved when integrating V2G capabilities of EVs into the energy grids which may lead to significant increase of electricity prices from the energy grid. This is mostly the case for real-time pricing, where the local energy production does not match local energy demand. This risk is also related with the current price of electricity from the energy grid, leading to risk of peaks of electricity demanded from the microgrid (da Silva and Santiago, 2019).

Overall, EVs have a large potential for decreasing CO_2 emissions and fossil fuels consumption. EV owners can now generate their own electricity directly from solar photovoltaic panels or other Renewable Energy Sources (RES), installed residentially. The generated electricity from RES can be commercialized with the energy grid or consumed by the residential owner. Such flexibility support EV owner to become an energy producers and consumers, termed as a prosumer (energy producer + energy consumer) (da Silva and Santiago, 2019). Thus, EVs connected to the grid can basically contribute as loads on demand or as generators. However, in smart cities for the fully potentials V2G to be achieved several EVs needs to be aggregated as fewer EVs may only have little impact on the energy grid frequency (Brandt et al., 2012). Evidently, there have been several studies on EV aggregation schemes, but only fewer studies have provided an extensive business model on the integration of EVs to implement energy as a service eco-system in smart cities.

Proposed Energy as a Service Business Model in Smart Cities

A business model comprises of a set of activities an enterprise or group of organizations performs, how they perform the activities, and when the activities are performed. It also entails how resources are used to perform these activities by the organization(s) to create lower cost, value added services and products to customers and stakeholders (Kley et al., 2011). In the context of this study a business model can be an ecosystem that comprises of technical components and stakeholders' capabilities and processes which specifies the services and functions that enabling cities to become smart cities. The business model aims to manage and aggregate information from a wide variety of stakeholders or actors as well as components (i.e., energy devices and energy sensors, energy assets, etc.), required to enable energy management and finally presentation of data as information to all stakeholders involved in the energy system within smart cities (Zuccalà and Verga, 2017). Accordingly, based on findings from prior studies (Dijk et al., 2013; Mustafa et al., 2014; Kirpes et al., 2019) the energy as a service business model for EV integration in smart cities is proposed as presented in **Figure 2**.

Figure 2 depicts the actors and components in the energy as a service business model for EV integration in smart cities, where each of the components are used by the actors in achieving a sustainable energy system in smart cities. The components work together for successful EV integration in smart cities to help achieve decarbonization strategies, reducing operational and maintainable cost of EV (Dijk et al., 2013). The interaction of the actors and connection of the components can help to develop EV adoption in smart cities which is important for harmonizing the interaction between the various energy systems and stakeholders, e.g., grid operators, car manufactures, charging station operators, energy suppliers, e-mobility service providers, and EV users (Kirpes et al., 2019). Next, each of the components and actors are described in **Table 1**.

Accordingly, **Table 1** describes the actors and components in the energy as a service business model in smart cities. The DSO is the energy grid operator or Transmission System Operator (TSO) who offers the grid technologies either directly to the EV fleet operator or to the charging station operator, where both actors are provided with electricity power from the energy supplier. The charging station operator mostly provided charging

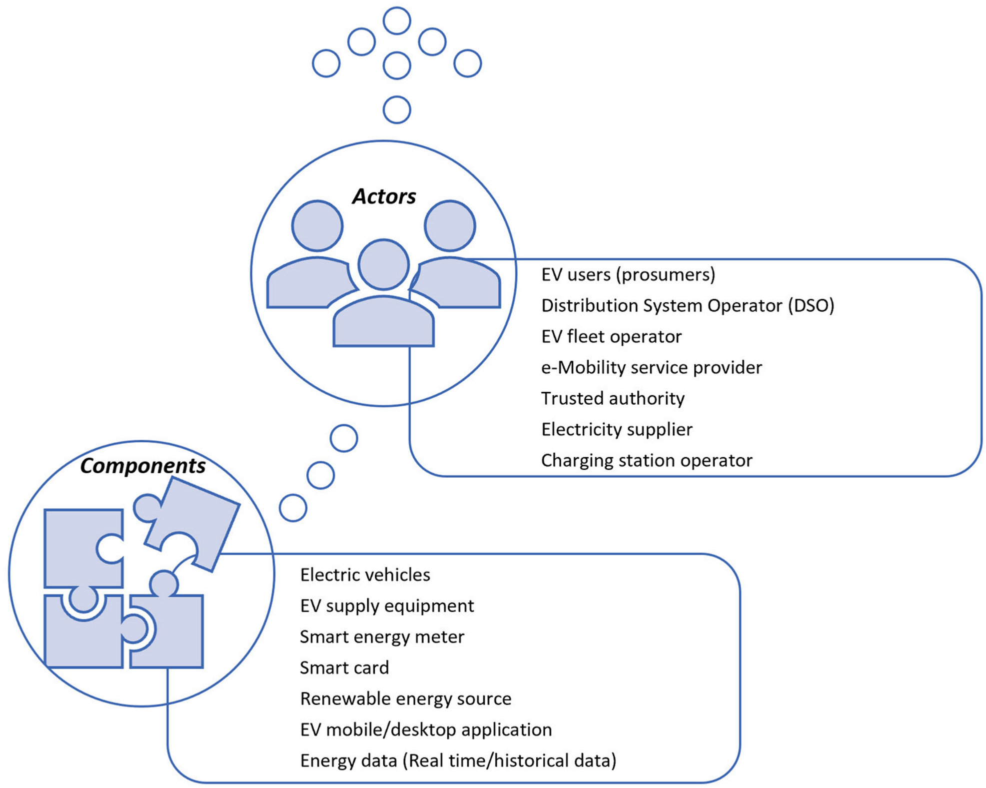

FIGURE 2 | Proposed energy as a service business model for EV integration in smart cities.

infrastructures to EV user and enters into a mutual agreement with the eMobility service provider (Kirpes et al., 2019). Thus, digitization and synergies among all actors and components presented in proposed energy as a service business model in smart cities not only including stakeholders from the energy sectors but may also other domains such as real time/historical data which are important to manage transportation in smart cities (Kirpes et al., 2019).

Optimization of Electric Vehicle Charging Stations

To realize sustainable energy transition, efficiently energy system, and zero-emission vehicles in smart cities the integration of EVs are envisioned to play an essential role (Kirpes et al., 2019). In smart cities EVs can be charged based on demand-side management which refers to the option to plan EV charging during low demand on the energy grid (Dijk et al., 2013). Presently, EV charging can be performed in several ways as EVs can utilize an off-board or on-board charger or use an inductive charging while parked via Inductive Power Transmission (IPT) infrastructure (Eider et al., 2017). EV batteries are charged by means of an onboard charger and Electric Vehicle Supply Equipment (EVSE), also referred to as charging stations. EVSEs can be installed at residential premises, parking lots of commercial buildings, and along roadside charging facility (Li et al., 2017). EV connected to the energy grid mostly consume from 3 to 50 kW energy but can also consume up to 100 þ kW of energy at fast-charging stations e.g., as used by superchargers (Weiller and Neely, 2014).

Prior studies in the literature explored smart charging of EVs which comprises of concepts facilitated by ICT to reduce the impact of EV charging operations on the energy grid from an economic and energetic perspective (Kirpes et al., 2019). Smart charging is enabled by ICT to reduce the impact of EV charging on the energy system on economic and energetic level (Kirpes and Becker, 2018). In smart cities the charging stations are geographically dispersed but integrated into a single network. All connected charging station are intelligently setup to provide data emitted on their electricity costs, individual status, geographical location, energy consumption, available voltage, power type, charging speed, plug type, cable available, and locker available (Karpenko et al., 2018), which is send to the EV mobile/desktop application used by the EV user (Tcholtchev et al., 2012). The classification of the charging facilities for EVs are shown in **Figure 3**.

Figure 3 depicts the different types of charging facilities for EVs. One of such charging stations is the individual stations which is deployed in residential areas or located in individual homes capable of charging a single EV. This comprises of single charging station for private or home garages and public charging. Also, there are EV charging stations installed in parking lots which comprises of public and private EVSEs within close

TABLE 1 | Actors and components in the energy as a service business model.

Actors and components	Description
EV users (prosumers)	An EV user who is in charge for paying for the EV charging sessions. The EV user drives the EV after charging and may also provide energy back to the energy grid as a prosumer.
Distribution System Operator (DSO)	The role of the DSO is to increase the inflows of energy from RES as well as ensure. That certain qualities are adhere to when amidst the energy demand and supply.
Electric vehicles	This is a battery-powered vehicle which includes e-cars, e-scooters, e-bikes, e-buses, and e-railway.
EV supply equipment	A device that connects EVs to the energy grid, measures the electricity utilized by the EV.
EV fleet operator	The EV fleet operators manage the fleet of EVs by optimizing charging in relation to costs, proportion of renewable energy uses, energy grid, and battery-friendliness (e.g., to sustain the durability and health of the battery). The fleet operators are presently evolving as a main contributor that influence the directions of EV commercialization and development.
e-Mobility service provider	The e-Mobility service provider provides different EV related as services to the EV customers, such as booking, parking, billing process, etc.
Smart energy meter	This is an advanced metering device that measures EV user's electricity usage and production in the EV user's residence or charging station.
Smart card	This is a tamper-proof hardware that records and retains EV user's personal data, employing secured techniques such as cryptographic keys, hash algorithms, etc.
Renewable energy source	An energy source from solar panel, wind turbine, etc. located at the EV user's residence or charging station.
Trusted authority	This is usually a trusted body such as an electricity market regulator that initializes and monitors the entire energy system and certifies other stakeholders using public keys to ensure transparency and authentication.
Electricity supplier	This is a utility firm that oversees supplying electricity to its users or customers that consume electricity.
Charging station operator	Mostly provides charging facilities to the EV user ensuring a bilateral agreement with the eMobility service provider. The charging station operator also aims to increase EV charging services and net profit via deployment of ICT to lessen the impact of EV charging operations on the energy grid from an economic viewpoint.
EV mobile/desktop application	The EV user utilize this application in their mobile devices or personal devices to select a charging station, for example based on greenness or cheapest indicators on the planned journey route. Also, the application provides information related to EV use within the cities. It provides data on number of EV charging connectors, EV charging type, status of EV charging connector, etc.) as related to EV charging stations.
Energy data (Real time/historical data)	Encompasses data from smart energy meters, EV energy on energy produced and consumed, journey information, parking, and charging. Also, data on sensors and controllers in the EV, EV battery-health service, and Battery State of Charge (SoC). The data is used by the on-board control and metering systems such as battery health suggestions, EV usage, and advanced charging services like dynamic prices, reservation, and grid-friendly charging or green charging via RES.

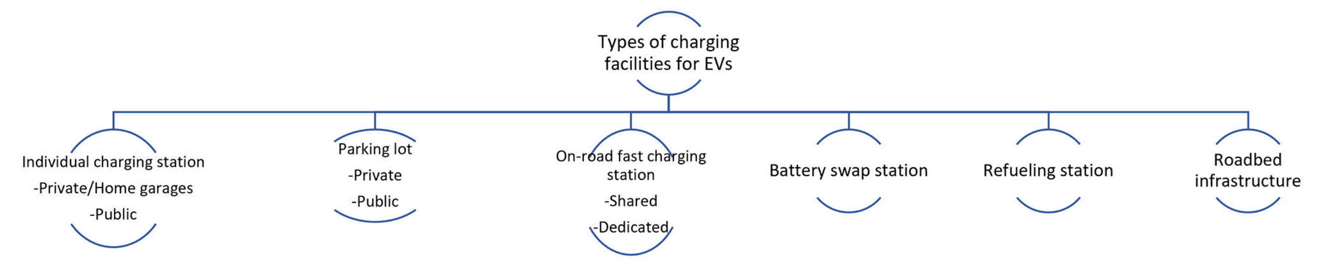

FIGURE 3 | The classification of the charging facilities for EVs adapted from Eider et al. (2017).

physical proximity. The public EV charging stations are mainly open to any EV, whereas the private EV charging provide access only to an explicit fleet or types of EVs. For example, EVs owned by a particular company. Another type of charging is the on-road charging stations which are deployed as relays for EVs on long distance journeys. The on-road type employs fast charging station which are dedicated and shared. Thus, EVs can generally charge their battery at the highest rate possible to reduce the delay. Accordingly, roadbed technologies are now provided for EVs based on wireless power transfer solutions (Eider et al., 2017).

Additionally, other types of charging facilities are battery swap stations where the EV user changes battery for newer charged battery for a subsidized fee from the manufacturer based on a stipulated agreement from the EV manufacturer. This is done when the EV us being used for a long-distance journey. The last two charging stations are the refueling station and roadbed infrastructure (Eider et al., 2017). The EV refueling station are used by EVs that have converters on board that plug into a high-capacity appliance outlet or standard electrical or outlet. Currently, these refueling stations can facilitate faster charging at higher currents and voltages as compared to residential charging infrastructures. Lastly, the roadbed infrastructure comprises of contact-less inductive power transfer system for specific EVs.

Barriers and Recommendations for EV Integration

Barriers That Impends the Integration of EV in Smart Cities

For cities to achieve a sustainable low carbon economy there is need for innovative and adoption of a range of carbon neutral technologies for providing sustainable energy and other environmental services (Anthony et al., 2019). Prior literature on sustainable energy production and storage suggest the integration of EVs can support sustainable development of smart cities (Anthony Jnr et al., 2020). In several countries such as Norway etc. EVs were subsidized and exempted from paying for road tax (Hinz et al., 2015; Zame et al., 2018), and adequate parking spaces are mostly reserved in the city centers for purely battery powered EVs without any time constraint (Lieven, 2015). But, while the integration of EVs are increasing around the world, major barriers still hinder the fully integration of EVs in smart cities (Kirpes and Becker, 2018). Issues such as procurement cost, inadequate awareness of governmental incentives, battery range, taxation policies, and charging interoperability are mitigating against the adoption of EVs (Kotilainen et al., 2017).

In relation to price of EV findings from the literature (Hinz et al., 2015), highlighted the importance of price which includes EV purchase price and EV charging costs. Besides, the price difference between EV original purchase price and an internal combustion engine vehicle is still extensive. Even though EV maintenance cost is less expensive, the initial money needed is the purchase of EV is quite high (Kotilainen et al., 2017). Hence, EVs integration is faced with techno-economic and societal challenges, varying from infrastructural requirements to users doubts concerning EV price, charging time, non-ubiquity of EV charging stations (Li et al., 2017), safety, reliability, distance range, maintenance service availability, and battery life durability (Rodríguezet al., 2015; Karpenko et al., 2018). Although newly developed battery technologies provide more power, longer ranges, and a reduced recharging time (e.g., the new water-based battery by General Electric and lithium-ion technology by Toyota) (Zame et al., 2018).

In addition, there are concerns that with increase in the EV market, the impact of EVs usage on the energy grid may result to adverse impacts such as increased losses, peak loading, voltage deviations or unbalance, and need for further network reinforcements (Li et al., 2017). This may lead to high stress on distribution systems of the smart grid. Due to increased energy consumption on the energy network during peak hours (Li et al., 2017). Although integration of EV delivers numerous benefits to the smart grid and enables consumers to be prosumers. In smart cities energy systems has increasingly become susceptible to a wide range of security issues and cyber-threats. Basically, these energy systems such as smart grid infrastructures and EVs collects citizens personal data that is utilized for several purposes such as real-time energy pricing and energy demand response. However, there is need to address data security and privacy issues (Vaidya and Mouftah, 2018).

Recommendations for Integration of EV in Smart Cities

The emerging prospect for EV to revolutionize both the energy and transportation sector over the next the coming years is immense. The integration and use of EVs contributes to lessen air-pollution in urban areas, decreases noise, and potentially uses environmentally friendly electricity from RES to charge the batteries. But, to achieve a smooth integration of EVs in smart cities there are technical, economic, and social issues that should be addressed. Technical issues related to infrastructural limitations within the different areas, economic, and regulatory setbacks need to be considered. As the continually evolving EV market also requires legal frameworks and innovative business models that can conform with future technological innovations (Kirpes al., 2019). Another social-techno challenge relate to compatibility and standardization polices. Thus, researchers such as Brown et al. (2010) argued that standardization can help promote the adoption of EV in cities.

Therefore, compatibility and standardization across EV-related infrastructure and technologies will be a crucial factor that will significantly influence the integration of EVs in smart cities. EV standardization is not only relevant for the mobility sector, but is also concern with how electricity is generated, stored, and distributed within the smart grid through V2G technologies (Brown et al., 2010). New standards and regulations can be put in place for EV related systems, infrastructures, and designs to promote integration of EV by establishing consistent and compatible design within the energy systems (Brown et al., 2010). Such polices can be directed to ensure that electricity generation from EVs should originate from low-carbon and cleaner sources (Brown et al., 2010). Additionally, battery management should be enhanced to increase the driving range and decrease charging impact on the smart grid (Kotilainen et al., 2017). The driving behavior of EV users and routing may be incentivized to further contribute to reducing battery discharge time (Eider et al., 2017).

EV fleet management firms should employ an optimized fleet routing and charging to contribute toward EV and smart grid integration RES utilization (Eider et al., 2017). EV charging stations should be managed in co-ordination with other actors as seen in the proposed business model (see **Figure 2**). Another area of concern is data security and privacy for EV user as a lack of security might impact consumers participation as prosumers within the smart grid (Giordano and Fulli, 2012). Data security should employ methods to ensure confidentiality and integrity of data and availability of ICT related systems deployed within EVs (Vaidya and Mouftah, 2018). Ensuring data security helps to reduce leaking of customers personal information, individual behaviors, daily activities, etc. Privacy is concern with the interests, rights, and values of EV users. As stated by Vaidya and Mouftah, (2018) data privacy should ensure privacy of personal data, privacy of the individuals, privacy of private behavior, and privacy of private communications. Similarly, data privacy emphasizes the consumer's ability to manage the use, collection, and dissemination of his/her personal data.

DISCUSSION AND IMPLICATIONS

Discussion

Over the decade the use of EVs in cities has increased mostly due to an efforts to mitigate climate change, government incentives for EV related to international competitiveness and economic stimulus, as well as a pressure by governments to promote sustainable energy production and usage (Brown et al., 2010). The integration of EV in smart cities supports sustainable energy more when RES is used to charge the EV battery and EV is employed for demand response via V2G connection to balance peak-off peak consumption to further assist in demand smoothing (Brown et al., 2010; Kotilainen et al., 2017). Overall, findings from this study show that prior works have explored the social, institutional, and regulatory issues relating to adoption of EVs in smart cities and in particular toward improving the technological development of smart grids. Also, literature addressing integration of EVs has primarily considered technical issues such as the optimal range of EV or EV charging facilities, adoption/acceptance of EVs to decrease greenhouse gas emission, and EV sales predictions (Lieven, 2015).

Accordingly, this study employs secondary data to explore and provide a business policy viewpoint on EV integration in smart cities. This study also presents an energy as a service business model in smart cities. The proposed business model depicts that the integration of EVs is highly dependent on the collaboration of actors or stakeholders and components. Findings from this study also suggest that EV usage have proved to be one of the main practices toward lessening CO_2 emission for sustainable energy and mobility. As EVs allow for synergies with a smart grid based on clean energy from RES (Schuh et al., 2013). On the one side, the integration of EVs in smart cities has emerge as a great challenge due to several issues as discussed in section Barriers and Recommendations for EV Integration, but it also provides an opportunity to develop the smart grid.

Implications for Policy and Practice

Given the increased demand for electricity resulting from rapid economic growth, issues related to environmental protection, climate change, and sustainable development have become important (Lin et al., 2013). Hence, it is crucial to abate carbon emissions and conserve energy by promoting employing environmentally friendly practices (Jnr, 2020; Jnr et al., 2020a,b). One of the environmentally friendly practices that can effectively decrease CO_2 emissions is the utilization of renewable energies, such as solar, geothermal heat, wind, tides, and rain to replace the combustion of fossil fuels (Lin et al., 2013). Additionally, the integration of EVs can contribute toward sustainable energy transition of cities. However, the issues relating EV integration policy have not been discussed considering the business model. Thus, the lack of research studies on business model approach for EV integration will make it difficult to specify the actors and components involved within smart cities toward effective development of the smart grid systems. In this context, this study provides a business-oriented approach to fulfill the vision of EV integration in urban context.

As cities now use EVs for environmentally friendly transportation and energy source to efficiently deliver green, secure, and economic energy supplies (Zame et al., 2018). Additionally, this study explicitly considers the prospects for a new business model innovation to support EV integration. Although prior studies (Brandt et al., 2012; Dijk et al., 2013; Anthony and Petersen, 2019; Jnr et al., 2020b), explored different EV adoption scenarios, such as eMaaS concepts, they do not explicitly investigate strategies for different actors and components or issues that impacts the integration of EVs in urban context. This research provides a business model (see **Figure 2**) to support policymakers in the energy sector to enhance their EV implementation, policies outcomes and quality of their environmental initiatives. By integrating this model into their current policy planning they can improve collaboration of stakeholders involved in EV adoption in smart cities.

This article also sought to contribute to the literature on energy sustainability by identifying barriers that impacts EV integration and to provide recommendations on how industry, researchers, and policymakers can effectively improve integration of EVs. As highlighted by Lin et al. (2013) this study contributes to advance the social economy of businesses involves in eMobility in urban context thereby providing a resource-saving and green society where energy supply is efficient, clean, secure, and reliable. Practically, this study contributing to sustainable development of energy production and use by enabling the optimal use of RES toward improving the energy grids' capability for improved allocation of electricity. The business model can be employed as a policy tools toward developing a roadmap improve the integration of EVs in smart cities.

CONCLUSION

The reduction of CO_2 emissions is a crucial goal particularly in the transport sector as this sector contributes roughly to one-fourth of the total global greenhouse gas emissions, which are projected to increase from 23 to 50 percent by 2030 (Wang et al., 2016). Thus, reducing CO_2 emission and increasing the energy efficiency of vehicles by exploiting sustainable energy strategies in transportation sector is viewed as important in an effort to lessen carbon footprint the emergence of EVs provides ample opportunity to improve sustainable mobility and energy. EV can provides opportunities for dispatch of storage units and load control making RES such as solar PV and wind more pertinent to the energy grid (Zame et al., 2018). Accordingly, this study proposes an energy as a service business model to explore how EVs can contribute to achieve sustainable energy in smart cities. Additionally, this study explores the emerging role of energy informatic, role of smart grids and sustainable energy systems, benefits of integrating EV within the energy grid as flexibilities and EV‘s implications for providing incentives to its users.

Moreover, findings discuss the optimization of electric vehicle charging stations, barriers, and recommendations for EV integration in smart cities. The study has some limitations. Firstly, only secondary data from the literature was used in this study. Secondly, the actors and components in the proposed model were not validated. Lastly, this study is mainly based on the business perspective and the technical viewpoint of EV integration was not explored. These limitations can provide a road map for future study of on EV integration. Further work may focus on conducting a case study to follow-up investigation on EV adoption, particularly because the number of stakeholders involved in EV integration in smart cities are increasing.

AUTHOR CONTRIBUTIONS

BA contributed in conducting the review and drafting the manuscript.

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REFERENCES

Anthony Jnr, B. (2020a). Smart city data architecture for energy prosumption in municipalities: concepts, requirements, and future directions. *Int. J. Green Energy* 17, 827–845. doi: 10.1080/15435075.2020.1791878

Anthony Jnr, B. (2020b). "Applying enterprise architecture for digital transformation of electro mobility towards sustainable transportation," in *Proceedings of the 2020 on Computers and People Research Conference* (Nuremberg), 38–46.

Anthony Jnr, B. (2020c). Managing digital transformation of smart cities through enterprise architecture–a review and research agenda. *Enterp. Inf. Syst.* 15, 299–331. doi: 10.1080/17517575.2020.1812006

Anthony Jnr, B. (2020d). Implications of telehealth and digital care solutions during COVID-19 pandemic: a qualitative literature review. *Inform. Health Soc. Care* 46, 68–83. doi: 10.1080/17538157.2020.1839467

Anthony Jnr, B., and Abbas Petersen, S. (2020). Examining the digitalisation of virtual enterprises amidst the COVID-19 pandemic: a systematic and meta-analysis. *Enterp. Inf. Syst.* 15, 617–650. doi: 10.1080/17517575.2020.1829075

Anthony Jnr, B., Abbas Petersen, S., Ahlers, D., and Krogstie, J. (2020). API deployment for big data management towards sustainable energy prosumption in smart cities-a layered architecture perspective. *Int. J. Sustain. Energy* 39, 263–289. doi: 10.1080/14786451.2019.1684287

Anthony, B., and Petersen, S. A. (2019). "A practice based exploration on electric mobility as a service in smart cities," in *European, Mediterranean, and Middle Eastern Conference on Information Systems* (Cham), 3–17.

Anthony, B., Petersen, S. A., Ahlers, D., Krogstie, J., and Livik, K. (2019). Big data-oriented energy prosumption service in smart community districts: a multi-case study perspective. *Energy Inform.* 2, 1–26. doi: 10.1186/s42162-019-0101-3

Anthony, B., Petersen, S. A., and Helfert, M. (2020). "Digital transformation of virtual enterprises for providing collaborative services in smart cities," in *Working Conference on Virtual Enterprises* (Cham), 249–260.

Bedogni, L., Bononi, L., Di Felice, M., D'Elia, A., Mock, R., Montori, F., et al. (2013). "An interoperable architecture for mobile smart services over the internet of energy," in *2013 IEEE 14th International Symposium on "A World of Wireless, Mobile, and Multimedia Networks"(WoWMoM)* (Madrid), 1–6.

Bellekom, S., Arentsen, M., and van Gorkum, K. (2016). Prosumption and the distribution and supply of electricity. *Energy Sustain. Soc.* 6, 1–17. doi: 10.1186/s13705-016-0087-7

Bohnsack, R., Pinkse, J., and Kolk, A. (2014). Business models for sustainable technologies: exploring business model evolution in the case of electric vehicles. *Res. Policy* 43, 284–300. doi: 10.1016/j.respol.2013.10.014

Brandt, T., Wagner, S., and Neumann, D. (2012). "Road to 2020: IS-supported business models for electric mobility and electrical energy markets," in Thirty *Third International Conference on Information Systems* (Orlando, FL), 1–10.

Brown, S., Pyke, D., and Steenhof, P. (2010). Electric vehicles: the role and importance of standards in an emerging market. *Energy Policy* 38, 3797–3806. doi: 10.1016/j.enpol.2010.02.059

Cavoukian, A., Polonetsky, J., and Wolf, C. (2010). Smartprivacy for the smart grid: embedding privacy into the design of electricity conservation. *Identity Inf. Soc.* 3, 275–294. doi: 10.1007/s12394-010-0046-y

da Silva, H. B., and Santiago, L. P. (2019). "Optimal energy trading policy for solar-powered microgrids: a modeling approach based on plug-in hybrid electric vehicles," in *Smart and Digital Cities* (Cham), 251–273.

Dijk, M., Orsato, R. J., and Kemp, R. (2013). The emergence of an electric mobility trajectory. *Energy Policy* 52, 135–145. doi: 10.1016/j.enpol.2012.04.024

Eider, M., Sellner, D., Berl, A., Basmadjian, R., de Meer, H., Klingert, S., et al. (2017). "Seamless electromobility," in *Proceedings of the Eighth International Conference on Future Energy Systems* (Shatin),316–321.

Ekman, P., Röndell, J., and Yang, Y. (2019). Exploring smart cities and market transformations from a service-dominant logic perspective. *Sustain. Cities Soc.* 51:101731. doi: 10.1016/j.scs.2019.101731

Giordano, V., and Fulli, G. (2012). A business case for smart grid technologies: a systemic perspective. *Energy Policy* 40, 252–259. doi: 10.1016/j.enpol.2011.09.066

Heo, T., Kim, K., Kim, H., Lee, C., Ryu, J. H., Leem, Y. T., et al. (2014). Escaping from ancient Rome! applications and challenges for designing smart cities. *Trans. Emerg. Telecomm. Technol.* 25, 109–119. doi: 10.1002/ett.2787

Hinz, O., Schlereth, C., and Zhou, W. (2015). Fostering the adoption of electric vehicles by providing complementary mobility services: a two-step approach using Best–Worst Scaling and Dual Response. *J. Bus. Econ.* 85, 921–951. doi: 10.1007/s11573-015-0765-5

Jnr, B. A. (2020). Examining the role of green IT/IS innovation in collaborative enterprise-implications in an emerging economy. *Technol. Soc.* 62:101301. doi: 10.1016/j.techsoc.2020.101301

Jnr, B. A., Majid, M. A., and Romli, A. (2020a). A generic study on Green IT/IS practice development in collaborative enterprise: insights from a developing country. *J. Eng. Technol. Manag.* 55:101555. doi: 10.1016/j.jengtecman.2020.101555

Jnr, B. A., Petersen, S. A., Ahlers, D., and Krogstie, J. (2020b). Big data driven multi-tier architecture for electric mobility as a service in smart cities. *Int. J. Energy Sect. Manag.* 14, 1023–1047. doi: 10.1108/IJESM-08-2019-0001

Karpenko, A., Kinnunen, T., Madhikermi, M., Robert, J., Främling, K., Dave, B., et al. (2018). Data exchange interoperability in IoT ecosystem for smart parking and EV charging. *Sensors* 18:4404. doi: 10.3390/s18124404

Kirpes, B., and Becker, C. (2018). "Processing electric vehicle charging transactions in a blockchain-based information system (pp. Pres-4)," in *Twenty-Fourth Americas Conference on Information Systems* (New Orleans, LA), 1–5.

Kirpes, B., Danner, P., Basmadjian, R., De Meer, H., and Becker, C. (2019). E-mobility systems architecture: a model-based framework for managing complexity and interoperability. *Energy Inform.* 2, 1–31. doi: 10.1186/s42162-019-0072-4

Kley, F., Lerch, C., and Dallinger, D. (2011). New business models for electric cars—a holistic approach. *Energy Policy* 39, 3392–3403. doi: 10.1016/j.enpol.2011.03.036

Kossahl, J., Busse, S., and Kolbe, L. M. (2012). "The evolvement of energy informatics in the information systems community-a literature analysis and research agenda," in *ECIS 2012 Proceedings* (Barcelona).

Kotilainen, K., Mäkinen, S. J., and Valta, J. (2017). "Sustainable electric vehicle-prosumer framework and policy mix," in *2017 IEEE Innovative Smart Grid Technologies-Asia (ISGT-Asia)* (Auckland), 1–6.

Li, B., Kisacikoglu, M. C., Liu, C., Singh, N., and Erol-Kantarci, M. (2017). Big data analytics for electric vehicle integration in green smart cities. *IEEE Commun. Mag.* 55, 19–25. doi: 10.1109/MCOM.2017.1700133

Lieven, T. (2015). Policy measures to promote electric mobility–a global perspective. *Transp. Res. Part A Policy Pract.* 82, 78–93. doi: 10.1016/j.tra.2015.09.008

Lin, C. C., Yang, C. H., and Shyua, J. Z. (2013). A comparison of innovation policy in the smart grid industry across the pacific: China and the USA. *Energy Policy* 57, 119–132. doi: 10.1016/j.enpol.2012.12.028

Mustafa, M. A., Zhang, N., Kalogridis, G., and Fan, Z. (2014). "Roaming electric vehicle charging and billing: an anonymous multi-user protocol," in *2014 IEEE International Conference on Smart Grid Communications (SmartGridComm)* (Venice), 939–945.

Rathnayaka, A. D., Potdar, V., and Ou, M. H. (2012). "Prosumer management in socio-technical smart grid," in *Proceedings of the CUBE International Information Technology Conference* (Pune), 483–489.

Rodríguez, R., Madina, C., and Zabala, E. (2015). "EV integration in smart grids through interoperability solutions," in *EVS28 Int Electric Veh Symp Exhibition* (Goyang), 1–12.

Sanseverino, E. R., and Sanseverino, R. R. (2018). "Smart urban energy districts and energy policies," in *2018 IEEE Green Technologies Conference (GreenTech)* (Austin, TX), 144–148.

Schuh, G., Fluhr, J., Birkmeier, M., and Sund, M. (2013). "Information system architecture for the interaction of electric vehicles with the power grid," in *10th IEEE International Conference on Networking, Sensing, and Control (ICNSC)* (Paris), 821–825.

Shuai, W., Maillé, P., and Pelov, A. (2016). Charging electric vehicles in the smart city: a survey of economy-driven approaches. *IEEE Trans. Intell. Transp. Syst.* 17, 2089–2106. doi: 10.1109/TITS.2016.2519499

Spickermann, A., Grienitz, V., and Heiko, A. (2014). Heading towards a multimodal city of the future? multi-stakeholder scenarios for urban mobility. *Technol. Forecast. Soc. Change* 89, 201–221. doi: 10.1016/j.techfore.2013.08.036

Tcholtchev, N., Farid, L., Marienfeld, F., Schieferdecker, I., Dittwald, B., and Lapi, E. (2012). "On the interplay of open data, cloud services and network providers towards electric mobility in smart cities," in *37th Annual IEEE Conference on Local Computer Networks-Workshops* (Clearwater, FL), 860–867.

Vaidya, B., and Mouftah, H. T. (2018). "Protecting the privacy of electricity consumers in the smart city," *Transportation and Power Grid in Smart Cities: Communication Networks and Services*, eds H. T. Mouftah, Melike, M. Erol-Kantarci, and M. H. Rehmani Hoboken, NJ: John Wiley and Sons Ltd), 529–554.

Wang, S., Fan, J., Zhao, D., Yang, S., and Fu, Y. (2016). Predicting consumers' intention to adopt hybrid electric vehicles: using an extended version of the theory of planned behavior model. *Transportation* 43, 123–143. doi: 10.1007/s11116-014-9567-9

Watson, R. T., Boudreau, M. C., and Chen, A. J. (2010). Information systems and environmentally sustainable development: energy informatics and new directions for the IS community. *MIS Q.* 23–38. doi: 10.2307/20721413

Weiller, C., and Neely, A. (2014). Using electric vehicles for energy services: Industry perspectives. *Energy* 77, 194–200. doi: 10.1016/j.energy.2014.06.066

Zame, K. K., Brehm, C. A., Nitica, A. T., Richard, C. L., and Schweitzer, I. I. I., G. D. (2018). Smart grid and energy storage: policy recommendations. *Renew. Sustain. Energy Rev.* 82, 1646–1654. doi: 10.1016/j.rser.2017.07.011

Zuccalà, M., and Verga, E. S. (2017). Enabling energy smart cities through urban sharing ecosystems. *Energy Proc.* 111, 826–835. doi: 10.1016/j.egypro.2017.03.245

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MINI REVIEW
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Digital Twin for Accelerating Sustainability in Positive Energy District: A Review of Simulation Tools and Applications

Xingxing Zhang [1]*, *Jingchun Shen* [1], *Puneet Kumar Saini* [1], *Marco Lovati* [1], *Mengjie Han* [2], *Pei Huang* [1] and *Zhihua Huang* [3]

[1] Energy and Community Building, Dalarna University, Falun, Sweden, [2] Micro Data Analysis, Dalarna University, Falun, Sweden, [3] Telenor Connexion AB, Stockholm, Sweden

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Edited by:
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***Correspondence:**
Xingxing Zhang
xza@du.se

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A digital twin is regarded as a potential solution to optimize positive energy districts (PED). This paper presents a compact review about digital twins for PED from aspects of concepts, working principles, tools/platforms, and applications, in order to address the issues of both how a digital PED twin is made and what tools can be used for a digital PED twin. Four key components of digital PED twin are identified, i.e., a virtual model, sensor network integration, data analytics, and a stakeholder layer. Very few available tools now have full functions for digital PED twin, while most tools either have a focus on industrial applications or are designed for data collection, communication and visualization based on building information models (BIM) or geographical information system (GIS). Several observations gained from successful application are that current digital PED twins can be categorized into three tiers: (1) an enhanced version of BIM model only, (2) semantic platforms for data flow, and (3) big data analysis and feedback operation. Further challenges and opportunities are found in areas of data analysis and semantic interoperability, business models, data security, and management. The outcome of the review is expected to provide useful information for further development of digital PED twins and optimizing its sustainability.

Keywords: positive energy district, digital twin, simulation tool, application, review

INTRODUCTION

Positive Energy Districts (PED) require integration of different systems and infrastructures for the optimal interactions among buildings, stakeholders, mobility, energy systems, and communication systems. According to European Strategic Energy Technology (SET) Plan Action 3.2, PEDs are the essential part of comprehensive approaches toward sustainable urbanization including technology, spatial, regulatory, financial, legal, social, and economic perspectives (Urban Europe, 2019). Urban development is moving from building solutions to PEDs in order to accelerating the clean energy transition and further achieve EU's energy and climate targets (SET-Plan action 3.2, 2018). PEDs are defined as energy-efficient and energy-flexible urban areas with surplus renewable energy production and net zero greenhouse gas emissions.

Active information exchange and analysis will be necessary so that they would enable balancing and optimization of energy flow across the PED, integration of mobility, communication, and trading between peers, as well as engaging more stakeholders. However, these are still the main challenges to most communities and cities.

The integration of digital methods can be a solution to the challenges in PEDs. Buildings and districts can be designed to be more vibrant, efficient, and resilient if they are modeled, analyzed, and tested before they are built. A digital twin is a coupled approach for new forms of modeling and analysis based on big data and machine learning/artificial intelligence (AI). "Digital twin" refers to the creation of digital models or platforms by monitoring, modeling, and optimizing the PEDs as a complex multi-physics system based on real-time big data sets (Woods and Freas, 2019). A digital twin integrates the Internet of things (IoT), AI, machine learning, and analytics, to create living digital simulation models that update and change information as needed. A digital twin model continuously learns and updates itself from multiple sources to represent its near real-time status.

Digital twin of PEDs enables a revolutionary way to accelerate sustainability of the society, in terms of energy transition, circular economic, and climate change (Grieves and Vickers, 2016). In a digital twin platform, sensors will be set up to collect all kind of information, such as occupancy (mobility), temperature, moisture, energy consumption, renewable production, CO_2 concentration, costs, waste, carbon footprint, etc., creating the "brain of PEDs." With such big data sets, digital twin model can be used to assess energy demand/supply, indoor air quality, thermal comfort, carbon emissions, expenses for operating and maintenance, building renovation and replacement needs (including recycle of waste construction materials), carbon emissions, and payback periods of energy saving measures over lifetime. This therefore optimizes PEDs' three functions in energy efficiency, energy production, and flexibility, toward energy surplus and climate neutrality.

Although there are several existing projects and reports about digital twin for PEDs, it significantly lacks a systematic review and summary about the current R and D status in this area, in order to identity current working limits and future research directions. This paper therefore presents a compact review about digital twins for PED from aspects of concepts, working principles, tools/platforms, and applications, in order to address the issues of both how digital PED twin is made and what tools can be used for digital PED twin. Further challenges and opportunities are also discussed.

CONCEPT AND WORKING PRINCIPLE FOR PEDs

A digital PED twin usually consists of four important components: (1) a virtual model of PED, (2) sensor network integration, (3) data analytics, and (4) stakeholder layer, which combines capacities of a virtual model, data management, analytics, simulation, system controls, visualization, and information sharing. **Figure 1** displays a schematic of how a digital PED twin is made. The virtual model is a visualization process for a PED that can derive from 3D models extracted from building information modeling (BIM) or the custom 3D models of PED. The information and data within a digital PED twin can be collected and transferred by various sensor networks to create real-time monitoring, which often includes weather conditions (temperature, solar irradiation, etc.), material (new or wasted), cost, carbon emissions and footprint, facility/system status, indoor air quality (IAQ), inhabitant behavior, electric vehicle (EV) mobility, energy demand, local energy supply, and social structural information. These data will be further analyzed by and exchanged in actions/decisions with different stakeholders for operations. In this sense, the stakeholders may refer to public institutions or government, property owners or managers, inhabitants, urban planners, engineers, financial company, utilities, and service providers, etc. This dynamic interaction allows for real-time analytics, informed decision making, resource efficiency, and comfort enhancement (Khajavi et al., 2019).

Ideally, in a digital PED twin, the real-time data are collected and transferred to a data analytic center, where all kinds of data are analyzed along with their complex systems for either prediction or optimization for a number of objectives of sustainability. The majority of energy data are used in improving energy self-consumption, maximizing economic benefits, and minimizing carbon emissions, etc. The growing platform also incorporates other real-time dynamics, such as climate data, occupancy, monitored air quality data, and traffic data, as well as information about socio-demographics. For individual buildings, some of these data can be interpreted for maintaining IAQ level as a virtual model provides an extra opportunity for analytical insights for urban planners to explore the microenvironment impact of constructing new buildings. At the district level, the possibilities of generated heat and noise maps can help planners to create a more comfortable and cooler living environment for residents. In view of the features of dynamics information, it is also possible to identify enormous potential in social dimension. The representations using 3D semantic modeling are capable of improving conceptual urban design, simulating emergency, and carrying out socio-economic impact studies. The predicted or optimized information is, if necessary, sent further to stakeholders for decisions, or returned to the individual systems in reality for regular operations. Such a digital twin increases system resilience by considering interdependent systems and optimizing the decisions and operations of the future.

The considerable benefits of a digital PED twin can be anticipated. The digital twin environment will facilitate interaction and collaboration between all stakeholders involved in a PED's life cycle, by enabling integrated data, information, knowledge, and decision sharing capabilities. Such activity will further increase public and individual awareness. Since data and feedback are provided in real time, they can increase energy systems' flexibility and robustness during operation. A PED-centered digital twin can aggregate all data through the whole life cycle of a PED from design and construction (renovation), to operational and demolishment phases, hence improving the sustainability by more resource-efficient, economic and environmental decision taking (Alonso et al., 2019).

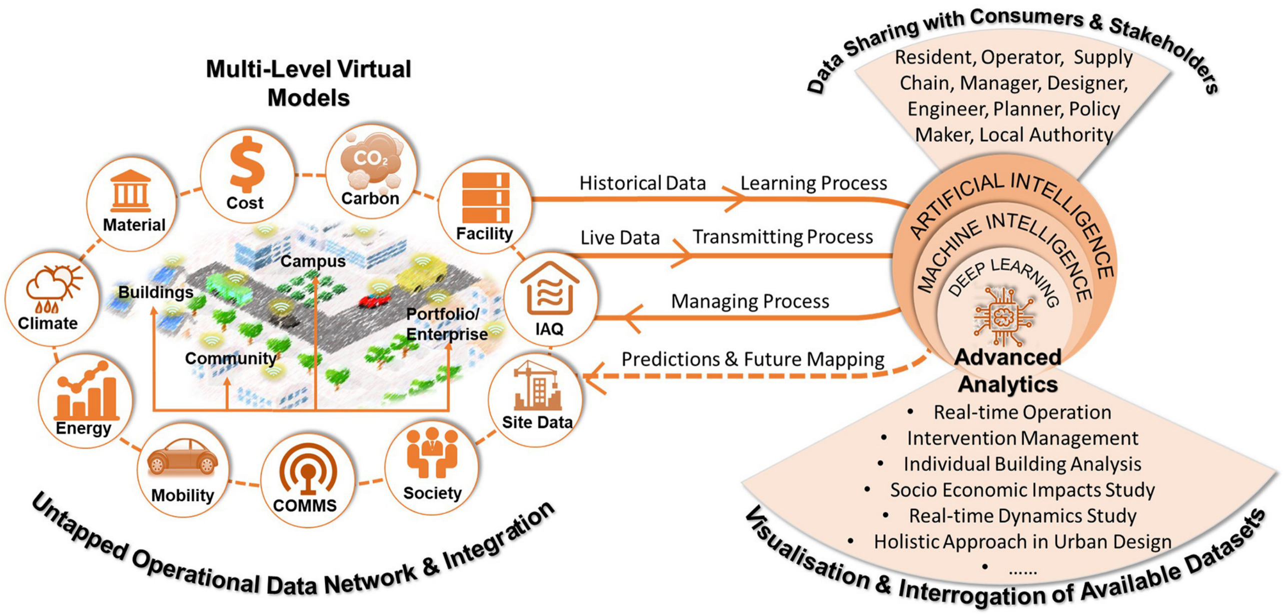

FIGURE 1 | Schematic design of key components in a digital PED twin.

DIGITAL TWIN PLATFORM AND TOOLS

A digital twin is a combination of several modules, such as a computer model, a physical model, communication services, and data analytics. These modules work in synchronization to monitor, learn, and optimize the complete system operation. However, the implementation of the digital twin concept may require new processes, methods, and novel platforms to interact with each of these modules (Qi et al., 2019). Similar to the diversification in the 3D modeling techniques, there is no common digital twin platform. The reason is that the solution to providing a digital twin does not lie in technology but the methodology and processes used to provide these solutions (Theiet, 2020). Therefore, this section intends to provide an overview of available tools that are used for digital twin in built environment and PED context.

Intelligent communities life cycle (ICL) provides a digital platform to create, analyze, and optimize the complex energy systems. The tool can assess a broad range of configurations for building and energy systems throughout their life cycle (IESVE, 2020). The digital model is created using an intelligent community design (iCD) tool that utilizes open street maps to build a three-dimensional model and BIM interoperability of the case building. The input from iCD is used for dynamic simulation performance of the system across the entire building life cycle. This is enabled by the virtual environment (VE) platform to carry daylight, energy performance, and life cycle assessment of the system. Furthermore, the data from real case building are analyzed to identify operational issues, risk mitigation, and understanding system interactions using an energy management information platform.

The building minds tool provides a common platform to obtain, integrate, and analyze data from various physical systems. However, the unique features of the tool lie in the use of a common data model that makes use of AI and data democratization techniques to efficiently process the databank to provide real-time feedback to the services. Initially, the data are clustered and prioritized based on a specific process and further validated using available tools and performance indicators. The data are stored as "common data" with specific attributes and entities for further analysis. This also enables users to import and analyze data from existing digital and analogy sources to build an interoperable real-time representation of existing building entities (BuildingMinds, 2020).

Ecodomus provides a constellation of four submodules required to create a digital twin of the asset. This tool addresses the full lifetime of building from the design phase to the decommissioning phase to achieve short- and long-term efficiency gains (Ecodomus.com, 2020). The conjunction of building management software and BIM models with facility operational tools helps to understand and get critical insights on the operational systems of the building. However, the geographical information for the asset such as topography and site-wide information is obtained using Ariel equipment, such as drones to scan the field, and used as input to create a realistic digital representation of the asset.

Other platforms/tools: Most of other tools have a focus on industrial applications, such as Akselos, iTwins, and Seebo (Warner, 2018). Tools such as feature manipulation engines also provide data integration platforms with applications in multiple sectors for transportation, commercial, and utilities. Moreover, there are several existing projects looking at digital twins to address various sectors, e.g., the food, water, and energy nexus (CRUNCH, 2018), as well as industrial maintenance. The rest of the possible platforms or tools are mainly developed based on existing GIS models of cities or districts, BIM models, data collection networks, and communication and visualization platforms.

APPLICATIONS OF DIGITAL PED TWIN

Until 2020, there were several digital PED twin developments (Research Markets, 2020). A digital twin project in Helsinki has been developed on CityGML, which is a semantic, expandable information Open Geospatial Consortium model (Heiskanen, 2019). Rennes, France, has established a digital 3D model for various urban studies (such as for urban mediation with citizens) and for urban development purposes (such as sunshine simulation, noise modeling, and tree shadow impact on buildings) (Poppe, 2016). Rotterdam, Holland, applies a digital twin for managing the city's infrastructure assets (Research Markets, 2020). Pasadena, California, in the USA, has developed a useful supervisory tool for the city's public sector players. Meanwhile, Portland, Oregon, in the USA, plans to construct a digital transportation activated by residents' cellular data (Fischer, 2019). The waterfront in Toronto, Canada, is using digital twin technology to launch a public advocate of waterfront revitalization, along with the urban innovation organization Sidewalk Labs (Doyle, 2019). A project in Dubai focuses on users' experience by using a digital twin. Jaipur, India, is using a digital twin project for urban planning and supervision (Research Markets, 2020). In Shanghai, China, immersive digital twins in railway engineering have established new practices to deliver a sewage treatment plant (Parrott and Warshaw, 2017). A detailed description of specific digital twin projects can be found in **Table 1**.

From the pilot projects demonstrated, it can be concluded that the digital twin concept usually consists of three distinct parts: (1) the physical asset, from community to city; (2) the logical constructed digital/virtual product, or the associated virtual three-dimensional digital replica; and (3) communications in between contained by specific applications. The communications usually take place on certain types of platform. The most popular digital twin city solution suppliers are Alphabet, Autodesk and Esri, Bentley, Cityzenith, Dassault systems, Engie Ineo/Siradel, Microsoft, NTT Data Corporation, Siemens, and IESVE (Research Markets, 2020; University of Cambridge, 2020).

The first-tier generation works almost like an enhanced version of BIM on construction sites for data. The limitations lie in information requirements for subsequent life cycle stages and extensibility in associated complex computations. Typically, the evolved maturity elements at this stage are (Savian, 2020):

- reality as-built data set capture (e.g., point cloud, drones, photogrammetry, or drawings/sketches);
- spatial information connected to 3D model;
- connect model to more static data (e.g. documents, drawings, asset management systems);

The second-tier generation moves a major progress forward with intelligent semantic platforms, providing a primary knowledge base development. But there are inadequate actuation capabilities in dealing with complex information interactions. Typically, the evolved maturity elements at this stage are added to Savian (2020):

- enrich with dynamic one-directional data flow (e.g., from the Internet of things, embedded sensors);
- establish two-way data integration and interaction (human-to-machine and machine-to-machine).

The third-tier generation has advanced knowledge leverages with the use of AI-enabled agents. Relying on the previous intelligent semantic platform, it elaborates AI technologies, such as machine learning, deep learning, data mining, and analysis capabilities to construct a self-reliant, self-updatable, and self-learning digital twin projects. Typically, the evolved maturity elements at this stage can be finalized with aspirational autonomous operations and maintenance (Savian, 2020).

Meanwhile, the connections between the physical items and the digital or virtual replica are continued data flows that stream from the physical product to the digital or virtual product, as well as information generated from the digital or virtual platform to the physical environment. In summary, the primary functions collected from the projects mentioned are prediction, simulation, monitoring, lifecycle, sensing, optimization, the Internet of things, AI, BIM, knowledge processing with data sets, and web-based data integration (Boje et al., 2020). Digital twins have evolved from monitoring platforms, intelligent semantic platforms, and agent-driven socio-technical platforms. The evolution represents a continuous growth in terms of both lifecycle and supply chain integration (Boje et al., 2020).

CHALLENGE AND OPPORTUNITY

Data Analysis and Semantic Interoperability

It is observed that most of the existing studies and applications emphasize the creation of a digital PED twin, rather than how to optimize it for operation and maintenance. Most studies have completed excellent virtual models of PED and integrated large-scale sensor network, but knowledge and skill in data analysis and interoperable interaction with different stakeholders are still lacking.

The ability of a digital PED twin is to capture the complex-and-dynamic relationships of different components in PEDs, which allows new levels of analysis of complex environments. However, now, also lacking are the studies to run analysis of real-time operations and different future scenarios, which aim to explore their impacts across the PED systems for new insights that enhance our ability to take more holistic approaches to building PED design, energy strategies, and transportation planning, etc. For instance, how inhabitants change their mobility behavior in response to the increase of EV numbers; the impact of distributed PV installation on local network and storage systems, as well as local electricity market *via* different business models;

TABLE 1 | Summary of existing application examples.

References	**Dundalk Institute of Technology, Ireland (IESVE, 2017)**	**West Campus of University of Cambridge in UK (Nochta et al., 2019; Institute for Manufacturing, University of Cambridge, 2020)**	**Boston 3D Model, USA (Patrick, 2018)**	**New South Wales state, Australia (New South Wales Government (NSWG), 2019; Policy Lab Spatial Services, 2019)**	**Virtual Singapore (Qi et al., 2019; Systèmes, 2019; National Research Foundation (NRF) and Prime Minister's Office Singapore, 2021)**
Project description	• Virtual campus energy model for yearly energy supply and demand. • Scenarios studies include lifecycle Cost, Net Present Value, projected savings and return of investment (ROI) over a 20-year period.	• City level digital twins use west campus of University of Cambridge in UK a case study to investigate how existing systems are influenced by digital solutions. • Focus on social, economic and environmental outcomes that meet citizens' needs and respond to contemporary urban challenges.	• City-level digital twins focus on environmental impacts. • GIS for public consumption. • Open data includes parcel ownership, districts, historic landmarks, and open space. • Analytical data includes sea-level rise projection.	• City-level digital twins to facilitate better planning, design and modeling for future needs. • Include digital visualizations of the local government areas. • Integration of live transport feeds as well as infrastructure building models.	• Country/City-level digital twins • Include typical map and land data, real-time dynamics, as well as information about demographics, climate or traffic.
Platform	Intelligent Communities Lifecycle (ICL)	(1) Bentley for 3D BIM modeling; (2) GeoSLAM for detailed context capture scan; (3) Topcon for a low-level-detailed 3D geometry and photogrammetry using drone and vehicle-based scanning and camera devices; and (4) Redbite for asset management solution	GIS-based 3D city model	Open sourced TerriaJS	3D EXPERIENCity platform
Objectives	• Energy supply and demand; • Transformer performance; • Energy storage performance; • Simulate energy demand data where it was missing or incomplete; • Validate pre-existing renewable investments and calculate ROI on improvement options.	• Analysis of infrastructure performance and use on organizational productivity; • Provide the foundation for integrating city-scale data to optimize city services such as power, waste, transport and understand the impact on wider social and economic outcomes; • Establish a "research capability platform" for researchers to understand and address the major challenges in implementing digital technologies at scale; • Improve the management and use of infrastructure systems.	• Capture the entire city and determine real-world impacts to make timely decisions. • Both quantitative and qualitative analysis workflows. • Designers are expected to use metrics and a standardized process and procedure to evaluate projects, including planning and development, flood modeling, shadow studies, and line-of-sight evaluation.	• Upgrade the existing state's spatial data from 2D to real-time 3D and 4D. • Engage with government agencies and industry bodies offering benefits at national, state and local government levels; • Disaster management through to bus schedules for city's future needs.	• Design better urban centers. • Optimizing a better accessibility solution in a specific area without any construction work; • Estimating emergency situations and establishing the most suitable evacuation protocols; • Providing real-time monitoring.
Limitations	• Only limited untapped operational data can be homogenized from any source in any format into virtual campus model.	• The pluralized private sector data owners • The lack of data sharing frameworks in place.	• The applications are limited only for tailored shadow impact analysis and planning review solutions.	• The limited accuracy • Challenges in interoperability with existing assets, products, systems and processes; • Data formats have short lifecycles. • Ownership and data sharing arrangements are challenging. • The affordability is an issue during design and build process.	• Requires a substantial resources for its development. • Complex modeling.

(Continued)

TABLE 1 | Continued

References	**Dundalk Institute of Technology, Ireland (IESVE, 2017)**	**West Campus of University of Cambridge in UK (Nochta et al., 2019; Institute for Manufacturing, University of Cambridge, 2020)**	**Boston 3D Model, USA (Patrick, 2018)**	**New South Wales state, Australia (New South Wales Government (NSWG), 2019; Policy Lab Spatial Services, 2019)**	**Virtual Singapore (Qi et al., 2019; Systèmes, 2019; National Research Foundation (NRF) and Prime Minister's Office Singapore, 2021)**
Potentials	• Data gap could be overcome to carry out interpolations over weeks or even months.	• Establish new governance structures and mechanisms.	• Visualize development and check potential impact. • Faster design review process.	• Real time monitoring and feedback; • Model different scenarios and test the feasibility and impact of changes with real time data; • Support planning decisions, detect issues and intervene sooner, and make predictions; • Measure performance. • Share information with citizens and business.	• Virtual experimentation • Virtual test-bedding, planning and decision-making • Further research and development

the impact of future climate, and the way to adapt PED to the future scenario. This will need more and more advanced machine learning and AI approaches to provide another level of analysis of the complex systems and component relationships that would be nearly impossible to realize in a real-world environment (Woods and Freas, 2019).

Current digital PED twins lack a semantic model to standardize concept descriptions and data representations for interoperable interactions with different stakeholders and energy information communication or management. Semantic models and their applications are now mostly designed to facilitate planning or analysis of urban energy systems through simulation or information representation and exchange, rather than facilitating energy-related operation and management or as part of a complex event processing system (Howell et al., 2017). Semantic heterogeneity between vocabularies and data representations is a common issue in existing digital twin models.

Business Models and Economic Analysis

Economic feasibility studies and business models of digital PED twins are also lacking. The concept of a digital twin will transform the business of energy production and supply from a centralized level to a decentralized one (Richter, 2013). Renewable energy systems and the energy saving technologies in a PED have an initial cost and also a savings potential during their lifetime. The business model of these technologies should consider the investment and maintenance costs with the savings (Qin et al., 2017) and revenues (IRENA, 2019). The costs associated with the creation of a digital twin are already considered when designing a PED energy system as most of the infrastructure needed for the operation is necessary in a decentralized energy market, regardless of the ownership structure of the infrastructure. In view of the profound interdependence of energy and monetary fluxes, it is paramount to have a detailed knowledge, hence a model, of the energy flows in a local grid (Roberts et al., 2019). In recent years researchers have started to study the interactions among prosumers within an energy producing district (Zhang et al., 2018; Jing et al., 2020), by proposing different business models, such as power purchase agreements (PPA), net-metering mechanisms, and peer-to-peer (P2P) trading mechanisms. Once the sensors and models of the local energy system are put in place, the use of a digital twin can provide a series of benefits from the design to the operation phase, which will facilitate energy sharing and trading based on different business models. Using a digital twin during the design phase helps to predict performance during the operation phase. Continuous learning can improve the profitability of energy investments and reduce investment risk.

Data Security and Management

PEDs gather dynamic energy and other information at a district level and generate a great amount of data when they are digitalized, which requires cloud storage and computing. Potential issues, such as insufficiency of data, accessibility, and governance aspects are challenging to data security and management.

Despite its potential in the collection of big data sets, there is a fundamental gap regarding data acquisition in PED regarding different dimensions, such as technical, economic, environmental, and social aspects. Under data protection regulations, it is not possible to collect all the parameters that are necessary for modeling and feedback operations (Lock et al., 2019). The concept of PED is still in its early stages, and the acquisition of high-quality data is usually difficult since data collection is costly and data management is time consuming. Without sufficient data at a micro-level, the optimization methods and decision making will be biased. However, advanced data generation mechanisms can be used to mitigate the situation (Han et al., 2021).

Providing authentication, authorization, and access control for data stored in the cloud may increase data security in terms of confidentiality, integrity, and availability. However, when multiple organizations share the data, there is a risk of misusing the data (Rao and Selvamani, 2015). First. confidentiality protects information from being accessed by unauthorized parties. It is an essential requirement to ensure the security of data in cloud storage and computing (Aloraini and Hammoudeh, 2017). Applying data encryption can limit the access to stored data for PEDs. In order to ensure the effective use of encryption, much consideration should be put into the encryption algorithms and key strength. As cloud computing involves large amounts of data transmission, storage, and handling, it also needs to consider processing speed and computational efficiency of encrypting large amounts of data (Chen and Zhao, 2012). Second, data integrity refers to the data and information storage in the cloud being valid and protected from modification or changes (Balogh and Turcani, 2016). A digital PED twin is an integrated system where digital information for each subsystem is highly correlated. Any alteration of data may jeopardize the connections between systems. Thus, cloud service providers should check and maintain the data and computation regularly. However, it is still a challenge to predict any future modification to the data based on historical performance. Last, availability ensures that authorized users have access to the information. PEDs comprise multiple agents, and cloud computing is also moving to multi-cloud computing (Aldossary and Allen, 2016). The subsystems may work independently, and they need a system that is always available. Substantial efforts are still needed for making the transition from single-cloud to multi-cloud computing.

CONCLUSION

This paper presents a compact review about digital twins for PEDs from aspects of concepts, working principles, tools or platforms, and applications, in order to address the issues of both how a digital PED twin is made and what tools can be used for a digital PED twin. A few available tools and platforms are reviewed for digital twins in built environments and PEDs, such as ICL, Building minds, and Ecodomus. Other platforms and tools either have a focus on industrial applications or are mainly developed based on existing GIS models of cities or districts, BIM models, data collection networks, and data communication and visualization platforms. Several successful applications of digital PED twins are summarized, where lessons and observations are gained so that digital PED twins can be categorized in three tiers: (1) an enhanced version of BIM model only, (2) semantic platforms for data flow, and (3) AI-enabled agents for data analysis and feedback operation. Further challenges and opportunities lie in data analysis and semantic interoperability, business models, data security, and management.

AUTHOR CONTRIBUTIONS

XZ contributed to supervision, concept development, structuring, and writing. JS and PS contributed to the review of simulation tools and applications. ML, MH, PH, and ZH are dedicated to future research directions. All authors contributed to the article and approved the submitted version.

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REFERENCES

Aldossary, S., and Allen, W. (2016). Data security, privacy, availability and integrity in cloud computing: issues and current solutions. *Int. J. Adv. Comput. Sci. Appl.* 7, 485–498. doi: 10.14569/IJACSA.2016.070464

Alonso, R., Borras, M., Koppelaar, R., Lodigiani, A., Loscos, E., and Yöntem, E. (2019). SPHERE: BIM digital twin platform. *Proceedings* 20:9. doi: 10.3390/proceedings2019020009

Aloraini, F., and Hammoudeh, M. (2017). "A survey on data confidentiality and privacy in cloud computing," in *ICFNDS '17* (Cambridge), 1–7. doi: 10.1145/3102304.3102314

Balogh, Z., and Turcani, M. (2016). Modeling of data security in cloud computing. *Proc. Annu. IEEE Syst. Confer.* 2016, 1–6. doi: 10.1109/SYSCON.2016.7490658

Boje, C., Guerriero, A., Kubicki, S., and Rezgui, Y. (2020). Towards a semantic construction digital twin: directions for future research. *Automation Construct.* 114:103179. doi: 10.1016/j.autcon.2020.103179

BuildingMinds (2020). *How Digital Building Twins Accelerate Your Sustainability.* Buildingminds. Available online at: https://buildingminds.com/article/how-digital-building-twins-accelerate-building-performance (accessed May 4, 2020).

Chen, D., and Zhao, H. (2012). "Data security and privacy protection issues in cloud computing," in *2012 International Conference on Computer Science and Electronics Engineering* (Hangzhou). 647–651. doi: 10.1109/ICCSEE.2012.193

CRUNCH (2018). CRUNCH. Available online at: http://www.fwe-nexus.eu/workshops.php (accessed May 4, 2020).

Doyle, S. (2019). *Digital Urban Planning: Twins Help Make Sense of Smart Cities.* Available online at: https://eandt.theiet.org/content/articles/2019/01/digital-urban-planning-twins-help-make-sense-of-smart-cities/ (Accessed on March 31, 2020).

Ecodomus.com (2020). *Ecodomus FM – Ecodomus*. Available online at: https://www.ecodomus.com/portal (accessed May 4, 2020).
Fischer, R. (2019). *Digital Transportation: The Future of Urban Mobility*. Available online at: https://usgtima.org/perspectives/digital-transportation-the-future-of-urban-mobility/ (accessed March 31, 2020).
Grieves, M., and Vickers, J. (2016). "Digital twin: mitigating unpredictable, undesirable emergent behavior in complex systems," in *Trans-Disciplinary Perspectives on System Complexity* (Springer).
Han, M., Wang, Z., and Zhang, X. (2021). An approach to data acquisition for urban building energy modeling using a gaussian mixture model and expectation-maximization algorithm. *Buildings* 11:30. doi: 10.3390/buildings11010030
Heiskanen, A. (2019). *Helsinki is Building a Digital Twin of the City*. Available online at: https://aec-business.com/helsinki-is-building-a-digital-twin-of-the-city/ (accessed March 31, 2020).
Howell, S., Rezgui, Y., Hippolyte, J. L., Jayan, B., and Li, H. (2017). Towards the next generation of smart grids: semantic and holonic multiagent management of distributed energy resources. *Renew. Sustain. Energy Rev.* 77, 193–214. doi: 10.1016/j.rser.2017.03.107
IESVE (2017). *Dundalk Institute of Technology*. Available online at: https://www.iesve.com/icl/case-studies/2886/dundalk-institute-of-tecnhnology (accessed March 30, 2020).
IESVE (2020). *The ICL Is Here! The New Environmental Digital Twin For Healthy Sustainable Communities | Discoveries | IES*. Available online at: https://www.iesve.com/discoveries/article/7734/the-icl-is-here (accessed May 4, 2020).
Institute for Manufacturing, University of Cambridge (2020). *Infrastructure Digital Twins*. Available online at: https://www.ifm.eng.cam.ac.uk/research/asset-management/research-projects/infrastructure-digital-twins/ (Accessed on March 31, 2020).
IRENA (2019). *Renewable Power Generation Costs in 2018*. Abu Dhabi: International Renewable Energy Agency.
Jing, R., Xie, M. N., Wang, F. X., and Chen, L. X. (2020). Fair P2P energy trading between residential and commercial multi-energy systems enabling integrated demand-side management. *Appl. Energy* 262:114551. doi: 10.1016/j.apenergy.2020.114551
Khajavi, S. H., Motlagh, N. H., Jaribion, A., Werner, L. C., and Holmström, J. (2019). Digital twin: vision, benefits, boundaries, and creation for buildings. *IEEE Access.* 7, 147406–147419. doi: 10.1109/ACCESS.2019.2946515
Lock, O., Bednarz, T., and Pettit, C. (2019). *HoloCity – Exploring the Use of Augmented Reality Cityscapes for Collaborative Understanding of High-Volume Urban Sensor Data.* doi: 10.1145/3359997.3365734
National Research Foundation (NRF) and Prime Minister's Office Singapore (2021). *Virtual Singapore*. Available online at: https://www.nrf.gov.sg/programmes/virtual-singapore#:~:text=Virtual%20Singapore%20is%20a%20dynamic,private%2C%20people%20and%20research%20sectors (accessed March 15, 2021).
New South Wales Government (NSWG) (2019). *Emerging Technology Guide: Digital Twin*. Available online at: https://www.digital.nsw.gov.au/transformation/policy-lab/emerging-technology-guide-digital-twin (accessed March 15, 2021).
Nochta, T., Badstuber, N., and Wahby, N. (2019). *On the Governance of City Digital Twins Insights From the Cambridge Case Study, CDBB (Centre for Digital Built Britain), July 2019*. Cambridge: University of Cambridge, Series No: CDBB_WP_012.
Parrott, A., and Warshaw, L. (2017). *Industry 4.0 and the Digital Twin-Manufacturing Meets Its Match, s.l.* New York, NY: Deloitte University Press.
Patrick, B. (2018). *Meet Boston's Digital Twin*. Available online at: https://www.esri.com/about/newsroom/blog/3d-gis-boston-digital-twin/ (accessed March 30, 2020).
Policy Lab and Spatial Services (2019). *Twinning! Spatial Services Has Created a Digital Twin of NSW*. Available online at: https://www.digital.nsw.gov.au/article/twinning-spatial-services-has-created-digital-twin-nsw (accessed March 30, 2020).
Poppe, S. (2016). *Digital 3D Modelling of Rennes Metropole*. Available online at: https://sharingcities.eu/eurocities/allcontent/Digital-3D-modelling-of-Rennes-Metropole-WSPO-A8JDUM (accessed March 31, 2020).
Qi, Q., Tao, F., Hu, T., Anwer, N., Liu, A., Wei, Y., et al. (2019). Enabling technologies and tools for digital twin. *J. Manufac. Syst*. 58, 3–21. doi: 10.1016/j.jmsy.2019.10.001
Qin, Q., Liang, F., Li, L., and Wei, Y. M. (2017). Selection of energy performance contracting business models: a behavioral decision-making approach. *Renew. Sustain. Energy Rev*. 72, 422–433. doi: 10.1016/j.rser.2017.01.058
Rao, R. V., and Selvamani, K. (2015). "Data security challenges and its solutions in cloud computing," in *International Conference on Intelligent Computing, Communication & Convergence,* 204–209. doi: 10.1016/j.procs.2015.04.171
Research and Markets (2020). *Digital Twin Cities. 2020: The Global Ecosystem, City-backed Projects, Main Application Sectors, and Solution Suppliers, s.l.* Dublin: Research and Markets.
Richter, M. (2013). Business model innovation for sustainable energy: German utilities and renewable energy. *Energy Policy* 62, 1226–1237. doi: 10.1016/j.enpol.2013.05.038
Roberts, M. B., Bruce, A., and MacGill, I. (2019). A comparison of arrangements for increasing self-consumption and maximising the value of distributed photovoltaics on apartment buildings. *Solar Energy* 193, 372–386. doi: 10.1016/j.solener.2019.09.067
Savian, C. (2020). *Digital Twins for the Built Environment: An Introduction to the Opportunities, Benefits, Challenges and Risks*. Hertfordshire: The Institution of Engineering and Technology.
SET-Plan action 3.2 (2018). *Implementation Plan: Europe to Become a Global Role Model in Integrated, Innovative Solution for the Planning, Deployment, and Replication of Positive Energy Districts*. Available online at: https://setis.ec.europa.eu/system/files/2021-04/setplan_smartcities_implementationplan.pdf (accessed March 11, 2020).
Systèmes, D. (2019). *Meet Virtual Singapore, the City's 3D Digital Twin*. Available online at: https://www.smartcitylab.com/blog/digital-transformation/singapore-experiments-with-its-digital-twin-to-improve-city-life/ (accessed March 30, 2020).
Theiet (2020). *Built Environment*. Available online at: https://www.theiet.org/impact-society/sectors/built-environment/?utm_source=redirect&utm_medium=legacyredirects&utm_campaign=2019relaunch (accessed May 4, 2020).
University of Cambridge (2020). *Infrastructure Digital Twins*. Available online at: https://www.ifm.eng.cam.ac.uk/research/asset-management/research-projects/infrastructure-digital-twins/ (accessed March 31, 2020).
Urban Europe (2019). *Framework Definition for Positive Energy Districts and Neighbourhoods*. Available online at: https://jpi-urbaneurope.eu/news/consultation-on-the-framework-definition-for-positive-energy-districts-and-neighbourhoods/ (accessed February18, 2020).
Warner, T. (2018). *Innovating the Future With Canada'S Digital Technology Supercluster | Safe Software*. Available online at: https://www.safe.com/blog/2018/10/innovating-future-canadas-digital-technology-supercluster/ (accessed May 4, 2020).
Woods, E., and Freas, B. (2019). *White Paper of Creating Zero Carbon Communities: The Role of Digital Twins, Commissioned by Integrated Environmental Solutions Limited*. Available online at: https://learn.iesve.com/digital-twin-white-paper/ (accessed September 2020).
Zhang, C., Wu, J., Zhou, Y., Cheng, M., and Long, C. (2018). Peer-to-peer energy trading in a microgrid. *Appl. Energy* 220, 1–12. doi: 10.1016/j.apenergy.2018.03.010

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Local Production and Storage in Positive Energy Districts: The Energy Sharing Perspective

Alberto Fichera[1†], Alessandro Pluchino[2†] and Rosaria Volpe[1†]*

[1] Department of Electrical, Electronics and Computer Engineering, University of Catania, Catania, Italy, [2] Department of Physics and Astronomy, University of Catania, and Sezione Istituto Nazionale di Fisica Nucleare (INFN) of Catania, Catania, Italy

In response to the Positive Energy District transition, this paper proposes an energy tool for the modeling of energy sharing configurations among buildings equipped with energy production systems and distributive storages. The model is targeted for urban planners and energy policymakers and gives insights into the role of buildings in fostering the achievement of net-zero energy balances in districts when virtual or physical peer-to-peer configurations are established in the area. A real urban district is considered as a case study and the energy performances are measured against properly defined Key Performance Indicators. Results confirm the strategic role played by energy sharing among buildings in achieving self-sufficient and carbon-neutral areas. In particular, the insertion of storages allows not only for higher self-sufficiency of the area (by facilitating the coupling of production and demand) but also for higher distribution rates among buildings. However, photovoltaic insertion and storages should be appropriately balanced since it has been observed that at increasing the number of production and storage systems, the distribution is reduced in favor of autonomy, thus limiting the usefulness of an interconnected local distribution grid.

Keywords: positive energy districts, energy modeling, buildings, storage, renewable energy, agent-based models, energy sharing, energy distribution

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****Correspondence:***
Rosaria Volpe
rosaria.volpe@unict.it

† These authors have contributed equally to this work

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INTRODUCTION

Built-up areas are responsible for a high level of energy consumption and consequent carbon emissions (United Nations Framework Convention on Climate Change, 2015). The integration of renewable energy production systems at the urban scale has proven to be a significant solution to target the EU's strategic objectives in terms of both energy efficiency and emissions reduction. In this sense, urban communities play a pivotal role in fostering the transition toward sustainability and climate neutrality. Beyond the widely acknowledged advantages of energy efficiency and carbon-neutrality, renewable sources have changed the way urban areas have been so far conceived. Indeed, the insertion of renewables implied, *de facto*, the rising of decentralized distribution configurations among buildings, able now to produce, self-consume, and distribute energy within their neighborhood (Parag and Sovacool, 2016). This emergent feature of the building sector paves the way for inclusive urbanization, in which the citizen's role of shaping sustainable and autonomous districts can no longer be neglected (Fichera et al., 2016a). Recently, the Strategic Energy Technology (SET) Plan, Action 3.2, stressed the need for planning the diffusion of Positive Energy Districts (PEDs), i.e., urban agglomerates with annual net-zero energy imports and net-zero emissions (European Commission, 2018). Among the peculiar characteristics of PEDs, "*interaction and integration between buildings*," as well as "*an integrative approach including technology, spatial, [...] perspectives*" are considered as fundamental pillars for strategic energy planning (European Commission, 2018). Therefore, the modeling of energy sharing among buildings, including physical or virtual distribution, peer-to-peer topologies, and infrastructure, is crucial to achieving a fruitful transition toward PEDs. Under these premises, any long-term urban energy strategy should build upon integrated energy models coupling local production, local distribution among buildings and local distributive energy storage as key interlinked characteristics for the achievement of sustainable urban energetic configurations.

Up to now, many studies and regulations have proposed energy modeling tools and energy efficiency measures targeted to the built environment and focusing on the building scale (*Directive 2010/31/EU*, 2010; *Directive 2012/27/EU*, 2012). Magrini et al. (2020) discussed the most recent European directives concerning a building chosen as a reference case for energy-independent urban areas. On the premises that newly built edifices should be nearly-zero energy buildings (Cellura et al., 2017) and that energy planning decisions should refer to the district level, Sougkakis et al. (2020) compared energy performances of new and retrofitted buildings of a Greek neighborhood highlighting the best combination in terms of installed technologies and financial incentives. Keiner et al. (2019) investigated several energy scenarios for the optimal covering of electrical, thermal, and mobility demands for the residential sector. Other studies enlarged the building-based perspective to comprehend residential blocks of up to 25 buildings. Among these, Dorneanu et al. (2019) proposed a mixed-integer linear programming model to optimize the design and operation of energy distribution systems integrated with heating/cooling networks and connected to the main grid. Soutullo et al. (2020) mapped the existing European living laboratories and pursued a statistical analysis to develop guidelines orienting the evaluation of suitable and energy-efficient urban configurations. An interesting application of energy flexibility at the building scale is represented by the review of Al Dakheel et al. (2020), who set guidelines for the implementation of retrofit measures in existing buildings.

Among the unquestionable merits of these studies, they contributed to the increased awareness of the need to develop energy actions focused on the specific features and characteristics of buildings, as well as on the use of renewable-based technologies for the net-zero target (Cellura et al., 2011). Nevertheless, despite highly detailed, some of these tools cannot be easily scaled to the district level due to the computational intensity that would inevitably derive from extending these features to a significant number of households. This is even more relevant if the chance for buildings to share the own produced energy is added to the analysis; in these cases the possible energy interactions that should be considered for proper modeling would exponentially increase at increasing the number of buildings. Therefore, the traditional building-based perspective needs to be enlarged to reach the district level (Fichera et al., 2016b; Eicker, 2019; Bossi et al., 2020). In this direction, Ali et al. (2018) proposed a GIS-based tool to inform urban planners for the definition of energy strategies aiming at reducing both energy consumption and emissions. For the optimal design of energy systems, Jing et al. (2019) proposed a hierarchical methodology constituted of an optimization model and a clustering technique.

As said, the diffusion of renewable sources within urban areas enhanced the autonomy of the built-up areas. However, to improve the competitiveness and the advantages deriving from self-produced energy, the mismatch between production and consumption needs to be solved. A solution in this sense consists of coupling energy storage to district energy systems (Thomsen and Overbye, 2016). Near-optimal and real-time operation of buildings with installed renewable systems and batteries can be achieved by implementing a non-linear programming model to obtain positive energy balances (Cortès et al., 2020), by optimal pricing strategies for economic viability in electricity markets (Lin and Wu, 2017), or by considering the optimal positing of storage within the grid (Korjani et al., 2018). On this topic, Sameti and Haghighat (2018) proposed a mixed-integer linear programming model for the optimal design of distributed thermal and electrical energy storage with an application for a district of seven residential buildings.

Overall, the aforementioned literature recognizes the important impact of storage in urban areas. Nonetheless, the insertion of renewable energy production systems coupled to storage still needs to be deepened from the distribution perspective. Indeed, the distributive behavior of storages is usually considered at the sole micro-grid level (Liu et al., 2019) and the debate on the role that buildings can play in energy sharing is still open to discussion.

To this aim, this work aims at contributing to the existing state-of-art by measuring to what extent energy distribution among buildings can represent a key characteristic in shaping positive energy districts. In this direction, an integrated tool is here proposed to model spatial, energetic, and technological features of future PEDs with particular attention to sharing configurations arising from energy distribution among buildings. The developed methodology is intended for urban planners and decision-makers, being it able to offer a comprehensive evaluation of urban districts in which energy sharing mechanisms are planned to be introduced. Going into the details, simulations run under the methodological framework of the agent-based theory, successfully implemented in literature for modeling interactions among parts, at both the building (Sun et al., 2018) and district-scale (Fichera et al., 2018). The output of the energy simulations is discussed against Key Performance Indicators (KPIs), useful metrics if aiming at evaluating the energy performances of buildings (Angelakoglou et al., 2020) and PEDs (Clemente et al., 2019). In particular, in this study, KPIs are formulated about the impact of local energy sharing on the achievement of a positive energy balance for the area.

That said, the novelties of this paper can be summarized as:

- Assessment of local energy sharing as a key feature for PEDs development;
- Coupling of local production and local distributive energy storage at the district level;

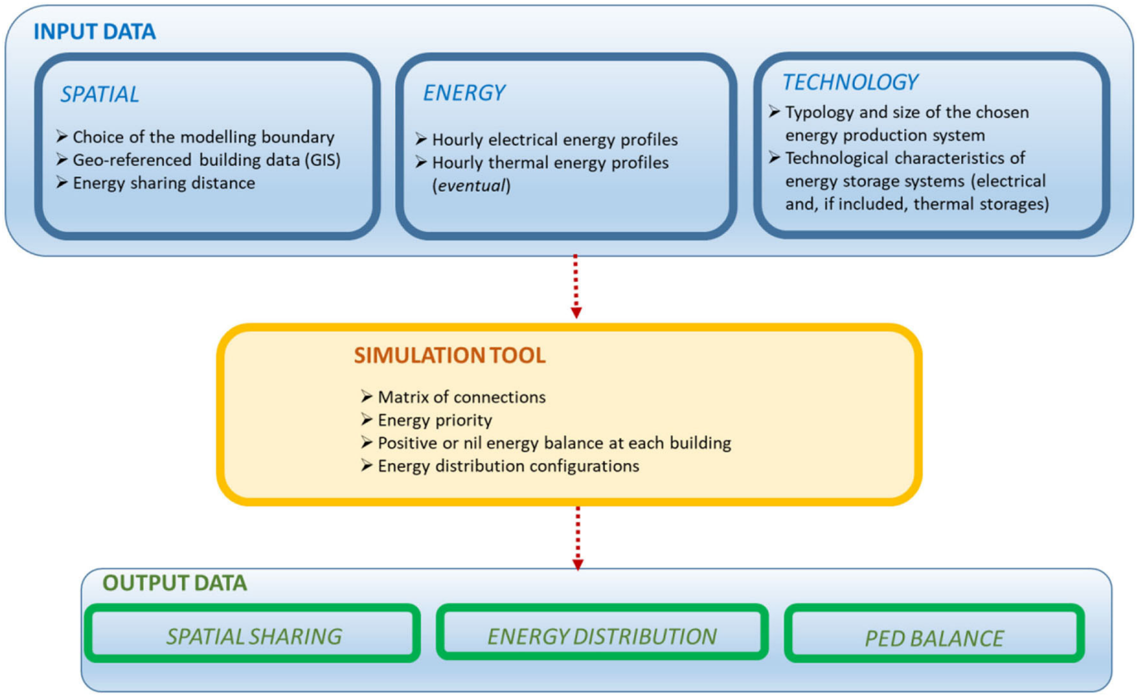

FIGURE 1 | Overview of the proposed methodology.

- Definition of an agent-based model able to highlight the high granularity of energy flows among interacting buildings;
- Definition of focused KPIs measuring to what extent local distribution may affect the energy performances of PEDs and formulated to be replicable for comparison among other studies.

The following of this paper is organized as follows: section "Methodology" presents the proposed methodological approach, section "District Modeling" describes the district chosen as a case study and section "Discussion" discusses the results. Conclusions on the main implications deriving from the output of the proposed methodology are reported in section "Conclusions".

METHODOLOGY

The proposed methodology aims at supporting urban planners and energy policymakers toward the definition of proper action plans targeted for PEDs with enabled energy sharing among buildings equipped with local energy production systems and energy storage. The modeling procedure relies on the following main pillars:

- On-site energy production from renewables;
- Energy storages to account for the mismatch between production and consumption;
- Sharing distance among connected buildings within the spatial boundary.

The adopted methodological path is reported in **Figure 1**, where three main divisions can be identified: the input data section, the simulation toolbox, and the output section.

Input Data

The input section collects data focusing on the spatial, energetic, and technological aspects.

The first module implements the modeling boundaries of the chosen urban district, featured within the GIS environment. Geo-referenced building-specific information such as location, construction data, rooftop area, orientation, and shading factors, is determined. In addition, the maximum distance along which buildings share energy has to be decided to balance energy flows exchanged within the districts and between each building and the main grid. It is worth noting that the required specifications for spatial input data may vary for the chosen technology. In this paper, an application with PV panels coupled to EESs is studied, being PV a leading technology due to its scalability, fast installation, and low maintenance and due to the presence of incentives that favor its diffusion in buildings (Lovati et al., 2020). To the scope, specifications on rooftops' area and typology (span/flat roof), inclination, orientation, and shading are included as input data for the simulation tool.

Case-by-case, urban planners may decide to include other relevant aspects, for example, surface and occupied volume, number of inhabitants, buildings' age, wall stratigraphy, and building function, depending on the simulation needs.

The second step consists of the definition of electrical and thermal consumption profiles for each building, taking also into account the information deriving from the spatial module. Electrical and thermal profiles are available on a daily basis for each household. Then, hourly profiles have been calculated matching the available data with the typical electrical consumption per person derived from the Italian Regulatory Authority for Energy (2020), and electrical profiles from the study of Capozzoli et al. (2016), considered as general and replicable for the Mediterranean basin. In this paper, the sole electrical profile is included in the simulation, being electrical energy suitable for the bidirectional peer-to-peer mechanism.

The third module gives detail on both the installed energy production technology and the energy storage systems. In this study, PV panels are coupled with electrical energy storage (EES) to account for the fluctuations between production and demand. EESs operate in a distribution mode, i.e., stored electricity can be distributed to neighboring buildings. Input data for this section are power sizes, determined by matching data from the spatial module (rooftop available area, typology, orientation, inclination, and so on) and data from the energy module (electrical and, if modeled, thermal loads). Electrical production profiles at varying the installed PV sizes are calculated for the site solar irradiance. Data on specific PV power output, direction normal irradiation, global and diffuse horizontal irradiations, and optimum tilt of the modules and hourly profiles for each month are extracted from the Global Solar Atlas (2021) for the geographical coordinates of the area deriving from the GIS-based information included in the spatial module. Data on EESs are included in terms of storage technology, storage capacity, inverter power and size, state of charge, and depth of discharge. As suggested by Huld (2011), good results on the overall performances between PV panels and EES can be achieved by assuming a conversion ratio of 65% to include any system losses (cables, DC/AC converter, charging and discharging, shadows, and dust on the modules).

Model

The simulation tool is developed within the theoretical framework of agent-based models, which have proven to be particularly suitable to solve problems characterized by a significant amount of interactions among the constituting parts (Khan et al., 2019), as in the case of districts with enabled energy distribution among buildings (Fichera et al., 2020). Agents represent interacting buildings aiming at both fulfilling their demands and achieving a positive energy balance at the district level. Interactions among buildings depend on a spatial-energetic constraint built upon their relative geographical location and their energy balance. Going into the detail of the spatial issue, the stakeholder (urban planner, policy-maker) has to define the geographical distance d along which energy distribution is enabled. All feasible connections respecting the selected spatial distance are collected under the spatial matrix M:

$$M = \begin{array}{c} \\ 1 \\ 2 \\ \vdots \\ i \\ \vdots \\ N \end{array} \begin{array}{c} \begin{array}{cccccc} 1 & 2 & \dots & i & \dots & N \end{array} \\ \boxed{\begin{array}{cccccc} 0 & & \dots & 1 & \dots & 0 \\ 1 & 0 & \dots & 1 & \dots & 1 \\ \dots & \dots & 0 & \dots & \dots & \dots \\ 1 & 1 & \dots & 0 & \dots & 1 \\ \dots & \dots & \dots & \dots & 0 & \dots \\ 0 & 1 & \dots & 1 & \dots & 0 \end{array}} \end{array} \tag{1}$$

The matrix reports which buildings from the set $i = 1, 2, \dots, i, \dots, N$ are connected on the ground of the chosen distance. Data are reported in a binary form, being a_{ij} the x connection between building i with spatial position (x_i, y_i) and building j with spatial position (x_j, y_j) in the space of matrix M:

$$a_{ij} = \begin{cases} 1, & \sqrt{(x_j - x_i)^2 + (y_j - y_i)^2} \leq d \\ 0, & otherwise \end{cases} \tag{2}$$

It is worth noting that the diagonal of the matrix contains 0, having connections $i - i$ no sense from the distribution perspective. The matrix represents the mathematical representation of the initial energy distribution scheme, from which energy balances will be calculated.

Referring to the energy aspect, energy balances between production and demand and balances at the EESs are calculated as:

$$en_{balance(it)} = en_{production(it)} - en_{demand(it)} \tag{3}$$

$$en_{stored(it)} = en_{balance(it)>0} - (en_{distributed(it)} \cdot a_{ij}) \tag{4}$$

The energy balance at each time t for each building i can be either positive or negative. A positive balance indicates that the production has covered the demand of the building and that residual energy can be either stored or shared among connected buildings. In this model, distribution has priority over storage and, in addition, the stored energy can be distributed to connected buildings if necessary. A negative balance indicates that the building's demand still needs to be covered: to this aim, energy may be supplied from other buildings with positive production balance or those with positive storage balance or, as the last option, from the main grid.

Electrical energy in EESs is stored at time $t - 1$ and is distributed at time t. The balance at the EESs is obtained by considering the residual amount of produced energy after the distribution within the district. The stored electrical energy needs to respect a maximum and minimum storage level, due to the physical and technological characteristics of the chosen battery. Therefore, the following constraint:

$$lower_{limit} \leq en_{stored(i,t-1)} + en_{stored(it)} \leq upper_{limit} \tag{5}$$

Therefore, considering the introduced spatial matrix and the energy balances, distribution occurs if buildings are connected and respecting the energy flow direction from buildings with a positive balance to buildings with a negative balance. In addition, the energy sharing among buildings respects a priority criterion for which the produced (and stored) energy satisfies the energy need of the building owning the equipment, then the eventual excess is distributed to other requiring buildings and, if further energy is available it can be again stored (if possible) and finally released to the main grid. According to this criterion, buildings cannot receive energy if their energy balance is already positive to avoid utilitarian and profit-oriented behaviors at the expense of the district's needs.

Key Performance Indicators

Properly defined Key Performance Indicators describing energy distribution among buildings are derived from the output data section.

The performances of the modeled district are measured against three indicators. The first evaluates to what extent buildings share energy along the (physical or virtual) enabled connections built in the matrix M. In particular, it compares the number of connections used for the distribution in a 24 h horizon for the number of connections established in the matrix M:

$$Sp_{conn} = \frac{\sum_{i=1}^{N} a_{ij,en_{balance(it)>0}} \ \forall j = 1, \ldots N \ \vee j \neq i}{\sum_{i=1}^{N} \sum_{j=1}^{N} a_{ij}} \tag{6}$$

The total useful connections Sp_{conn} in Equation (6) gives important insights on the spatial distance considered for the energy sharing balance among buildings since it calculates the percentage of connections effectively used for the exchange with respect to the initial allowed configuration. This indicator varies within the interval $[0, 1]$, being $Sp_{conn} = 0$ indicative of a disconnected district and $Sp_{conn} = 1$ suggesting that all feasible connections (depending on the distance chosen by the energy planner) are effectively exploited.

The amount of energy distributed within the district as part of the production is measured referring to the KPI reported in the following:

$$En_{district} = \frac{\sum_{t=0}^{T} \sum_{i=1}^{N} (distribution_{it} \cdot a_{ij})}{\sum_{t=0}^{T} \sum_{i=1}^{N} production_{it}} \tag{7}$$

The distributed energy $En_{district}$ returns the rate of energy production shared among buildings and net of the rate used for self-consumption. The lower limit of this indicator, the distributed energy $En_{district} = 0$, indicates the case for which buildings do not exchange energy, either because they are not connected or because the produced energy has been used to cover the energy demand of installers.

Hourly energy balances at the district level are finally displayed to verify if the area is eligible for the transition toward the PED configuration.

District Modeling

The modeled district is located in Catania, Sicily, and counts 108 buildings, represented in **Figure 2**. Buildings are heterogeneous in terms of use, including residential households, a few single-houses, offices, and commercial edifices, distributed as in **Figure 3**. For each building, the roof surface and typology, volume, number of floors, surface exposition are known and used for the simulation. The overall available surface for PV installation is around 11,095 m^2. On average, residential buildings have 3–4 floors. For residential buildings, the number of inhabitants has also been evaluated to eventually calibrate the hourly electrical consumption.

Detailed information about the electrical consumption profile of each building has been made available thanks to a dedicated mapping campaign. The electrical production profile of the installed PV panels is calculated by coupling the available data on rooftop areas and typologies for each building (spatial data from module 1) to the direct normal irradiation per square meter extracted from Global Solar Atlas (2021). The hourly electrical profile of the area for a typical summer day and the direct normal irradiation are reported in **Figure 4**.

Concerning the storage technology, lithium-ion batteries have been selected in this study for their diffusion at the building scale (Speidel and Braeunl, 2016). Technological and operational characteristics of batteries have been derived from the current literature (Shen et al., 2017; Hoang and Lee, 2018) as summarized in **Table 1**.

The storage capacity measures the amount of electricity that can be stored in the battery. State of Charge (SoC) and Depth of Discharge (DoD) are two operational parameters affecting the functioning of the battery. In particular, SoC measures the amount of electricity stored in the battery with respect to its capacity. DoD measures the usable storage capacity, i.e., rate of usable energy at a given time t with respect to the total capacity of the battery. Both are given as percentages, being defined as ratios between capacities.

Two modeling scenarios are discussed, each of them characterized by different percentages of PV diffusion in the territory. In detail, scenarios differ concerning the percentage of rooftops' area covered by PV panels. It is worth pointing that PV panels are randomly inserted in buildings and that the insertion respects the spatial constraints derived from the spatial input data section. Each scenario is then modeled with and without EESs to assess if EESs have a beneficial impact on both the distribution and the positive energy balance at the district level. A summary of the two scenarios, labeled as #Sc1 and #Sc2 and distinguished for the presence or not of EES, is reported in **Table 2**.

Finally, simulations run in NetLogo (Wilensky, 1999) for a 24 h cycle and respecting an energy priority rule regulating the energy distribution mechanisms within the district. Assuming that the spatial-energy criterion is satisfied, buildings are allowed to share the produced energy if the following conditions take place:

- Energy flows can be shared following the direction from a building with positive energy balance to a building with negative energy balance;
- Energy production is first used to satisfy the own energy needs;
- Exceeding production is firstly distributed and then stored;
- Eventual exceeding production (that can not be further stored or distributed) is sent to the main grid and, conversely, buildings with residual demand are supplied from the main grid.

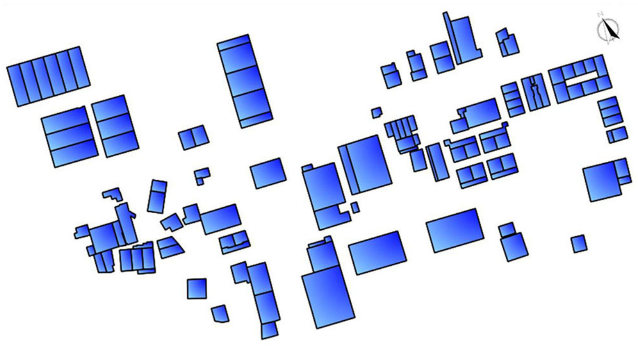

FIGURE 2 | Topological configuration of the modeled district.

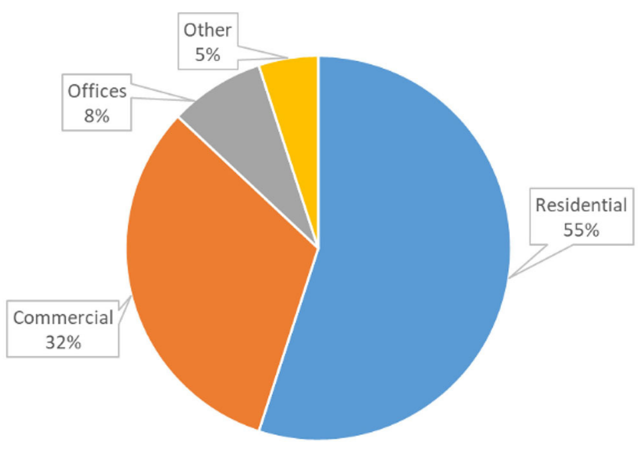

FIGURE 3 | Distribution of buildings' final use in the territory.

TABLE 1 | Technology and operation features of EES.

Lithium-ion batteries characteristics	
Storage size	6.4 kW
Storage capacity	22 kWh
Inverter power	4400 W
State of charge SoC	15–85%
Depth of discharge DoD	<15%

TABLE 2 | Overview of the modeled electricity distribution scenarios.

	#Sc1 w EES	#Sc1 w/o EES	#Sc2 w EES	#Sc2 w/o EES
PV panels diffusion	30% of the total roof area covered	30% of the total roof area covered	50% of the total roof area covered	50% of the total roof area covered
EES	y	n	y	n

DISCUSSION

Results are discussed against the KPIs introduced in subsection Key Performance Indicators. As previously introduced, the achievement of a positive energy balance within a district cannot neglect the evaluation of the energy sharing impact. This aspect can be measured from different perspectives and under several scenarios, In this study, the district energy performances and the sharing impact are analyzed at varying the installed energy production on the territory and including or not EESs, as summarized in **Table 2**.

The values of the useful connections exploited among buildings, Sp_{conn}, are reported in **Table 3** at varying the distance at which distribution may occur and for the identified scenarios.

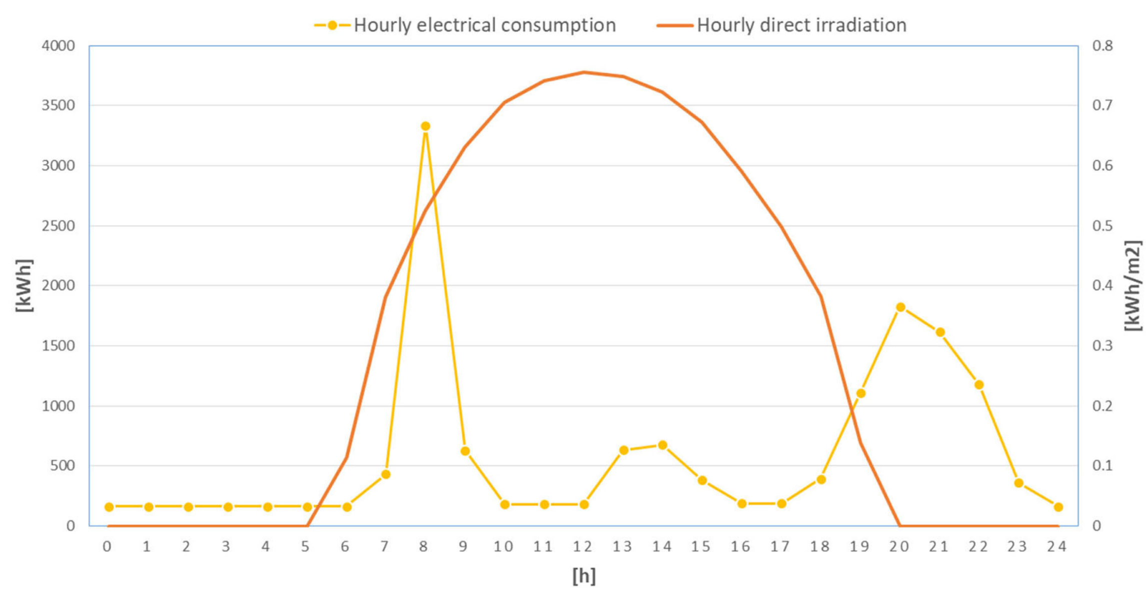

FIGURE 4 | Hourly electrical consumption of the area [kWh] and hourly direct irradiation [kWh/m^2].

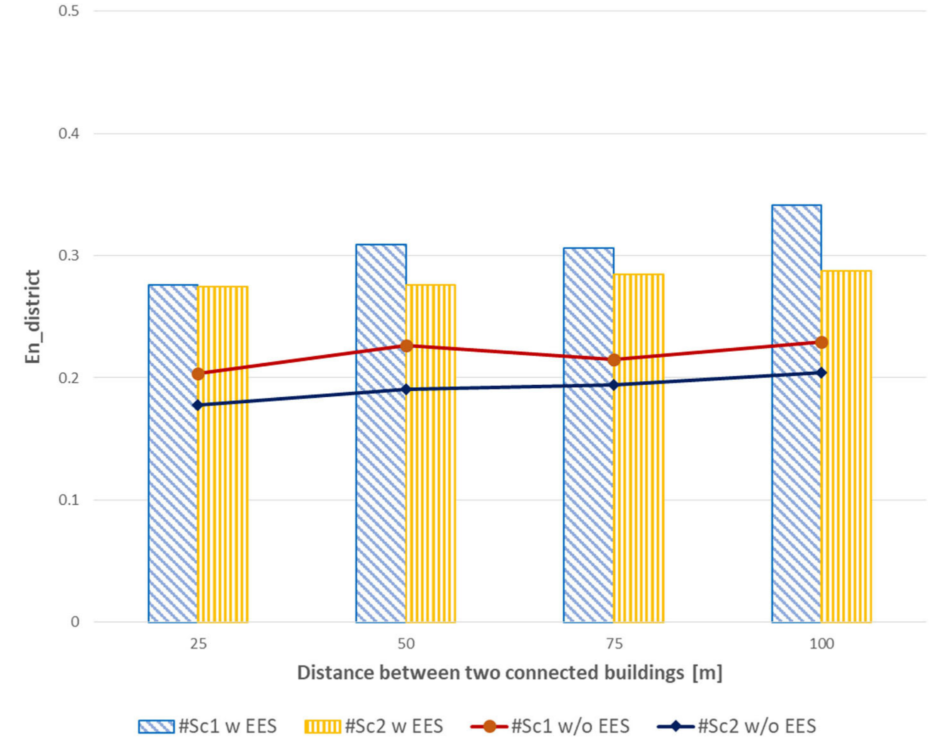

FIGURE 5 | Energy distribution among buildings.

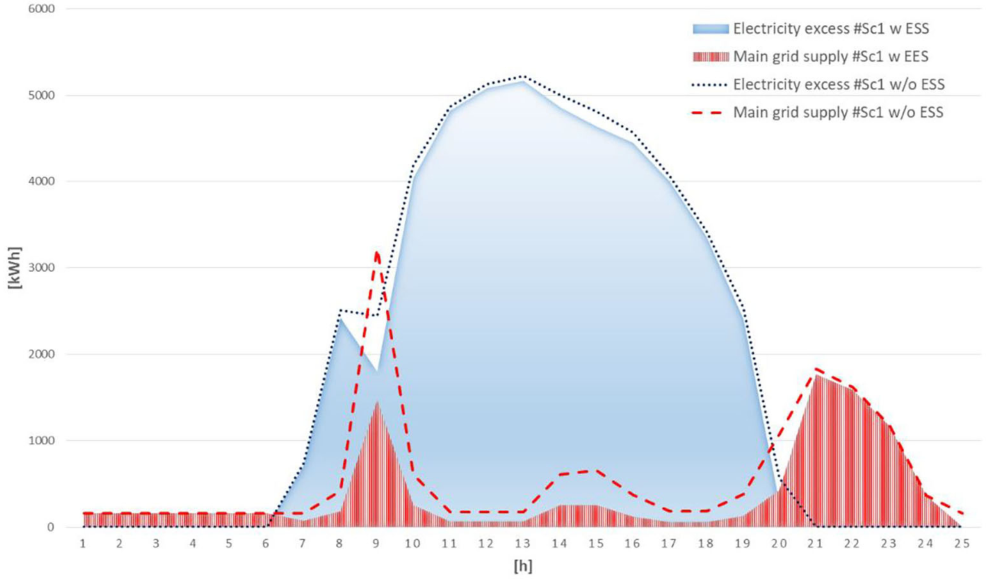

FIGURE 6 | Hourly electricity balance and main grid supply for #Sc1.

As a remark, the useful connections Sp_{conn} indicator evaluates the rate of connections used for energy sharing with respect to the number of initial connections established on the ground of the allowed distance *d*. The first initial consideration arising from the graph regards the impact of distributive storages in terms of exchanged energy flows. In particular, when EES is not included in the simulation, the rate of connected buildings decreases and, consequently, energy distribution decreases as well. This

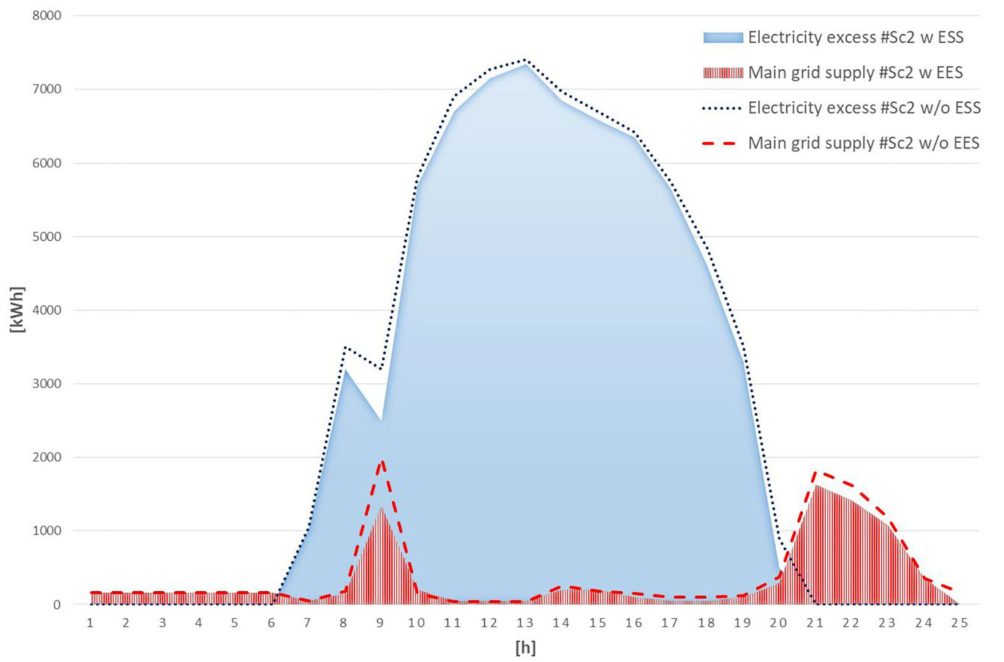

FIGURE 7 | Hourly electricity balance and main grid supply for #Sc2.

TABLE 3 | Rate of exploited connections among buildings for the different scenarios.

Distance [m]	Sp_{conn} #Sc1 w EES (%)	Sp_{conn} #Sc1 w/o EES (%)	Sp_{conn} #Sc2 w EES (%)	Sp_{conn} #Sc2 w/o EES (%)
25	76.27	69.49	72.49	67.44
50	78.21	57.69	79.08	66.32
75	76.92	61.54	76.15	72.80
100	79.49	58.97	78.24	69.04

is more evident at increasing the distance of connection, being higher distances bearer of higher sharing connections (virtual or physical, as specified). Precisely, this gap increases correspondently for each partial increase in the spatial distance among buildings. Otherwise, a general improvement regarding the sharing performances of the district can be noticed if EESs are coupled to PV panels, independently of the size of installed PV systems. This can be explained by the fact that even if energy production increases, the energy storage capacity of batteries remains unchanged, thus yielding no significant differences between the two scenarios. In addition, for buildings equipped with PV and EES systems, the impact of the distance is less significant, i.e., available energy connections have a good exploitation rate even among buildings in close spatial proximity. Overall, distances around 100 m permit to have a more connected district, and energy sharing among buildings is significant, with percentages around 80% of total and feasible connections crossed by energy flows during the day.

Moving forward, the distributed energy $En_{district}$ indicator is now analyzed. Results are reported in **Figure 5** at varying the distance of connection among buildings and for the two scenarios introduced in **Table 2**.

Again, the inclusion of EESs meaningfully affects the amount of energy distributed among buildings, yielding a higher share of energy distributed within the district. This consideration is valid independently from the modeled distance and scenario. Thus, the impact of EESs to reach any self-sufficient and autonomous targets for urban areas is significant not only from the spatial connection perspective (as reported in **Table 3**) but also considering the effective amount of energy production shared among buildings. As can be observed from **Figure 5**, indeed, an increase of circa 10–15% of total distributed energy is achieved within the territory, corresponding to higher participation of buildings in the energy sharing mechanisms and improving the energy efficiency of the area.

Surprisingly, the rate of energy shared among buildings is higher for #Sc1, i.e., for the scenario characterized by a lower energy production capacity. This can be explained by considering that, consistently with the results reported in **Table 3** for fixed energy production, #Sc1 ensures for a more connected district, being the majority of established connections among building effectively crossed by energy flows; therefore, a higher amount of energy is distributed within the district.

Finally, the hourly electricity balances at the district level are shown in **Figures 6**, **7** for both scenarios. Considering both Figures, it emerges how the chosen area can be effectively candidates for planning the transition toward the PED configuration. A significant excess of electricity production can be recorded both in #Sc1 and #Sc2, despite the self-consumption and the distribution among buildings. This electricity excess can be exploited to balance nightly consumption and, generally, to fulfill any electrical demand not covered from the PV production. In addition, being the excess particularly significant, strategic planning can include the insertion of electric vehicles to the electricity needs of the area (Inturri et al., 2017).

Going into the detail of both **Figures 6**, **7**, the significant impact of distributed storages within the area can be again recognized. As can be seen, EESs are beneficial to increase both the rate of self-sufficiency and energy sharing among buildings by passing the main grid and thus contributing toward the hourly net-zero balance, as recommended by the Directive (European Commission, 2018).

The decrease of the electricity supply from the main grid is much more evident in #Sc2 due to the higher diffusion of PV panels (and, therefore, higher production). Coherently, being higher the electricity production capacity of the area, the electricity excess is more significant than in #Sc1. In this scenario, the role of distributive EESs is less evident being more buildings able to reach self-sufficiency without requesting electricity from either the neighborhood or the main grid. Finally, it is worth pointing that, despite the insertion of PVs and EESs, a residual amount of electricity is still requested to the main grid: this is due to the fact that both Figures record the electricity balances of the area separately, and that amount of electricity from the main grid is going to balance the buildings' electricity demands not covered by PV production or by district sharing.

CONCLUSIONS

In this study, a model for the carbon-neutral and sustainable energy transition toward PEDs is proposed and targeted for the definition of strategic urban planning. Taking inspiration from the existing literature on the field of energy modeling and bearing in mind the guidelines of the SET-Plan Action 3.2, the proposed methodology includes the energy sharing among buildings and the presence of local storage as characterizing features of urban energy modeling. Spatial, energy, and technological input data are used to simulate energy exchange among buildings. Results are discussed against properly defined KPIs highlighting the spatial connection and energy distribution rates within the areas, as well as by measuring the hourly energy balance in the area. The developed simulation tool can be used for any district, being each step of the proposed methodology replicable at varying the input data.

The model has been tested in a district in South Italy and simulating the insertion of PV panels and Lithium-Ion batteries (the most diffused and scalable technological choice at the building level). Two main energy production scenarios are then simulated to account for different rates of PV penetration in the area and including or not electrical storage systems.

In particular, if considering the topological configuration of the distribution among buildings, it is worth noting that the insertion of EESs coupled to PV systems can be considered as beneficial to stress the decentralization of energy distribution and, consequently, the autonomy of the area. Into the details, allowed distance around 100 m can achieve a widely connected district. If evaluating the electricity flows exchanged into the area, again, EESs can guarantee higher rates of energy distribution among virtual or physically connected buildings, with an impact of circa 10–15% compared to the sole production scenario (without EESs). In addition, posing attention to the PED balance of the area, it can be effectively argued that there is the chance for the neighborhood to be designed as an eligible candidate for PED transition, being exceeding production sensitively higher than the overall demand. Careful scenarios' analyses can be dedicated to evaluating how to exploit the electricity excess. Strategic solutions in this sense could be directed to promote sustainable mobility for the considered area or to match nightly demand with diurnal production from PV systems.

From a broader perspective, results confirm the strategic role of connected and sharing buildings toward the net-zero or positive energy district configuration. In this direction, any urban action plan focusing on the definition of strategic measures favoring the insertion of renewable-based production systems coupled to energy storages should take the impact of energy distribution among buildings as crucial to increasing energy efficiency, carbon neutrality, and competitiveness of the area.

Further research should be focused on assessing the economic and environmental impact of buildings' sharing decisions on the area, as well as on the definition of the optimal energy production systems position for fostering energy exchanges.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author/s.

AUTHOR CONTRIBUTIONS

All authors listed have made a substantial, direct and intellectual contribution to the work, and approved it for publication.

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REFERENCES

Directive 2010/31/EU of the European Parliament and of the Council on the Energy Performance of Building (Recast). (2010).

Directive 2012/27/EU of the European Parliament and of the Council of 25 October 2012 on Energy Efficiency, Amending Directives 2009/125/EC and 2010/30/EU and Repealing Directives 2004/8/EC and 2006/32/EC. (2012).

Al Dakheel, J., Del Pero, C., Aste, N., and Leonforte, N. (2020). Samrt buildings features and key performance indicators: a review. *Sustain. Cities Soc.* 61:102328. doi: 10.1016/j.scs.2020.102328

Ali, U., Shamsi, M. H., Hoare, C., and ODonnell, J. (2018). "GIS-based residential building energy modeling at district scale," in *Proceedings of BSO 2018: 4th Building Simulation and Optimization Conference* (Cambridge).

Angelakoglou, K., Kourtzanidis, K., Giourka, P., Apostolopoulos, V., Nikolopoulos, N., and Kantorovich, J. (2020). From a comprehensive pool to a project-specific list of key performance indicators for monitoring the positive energy transition of smart cities - an experience-based approach. *Smart Cities* 3, 705–735. doi: 10.3390/smartcities3030036

Bossi, S., Gollner, C., and Theierling, S. (2020). Towards 100 positive energy districts in Europe: preliminary data analysis of 61 European cases. *Energies* 13:6083. doi: 10.3390/en13226083

Capozzoli, A., Corgnati, S. P., Di Nicoli, M. V., Fabi, V., Piscitelli, M. S., and Spigliantini, G. (2016). *Report RdS/PAR2016/008, Attività di monitoraggio energetico e ambientale, diagnostica ed energy engagement degli utenti degli use case (in Italian)*. Italian National Agency for New Technologies, Energy and Sustainable Economic Development (ENEA).

Cellura, M., Campanella, L., Ciulla, G., Guarino, F., Brano, V., Cesarini, D., et al. (2011). "A net zero energy building in Italy: design studies to reach the net zero energy target," in *Proceedings of Building Simulation 2011: 12th Conference of International Building Performance Simulation Association* (Sydney, NSW).

Cellura, M., Ciulla, G., Guarino, F., and Longo, S. (2017). Redesign of a rural building in a heriatge site in Italy: towards the net zero energy target. *Buildings* 7:68. doi: 10.3390/buildings7030068

Clemente, C., Civiero, P., and Cellurale, M. (2019). Solutions and services for smart sustainable districts: innovative key performance indicators to support transition. *Int. J. Sustain. Energy Plan. Manag.* 24, 95–106. doi: 10.5278/ijsepm.3350

Cortès, P., Auladell-Leòn, P., Munuzuri, J., and Onieva, L. (2020). Neat-optimal operation of the distributed energy resources in a smart microgrid district. *J. Clean. Product.* 252:119772. doi: 10.1016/j.jclepro.2019.119772

Dorneanu, B., Sidnell, T., Clarke, F., Mechleri, E., and Arellano-Garcia, H. (2019). A mixed-integer linear programming model for the optimal operation and design of residential neighbourhoods. *IFAC Papers Online Conf. Paper Arch.* 52, 934–939. doi: 10.1016/j.ifacol.2019.06.182

Eicker, U. (ed). (2019). "Introduction: the challenges of the urban energy transition," in *Urban Energy Systems for Low-Carbon Cities* (Elsevier Inc.), 1–15. doi: 10.1016/B978-0-12-811553-4.09993-5

European Commission (2018). *European Commission, SET-Plan ACTION 3.2 Implementation Plan. Europe to Become a Global Role Model in Integrated, Innovative Solutions for the Planning, Deployment, and Replication of Positive Energy Districts*.

Fichera, A., Frasca, M., Palermo, V., and Volpe, R. (2016a). Application of the complex network theory in urban environments. A case study in Catania. *Energy Proced.* 101, 345–351. doi: 10.1016/j.egypro.2016.11.044

Fichera, A., Inturri, G., La Greca, P., and Palermo, V. (2016b). A model for mapping the energy consumption of buildings, transport and outdoor lighting of neighbourhoods. *Cities* 55, 49–60. doi: 10.1016/j.cities.2016.03.011

Fichera, A., Pluchino, A., and Volpe, R. (2018). A multi-layer agent-based model for the analysis of energy distribution networks in urban areas. *Phys. A* 508, 710–725. doi: 10.1016/j.physa.2018.05.124

Fichera, A., Pluchino, A., and Volpe, R. (2020). Modelling energy distribution in residential areas: a case study including energy storage systems in Catania, Southern Italy. *Energies* 13:3715. doi: 10.3390/en13143715

Global Solar Atlas (2021). *Data obtained from the "Global Solar Atlas 2.0, a Free, Web-Based Application is Developed and Operated by the Company Solargis s.r.o. on behalf of the World Bank Group, utilizing Solargis data, with Funding Provided by the Energy Sector*.

Hoang, K., and Lee, H. (2018). Accurate power sharing with balanced battery state of charge in distributed DC microgrid. *IEEE Trans. Industr. Electron.* 66, 1883–1893. doi: 10.1109/TIE.2018.2838107

Huld, T. (2011). "Estimating solar radiation and photovoltaic system performance, the PVGIS Approach," in *AFRETEP 1ST Regional Workshop* (Kampala).

Inturri, G., Ignaccolo, M., Le Pira, M., Caprì, S., and Giuffrida, N. (2017). Influence of accessibility, land use and transport policies on the transport energy dependence of a city. *Transport. Res. Proced.* 25, 3273–3285. doi: 10.1016/j.trpro.2017.05.165

Italian Regulatory Authority for Energy, Networks, and Environment (2020). *Delibera 602/2020/R/eel*. ARERA.

Jing, R., Wang, M., Zhang, Z., Wang, X., Li, N., Shah, N., et al. (2019). Distributed or centralized? Designing district-level urban energy systems by a hierarchical approach considering demand uncertainties. *Appl. Energy* 252:113424. doi: 10.1016/j.apenergy.2019.113424

Keiner, D., Breyer, C., and Sterner, M. (2019). Cost and self-consumption optimised residential PV prosumer systems in Germany covering residential electricity, heat and mobility demand. *Int. J. Sustain. Energy Plan. Manag.* 21:35–58. doi: 10.5278/ijsepm.2019.21.4

Khan, M. W., Wang, J., Ma, M., Xiong, L., Pengham, L., and Wu, F. (2019). Optimal energy management and control aspects of distributed microgrid using multi-agent systems. *Sustain. Cities Soc.* 44, 855–870. doi: 10.1016/j.scs.2018.11.009

Korjani, S., Facchini, A., Mureddu, M., Caldarelli, G., and Damiano, A. (2018). Optimal positioning of storage systems in microgrids based on complex networks centrality measures. *Sci. Rep.* 8:16658. doi: 10.1038/s41598-018-35128-6

Lin, B., and Wu, W. (2017). Economic viability of battery energy storage and grid strategy: a special case of China electricity market. *Energy* 124, 423–434. doi: 10.1016/j.energy.2017.02.086

Liu, X., Yan, Z., and Wu, J. (2019). Optimal coordinated operation of a multi-energy community considering interactions between energy storage and conversion devices. *Appl. Energy* 248, 256–273. doi: 10.1016/j.apenergy.2019.04.106

Lovati, M., Zhang, X., Huang, P., Olsmats, C., and Maturi, L. (2020). Optimal simulation of three peer to peer (P2P) business models for individual PV prosumers in a local electricity market using agent-based modelling. *Buildings* 10:138. doi: 10.3390/buildings10080138

Magrini, A., Lentini, G., Cuman, S., Bodrato, A., and Marenco, L. (2020). From nearly zero energy buildings (NZEB) to positive energy buildings (PEB): The next challenge - The most recent European trends with some notes on the energy analysis of a forerunner PEB example. *Develop. Built Environ.* 3:100019. doi: 10.1016/j.dibe.2020.100019

Parag, Y., and Sovacool, B. K. (2016). Electricity market design for the prosumer era. *Nat. Energy Perspect.* 1:16032. doi: 10.1038/nenergy.2016.32

Sameti, M., and Haghighat, F. (2018). Integration of distributed energy storage into net-zero energy district systems: optimum design and operation. *Energy* 153, 575-591. doi: 10.1016/j.energy.2018.04.064

Shen, X., Shahidehpour, M., Han, Y., Zhu, S., and Zheng, J. (2017). Expansion planning of active distribution networks with centralzied and distributed energy storage systems. *IEEE Trans. Sustain. Energy* 8, 126–134. doi: 10.1109/TSTE.2016.2586027

Sougkakis, V., Lymperopoulos, K., Nikolopoulos, N., Margaritis, N., Giourka, P., and Angelakoglou, K. (2020). An investigation on the feasibility of near-zero and positive energy communities in the greek context. *Smart Cities* 3, 362–384. doi: 10.3390/smartcities3020019

Soutullo, S., Aelenei, L., Nielsen, P., Ferre, J., and Goncalves, H. (2020). Testing platforms as drivers for positive-energy living laboratories. *Energies* 13:5621. doi: 10.3390/en13215621

Speidel, S., and Braeunl, T. (2016.). Leaving the grid - the effect of combining home energy storage with renewable energy generation. *Renew. Sustain. Energy Rev.* 60, 1212–1224. doi: 10.1016/j.rser.2015.12.325

Sun, Y., Silva, E., Tian, W., Choudhary, R., and Leng, H. (2018). An integrated spatial analysis computer environment for urban-building energy in cities. *Sustainability* 10:4235. doi: 10.3390/su10114235

Thomsen, P., and Overbye, P. (2016). “Energy storage for district energy systems,” in *Advanced District Heating and Cooling (DHC) Systems*, ed R. Wiltshire (Ramboll Group, Elsevier Ltd.), 145–166. doi: 10.1016/B978-1-78242-374-4.00007-0

United Nations Framework Convention on Climate Change (2015). *UNFCCC, 2015: Adoption of the Paris Agreement FCCC/CP/2015/L.9/Rev.1.* United Nations Framework Convention on Climate Change.

Wilensky, U. (1999). *NetLogo: Center for Connected Learning and COmputer-Based Modeling*. Evanston, IL: Northwestern University. Available online at: http://ccl.northwestern.edu/netlogo

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A Critical Framework to Develop Human-Centric Positive Energy Districts: Towards Justice, Inclusion, and Well-Being

Minh-Thu Nguyen and Susana Batel*

Instituto Universitário de Lisboa (ISCTE-IUL), Cis-IUL, Lisbon, Portugal

Positive Energy Districts (PEDs) are a new energy initiative from European member states. They are, simply put, local districts which produce more energy than they consume. PEDs are expected to adopt a more human-centric perspective in order to create more liveable and sustainable urban neighbourhoods. However, as previous research on energy transitions has demonstrated, the mainstream approach and technocratic tradition of research and policy vis-à-vis energy transitions could result in the perpetuation of social inequalities, energy injustices, and the passive participation of citizens also within PEDs. Hence, it is crucial in these early days of PEDs to discuss what a human-centric approach should entail and how it should be enacted. Based on a narrative literature review of critical social sciences' energy research (and specifically from social and environmental psychology), this paper will propose a critical framework containing five key dimensions which are relevant for creating more just and inclusive PEDs. These are: uncertainty, risk perception and trust; distributive justice; recognition justice and people-place relations; procedural justice; and, routines, capabilities and lived experiences. To that end, it will also discuss the different implications of mainstream and critical approaches in energy research and social sciences in relation to the deployment of human-centric PEDs. The review concludes that in order to successfully deploy human-centric PEDs, a critical approach is needed and presents some concrete recommendations for future research and policy in order to adopt such an approach. These include: considering justice, inclusion and the well-being of affected socio-ecological systems in the whole-life cycle of PEDs; better integration of indigenous capabilities; and, an ethos of de-growth and circularity in their deployment.

Keywords: human-centric perspective, postivie energy districts, social psychology, environmental psychology, critical approach, interdisciplinarity

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Matthias Haase, SINTEF, Norway

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Emma Elizabeth Heffernan, University of Wollongong, Australia
Sujit Sikder, Leibniz Institute for Ecological Urban and Regional Development (IOER), Germany

****Correspondence:***
Minh-Thu Nguyen
mtnnu@iscte-iul.pt

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INTRODUCTION

Positive Energy Districts Within a Human-Centric Perspective: What Does It Mean?

The transition to low-carbon energy sources has been a key focus amongst efforts to mitigate climate change in European countries (EU-27). Therein, the energy sector accounts for 78% of green-house gas (GHG) emissions from fossil-fuel sources in 2018, including from transportation (Eurostat, 2020). Bound by the Paris Agreement target of reducing 40% of GHG emissions by

2030, the EU 2030 climate and energy framework has committed to producing (or sourcing) more renewable energy forms. Furthermore, it intends to make energy distribution more efficient, and thus pro-actively encourages energy saving behaviours from end-consumers (European Commission, 2018).

To achieve this target, the EU and its member states have been building large scale renewable energy projects both within and outside Europe (e.g., wind farms in Mexico exploited by international energy utility companies, Velasco-Herrejon and Bauwens, 2020). This has been accompanied by high voltage transmission and distribution grids whilst simultaneously controlling the energy demands of consumers via energy efficiency, market rules, and flexible prices (European Commission, 2019). The energy centralisation model of the previous fossil-fuel and nuclear based system is argued to be incompatible with intermittent sources of renewable energy. Moreover, the perpetuation of top-down decision-making, which is often met with local opposition, is also problematic (Wolsink, 2020). Hence, many European countries are developing digital technology and infrastructure which enables local renewable energy production and exchange. This reduces dependence upon the central grid, whilst aiming to also empower citizens and stakeholders to join the state in governing their energy system. This is especially the case in smart and/or sustainable cities (Caramizaru and Uihlein, 2020; Levenda et al., 2020).

Positive Energy Districts and Neighbourhoods (PEDs) represent one such decentralised energy initiative. The program aims to facilitate the design, implementation and scaling-up of 100 districts across Europe which produce more renewable energy than they consume by 2025. Established in 2018 by the Action 3.2 on Smart Cities and Communities of the European Strategic Energy Technology (SET) Plan, the PEDs program framework was co-created by city representatives, research and innovation representatives, and urban stakeholders via workshops and working groups organised by the Joint Programming Initiative (JPI) Urban Europe in 2019. Within the PEDs framework, the three main functions of energy production, energy efficiency and energy flexibility are leveraged are leveraged in order to achieve climate neutrality and energy surplus (JPI Urban Europe/SET Plan Action 3.2, 2020a). This means that in order to meet zero emission targets, PEDs require local renewable energy production at municipal and household scales for self-consumption and feeding to the grid. This surplus of electricity could then be utilised to power district heating and/or cooling, but also electrical vehicle charging. On the demand side, energy efficiency measures such as retrofitting buildings, smart-meters, and public or shared transportation are implemented in order to reduce energy consumption. With smart-grids, energy storage, and ICT technologies, the energy flexibility function is set to optimise energy systems by shifting the load in peak hours and thereby exchange the energy surplus (see Sikder et al., 2016, for an example of optimised energy systems and the actors involved at the neighbourhood scale).

In addition to this, "human-centric" is one of the key guiding principles used by PEDs to ensure the quality of life of cities and citizens, including preventing energy poverty as well as promoting sustainability and resilience of energy supply (JPI Urban Europe/SET Plan Action 3.2, 2020b, p. 8). However, within this PEDs framework, no specific nor concrete definitions of what that means exactly, and recommendations on how to implement it, are identified. Rather, this is left to local authorities and other stakeholders to interpret what those human-centric principles should signify and imply. In turn, a recent review by Ingeborgrud et al. (2020) highlights that energy and urban policy makers are still routinely in favour of top-down and centralised economic and technological interventions to address energy problems. This mainstream approach normally only accounts for the human dimensions of energy decision-making in a very superficial, cost-benefit and normative way. Taking social and psychological aspects into account in an in-depth, contextual and political way is often overlooked. Alternatively, social sciences' critical approaches which focus upon the promotion of the well-being of people and ecological systems alike, are able to consider and also address social inequalities and related injustices in a transformative manner. In fact, recent research on smart cities and associated policies and initiatives towards decentralisation and sustainability, has been demonstrating how these are still often performed within business-as-usual, neoliberal capitalist, rationales, and associated green growth logics (Levenda et al., 2020). The implications of perpetuating this type of rationale, namely in terms of the reproduction of social inequalities and environmental destruction, have been increasingly pointed out by the so-called critical turn in social sciences and humanities (SSH) energy research (see Batel, 2020; Silva and Sareen, 2021). Such an approach can then give useful insights to develop a critical framework on what should be human-centric PEDs, what this should mean, and how it should be materialised.

The Need for Critical SSH Energy Research for PEDs

A critical SSH approach can be described as recognising that people-expert-place-technology relations are socially co-constructed throughout time and space (Walker et al., 2011). However, it can also show that they reflect and often reproduce certain power asymmetries and related inequalities and injustices (Levenda et al., 2021). In other words, this critical approach contests the idea that science and research are value-free and apolitical. Instead, it aims to unveil, both in research, policy-making, planning and practise, how groups and individuals advance and promote certain interests and privileges instead of others, who benefits from this, and with what consequences (Batel, 2020). A relevant example of the type of questions that an SSH critical approach asks, examines and addresses in the context of PEDs could be: to what extent does the way PEDs are being developed and implemented promote or else explicitly avoid environmental gentrification? The latter is "characterised by the implementation of environmental or sustainability initiatives that leads to the exclusion, marginalisation and displacement of economically marginalised residents" (Pearsall and Anguelovski, 2016, p. 2).

The main aim of this paper is two-fold. Firstly, it argues for (and demonstrates) the relevance of adopting a critical SSH framework—in opposition to a mainstream SSH approach—for supporting the implementation of human-centric PEDs. Such PEDs are just, inclusive and promote people's and ecological systems' well-being, and enable design of related research, planning and policy agendas. Secondly, it proposes and describes a critical SSH framework by systematising its key dimensions based on a narrative literature review.

SSH research on energy transitions and sustainability and, particularly, contributions from critical social and environmental psychology, can offer many useful insights and lessons for PEDs. These enable researchers and planners to reflect upon what a human-centric approach should entail in order to safeguard "real" justice and sustainability in their transformational implementation. Firstly, this research has demonstrated that the siting of renewable energy infrastructures often also gives rise to *socio-ecological injustices*. This transpires when the political, economic, environmental, psycho-social and health impacts of those infrastructures and related technologies are not recognised, considered nor distributed equally (Jenkins et al., 2016; Batel and Devine-Wright, 2017). Secondly, this specific body of research has highlighted how *energy poverty and related well-being* have become an alarming issue across European countries, given that private energy services and low-carbon technologies' companies tend to discriminate against customers who generate less profit (or, are less capable of investing in and adapting to new technologies). Hence, such customers are excluded from affordable, efficient and quality low-carbon innovations (Sovacool et al., 2019a). Another key focus of this body of research has been on how energy-related policies and planning still often only incentivise a *low and passive participation* from citizens. This reflects traditional top-down and technocratic mainstream models of energy governance which fail to include, understand and address citizens' and communities' concerns from the beginning of energy-related projects, which often leads to opposition later on in their implementation phase (Carvalho et al., 2019; Levenda et al., 2020). At the same time, most citizens lack access to and engagement with technological innovations in their everyday lives—such as smart meters, photovoltaic panels and electric cars—due to socio-economic inequalities, lack of knowledge and other reasons. This has been shown to reduce active participation in energy issues (Ryghaug et al., 2018). Even when the impacts of energy are omnipresent, visible and invisible, in everyone's everyday life (Ambrose, 2020), the dominant consumerism focus of energy governance has been shown to alienate people from being political subjects—or energy citizens—in the public realm. Namely, to actually engage with have a voice, and be able to influence energy decision-making processes (Lennon et al., 2020; Levenda et al., 2020).

Hence, in this paper, we argue and propose that a critical human-centric perspective vis-à-vis PEDs needs to consider key socio-psychological aspects, namely *the well-being of energy citizens*, including the impacts of PEDs on their lived experiences, health and subjectivities. Moreover, *socio-environmental justice and equity*, in terms of inclusion, process and outcome must also be considered. To further clarify the relevance of considering these factors within a critical perspective for deploying human-centric PEDs, as opposed to considering them within a more mainstream, positivist perspective, we will also accentuate if and how these distinct approaches have been defined and considered, and the associated implications for human-centric PEDs.

METHODOLOGY—NARRATIVE LITERATURE REVIEW OF CRITICAL SSH ENERGY RESEARCH

Given that social science research on the human dimensions of PEDs and related smart city initiatives is still limited (see, for exceptions, Sadowski and Levenda, 2020; Levenda et al., 2021), an interdisciplinary narrative literature review of critical SSH energy research was conducted as a methodology. This was done in order to systematise the key dimensions to be considered within a critical framework for human-centric PEDs, and to gather insights from existing relevant studies in social science energy research (see Sovacool et al., 2018). This methodology also enabled an in-depth discussion of the implications of adopting a *critical* vs. a *mainstream* approach. Overall, this narrative literature review consisted of three main steps.

Firstly, the identification of key articles, books and other published research and essays which adopted and contributed to a critical approach to SSH energy research. This included underrepresented disciplines in social science energy research, such as from critical social and environmental psychology. Despite the latter's potential to contribute to more just and inclusive energy transitions (Di Masso, 2012; Batel et al., 2016; de Carvalho and Cornejo, 2018), it has often been left unexplored in this regard. The social and environmental psychology field has been contributing to understanding and explaining the human dimensions and psycho-social impacts of society-environment-technology interactions as well as studying how human dimensions could be integrated into the solution to problems emerging from those interactions (Clayton et al., 2016; Räthzel and Uzzell, 2019a). Hence, it can provide useful insights in understanding the significant processes and impacts associated with people's psychosocial relations with PEDs.

Critical approaches in social and environmental psychology highlight that "individuals are the sum of their social relations, i.e., they are the cause and consequence of their relations to others and the environment," including power relations which create and reproduce socio-environmental inequalities and injustices (Uzzell and Räthzel, 2009; Batel et al., 2016). In relation to creating sustainable societies, the research focus should change from the individual (the still current focus of more mainstream, positivist approaches) to "the relations of production and consumption and the social and political relations within which values, attitudes and behaviours are formed, and unsustainable ways of living and working as well as the environment are produced and reproduced" (Uzzell and Räthzel, 2009, p. 340, Räthzel and Uzzell, 2019a). This means that instead of only trying to understand and change individuals' behaviours towards more energy efficient practises, acceptance of renewable energy infrastructures, use of electric cars, and so on and so forth, critical research focus more on examining and contesting the way current social, economic and political relations that contribute to unsustainability and socio-ecological injustices are collectively formed and maintained (see also Groves et al., 2013; Räthzel and Uzzell, 2019b).

This first step included publications which had an applied focus on any social aspects of energy transitions and, at an epistemological and conceptual level, departed from critical perspectives or assumptions. More specifically, these perspectives recognised that people-environment-technology relations and related meanings are socially co-constructed throughout time and space. Furthermore, they included recognition of the political dimensions of meaning-making in general, including academic research and had an openness to interdisciplinary investigation. Many also included an acknowledgement of the global, cultural, local/community and psycho-social dimensions and impacts of energy transitions associated with these factors (see also Batel and Rudolph, 2021).

As a second step, those publications were then analysed with the aim of identifying the key and transversal factors therein identified and associated discussions. These were the factors identified as required for a critical human-centric approach to energy transitions, systems and issues. In turn, this also allowed us to systematise the critical framework proposed below.

Thirdly, definitions and examples of the five key transversal factors identified in the previous step were collected with a view to defining and applying them in a critical way in the context of PEDs. However, they were also used to provide a clear distinction in relation to defining and applying them within a mainstream approach. This step resulted in the subsections within the section Results—the Five Key Dimensions of a Critical Conceptual Framework for Human-Centric PEDs, and is summarised in **Table 1**.

RESULTS—THE FIVE KEY DIMENSIONS OF A CRITICAL CONCEPTUAL FRAMEWORK FOR HUMAN-CENTRIC PEDS

Based on the narrative literature review as described above (and the subsequent iterative process of identifying, defining, separating, combining and systematising key factors), these socio-psychological factors are grouped into five interconnected dimensions, here proposed as the critical conceptual framework for fostering human-centric PEDs. Those five dimensions are:

- Uncertainty, risk perception and trust;
- Distributive justice;
- Recognition justice and people-place relations;
- Procedural justice;
- Routines, capabilities and lived experiences.

The following sections will define, exemplify and discuss these key socio-psychological dimensions, their differential uptake by mainstream/critical approaches, and their relevance in the context of PEDs.

Uncertainty, Risk Perception and Trust—Background in PEDs and General Definition

According to the SET-Plan Action 3.2 (SET-Plan Working Group, 2018), energy production for building stock, transportation and other demands in PEDs needs to be generated from renewable sources to ensure a net zero CO_2 emission target. To make this easier, energy service companies (ESCO) would research, develop and provide micro-generation technologies and smart meters for citizens to produce and consume their own energy individually (or collectively) as an energy prosumer. Previous studies on public attitudes towards new energy technologies, and the siting of energy facilities and similar facilities, have indicated that risk perception and trust are normally strongly associated with specific attitudes (Lima, 2006). Namely, the higher the risk perception and the lack of trust in the social actors involved in the related decision-making process, the more people tend to reject them.

The tradition and technocratic definition of risk perception concerns the individual's evaluation, emotions and beliefs towards a potential threat (Lima, 2006; Weber and Stern, 2011). Meanwhile, trust is found to shape how people perceive risk, which depends on whether the parties involved can be relied upon to handle the technology by having expertise and values which the public is expecting and/or identifies with (Greenberg, 2014). Hence, it is crucial to consider risk perception and trust when deploying human-centric PEDs.

Mainstream Approach

Thus far, traditional, normative approaches have tended to explain risk perception and trust as individual processes by simply reflecting the publics' lack of information and cognitive biases in perceptions (see Steg et al., 2015). This manner of approaching risk perception and trust, in turn, favours planning and policy interventions which attempt to quantify, calculate and estimate risks in order to provide more and better information. However, they likewise dismiss the emotional, experiential, values and cultural dimensions that shape risk perception and trust (Douglas and Wildavsky, 1983; Lima et al., 2005; Groves et al., 2013). Indeed, research has shown that independently of technical-expert assessments of risks and of health impacts for certain technologies, if they are perceived to exist by the public, they can nonetheless negatively affect people's health. For instance, the work of Lima (2004) showed that communities living near a waste incinerator reported increased anxiety, stress and sleep deprivation due to the perceived health risks. Another consequence of a mainstream approach to risk and uncertainty is the tension between citizens' and state responsibilities in mitigating these risks. This increases the personal sense of responsibility in order to reduce risk e.g., moving home and place of living. However, the accountability to manage the risks should lie with those who create and propose them (Bickerstaff et al., 2008; Rolfe, 2018).

Critical Approach

Critical approaches to risk perception and trust have focused instead on showing that reactions to environmental or technological risks are influenced by social meaning-making processes of risk representation. These are shaped by social, cultural and political contexts and relations (Joffe, 2003; Bickerstaff, 2004; Lima and Castro, 2005). For instance, traditional and social media communication are key agents in the amplification or attenuation of certain risks: this has also

TABLE 1 | Summary of mainstream and critical approaches to relevant socio-psychological factors for human-centric PEDs.

Dimensions	Related PEDs configurations	Mainstream approach	Critical approaches
Uncertainty, risk perception, and trust	New energy and mobility technologies and facilities	DEFINITION (D): Risk perception is the irrational, uninformed and biased reaction by the public/community to a new, unknown and uncertain technology. It is mediated by trust in the proponents of the technology. SHORTCOMINGS OF INTERVENTIONS (SI): Mainly managed by risk analysis and by providing technical information to citizens; often do not address more subjective and cultural concerns.	DEFINITION (D): Risk perception and trust are shaped by wider collective, social, economic and political processes as well as related, unequal power relations. INTERVENTIONS (I): Considering how perceived risk affects people's subjective well-being and affects; considering how risks are socio-environmentally distributed; and, mitigating these effects by involving all affected and interested publics in defining risks in planning and decision-making processes, including the cultural, affective and symbolic dimensions of risks.
Distributive justice	Siting district energy and mobility facilities; Importing/ exporting energy surplus and low-carbon technologies	D: Distributive justice is the sense of equal costs and benefits distribution from the outcomes of an energy project. SI: Mainly managed by economic cost-benefit analysis, financially fair redistribution, and monetary/ material compensations, without considering current political economies and more historical, cultural, and symbolic dimensions.	D: Distributive injustice is the abstraction and commodification of economic value from other symbolic, spiritual and cultural values of the affected site and community. Distributive injustice is also the unequal distribution of rights and responsibilities. I: Considering how symbolic and cultural dimensions shape present senses of fairness; considering distributive justice across time (from extraction to decommission) and space (from local to global) in order to avoid energy colonialism and related psychosocial impacts.
Recognition justice and people-place relations	Flexible energy tariffs; Low-carbon technology investments; Changes in physical and social settings of neighbourhoods	D: Recognition justice is the recognition and inclusion of different needs of under-represented groups and places. SI: Mainly providing different financial packages to vulnerable socio-demographic groups to enhance their energy efficacy; providing green innovations to stigmatised locations to increase their market value, whilst marginalising those who cannot afford it (green gentrification).	D: Recognition injustice is the social and political process of disrespect, insult and degradation which devalue some people and some places and communities in comparison to others. I: Considering people-place relations; contesting structural gender mainstreaming and ethnic-racial inequalities which cause energy and transport poverty; recognising and valuing alternative feminist, de-colonial, intersectional and indigenous knowledge; avoiding place stigmatisation and physical and psychological displacement.
Procedural justice	Stakeholder involvement in decision-making; Public participation	D: Procedural justice ensures that energy decision-making respects due process and representation to increase public acceptance and minimise local opposition. SI: Understanding local opposition as only NIMBY, leading to consensus making techniques to legitimise interventions and avoid opposition; a soft way of controlling people's responses to energy projects.	D: Procedural injustice often reflects power imbalances in public participation due to structural constraints (e.g., gender relations) and lay-expert relations. I: Acknowledging public as not NIMBY, not homogenous and static, but indigenous, common-sense, and experiential; involving citizens and communities in co-creation processes from the beginning of any initiative; being aware of, and dismantling, lay-expert power relations in knowledge co-production.
Routines, capabilities and lived experiences	Energy and mobility everyday practises; The use of energy efficiency and flexibility technologies such as smart-meters and smart homes	D: Routines are individual habits based on personal attitudes, values, beliefs, and norms. SI: Changing energy inefficient routine behaviours by targeted communications and nudging to relevant socio-demographic groups, but which often result in short run, individual effects, and counter-productive outcomes (rebound effect).	D: Routines are shaped by structural and material infrastructures, meanings and power relations. I: Acknowledging structural constraints for changing routines such as political-economic governance including: rhythm of life; working schedules; and, infrastructures. Moreover, contesting energy efficiency imperatives or consumerism as usual, and focusing on lived experiences and capabilities.

been recently highlighted with the COVID-19 pandemic (Cori et al., 2020). However, risk representations and people's relations with uncertainty are also markedly shaped by social factors and power relations, such as by current neoliberal capitalist dynamics (Groves, 2015). This can deeply impact upon and menace people's values, emotions, attachments and related well-being since they have to deal with uncertainty every day and in every domain. This includes the climate crisis, job precariousness, and housing instability (Casanova et al., 2019). For example, a study concerning the public acceptance of smart meters in Portugal has shown that people represented smart meters as not only potentially involving health risks and financial risks, but also as a loss of control and privacy. These factors were highly associated with the lack of acceptance and use of smart meters (Guerreiro et al., 2015). Another example relating to the relevance of trust and due process in the perception of risks (and other impacts of energy infrastructures), is given by Rudolph et al. (2017). These authors demonstrated how the annoyance felt by local communities living near "the world's largest wind turbine test centre in Denmark" was increased by their lack of involvement in that decision. This indicated that "the emotional constitution of perceived annoyance may not only be grounded in the actual source of nuisance, but also entangled in related issues, in our case the perception of an unfair planning process, which for some has even made them question their democratic rights in Denmark" (p. 88). This points out to the need for citizen and community engagement in a substantial way: but moreover in a way which considers the emotional and experiential dimensions of people's risk perceptions and related trust issues. This must concern not only the planning phase of an energy project, but also the very stage of making a decision whether or not to deploy a given energy initiative, project, and/or policy.

Given this, several changes of approach must be made. Firstly, not reproducing the deficit model of the public (or the idea that the public only needs to be provided with technically relevant information in a sufficient and easy to understand way) (Rodhouse et al., 2021). Secondly, not focusing on the artificial and stereotypical distinction between subjective lay perceptions and objective expert knowledge about risks. Both of these latter approaches must be met with a critical turn to the social and political construction of risk which emphasises the "politics of uncertainty" that shape contemporary societies (Beck, 1992; Giddens, 1999). This perspective critically challenges the singular and homogenous definition of risk and uncertainty prevailingly put forward by techno-scientific and political experts (Scoones et al., 2020). It thus allows for open discussion about who wins and who loses when uncertainties and risks are proposed, negotiated and tamed by different stakeholders (Groves, 2015; Scoones and Stirling, 2020). In other words, it clearly reveals and examines how certain risks and harms are constructed in certain ways by specific groups, such as harmless smart meters as presented by energy companies in order to pre-empt potential resistance to their deployment by the public (Guerreiro et al., 2015). Another example is when the Dutch heat transition was presented to the public as "technical, complex, urgent, sensitive, and high-risk," which can lead vulnerable households to feel like they have less agency and active role to play in this collective decision-making process (Rodhouse et al., 2021, p. 10).

Distributive Justice—Background in PEDs and General Definition

Decentralisation is believed to distribute energy production and consumption infrastructures more evenly across regions. Thereby, it ensures access, shared burdens *and* benefits. However, this might not entirely be the case. To be self-sufficient and in order to ensure a secured supply of energy, PEDs' inhabitants will potentially use more solar photovoltaic (PV) for micro-generation, electric vehicles (EV) to reduce emissions, and batteries to store any energy surplus. Furthermore, distribution system operators (DSO) would develop smart grids to shift the load in peak hours and/or exchange energy supply with other regions outside of the PED's geographical boundary, as in the case of "virtual PEDs," which remain under discussion (JPI Urban Europe/SET Plan Action 3.2, 2020a, p. 6). These solutions not only require investment and engagement from the community within PEDs, but also require materials extraction and workforces outside PEDs such as from solar PV manufacturers, lithium mining for energy storage technology and infrastructures, or data centres for smart grid operations (Levenda et al., 2021; Sovacool, 2021). These characteristics of PEDs might then raise problems with one of the key dimensions of environmental and energy justice which has been at the centre of social sciences' energy research for some time, namely distributive injustice.

In general, energy justice has been concerned with the generation (or worsening) of social inequalities by energy systems and transitions. This can include distributive, recognition and procedural justice (see also sections Recognition justice and people-place relations—Background in PEDs and general definition and Procedural justice—Background in PEDs and general definition below)[1]. These have been shown to be significant factors in public responses to energy and transportation technologies' deployment (Sovacool et al., 2017). Distributive justice is normally defined as the sense of equal distribution of costs and benefits, or of responsibilities and rights (Walker, 2009). As described by Sovacool et al. (2017, p. 677), "costs is how the hazards and externalities of the energy system are disseminated throughout society (...) benefits is how the ownership of and access to modern energy systems and services are distributed throughout society."

Mainstream Approach

Traditionally, mainstream approaches have mostly focused upon distributive justice as a financial issue, based on a conception of individuals as *homo-economicus*, namely, as those who take decisions based only upon economic and functional cost-benefit analyses (see Batel et al., 2016 for a review). For example, normative approaches to distributive injustice are often concerned with how communities which are locally affected by the deployment of a wind farm can be financially compensated in the most cost-effective way possible for the energy companies (see Wolsink, 2018). Moreoever, they might focus on the extent of financial incentives necessary to motivate citizens to buy electric cars or solar PV for their households, whilst disregarding the fact that this will only benefit a few high-income groups who have economic capital and capabilities to invest in such new

[1] More recent and extended conceptualisations of energy justice have also included other dimensions, such as cosmopolitan or global justice, restorative justice and intergenerational justice (Sovacool et al., 2017, 2019a). However, our narrative literature review showed that these dimensions have not been as focused as such by research thus far. Furthermore, we also consider that, within a critical approach, these should be seen as transversal aspects to be included within the other key tenets of energy justice (i.e., distributive, recognition and procedural) since all of these should entail acknowledging the co-construction and implications of people-energy relations throughout time and across space, from the global to the local (see Walker, 2009; also Batel and Devine-Wright, 2017).

technologies (Sovacool et al., 2019b). In other words, by focusing on the willingness-to-pay for minimising the visual impact of energy infrastructures (or investing in low-carbon technologies), mainstream approaches assume that local opposition to those infrastructures (or up-take of those technologies) is based mainly on people's economic capacities and concerns (see Wolsink, 2018 for a critical discussion). Hence, this research often quantifies the impacts of a certain energy facility and policy through cost-benefit analyses and related monetary and material compensations for their deployment.

Critical Approach

However, critical research has also noted that there are other, symbolic, cultural and emotional, dimensions of distributive justice which cannot be quantified and compensated instrumentally. One example is the spiritual relationship of local people with ecological systems. This has been illustrated by Vargas Payera (2018) in Chile, where indigenous' communities resisted the deployment of a geothermal plant given their relations with volcanoes. Past intergroup relations and injustices regarding people-place relations and associated collective memories are also important, however, they are not usually considered in energy projects. This was evident in the deployment of high voltage power lines and wind farms in Wales to connect to the English energy grid, which created local opposition because it was seen as perpetuating the colonial history of England exploiting Wales in past energy projects. In turn, it therefore had a deep impact on people's lives and senses of place (Batel and Devine-Wright, 2017). If these non-quantifiable dimensions of energy projects are not considered, the mal-distribution of costs and benefits can induce several psycho-social harms. These include reduced well-being, depression, and anxiety amongst those who experience these inequalities (Lima and Morais, 2015). Beyond this, other under-acknowledged eco-psycho-geographical impacts of energy infrastructures have also been observed (see Dunlap, 2020).

As such, critical energy justice research has been moving away from normative, aspirational and utopian justice imperatives (which are more characteristic of mainstream approaches), in order to highlight the unjust consequences of current capitalist political economies within an inter-sectional, decolonial framework (Jenkins et al., 2020; Menton et al., 2020). Dunlap and Sullivan (2020) term this problem of distributive injustice as "accumulation-by-alienation" following Harvey's (2018) "accumulation-by-dispossession," an abstraction of economic value from ecological systems (in this case land and energy resources) which alienate their symbolic relation to humans in order to quantify, commodify, and pay it off (see more in section Recognition Justice and People-Place Relations—Background in Peds and General Definition below). Other proposals from critical approaches to distributive justice have suggested the importance of acknowledging and better unveiling the global consequences of transnational energy projects and transitions through concepts such as *energy or green colonialism* (Batel and Devine-Wright, 2017; Normann, 2021). Both concepts draw attention to the global and historical injustices of energy generation and low-carbon technologies' production as they build upon structural, historical power asymmetries between the privileged and the dispossessed. This has been done by transferring or delegating the cost of energy and related material extractions to other, less powerful, socio-geographical areas, including their inhabitants and ecological systems.

Recognition Justice and People-Place Relations—Background in PEDs and General Definition

To secure the efficiency and flexibility of the energy system, PEDs may require several features. These include: flexible tariffs to manage the energy demand and supply dynamics; retrofitting houses to improve building stock efficiency; and, altering transportation infrastructure to allow more electric vehicles (SET-Plan Working Group, 2018). However, these changes in energy practises and spatial settings may also affect the physical and social lives of residents in different ways. Without considering the needs of different people such as the poor, the elderly, the homeless, the unemployed and citizen's place relations, PEDs policies and technologies can further exclude them from their design and outcomes, which gives rise to (mis)recognition of justice concerns regarding energy and transport poverty as well as people-place relations.

Recognition injustice is defined as "the processes of disrespect, insult and degradation that devalue some people and some place identities in comparison to others" (Walker, 2009, p. 615). Flexible pricing of electricity or "time of use" tariffing, for example, has been found to disregard or fail to recognise the need of single parents or long hours working parents. Frequently, they have children who often concentrate all family activities at certain times of the day, thus making them pay higher electricity bills than other more flexible households (Sovacool et al., 2019b). In turn, the stigmatisation of places and of associated identities and attachments can occur when the construction of wind turbines and solar panels in a community (or the renovation of its buildings), changes how that community and place are not only experienced (Groves, 2015; Rudolph and Kirkegaard, 2019), but also their socio-economic characteristics. This may lead to community members' physical and/or psychological displacement and related impacts on well-being and empowerment (Brown and Perkins, 1992; Manzo and Devine-Wright, 2013; Ropert and Di Masso, 2021).

Mainstream Approach

Mainstream approaches to recognition justice have focused around household-scale material and economic factors promoting energy and transport poverty. Specifically, these include the affordability and accessibility of energy and transport services to different groups and regions (see Simcock et al., 2021). Scholars have contributed to evaluating affordability by uncovering which demographic groups (i.e., by age, gender, economic status) have high energy and transport spending relative to their income levels (Simcock et al., 2020). By highlighting these vulnerable cases, current policies not only favour targeted economic subsidies, such as reducing energy and transport tariffs for vulnerable regions and households, but also promote behaviour change programs aimed at improving the cognitive capacity and energy efficacy of people's behaviours (see Jenkins et al., 2016). However, this type of approach builds upon imperatives of self-responsibility in energy governance, which can in turn create greater stress for those who are already lacking time and resources in their everyday lives, such as single parents, or those who are incapable of implementing changes due to ageing or disability.

Furthermore, the spatialising of domestic and transport energy poverty in mainstream research also has aided policy makers in detecting "energy peripheries" which lack access to networked energy and transport infrastructures (Robinson and Mattioli, 2020). To rectify these stigmatised regions of poverty and unsustainability, many cities in Europe have seen the burgeoning of "green regeneration" projects which renew deprived urban neighbourhoods with green spaces and low-carbon initiatives, but also increase housing market prices (Ali et al., 2020). By recognising and improving the financial value of the area, this environmental gentrification often leads to the displacement of vulnerable residents who are unable to afford or accommodate such renovations. As their voices and relations with their homes, neighbourhoods and communities are marginalised, this mainstream approach can, in turn, perpetuate energy poverty and marginalisation (de Carvalho and Cornejo, 2018).

Critical Approach

Critical approaches to this issue have tried to understand why there is energy vulnerability and place stigmatisation in the first instance. They have also sought to explain how this is a result of the misrecognition or non-recognition of certain groups and places at the societal and political level rather than at individual, cognitive levels (Jenkins et al., 2016; Simcock et al., 2021). Research in the feminist energy development field, for example, has contested the distorted view of "gender mainstreaming" in subsidising female-headed families to tackle energy poverty. Such an approach essentialises the vulnerability of women to poverty whilst obscuring the structural cause of said poverty such as gender norms. In turn, this leads to the marginalising of women in need within non-female-headed households (Listo, 2018). In the same vein, the unequal gender distribution of labour, especially in positions of power, might not allow women to participate in the decision-making processes of electricity production. Consequently, this then excludes their needs and lived experiences from project design (Fraune, 2015). Another crucial example is given by Lennon (2017) who highlights the need to acknowledge, examine and contest how colonial legacies shape ethnic-racial inequalities in engaging with and accessing mobility as well as electricity. This emphasises the need not only to act at more structural, societal levels to change systemic inequalities, but also to consider how this might be challenged through local initiatives and practises such as in PEDs (see also Lennon, 2021).

Furthermore, instead of stigmatising some places as poor and unsustainable in order to legitimise economic and environmental development projects as in mainstream approaches, critical research is mindful of other pertinent factors. For instance, how promoted changes in the physical and social composition of buildings, neighbourhoods and cities might deeply affect people's well-being, through further reproducing (or even creating) new exclusions and inequalities (de Carvalho and Cornejo, 2018). As already mentioned, PEDs might displace those who cannot afford a low-carbon settlement from not only a given house or apartment as a building made of bricks, but also from their home, neighbourhood and community, with all their emotional and symbolic meanings and relations as well as associated psycho-social impacts (Manzo and Devine-Wright, 2013). By adopting a more critical approach which argues for a non-static, non-essentialist view of places and groups, PEDs can include the voices of under-represented groups and promote their local, indigenous knowledge, experiences and relations, instead of prescribing top-down, non-contextual and commodified interventions that reproduce exclusions and stigmatised representations of places and of certain groups (Devine-Wright et al., 2019; Ropert and Di Masso, 2021).

Procedural Justice—Background in PEDs and General Definition

As is already clear from the above, PEDs technological and social innovations require the participation of multiple actors including the local authorities, private companies, and civil society. For example, to encourage citizens to use low-carbon public modes of transport instead of private cars, city planners need to improve the inclusive design of the transport system through public engagement processes so that it can serve the various needs of different groups of the population.

Considered to be a key factor in the social acceptance of energy and transport technology, procedural justice ensures that energy decision-making respects due process and representation (Sovacool et al., 2017). This is because undemocratic processes can create unequitable outcomes to under-represented or misrepresented groups (see recognition justice in section Recognition Justice and People-Place Relations—Background in PEDs and General Definition above). Therefore, under the multi-level governance perspective, institutionalised public participation procedures, such as the United Nations' Agenda 21, are encouraged at the local level (Geissel, 2009) through various democratic and participatory practises. These include public opinion surveys, community consultancy, participatory budgeting, and co-creation workshops (Becker and Naumann, 2017; Itten et al., 2021).

Mainstream Approach

Current mainstream approaches to public participation mostly conceives of people's negative responses to energy projects as NIMBY- Not in my back yard—and assumes that responses to energy projects are based on ignorance, proximity and self-interest (Devine-Wright, 2011). Despite other factors that explain better the "back yard motives" (such as place attachment and energy justice issues as mentioned above) (see Wolsink, 2007; Devine-Wright and Howes, 2010; Batel, 2020), NIMBY-ism is still used by many researchers, policy-makers and energy companies. NIMBY-ism interprets local resident's opposition to energy projects as irrational, selfish and ignorant by lacking objective information. This leads to a "tokenistic level" of citizens' engagement, including informing, consulting and placation (Arnstein, 1969). These are often regarded as sufficient to create social acceptance in an instrumental way (see also Devine-Wright, 2011; Jenkins et al., 2016; Levenda et al., 2020). For example, qualitative research into public consultation and participatory budgeting points out that invited participation, understood as one-way dialogue or discursive justification of interventions from formal institutions towards citizens, is often used to simulate participation and pre-empt social conflicts (Cuppen, 2018; Carvalho et al., 2019; Santos et al., 2019). In other words, consensus-making techniques which reduce political debate to technical and management activities make it seem like all voices are heard and considered. Of course, this is done to ease local resistance, even when final decisions are still mainly based on cost-benefit analyses and regulatory constraints that benefit authorities and corporations (Santos et al., 2019).

Critical Approach

Critical approaches to procedural justice propose ways to overcome tokenistic practises of participation by challenging the biased representations about the public often held by energy project developers and policy-makers (Walker et al., 2010a,b; Barnett et al., 2012). These powerful stakeholders tend to negatively represent citizens' opposition towards local energy projects as merely being NIMBY, as outlined above. Critical inquiries into this issue pay attention specifically to the unequal power relations between experts and citizens within technocratic, low-carbon transitions and governance, and how those tend to preclude citizens from actually being able to influence decision-making processes since they are projected until decommission (Knudsen et al., 2015; Carvalho et al., 2019). Research in this area, therefore, has been challenging developers' conventional imaginaries of the public. By contrast, it seeks to advance alternative representations of the public as non-homogenous and non-static, but rather indigenous, common-sense, experiential, and affective (Rodhouse et al., 2021). Thus, their lived experiences and bottom-up forms of knowledge are legitimate and relevant to include in energy related decision-making processes (Velasco-Herrejon and Bauwens, 2020; Elkjær et al., 2021).

The recent co-creation turn in governance practises has the potential to empower citizens and communities alongside traditional experts for collaborative knowledge generation and decision-making by reconsidering citizen's roles from consulted citizens to active co-producers and political actors in the participative process (Elkjær et al., 2021). Indeed, Itten and colleagues' study (Itten et al., 2021) has shown that co-creation is a potential solution for sustainable heat transitions as it is possible to see how citizens and house owners' shared meanings of heating. In turn, this has helped stakeholders to include those meanings in their energy programme design. Another study about living labs in Switzerland concludes that this type of co-creation could create a protected space for citizens, innovation entities and public authorities in order to build reciprocal trust to discuss contested topics such as future mobility scenarios (Cellina et al., 2020). Furthermore, community renewable energy ecologies (CREE) have been discussed as having a more transformative potential amongst co-creation practises as they are built on principles of collective ethic-political decision-making, based on care and affective relations amongst humans and non-humans. Hence, CREE adopt "non-capitalist relations of ownership, production, exchange and circulation" (Siamanta, 2021, p. 47).

Routines, Capabilities and Lived Experiences—Background in PEDs and General Definition

Regarding energy efficiency aspects, energy users (including transport users and property owners) are the main targets of the PEDs framework (JPI Urban Europe/SET Plan Action 3.2, 2020b). With the availability of energy efficient appliances, energy users are expected to adopt more energy conservation behaviours based upon feedback from smart meters. Similarly, house or building owners should invest in retrofitting to save energy costs in the long run. Furthermore, to adapt to energy flexibility, energy users are responsible for adjusting their practises to avoid high electricity prices and accommodate for low energy supply scenarios.

A large part of energy consumption behaviours—such as heating, cleaning and showering—are found to be routine and habitual (Hess et al., 2018). Hence, how to change inefficient routines and set up new habits have been the main aims of many efficiency and flexibility interventions in smart cities. This trend is captured in Sovacool (2014) review paper which concludes that human-centred research has paid more attention to the routines and habits of energy users instead of the general technological and economic configurations shaping said routines.

Mainstream Approach

A vast amount of research in psychology and behavioural economics has been invested in understanding and changing individual patterns of energy consumption (Burger et al., 2015; Steg et al., 2015). This mainstream approach examines how individuals' routines are formed not only by personal attitudes towards environmental problems based on their values and beliefs, but also by social norms i.e., the perceived expectations and behaviours of others (Ingeborgrud et al., 2020). Within this approach, recommended policies tend to use targeted communication strategies to appeal to audiences' values and beliefs (Ingeborgrud et al., 2020). This can include cost-effective benefits for utilitarian values and environmental impacts for altruistic, bio-spheric concerns (Hess et al., 2018). It also harnesses social norms to nudge energy users into energy saving behaviours, for example, via feedback of average household energy consumption on a smart meter (DellaValle and Sareen, 2020). For more effectively targeted behaviour change policies, mainstream research has been predicting which socio-demographic groups are more impacted by which underlying psychological factors. These include: beliefs and attitudes; motives and intentions; perceived behavioural control; cost-benefit appraisals; and, personal and social norms (Frederiks et al., 2015). However, these nudging and economic incentive interventions (which dominate in energy governance and policies) have been shown to have a short run, individual impact, and even counter-productive outcomes

(Dholakia et al., 1983; Roberts, 2017; see more in critical approach below).

Critical Approach

More recent, critical-led research, points out that the "energy efficiency" imperative in energy conservation behaviour research and intervention not only "purifies" energy consumption from its everyday practises (Shove, 2018) but also assumes consumerism as usual, i.e., energy users are locked into the consumer culture of appliances and lifestyles that require extensive and continuous energy consumption (McDonald et al., 2017). Furthermore, smart technologies for energy efficiency could lead to a "rebound effect" by increasing overall energy usage after saving from energy efficient appliances and practises, which could render the effort of reducing environmental impacts from energy consumption futile in human-centric PEDs (Shove, 2018).

Critical research on this, such as that utilising social practise theory, sees rhythm of life, working schedules, and infrastructures as structural constraints to changing routines (Murtagh et al., 2014; Sovacool et al., 2018). For instance, a study on smart-meters in France points out that citizens complain about the pre-setting of some home devices that they are unable to turn-off (Bertoldo et al., 2015). Consequently, they lose their capability to control and thus sense of agency in their interaction with energy facilities (Marres, 2012; Sadowski and Levenda, 2020). In another example, qualitative research based on social practises theory has unravelled how practises of heating the homes of old residents in the UK closely connects to the cultural meaning of comfort, cosiness and glow. This associates heating the house with burning wood, or turning on the heater even when other less energy-intensive actions could be taken, such as wearing more clothes or insulating the house to ensure thermal comfort (Devine-Wright et al., 2014; Wrapson and Devine-Wright, 2014). Critical research on mobility also finds that the routine of frequent, low-cost and private travel experiences (or hypermobility) is deeply driven by the dominant neoliberal connotations of autonomy and individual freedom, but also social status in relation to personal success as well as wider frames about national progress (Barr, 2018). As such, more structural, political and economic changes must happen to allow for less energy intensive practises within a degrowth and energy justice framework (Schneider et al., 2010).

In summary, critical approaches call for the need of a human-centric approach in PEDs which pays more attention to the lived experiences and valued capabilities of energy users, such as keeping good health, feeling respected, preserving indigenous identities and feeling a sense of agency over one's life and community (see Edwards et al., 2016; Velasco-Herrejon and Bauwens, 2020; also Holifield et al., 2017). By connecting these lived experiences and valued capabilities to existent social, political, economic and cultural conditions, critical approaches allow for the modification of routines and practises by allowing the re-configuration of their meanings without negatively impacting people's and ecosystems' well-being.

CONCLUSIONS

As emerging PEDs are currently proposed based on the technocratic and economic traditions of the energy sector, a better understanding of the human and social dimensions of PEDs is needed to break the "silo thinking" found therein (Yoo et al., 2020). However, SSH energy research has already started to show that not all approaches to considering the social dimensions of energy systems and related initiatives towards increased environmental sustainability are similar. For instance, some tend to reproduce and further reify the political economy of the fossil-fuel status quo and associated neglect of the social and environmental injustices and inequalities it has created and continues to accentuate. However, critical SSH approaches work towards unveiling and contesting those injustices and inequalities. As such, this paper, based on a narrative-style inter-disciplinary literature review of critical SSH energy research (with a special focus on environmental and social psychology), aimed to develop a critical framework towards a human-centric approach to PEDs. Specifically, one that is able to consider and integrate issues of justice, inclusion and well-being. As a result, the critical framework that we proposed is based on five interrelated dimensions: uncertainty; risk perception and trust; distributive justice; recognition justice and people-place relations; procedural justice; and, routines, capabilities, and lived experiences.

As such, this paper also contributes to advance SSH scholarship on energy and environmental justice in general, and specifically in relation to people's engagements with renewable and smart energy transitions. It does so by shedding light on why and how a critical approach is needed (see also Menton et al., 2020), but also by contributing some insights to this literature from social and environmental psychology perspectives. These are: (i) the role of socio-historical dimensions and related collective memories and psychosocial impacts on distributive injustice; (ii) the consideration of place attachment and associated psychosocial subjectivities in relation to recognition justice; and, (iii) the power dynamics between lay and experts which shape the imagined roles and agency of the public in procedural justice concerns.

In this vein, this paper contributes to a more reflexive and holistic view in understanding the human dimension in PEDs. Through the critical review and framework, it is noticeable that the status quo or mainstream approaches tend to study different factors separately. They also quantify their effects on individuals by isolating them from other contextual, social, and political relevant dimensions. On the contrary, critical perspectives regard this abstraction and alienation process as problematic. This critical perspective, therefore, allows us to consider, discuss and include specific measures and interventions in the deployment of PEDs. These measures consider energy consumption and production not as a given, but as social, cultural, political, economic and collective endeavours. To that end, they also impact upon their specific components and configurations when being implemented (see Sovacool, 2014).

DISCUSSION AND RECOMMENDATIONS FOR FUTURE RESEARCH AND POLICIES

As a last remark, this paper discusses some recommendations for future research and policy interventions to achieve human-centric PEDs which are attentive to justice, inclusion, and well-being of citizens and ecological systems alike.

Assess the Whole Life-Cycle of Energy Systems in PEDs Impact Analysis

Instead of only tackling the downstream social and ecological consequences of energy systems in local areas, critical approaches recommend that researchers and policy makers redefine and recognise energy justice as relevant across local to global scales to avoid shifting the social, environmental, psychological and health costs of sustainable energy transitions from the Global North to the Global South, or to more vulnerable and marginalised communities and territories in general (Batel and Devine-Wright, 2020; Menton et al., 2020). This implies a more reflexive connection of energy consumption with energy production. This would consider the whole lifecycle of the infrastructures and technologies needed to deploy PEDs, such as lithium extraction for batteries and storage for EV. As Sovacool (2021, p. 14) suggests: "more attention to multi-scalar and whole-systems thinking would better appreciate how climate mitigation efforts depend on resource extraction and mining, manufacturing, transport and construction, policy and planning, operation and use, and disposal and waste streams. Whole systems approaches would ensure that the suffering of others is no longer obscured or distorted by distance."

Unveil and Challenge the Political Economy of Conventional Interventions to Encourage Transformative Alternatives for PEDs' Social-Ecological-Technological Configurations

By inspiring collective action against the import of energy sources that are considered unethical, such as the divestment movement against fossil fuel-based energy (Healy and Barry, 2017), critical approaches challenge the ""capitalist valuation" [...] towards deeper contestation of the alienating accumulation structures effected through neoliberal environmental governance" (Dunlap and Sullivan 2020, p.570). Hence, it can contribute to creating "an alliance of the dispossessed, including a coalition of the global social and environmental justice movements" (Kallis et al., 2018, p. 29). Alternatives to the dominant neoliberal capitalist rationality of energy governance have been explored in post-development, decolonisation and degrowth pathways. These conceptualise production as based on alternative socio-ecologies which are more community-based, circular, inclusive and based on mutual aid (Nirmal and Rocheleau, 2019; Siamanta, 2021). More focus should be given to the lived experiences, everyday practices and informal economies of some self-governed communities around the world and in some cities in the Global South (e.g., Butcher and Maclean, 2018). In turn, this can challenge neoliberal capitalist practises and offer alternative configurations for human-centric PEDs.

Prioritise Human and Ecosystems Well-Being and Lived Experiences in PEDs Design

PEDs could foster transformative, structural changes by recognising and including other concerns in their development and implementation such as communalist values and well-being (Edwards et al., 2016) as well as equity principles (Sovacool et al., 2017). These could be deployed to address energy poverty and inequalities at their source. "Feminist energy systems," for example, would propose that PEDs' energy technologies and economic model need to be contextualised to respect the specific needs of different groups of people in different localities (Bell et al., 2020). To do so, an empirical focus on lived experiences, routines and valued capabilities, which engages with communities through ethnography, living labs, walking and in-depth interviews, could create opportunities for energy citizens to re-negotiate and question how they are pushed by and embedded in both every day, needed demands that they value, but also the larger demands of energy systems and associated political economies (Waitt et al., 2016; Barr, 2018).

Empowered Citizens and Communities Through Co-creation of PEDs

The aim should then be to only deploy PEDs innovations (such as micro-generation, smart meters, retrofitted homes, electric vehicles, district waste heat etc.) by openly co-creating them with citizens. Attention must be paid to their concerns and values, and from a collective, local to global perspective, being considerate of social and ecological systems alike (Williams et al., 2014; Devine-Wright et al., 2019). This move from public participation to co-creation of PEDs not only requires the re-examination of mainstream knowledge, i.e., the decolonisation of energy (Lennon, 2017), but also the valuation of the lay public's energy conceptions through the reappraisal of indigenous and informal energy knowledge and practises (Normann, 2021). Future research should therefore further inquire into how this can be done outside structural, institutional constraints, and be based on bottom-up, community-led and aimed initiatives. The goal of such an approach would be a sustainable, just and socio-environmental alternative to State and corporate-led smart and renewable energy transitions.

In conclusion, critical approaches to human dimensions in PEDs help to uncover the structural exclusions implied in many current "sustainable" governance structures and associated political economies of smart cities initiatives including PEDs. They are also vital to unearth relevant psycho-social dimensions and impacts by proactively reaching out for often ignored alternative stories and people. As such, critical approaches have the potential to support PEDs deployment via more just and equitable human-centric local energy transitions. This means to reveal, in a clear and evidence-based way, why and how these objectives are not "truly" feasible unless we start to actually transform not only the energy system, but also the politics of energy towards degrowth and an ethics of care and responsibility for all socio-ecological systems both locally and globally, and in the short and long terms.

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M-TN and SB reviewed the literature, conceptualized, and wrote the paper.

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REFERENCES

Ali, L., Haase, A., and Heiland, S. (2020). Gentrification through green regeneration? Analyzing the interaction between inner-city green space development and neighborhood change in the context of regrowth: the case of Lene-Voigt-Park in Leipzig, Eastern Germany. *Land* 9:24. doi: 10.3390/land9010024

Ambrose, A. (2020). Walking with Energy: Challenging energy invisibility and connecting citizens with energy futures through participatory research. *Futures* 117:102528. doi: 10.1016/j.futures.2020.102528

Arnstein, S. R. (1969). A ladder of citizen participation. *J. Am. Plann. Assoc.* 35, 216–224. doi: 10.1080/01944366908977225

Barnett, J., Burningham, K., Walker, G., and Cass, N. (2012). Imagined publics and engagement around renewable energy technologies in the UK. *Public Underst. Sci.* 21, 36–50. doi: 10.1177/0963662510365663

Barr, S. (2018). Personal mobility and climate change. *Wiley Interdicip. Rev. Clim. Change* 9:e542. doi: 10.1002/wcc.542

Batel, S. (2020). Research on the social acceptance of renewable energy technologies: past, present and future. *Energy Res. Soc. Sci.* 68:101544. doi: 10.1016/j.erss.2020.101544

Batel, S., Castro, P., Devine-Wright, P., and Howarth, C. (2016). Developing a critical agenda to understand pro-environmental actions: contributions from social representations and social practices theories. *Wiley Interdicip. Rev. Clim. Change* 7, 727–745. doi: 10.1002/wcc.436

Batel, S., and Devine-Wright, P. (2017). Energy colonialism and the role of the global in local responses to new energy infrastructures in the UK: a critical and exploratory empirical analysis. *Antipode* 49, 3–22. doi: 10.1111/anti.12261

Batel, S., and Devine-Wright, P. (2020). Using NIMBY rhetoric as a political resource to negotiate responses to local energy infrastructure: a power line case study. *Local Environ.* 25, 338–350. doi: 10.1080/13549839.2020.1747413

Batel, S., and Rudolph, D. (eds.). (2021). *A Critical Approach to the Social Acceptance of Renewable Energy Infrastructures: Going Beyond Green Growth and Sustainability*. New York, NY: Springer.

Beck, U. (1992). From industrial society to the risk society: questions of survival, social structure and ecological enlightenment. *Theor. Cult. Soc.* 9, 97–123. doi: 10.1177/026327692009001006

Becker, S., and Naumann, M. (2017). Energy democracy: mapping the debate on energy alternatives. *Geogr. Compass* 11, 1–13. doi: 10.1111/gec3.12321

Bell, S. E., Daggett, C., and Labuski, C. (2020). Toward feminist energy systems: why adding women and solar panels is not enough?. *Energy Res. Soc. Sci.* 68:101557. doi: 10.1016/j.erss.2020.101557

Bertoldo, R., Poumadère, M., and Rodrigues, L. C. (2015). When meters start to talk: the public's encounter with smart meters in France. *Energy Res. Soc. Sci.* 9, 146–156. doi: 10.1016/j.erss.2015.08.014

Bickerstaff, K. (2004). Risk perception research: socio-cultural perspectives on the public experience of air pollution. *Environ. Int.* 30, 827–840. doi: 10.1016/j.envint.2003.12.001

Bickerstaff, K. J., Simmons, P., and Pidgeon, N. (2008). Constructing responsibilities for risk: negotiating citizen - state relationships. *Environ. Plann. A.* 40, 1312–1330. doi: 10.1068/a39150

Brown, B. B., and Perkins, D. D. (1992). "Disruptions in place attachment," in *Place Attachment*, eds I. Altman, and S.M. Low (New York, NY: Springer US), 279–304. doi: 10.1007/978-1-4684-8753-4_13

Burger, P., Bezençon, V., Bornemann, B., Brosch, T., Carabias-Hütter, V., Farsi, M., et al. (2015). Advances in understanding energy consumption behavior and the governance of its change - outline of an integrated framework. *Front. Energy Res.* 3, 1–19. doi: 10.3389/fenrg.2015.00029

Butcher, M., and Maclean, K. (2018). Gendering the city: the lived experience of transforming cities, urban cultures and spaces of belonging. *Gend. Place Cult.* Luxembourg 25, 686–694. doi: 10.1080/0966369X.2018.1462773

Caramizaru, E., and Uihlein, A. (2020). *Energy communities: an overview of energy and social innovation*, EUR 30083 EN. Luxembourg: Publications Office of the European Union.

Carvalho, A., Pinto-Coelho, Z., and Seixas, E. (2019). Listening to the public–enacting power: citizen access, standing and influence in public participation discourses. *J. Environ. Policy Plan.* 21, 563–576. doi: 10.1080/1523908X.2016.1149772

Casanova, M. L., Menezes, I., Lawthom, R., and Coimbra, J. L. (2019). Precarious living: the social origins of uncertainty. *Port. J. Soc. Sci.* 18, 319–340. doi: 10.1386/pjss_00013_1

Cellina, F., Castri, R., Simão, J. V., and Granato, P. (2020). Co-creating app-based policy measures for mobility behavior change: a trigger for novel governance practices at the urban level. *Sustain. Cities Soc.* 53:101911. doi: 10.1016/j.scs.2019.101911

Clayton, S., Devine-Wright, P., Swim, J., Bonnes, M., Steg, L., Whitmarsh, L., et al. (2016). Expanding the role for psychology in addressing environmental challenges. *Am. Psychol.* 71, 199–215. doi: 10.1037/a0039482

Cori, L., Bianchi, F., Cadum, E., and Anthonj, C. (2020). Risk perception and covid-19. *Int. J. Environ. Res. Public Health* 17:3114. doi: 10.3390/ijerph17093114

Cuppen, E. (2018). The value of social conflicts. *Critiquing invited participation in energy projects. Energy Res. Soc. Sci.* 38, 28–32. doi: 10.1016/j.erss.2018.01.016

de Carvalho, L. P., and Cornejo, M. (2018). Towards a critical approach to place attachment: a review in contexts of infringement of the right to adequate housing. *Athenea Digit.* 18, 1–39. doi: 10.5565/rev/athenea.2004

DellaValle, N., and Sareen, S. (2020). Nudging and boosting for equity? Towards a behavioural economics of energy justice. *Energy Res. Soc. Sci.* 68:101589. doi: 10.1016/j.erss.2020.101589

Devine-Wright, P. (2011). Public engagement with large-scale renewable energy technologies: Breaking the cycle of NIMBYism. *Wiley Interdicip. Rev. Clim. Change* 2, 19–26. doi: 10.1002/wcc.89

Devine-Wright, P., and Howes, Y. (2010). Disruption to place attachment and the protection of restorative environments: a wind energy case study. *J. Environ. Psychol.* 30, 271–280.

Devine-Wright, P., Smith, J., Batel, S., Devine-Wright, P., Smith, J., and Batel, S. (2019). "Positive parochialism," local belonging and ecological concerns:

revisiting common ground's parish maps project. *Trans. Inst. Br. Geogr.* 44, 407–421. doi: 10.1111/tran.12282

Devine-Wright, P., Wrapson, W., Henshaw, V., and Guy, S. (2014). Low carbon heating and older adults: comfort, cosiness and glow. *Build. Res. Inf.* 42, 288–299. doi: 10.1080/09613218.2014.883563

Dholakia, R. R., Dholakia, N., and Firat, A. F. (1983). From social psychology to political economy: a model of energy use behavior. *J. Econ. Psychol.* 3, 231–247. doi: 10.1016/0167-4870(83)90004-1

Di Masso, A. (2012). Grounding citizenship: toward a political psychology of public space. *Polit. Psychol.* 33, 123–143. doi: 10.1111/j.1467-9221.2011.00866.x

Douglas, M., and Wildavsky, A. (1983). *Risk and Culture: An Essay on the Selection of Technological and Environmental Dangers*. Berkeley, CA: University of California Press. doi: 10.1525/9780520907393

Dunlap, A. (2020). Bureaucratic land grabbing for infrastructural colonization: renewable energy, L'Amassada, and resistance in southern France. *Hum. Geogr.* 13, 109–126. doi: 10.1177/1942778620918041

Dunlap, A., and Sullivan, S. (2020). A faultline in neoliberal environmental governance scholarship? Or, why accumulation-by-alienation matters. *Environ. Plan. E. Nat. Space* 3, 552–579. doi: 10.1177/2514848619874691

Edwards, G. A. S., Reid, L., and Hunter, C. (2016). Environmental justice, capabilities, and the theorization of well-being. *Prog. Hum. Geogr.* 40, 754–769. doi: 10.1177/0309132515620850

Elkjær, L. G., Horst, M., and Nyborg, S. (2021). Identities, innovation, and governance: a systematic review of co-creation in wind energy transitions. *Energy Res. Soc. Sci.* 71:101834. doi: 10.1016/j.erss.2020.101834

European Commission (2018). *2030 Climate & Energy Framework - Climate Action. 2030 Climate & Energy Framework*. Available online at: https://ec.europa.eu/clima/policies/strategies/2030_en (accessed August 13, 2020).

European Commission (2019). "Clean Energy for All Europeans," in *Euroheat and power (English Edition)*, Vol. 14. Luxembourg: EU Publications.

Eurostat (2020). "*Greenhouse Gas Emission Statistics - Emission Inventories - Statistics Explained." Eurostat. 2020*. Available online at: https://ec.europa.eu/eurostat/statisticsexplained/ (accessed August 13, 2020).

Fraune, C. (2015). Gender matters: women, renewable energy, and citizen participation in Germany. *Energy Res. Soc. Sci.* 7, 55–65.

Frederiks, E. R., Stenner, K., and Hobman, E. V. (2015). The socio-demographic and psychological predictors of residential energy consumption: a comprehensive review. *Energies* 8, 573–609. doi: 10.3390/en8010573

Geissel, B. (2009). Participatory governance: hope or danger for democracy? A case study of local agenda 21. *Local Gov. Stud.* 35, 401–414. doi: 10.1080/03003930902999522

Giddens, A. (1999). Risk and responsibility. *Modern Law Rev*. 62, 1–10. doi: 10.1111/1468-2230.00188

Greenberg, M. R. (2014). Energy policy and research: the underappreciation of trust. *Energy Res. Soc. Sci.* 1, 152–160. doi: 10.1016/j.erss.2014.02.004

Groves, C. (2015). The bomb in my backyard, the serpent in my house: environmental justice, risk, and the colonisation of attachment. *Environ. Polit.* 24, 853–873. doi: 10.1080/09644016.2015.1067348

Groves, C., Munday, M., and Yakovleva, N. (2013). Fighting the pipe: neoliberal governance and barriers to effective community participation in energy infrastructure planning. *Environ. Plann. C. Gov. Policy* 31, 340–356. doi: 10.1068/c11331r

Guerreiro, S., Batel, S., Lima, M. L., and Moreira, S. (2015). Making energy visible: sociopsychological aspects associated with the use of smart meters. *Energy Efficiency* 8, 1149–1167. doi: 10.1007/s12053-015-9344-4

Harvey, D. (2018). Universal alienation. *J. Cult. Res.* 22, 137–150. doi: 10.1080/14797585.2018.1461350

Healy, N., and Barry, J. (2017). Politicizing energy justice and energy system transitions: Fossil fuel divestment and a "just transition." *Energy Policy* 108, 451–459. doi: 10.1016/j.enpol.2017.06.014

Hess, A. K., Samuel, R., and Burger, P. (2018). Informing a social practice theory framework with social-psychological factors for analyzing routinized energy consumption: a multivariate analysis of three practices. *Energy Res. Soc. Sci.* 46, 183–193. doi: 10.1016/j.erss.2018.06.012

Holifield, R., Chakraborty, J., and Walker, G. (eds.). (2017). *The Routledge Handbook of Environmental Justice*. London: Routledge. doi: 10.4324/9781315678986

Ingeborgrud, L., Heidenreich, S., Ryghaug, M., Skjølsvold, T. M., Foulds, C., Robison, R., et al. (2020). Expanding the scope and implications of energy research: a guide to key themes and concepts from the social sciences and humanities. *Energy Res. Soc. Sci.* 63:101398. doi: 10.1016/j.erss.2019.101398

Itten, A., Sherry-brennan, F., Hoppe, T., Sundaram, A., and Devine-wright, P. (2021). Energy research & social science co-creation as a social process for unlocking sustainable heating transitions in Europe. *Energy Res. Soc. Sci.* 74:101956. doi: 10.1016/j.erss.2021.101956

Jenkins, K., McCauley, D., Heffron, R., Stephan, H., and Rehner, R. (2016). Energy justice: a conceptual review. *Energy Res. Soc. Sci.* 11, 174–182. doi: 10.1016/j.erss.2015.10.004

Jenkins, K. E. H., Stephens, J. C., Reames, T. G., and Hernández, D. (2020). Towards impactful energy justice research: transforming the power of academic engagement. *Energy Res. Soc. Sci.* 67:101510. doi: 10.1016/j.erss.2020.101510

Joffe, H. (2003). Risk: from perception to social representation. *Br. J. Soc. Psychol.* 42, 55–73. doi: 10.1348/014466603763276126

JPI Urban Europe/SET Plan Action, 3.2 (2020a). *Europe Towards Positive Energy Districts*. PED Booklet. Vienna: JPI Urban Europe.

JPI Urban Europe/SET Plan Action, 3.2 (2020b). *White Paper on PED Reference Framework for Positive Energy Districts and Neighbourhoods*. Available online at: https://jpi-urbaneurope.eu/ped/

Kallis, G., Kostakis, V., Lange, S., Muraca, B., Paulson, S., and Schmelzer, M. (2018). Research on degrowth. *Annu. Rev. Environ. Res.* 43, 291–316. doi: 10.1146/annurev-environ-102017-025941

Knudsen, J. K., Wold, L. C., Aas, Ø., Kielland Haug, J. J., Batel, S., Devine-Wright, P., et al. (2015). Local perceptions of opportunities for engagement and procedural justice in electricity transmission grid projects in Norway and the UK. *Land Use Policy* 48, 299–308. doi: 10.1016/j.landusepol.2015.04.031

Lennon, B., Dunphy, N., Gaffney, C., Revez, A., Mullally, G., and O'Connor, P. (2020). Citizen or consumer? Reconsidering energy citizenship. *J. Environ. Policy Plan.* 22, 184–197. doi: 10.1080/1523908X.2019.1680277

Lennon, M. (2017). Decolonizing energy: black lives matter and technoscientific expertise amid solar transitions. *Energy Res. Soc. Sci.* 30, 18–27. doi: 10.1016/j.erss.2017.06.002

Lennon, M. (2021). Energy transitions in a time of intersecting precarities: from reductive environmentalism to antiracist praxis. *Energy Res. Soc. Sci.* 73:101930. doi: 10.1016/j.erss.2021.101930

Levenda, A. M., Behrsin, I., and Disano, F. (2021). Renewable energy for whom? A global systematic review of the environmental justice implications of renewable energy technologies. *Energy Res. Soc. Sci.* 71:101837. doi: 10.1016/j.erss.2020.101837

Levenda, A. M., Keough, N., Rock, M., and Miller, B. (2020). Rethinking public participation in the smart city. *Can. Geogr.* 64, 344–358. doi: 10.1111/cag.12601

Lima, M. L. (2004). On the influence of risk perception on mental health: living near an incinerator. *J. Environ. Psychol.* 24, 71–84. doi: 10.1016/S0272-4944(03)00026-4

Lima, M. L. (2006). Predictors of attitudes towards the construction of a waste incinerator: two case studies. *J. Appl. Soc. Psychol.* 36, 441–466. doi: 10.1111/j.0021-9029.2006.00014.x

Lima, M. L., Barnett, J., and Vala, J. (2005). Risk perception and technological development at a societal level. *Risk Anal.* 25, 1229–1239. doi: 10.1111/j.1539-6924.2005.00664.x

Lima, M. L., and Castro, P. (2005). Cultural theory meets the community: worldviews and local issues. *J. Environ. Psychol.* 25, 23–35. doi: 10.1016/j.jenvp.2004.11.004

Lima, M. L., and Morais, R. (2015). Lay perceptions of health and environmental inequalities and their associations to mental health. *Cadernos de Saúde Pública* 31, 2342–2352. doi: 10.1590/0102-311X00105714

Listo, R. (2018). Gender myths in energy poverty literature: a critical discourse analysis. *Energy Res. Soc. Sci.* 38, 9–18. doi: 10.1016/j.erss.2018.01.010

Manzo, L., and Devine-Wright, P. (2013). *Place Attachment: Advances in Theory, Methods and Applications*. Routledge.

Marres, N. (2012). *Material Participation: Technology, the Environment and Everyday Publics*. London: Palgrave Macmillan UK. doi: 10.1057/9781137029669

McDonald, M., Gough, B., Wearing, S., and Deville, A. (2017). Social psychology, consumer culture and neoliberal political economy. *J. Theor. Soc. Behav.* 47, 363–379. doi: 10.1111/jtsb.12135

Menton, M., Larrea, C., Latorre, S., Martinez-Alier, J., Peck, M., Temper, L., et al. (2020). Environmental justice and the SDGs: from synergies to gaps and contradictions. *Sustain. Sci.* 15, 1621–1636.

Murtagh, N., Gatersleben, B., and Uzzell, D. (2014). A qualitative study of perspectives on household and societal impacts of demand response. *Technol. Anal. Strat. Manage.* 26, 1131–1143. doi: 10.1080/09537325.2014.974529

Nirmal, P., and Rocheleau, D. (2019). Decolonizing degrowth in the post-development convergence: questions, experiences, and proposals from two Indigenous territories. *Environ. Plan. E. Nat. Space* 2, 465–492. doi: 10.1177/2514848618819478

Normann, S. (2021). Green colonialism in the Nordic context: Exploring Southern Saami representations of wind energy development. *J. Commun. Psychol.* 49, 77–94.

Pearsall, H., and Anguelovski, I. (2016). Contesting and resisting environmental gentrification: Responses to new paradoxes and challenges for urban environmental justice. *Sociol. Res. Online* 21, 121–127. doi: 10.5153/sro.3979

Räthzel, N., and Uzzell, D. (2019a). Critical Psychology – 'Kritische Psychologie' : challenging environmental behavior change strategies. *Annu. Rev. Crit. Psychol.* 16, 1375–1413.

Räthzel, N., and Uzzell, D. (2019b). The future of work defines the future of humanity and all living species. *Int. J. Labour Res.* 9, 145–171.

Roberts, J. (2017). Nudge-proof: distributive justice and the ethics of nudging. *Michigan Law Rev.* 116, 1045–1066. Available online at: https://repository.law.umich.edu/mlr/vol116/iss6/13

Robinson, C., and Mattioli, G. (2020). Double energy vulnerability: spatial intersections of domestic and transport energy poverty in England. *Energy Res. Soc. Sci.* 70:101699. doi: 10.1016/j.erss.2020.101699

Rodhouse, T. S. G. H., Pesch, U., Cuppen, E. H. W. J., and Correljé, A. F. (2021). Public agency and responsibility in energy governance: a Q study on diverse imagined publics in the Dutch heat transition. *Energy Res. Soc. Sci.* 77:102046. doi: 10.1016/j.erss.2021.102046

Rolfe, S. (2018). Governance and governmentality in community participation: the shifting sands of power, responsibility and risk. *Soc. Policy Soc.* 17, 579–598. doi: 10.1017/S1474746417000410

Ropert, T., and Di Masso, A. (2021). Living there, leaving there: identity, sociospatial mobility, and exclusion in "Stigmatized Neighborhoods." *Polit. Psychol.* 42, 53–69. doi: 10.1111/pops.12682

Rudolph, D., Kirkegaard, J., Lyhne, I., Clausen, N. E., and Kørnøv, L. (2017). Spoiled darkness? Sense of place and annoyance over obstruction lights from the world's largest wind turbine test centre in Denmark. *Energy Res. Soc. Sci*. 25, 80–90. doi: 10.1016/j.erss.2016.12.024

Rudolph, D., and Kirkegaard, J. K. (2019). Making space for wind farms: practices of territorial stigmatisation in rural Denmark. *Antipode* 51, 642–663. doi: 10.1111/anti.12428

Ryghaug, M., Skjølsvold, T. M., and Heidenreich, S. (2018). Creating energy citizenship through material participation. *Soc. Stud. Sci.* 48, 283–303. doi: 10.1177/0306312718770286

Sadowski, J., and Levenda, A. M. (2020). The anti-politics of smart energy regimes. *Polit. Geogr.* 81:102202. doi: 10.1016/j.polgeo.2020.102202

Santos, M., Batel, S., and Gonçalves, M. E. (2019). Participatory budgeting in the age of post-politics: Examining the discourses of citizens and representatives of expert-political systems in three municipalities in Portugal. *Port. J. Soc. Sci.* 18, 153–172. doi: 10.1386/pjss_00003_1

Schneider, F., Kallis, G., and Martinez-Alier, J. (2010). Crisis or opportunity? Economic degrowth for social equity and ecological sustainability. Introduction to this special issue. *J. Clean. Prod.* 18, 511–518. doi: 10.1016/j.jclepro.2010.01.014

Scoones, I., and Stirling, A. (2020). *The Politics of Uncertainty*. Oxford: Routledge. doi: 10.4324/9781003023845-1

Scoones, I., Stirling, A., and van Zwanenberg, P. (2020). "The unravelling of technocratic orthodoxy?," in *The Politics of Uncertainty*, eds I. Scoones and A. Stirling (Oxford: Routledge), 58–72. doi: 10.4324/9781003023845-4

SET-Plan Working Group (2018). *Europe to Become a Global Role Model in Integrated, Innovative Solutions for the Planning, Deployment, and Replication of Positive Energy Districts. In SET-Plan Action No 3.2 Implementation plan*, 1–72. Available online at :https://setis.ec.europa.eu/system/files/setplan_smartcities_implementationplan.pdf (accessed January 3, 2021).

Shove, E. (2018). What is wrong with energy efficiency? *Build. Res. Inf.* 46, 779–789. doi: 10.1080/09613218.2017.1361746

Siamanta, Z. C. (2021). Conceptualizing alternatives to contemporary renewable energy development: Community Renewable Energy Ecologies (CREE). *J. Polit. Ecol.* 28, 47–69. doi: 10.2458/jpe.2297

Sikder, S. K., Eanes, F., Asmelash, H. B., Kar, S., and Koetter, T. (2016). The contribution of energy-optimized urban planning to efficient resource use-a case study on residential settlement development in Dhaka City, Bangladesh. *Sustainability (Switzerland)* 8:119. doi: 10.3390/su8020119

Silva, L., and Sareen, S. (2021). Solar photovoltaic energy infrastructures, land use and sociocultural context in Portugal. *Local Environ.* 26, 347–363.

Simcock, N., Frankowski, J., and Bouzarovski, S. (2021). Rendered invisible: institutional misrecognition and the reproduction of energy poverty. *Geoforum* 124, 1–9.

Simcock, N., Jenkins, K., Mattioli, G., Lacey-Barnacle, M., Bouzarovski, S., and Martiskainen, M. (2020). *Vulnerability to Fuel and Transport Poverty*. CREDS Policy Brief 010. Oxford: Centre for Research into Energy Demand Solutions.

Sovacool, B. K. (2014). What are we doing here? Analyzing fifteen years of energy scholarship and proposing a social science research agenda. *Energy Res. Soc. Sci.* 1, 1–29. doi: 10.1016/j.erss.2014.02.003

Sovacool, B. K. (2021). Who are the victims of low-carbon transitions? Towards a political ecology of climate change mitigation. *Energy Res. Soc. Sci.* 73:101916. doi: 10.1016/j.erss.2021.101916

Sovacool, B. K., Axsen, J., and Sorrell, S. (2018). Promoting novelty, rigor, and style in energy social science: towards codes of practice for appropriate methods and research design. *Energy Res. Soc. Sci.* 45, 12–42. doi: 10.1016/j.erss.2018.07.007

Sovacool, B. K., Burke, M., Baker, L., Kotikalapudi, C. K., and Wlokas, H. (2017). New frontiers and conceptual frameworks for energy justice. *Energy Policy* 105, 677–691. doi: 10.1016/j.enpol.2017.03.005

Sovacool, B. K., Lipson, M. M., and Chard, R. (2019a). Temporality, vulnerability, and energy justice in household low carbon innovations. *Energy Policy* 128, 495–504. doi: 10.1016/j.enpol.2019.01.010

Sovacool, B. K., Martiskainen, M., Hook, A., and Baker, L. (2019b). Decarbonization and its discontents: a critical energy justice perspective on four low-carbon transitions. *Clim. Change* 155, 581–619. doi: 10.1007/s10584-019-02521-7

Steg, L., Perlaviciute, G., and van der Werff, E. (2015). Understanding the human dimensions of a sustainable energy transition. *Front. Psychol.* 6, 1–17. doi: 10.3389/fpsyg.2015.00805

Uzzell, D., and Räthzel, N. (2009). Transforming environmental psychology. *J. Environ. Psychol.* 29, 340–350. doi: 10.1016/j.jenvp.2008.11.005

Vargas Payera, S. (2018). Understanding social acceptance of geothermal energy: case study for Araucanía region, Chile. *Geothermics* 72, 138–144. doi: 10.1016/j.geothermics.2017.10.014

Velasco-Herrejon, P., and Bauwens, T. (2020). Energy justice from the bottom up: a capability approach to community acceptance of wind energy in Mexico. *Energy Res. Soc. Sci.* 70:101711. doi: 10.1016/j.erss.2020.101711

Waitt, G., Roggeveen, K., Gordon, R., Butler, K., and Cooper, P. (2016). Tyrannies of thrift: Governmentality and older, low-income people's energy efficiency narratives in the Illawarra, Australia. *Energy Policy* 90, 37–45. doi: 10.1016/j.enpol.2015.11.033

Walker, G. (2009). Beyond distribution and proximity: exploring the multiple spatialities of environmental justice. *Antipode* 41, 614–636. doi: 10.1111/j.1467-8330.2009.00691.x

Walker, G., Cass, N., Burningham, K., and Barnett, J. (2010a). Renewable energy and sociotechnical change: imagined subjectivities of "the public" and their implications. *Environ. Plan. A.* 42, 931–947. doi: 10.1068/a41400

Walker, G., Devine-Wright, P., Barnett, J., Burningham, K., Cass, N., Devine-Wright, H., et al. (2011). "Symmetries, expectations, dynamics and contexts: a framework for understanding public engagement with renewable energy projects," in *Renewable Energy and the Public: From NIMBY to Participation*, ed P. Devine-Wright (London: Routledge), 1–14.

Walker, G., Devine-Wright, P., Hunter, S., High, H., and Evans, B. (2010b). Trust and community: exploring the meanings, contexts and dynamics of community renewable energy. *Energy Policy* 38, 2655–2663. doi: 10.1016/j.enpol.2009.05.055

Weber, E. U., and Stern, P. C. (2011). Public understanding of climate change in the United States. *Am. Psychol.* 66, 315–328. doi: 10.1037/a0023253

Williams, A., Mark, G., and Paul, C. (2014). Neoliberalism, big society, and progressive localism. *Environ. Plan. A.* 46, 2798–2815. doi: 10.1068/a130119p

Wolsink, M. (2007). Wind power implementation: the nature of public attitudes: equity and fairness instead of "backyard motives." *Renew.Sustain. Energy Rev.* 11, 1188–1207. doi: 10.1016/j.rser.2005.10.005

Wolsink, M. (2018). Co-production in distributed generation: renewable energy and creating space for fitting infrastructure within landscapes. *Landsc. Res.* 43, 542–561. doi: 10.1080/01426397.2017.1358360

Wolsink, M. (2020). Framing in renewable energy policies: a glossary. *Energies* 13:2871. doi: 10.3390/en13112871

Wrapson, W., and Devine-Wright, P. (2014). "Domesticating" low carbon thermal technologies: Diversity, multiplicity and variability in older person, off grid households. *Energy Policy* 67, 807–817. doi: 10.1016/j.enpol.2013.11.078

Yoo, H. K., Nguyen, M.-T., Lamonaca, L., Galanakis, K., and Ackrill, R. (2020). *Smart-BEEjS Deliverable D3.2 - Socio-Economic Factors & Citizens' Practices, Enabling Positive Energy Districts Challenging "Silo Thinking" for Promoting PEDs*. Available online at: https://smart-beejs.eu/wp-content/uploads/2021/01/WP3-Deliverable-D3.2_Silo-thinking.pdf (accessed January 26, 2021).

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Analysis of Urban Energy Resources to Achieve Net-Zero Energy Neighborhoods

Caroline Hachem-Vermette and Kuljeet Singh*

School of Architecture, Planning and Landscape, University of Calgary, Calgary, AB, Canada

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****Correspondence:***
Caroline Hachem-Vermette
caroline.hachem@ucalgary.ca

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This paper summarizes a methodology developed to optimize urban-scale energy mix. An optimal capacity estimation method based on energy credits is proposed, the objective of which is to plan renewable and alternative energy sources to yield zero (or positive) year-end energy credits. Several renewable and alternative energy resources are considered, including photovoltaic systems, solar thermal collectors, wind turbines, waste to energy (WtE) potential, as well as thermal seasonal storage. The methodology employs several energy simulation and optimization tools, including Energy Plus, TRNSYS and MATLAB. The optimization employs a non-linear process that uses objective function, boundaries and non-linear/linear constraints as input. The methodology is demonstrated on a hypothetical mixed-use neighborhood, designed to achieve high-energy performance objectives, with three scenarios of energy operations: 1) all electric, 2) all-electric except for DHW, and 3) DHW and space heating arenon-electric. The pilot location of this mixed-use neighborhood, including residential and commercial buildings, is Calgary (AB, Canada). For the all-electric scenario, PV systems implemented in all available south facing roof areas together with a limited number of wind turbines can achieve NZE status. For the other two scenarios, solar thermal collectors coupled to borehole thermal storage (STC and BTES) need to be considered. Although in all cases of the considered scenarios waste-based energy is not required, it can be used to shave the peak electric load, reducing the stress on the grid. This methodology can be employed for the design of an integrated urban energy systems, in different neighborhood designs, to achieve energy self-sufficient, or energy positive status.

Keywords: optimization methodology, urban energy mix, renewable energy, alternative energy, waste to energy, net zero energy

INTRODUCTION

The worldwide rapid increase of urbanization is leading to significant surge in energy requirement and related negative environmental impact. To mitigate such impact, urban-scale targeted efforts should focus on switching from fossil fuel to renewable and low carbon energy sources, and on enhancing urban scale integrated energy solutions.

Such efforts should consider various aspects of an urban area planning, including the energy landscape that encompasses the conventional energy grid, potential renewable energy and low impact alternative energy solutions. The design of high-energy performance neighborhoods is anticipated to be heavily dependent on the integration of renewable and alternative energy sources (RES and AES) with the existing grid. RES includes electricity-generating technologies (e.g., PV, small wind turbine, fuel cells), heat generating (e.g., PV/T, thermal collectors), and energy efficient technologies (Loonen et al., 2013). AES include various low environmental impact technologies, such as Waste to Energy (WtE), biomass and other co-generation/tri-generation combinations. Although RES and AES technologies are increasingly employed, methods to determine potential synergy between these technologies, and their optimal mix within a specific urban development, as well as the impact of the design and characteristics of this development on the optimal energy mix are yet to be explored.

A number of research works are available focusing on developing methodologies for the optimization of distributed energy sources, in given building and neighborhood types, in order to achieve specific objectives. For instance, Li et al. (2016) implemented multi-objective optimization of distributed energy resources aiming at minimizing annual cost and CO_2 emissions, for a cluster of two residential and two office buildings. Falke et al. (2016) proposed a multi-objective optimization methodology for the design of heat and power generation units within a small cluster of buildings. Fonseca et al. (2016) employed City Energy Analyst (CEA) in the multi-objective optimization to minimize CO_2 emissions, total annual cost and primary energy needs for various scenarios of neighborhood usage. Murray et al. (2018) not only considered the onsite generation from various resources for the neighborhood, but optimized energy storage technologies to minimize both cost and GHG emissions. Jing et al. (2018) explored a game theory-based optimization of the energy network of a number of commercial buildings. Other research focused on the potential of energy storage to achieve optimal load management (Parra et al., 2017). Sikder et al. (2016) developed a conceptual energy optimization model to improve energy use in residential developments. The study involved various methods such as interviews and collection of data a from local sources. The work highlights the role of governance in a successful planning of urban energy systems.

Abbreviations: AES, alternative energy sources; A_{PV}, area of PV installation [m^2]; $A_{SR,max}$, maximum available area for solar installations [m^2]; $A_{PV,STC}$, area of solar thermal installation [m^2]; CHP, combined heat and power; DHW, domestic hot water; G_{PV}, electricity generated by PV [kWh]; G_{STC}, STC generation for per m^2 of area [kWh]; G_{WT}, electricity generated by WT [kWh]; $G_{e,WTE,t}$, electricity generated by WtE-CHP per ton of waste [kWh]; EC, energy credits [kWh]; L, electrical load [kWh]; n_{WT}, number of WT; NZE, Net zero energy; PELDs, peak electric load days; PHLDs, Peak heat load days; Q, heat [kWh]; RES, renewable energy sources; SC, neighborhood energy scenario; STC, solar thermal collectors; W, quantity of waste [t]. **Subscripts**: BTES, borehole thermal storage; c, heat charged into BTES; d, heat discharged from BTES; h, hourly; g, guessed value; max, maximum value; min, minimum value; NG, natural gas; PV, photovoltaic; WT, wind turbines; WtE, waste to energy.

Apart from designing the energy infrastructure, focusing on the operation side, La Scala et al. (2014) proposed the optimization methodology to optimize the energy flow in multicarrier energy network including various electrical and thermal energy resources. A similar energy dispatch optimization problem is also addressed by Wang et al. (2019) for multiple stake holders. Hachem-Vermette and Singh (2020) proposed an optimization methodology to plan the mix of energy resources, including renewable and alternative energy, and the interaction with the conventional grid employing two neighborhood concepts; a stand-alone mixed-use neighborhood and, and a grid-tied mixed-use neighborhood. This study did not take into account however solar thermal collectors and thermal storage. Further, the economic aspects of energy resources including tariff schemes, return on investment and payback period is investigated by Singh and Hachem-vermette (2021).

The work presented in this paper is a part of an ongoing research that aims at determining optimal mixtures of energy resources, within an integrated urban energy system, for various types and designs of building clusters. The current paper proposes a methodology to optimize the energy resources mix, for a grid-tied hypothetical mixed-use neighborhood, focusing on the technical aspects of energy resources and their theoretical application to the hypothetical neighborhood. The explored energy resources include PV and solar thermal collectors (STC) integrated in roofs, wind turbines, waste-to-energy, and borehole thermal energy (BTES) storage. The optimization methodology accounts simultaneously for the neighborhood hourly electrical load, space heating and domestic hot water loads.

METHODOLOGY

This paper assumes a grid-tied neighborhood concept. As such, this neighborhood supplies excess energy generated on site (from various energy sources) to the grid, while the grid supplements the on-site energy to meet its demand, when it is needed. Three scenarios of neighborhoods are studied: SC1 is an all electrical neighborhood; SC2, is similar to SC1 with the exception that domestic hot water (DHW) is fulfilled by other energy sources than electricity; and SC3 assumes that heating and DHW are non-electric.

A high performance mixed-use neighborhood example is employed to develop the methodology (Hachem, 2016; Hachem et al., 2016). The neighborhood consists of residential buildings of different types–detached houses, attached townhouses and apartment buildings, and of various commercial buildings including a supermarket, office buildings, retail buildings and a school. Houses are designed to optimize the utilization of passive solar energy for space heating, through the window to wall ratio and the plan layout. Spaces between buildings are designed to reduce mutual shading between buildings (Hachem, 2016; Hachem et al., 2016).

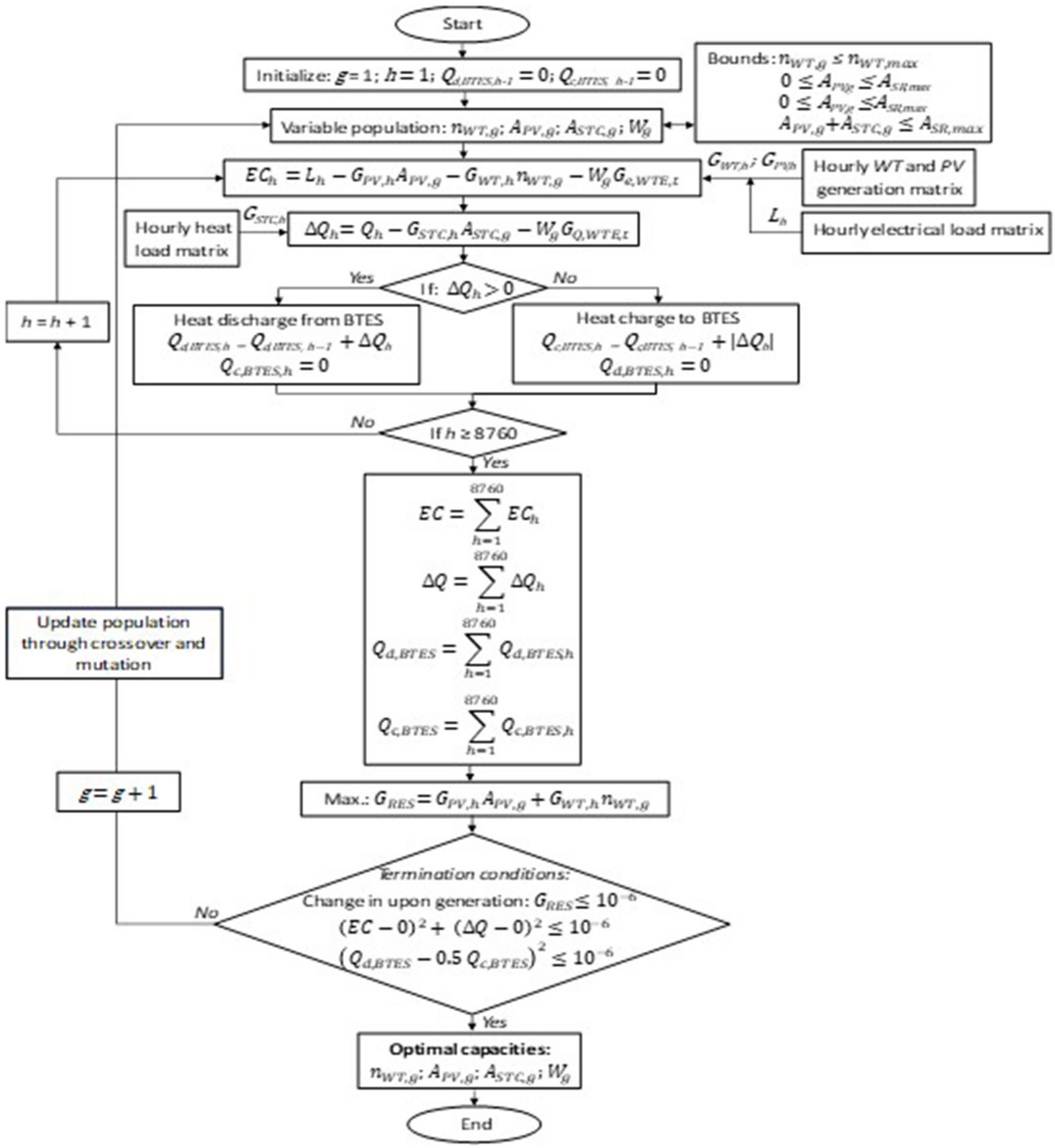

FIGURE 1 | Proposed optimization methodology.

A Northern cold climate location–Calgary, Canada, 51°N, is assumed in the study. Energy Plus [National Renewable Energy Laboratory (NREL), (2016)] is employed to determine the yearly base load of the whole neighborhood. In addition, energy consumption for heating and cooling assuming heat pump is estimated using TRNSYS (University of Wisconsin Solar Energy Lab, 1990) (for SC1 and SC2). The base load accounts as well for all electrical energy load associated with various appliances and equipment according to the building types and occupation (schedule, density, etc.).

The general methodology consists of first optimizing the size of renewable and alternative energy resources to fulfill all (or portion of) the electrical needs of the neighborhood scenarios described above. The potential of fulfilling the thermal energy, for Scenarios 2 and 3, employing STC, WtE and thermal storage is then addressed.

The different energy sources employed in this study and related assumptions are summarized in the following:

- PV systems: PV modules are assumed to be integrated in south facing roof areas of the studied neighborhood buildings, with an upper limit of 52,451 m^2 corresponding to the maximum available south facing roof areas. PV panels with 18.65% efficiency are assumed to be installed on potential surfaces (identified from the neighborhood configuration and optimally used by the proposed optimization process) (Hachem-Vermette and Singh, 2020). The hourly per m2 output from PV panels (as per various orientations) is extracted from Energy Plus using appropriate weather file (representing Calgary weather in this case). The weather file provides the input hourly radiation data for whole year (8,760 values).
- Wind turbines (WT): vertical axis wind turbines of 5 kW capacity are employed in this work (Windspire, 2019). These WT are assumed to be installed along the main streets of the neighborhood, employing a distance and turbine settings that aims at reducing potential turbulence [cluster staggered approach (Hezaveh et al., 2018)]. Based on this method, an upper bound of 1,200 turbines installation is estimated. Energy Plus simulations are used to obtain the output from wind turbines. The above-mentioned wind turbine is assumed and subjecting to weather file (consist of hourly wind speed and direction values), the output from a given wind turbine is evaluated.
- Waste to Energy (WtE): WtE-CHP plant size is estimated based upon the unavailability of energy from RES, assuming that waste can be provided by the neighborhood waste disposal. Likewise, based on the literature it is assumed that 1 t of waste can generate 650 kWh/t of electricity [Harley and Infrastructure, 2012; International Solid Waste Association (ISWA), 2013; Llanes and Kalogirou, 2019; Tsai, 2019], whereas, using CHP concept additional heat of around 2,000 kWh/t can be also produced (heat to power ratio varies between 2.3 and 4) [International Solid Waste Association (ISWA), 2013; Catalogue of WtE Facilities in the Sweden, 2015; Yin et al., 2020].
- Solar thermal collectors (STC): STC are assumed to be integrated within the areas of south facing roof. The maximum sum of PV and STC areas is equal to 52,451 m^2 corresponding to the total available areas of south facing roofs (of the studied neighborhood). The output of STC is estimated using Energy Plus simulations using local yearlong weather data.

Optimization Methodology

An optimal capacity estimation method based on energy credits is developed to yield zero year-end energy credits. The optimization employs a non-linear process that use objective function, energy resource installation bounds and non-linear/linear constraints as input.

The optimization methodology, illustrated in the flowchart of **Figure 1**, aims at resolving the objective function, defined in Equation 1, formulated to maximize the on-site energy generation by RES, while considering various constraints (Equations 2a–d).

$$\text{Max: } G_{RES} = \sum_{h=1}^{8760} G_{PV,h} A_{PV,g} + \sum_{h=1}^{8760} G_{WT,h} n_{WT,g} \quad (1)$$

$$\text{bounds: } 0 \leq n_{WT,g} \leq n_{WT,max} \quad (2a)$$

$$0 \leq A_{PV,g} \leq A_{SR,max} \quad (2b)$$

$$\text{constraints: } (EC-0)^2 + (\triangle Q - 0)^2 \leq 10^{-6} \quad (2c)$$

$$\left(Q_{d,BTES} - 0.5\, Q_{c,BTES}\right)^2 \leq 10^{-6} \quad (2d)$$

In Equation 1, the hourly electrical generation matrices (with hourly 8,760 values of $G_{PV,h}$ and $G_{WT,h}$) are estimated on per unit area basis for PV and for vertical wind turbine (WT) of 5 kW using EnergyPlus. $A_{PV,g}$ and $n_{WT,g}$ are the guessed values of the total PV area and of the number of WT, that are continuously updated by the optimization algorithm. Equations 2a,b represents lower and upper bounds for $A_{PV,g}$ and $n_{WT,g}$. Lower bounds for both these variables are kept at 0, whereas upper bounds $A_{SR,max}$ and $n_{WT,max}$ are assumed as 52,451 m^2 and 1,200 as per the available surfaces within the neighborhood (see above). Equations 2c,d represent non-linear constraints for the problem. Equation 2d is formulated to design the BTES within this optimization process to meet the thermal load. Equation 3 presents EC which is the annual difference between annual electrical load (yearly summation of L_h) and generations by PV, WT and WtE-CHP is estimated.

$$EC = \sum_{h=1}^{8760} L_h - \sum_{h=1}^{8760} G_{PV,h} A_{PV,g} - \sum_{h=1}^{8760} G_{WT,h} n_{WT,g} - \left(W_g G_{e,WTE,t}\right) \quad (3)$$

To evaluate EC, the hourly yearly electrical load matrix presenting 8,760 values of L_h is supplied as input. This matrix is evaluated using Energy Plus simulations. $G_{PV,h}A_{PV,g}$ and $G_{WT,h}n_{WT,g}$ indicate the electrical generations by PV and WT. $W_g G_{e,WTE,t}$ represents the yearly generation by WTE-CHP plant, where, W_g is the guessed value of annual waste input and $G_{e,WTE,t}$ is electricity generation by one ton of municipal waste (i.e., 650 kWh) (Hachem and Grewal, 2019). First the problem is minimized limiting W_g at zero. If the value of EC doesn't approach zero, then the guessed value of W_g becomes non-zero. In summary, the given objective function (Equation 1) is first minimized using renewable energy sources, and then, if the generation by renewable energy resources is not sufficient, WtE-CHP is employed to bridge the gap in electric energy requirement.

TABLE 1 | Near optimal combinations of energy resource mixture for net-zero energy mixed-use neighborhood.

S. No.	Number of WT	PV area (m^2)	STC area (m^2)	WtE waste input (t)	Total electrical load (MW/y)	Total WT output (MW/y)	Total PV output (MW/y)	Total heat load (MW/y)	STC output (MW/y)	Heat charge to BTES (MW/y)	Heat discharge from BTES (MW/y)	BTES volume (m^3)
SC1: All electrical												
1	38	52,450	0	0	11,295	47	11,248	0	0	0	0	0
2	42	52,430	0	0	11,295	51	11,244	0	0	0	0	0
3	140	51,875	0	0	11,295	170	11,125	0	0	0	0	0
4	401	50,401	0	0	11,295	486	10,809	0	0	0	0	0
5	39	52,449	0	0	11,295	47	11,248	0	0	0	0	0
SC2: DHW non-electrical												
1	0	39,204	9,508	0	8,408	0	8,408	4,047	7,123	6,153	3,077	2,05,106
2	495	36,402	9,508	0	8,408	601	7,807	4,047	7,123	6,153	3,077	2,05,106
3	839	34,457	9,508	0	8,408	1,018	7,390	4,047	7,123	6,153	3,077	2,05,106
4	218	37,970	9,508	0	8,408	265	8,143	4,047	7,123	6,153	3,077	2,05,106
5	331	37,330	9,508	0	8,408	402	8,006	4,047	7,123	6,153	3,077	2,05,106
SC3: Space heating and DHW non-electrical												
1	0	30,329	1,7066	0	6,504	0	6,504	7,192	12,787	11,190	5,595	3,73,001
2	362	28,282	17,066	0	6,504	439	6,065	7,192	12,787	11,190	5,595	3,73,001
3	606	26,900	17,066	0	6,504	735	5,769	7,192	12,787	11,190	5,595	3,73,001
4	879	25,355	17,066	0	6504	1,067	5,438	7,192	12,787	11,190	5,595	3,73,001
5	262	28,846	17,066	0	6,504	318	6,186	7,192	12,787	11,190	5,595	3,73,001

Thermal Energy in SC2 and SC3

For SC2 and SC3, the thermal loads need to be satisfied. The generation from flat plate solar thermal collectors and WtE-CHP is considered simultaneously (see Equation 4). The difference between thermal load and thermal generation by STC and WtE-CHP ($\triangle Q$ in Equation 2c) is evaluated using Equation 4 below:

$$\triangle Q = \sum_{h=1}^{8760} Q_h - \sum_{h=1}^{8760} G_{STC,h} A_{STC,g} - \left(W_g G_{Q,WTE,t}\right) \qquad (4)$$

$$\text{subject to: } 0 \leq A_{STC,g} \leq A_{SR,max} \qquad (4a)$$

where, Q_h and $G_{STC,h}$ are hourly thermal load and STC generation for per m^2 area estimated using Energy Plus. The positive value of $\triangle Q$ means that the generation by STC and WtE-CHP is insufficient, while its negative value indicates the availability of excessive thermal energy. This excess heat is stored in BTES, represented by the term $Q_{c,BTES}$ in Equation 2d. $Q_{d,BTES}$ indicates the heat discharged from BTES when the value of $\triangle Q$ is non-positive. Around 50% of heat charged into BTES is assumed to be utilized in the neighborhood, leading to the formulation of the constraint in Equation 2d (Cabeza, 2014). Equation 2c ensures meeting of electrical and heating loads.

Furthermore, since the total south facing roof area ($A_{SR,max}$) can be used for PV and STC installations, the formulation of the following constraint (Equation 5) is required in solving the optimization problem.

$$A_{PV,g} + A_{STC,g} \leq A_{SR,max} \qquad (5)$$

The genetic algorithm (GA) (Singh and Hachem-Vermette, 2019) is employed for the optimization process presented in the flowchart of **Figure 1**. GA toolbox of Mat lab is employed in this process (Math Works, 2020b), which starts with the generation or iteration ($g = 1$) of GA along with initialization of hour, h = 1, $Q_{d,BTES,h-1} = 0$, and $Q_{c,BTES,h-1} = 0$. Then GA creates initial random population for given variables – $A_{PV,g}$, $n_{WT,g}$, $A_{STC,g}$ and W_g. In the next step energy credits at given hour (EC_h) followed by of $\triangle Q_h$ are estimated. Accordingly, heat storage or extraction from BTES is decided as explained above. This process repeats till the value of hour reaches 8,760 (annual number of hours). Thereafter, cumulative yearly values of EC, $\triangle Q$, $Q_{d,BTES}$, and $Q_{c,BTES}$ are evaluated. Finally, the objective function G_{RES} is evaluated followed by a check on termination conditions. There are three criteria for termination of the optimization process and all three have to be met: (i) change in objective function upon successive generation is $<10^{-6}$, (ii) year-end EC and total heat load have to be fulfilled, $(EC - 0)^2 + (\triangle Q - 0)^2 \leq 10^{-6}$, and (iii) heat discharge y can be applied to different sites employing yearlong hourly matrices for solar and from BTES must be equal to 50% of heat charged into BTES $\left(Q_{d,BTES} - 0.5\, Q_{c,BTES}\right)^2 \leq 10^{-6}$. This calculation process is supplied to GA toolbox as a function (Math Works, 2020a).

If termination conditions remain unsatisfied, next generation/iteration is performed ($g = g + 1$) by updating

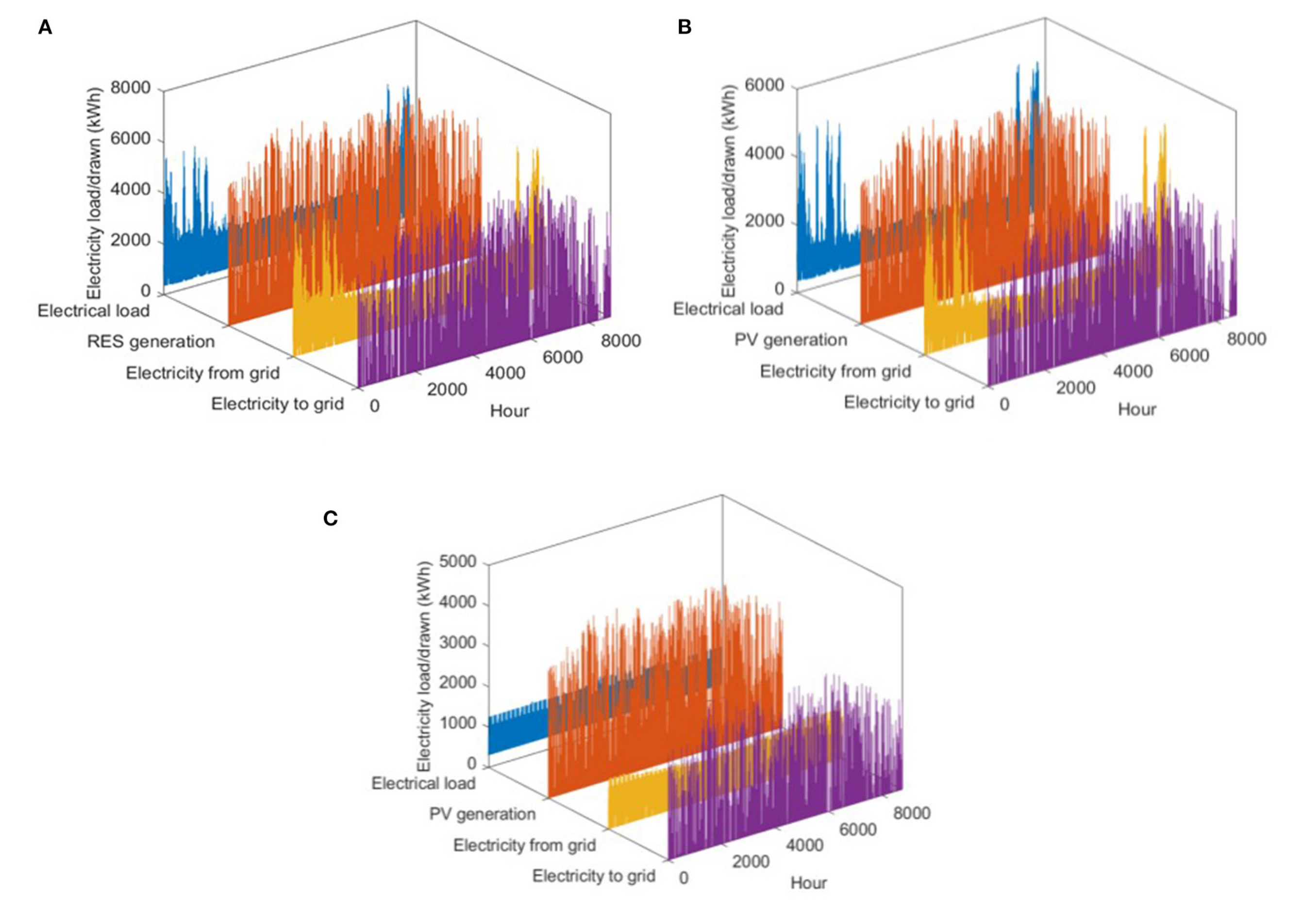

FIGURE 2 | Hourly electrical load, PV generation, electricity sold to grid and bought from grid for **(A)** SC1, **(B)** SC2 and **(C)** SC3.

the population using mutation and crossover processes. Once all the termination conditions are satisfied, the optimal mixture of energy resources is identified.

The proposed methodology can be applied to different sites employing yearlong hourly matrices for solar and wind. Hence, user can perform Energy Plus simulations with local weather data file to plug the site-specific matrices to the optimization process.

RESULTS

This section summarizes the main results in two sub-sections. In the first sub-section, the optimal mixtures of energy resources obtained by employing the proposed optimization methodology are discussed. Thereafter, the hourly energy generation and demand profiles are simultaneously analyzed to visualize the interaction between various energy resources, on a yearly basis as well as on peak electrical load days (PELDs) and peak heat load days (PHLDs).

Optimal Mixtures

The developed optimization methodology is applied to a mixed-use sample neighborhood (see description above). The results aim at determining optimal and near optimal mix of renewable and alternative energy sources, to achieve net zero energy status. **Table 1** presents the near optimal combinations of energy mixture, associated with the three scenarios SC1, SC2 and SC3 (characterized by the source of energy for various building operations–see above).

For SC1–an all-electrical neighborhood, the satisfaction of the total electrical load can be ensured by utilizing a maximum south facing roof area for PV panels (52,450 m^2) and 38 wind turbines (WT). For this scenario, no STC and BTES are required since space heating and DHW are satisfied by electricity. Various near optimal combinations are presented for SC1 (see **Table 1**), as well.

The analysis of SC2-all electrical except for DWH-, combination one shows that no wind turbine (WT) is required to achieve net-zero energy status, whereas, 39,204 m^2 and 9,508 m^2 of PV and STC, associated with 75% (for PV) and 25% (for STC) of the total available roof area, are needed. The thermal energy is served partially by STC (about 24%) and by the BTES (76%) which store the excess generation of the STC system. A BTES volume of 2,05,106 m^3 is estimated to fulfill the total thermal load. Interestingly, no WtE generation is required to achieve net-zero energy for this scenario (SC2). Alternatively,

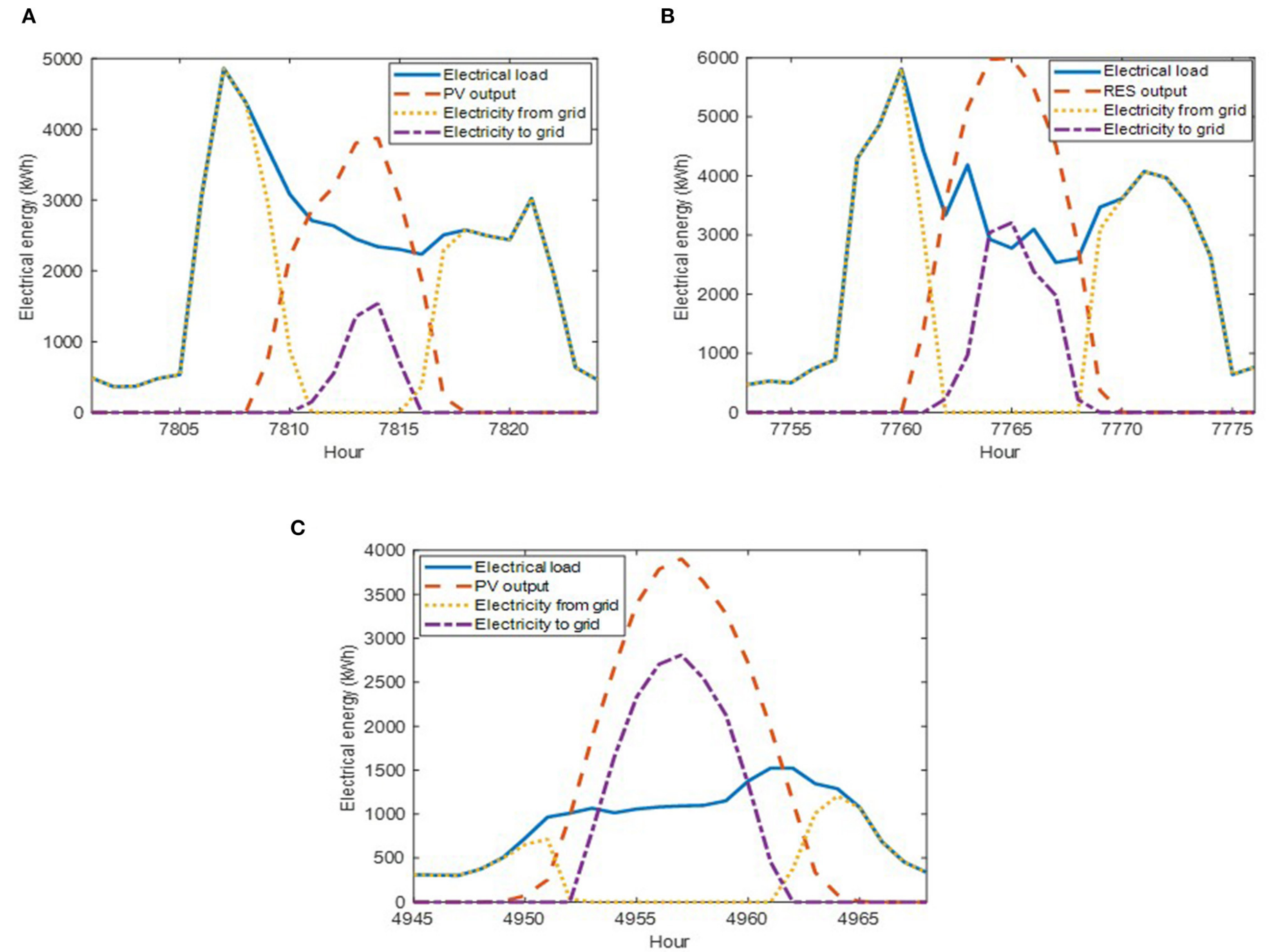

FIGURE 3 | Electrical load, PV output, electricity received from grid, and electricity supplied from grid for peak electrical load days (PELDs) in **(A)** SC2 SC1, **(B)** SC2 and **(C)** SC3.

other mixtures of wind turbines and PV panels reaching net-zero energy mixed-use neighborhood can be obtained (see combinations two to five). STC area and BTES volume along with energy contents remain unchanged.

Similarly, near optimal combinations are estimated for SC3–where both heating and DHW are non-electric. Due to less electrical load, a PV area of 30,329 m^2 (58% of available roof area) and STC area of 17,066 m^2 (32% of available roof) are required. No wind turbines are needed in this combination. To serve the yearly heat load of 7,192 MW, STC produce 12,787 MW/y of thermal output, out of which 11,190 MW is charged to the BTES. To fulfill the hourly demand of heat load, 5,595 MW (50%) of thermal energy is discharged from the BTES. Other near optimal combinations of WT and PV to achieve net-zero energy status SC3 are presented in **Table 1**.

Hourly Load Variation

This sub-section presents selected results of the interaction between the energy generated by renewable sources and the electric grid. This is discussed on a yearly basis (**Figure 2**) and for specific days–peak electric load days (PELDs) (see **Figure 3**). The peak heat load days (PHLDs) and interaction between demand, STC and BTES, for SC2 and SC3 are presented as well (**Figure 4**).

In **Figure 2A**, the hourly variation in electrical load, RES generation (PV + WT), and electricity drawn from and supplied to the grid of SC1 are presented. The maximum hourly load reaches 5,810 kWh (8 a.m. in the morning of a winter day) and to fulfill this load all the electricity is drawn from the grid due to non-availability of electricity from RES. The RES generation hourly peak reaches 7,252 kWh and the maximum peaks electricity supplied to the grid is about 6,209 kWh.

Figure 2B presents the energy interaction of the first combination of SC2 (no WT required), including the hourly electrical load, the hourly variation of PV generation, electricity drawn from grid, and supply of excessive electricity to the grid. It can be noticed that excess electricity is generated in non-winter months from PV panels, the majority of which can be sold to the

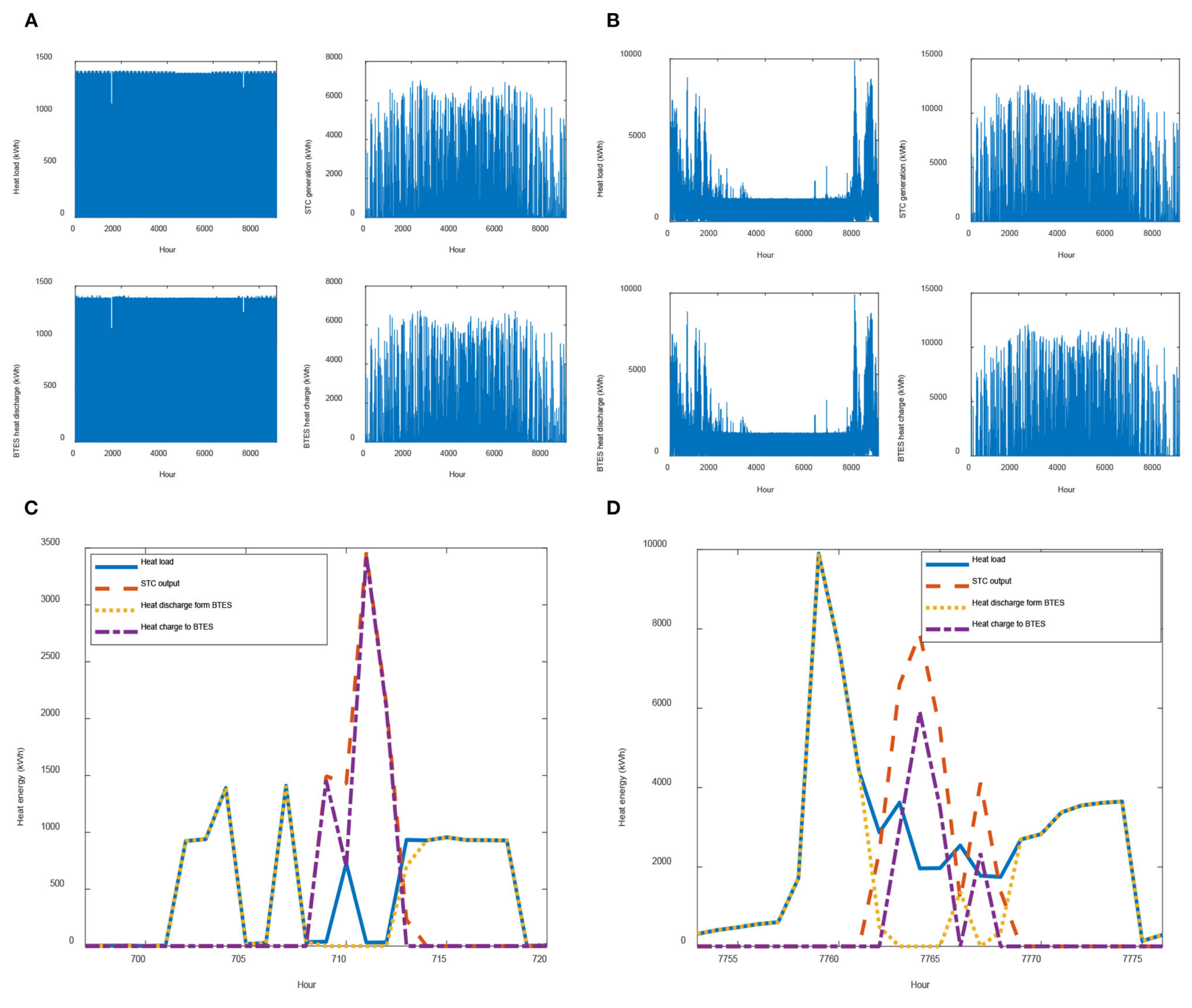

FIGURE 4 | Hourly heat load, STC generation, heat discharged from BTES and charged to BTES for **(A)** SC2 and **(B)** SC3; for peak heat load days (PHLDs) in **(C)** SC2 and **(D)** SC3.

grid, earning energy credits. During winter peak load months, electricity can be withdrawn from the grid against earned energy credits. Maximum hourly PV generation reaches around 5,400 kWh during summer months, whereas, excessive hourly supply to the grid reaches around 4,700 kWh. Similarly, results of SC3 are presented in **Figure 2C**. In this case the maximum hourly PV generation reaches around 4,200 kWh and maximum hourly electricity sold to the grid reaches 3,650 kWh during summer months. The maximum hourly electrical load is about 1,522 kWh, whereas, a maximum of 1,269 kWh of electricity is drawn from the grid during the insufficient on-site generation. The analysis of days with peak electrical load (PELD-yearly maximum) is briefly discussed below.

Figure 3 presents the electrical load, generation and grid interaction profiles of three PELDs associated with SC1, SC2 and SC3. In **Figure 3A**, for SC1 an hourly peak load of around 5,810 kWh is satisfied using the grid due to non-availability from RES (8 a.m. in the morning, winter day). The excess generation by RES supplied to the grid reaches a maximum of 3,000 kWh during daytime due to excess production by the PV system at 12 p.m.

Similarly, for SC2, the peak load is observed during the non-availability of PV electricity (**Figure 3B**). This peak is due to excessive space heating requirements of the mixed-use neighborhood. During the daytime, the peak load decreases while the PV generation surges. An excess electricity generation by PV panels is supplied to the grid (maximum reaches around 1,400 kWh).

For SC3 in **Figure 3C**, the maximum hourly electrical load is significantly less than the two other scenarios. The maximum electricity supplied to the grid is around 2,700 kWh during the maximum peak load day. The comparison between SC2 and SC3 shows that, to achieve net-zero energy status, SC3 imposes less stress on the grid.

The hourly variations in thermal load, generation by STC, and heat charge and discharge flows to/from BTES are indicated in **Figure 4**, for SC2 and SC3. The maximum yearly thermal load for SC2 (DHW only) is around 1,409 kWh (**Figure 4A**), and the maximum STC thermal output reaches around 7,000 kWh. The maximum thermal energy hourly employed to charge the BTES is around 6,750 kWh, whereas, the maximum hourly heat discharge is equal to the maximum heat load (i.e., 1409 kWh). Similarly, for SC3 (**Figure 4B**), the yearly maximum hourly heat load is around 9,897 kWh. The maximum thermal output by STC is close to 12,580 kWh, while the maximum hourly charge and discharge are 12,086 kWh and 9,897 kWh, respectively.

The hourly variations of peak heat load days (PHLDs) in case of SC2 and SC3, are presented in **Figures 4C,D**. Two morning peaks are observed for SC2 (**Figure 4C**) due to DHW demand. These peaks are satisfied using heat discharged from the BTES. The maximum STC thermal output during the PHLD reaches around 3,500 kWh, which is employed to charge the BTES. Similarly, during the evening, the DHW heat load is served using the BTES. For SC3, as depicted in **Figure 4D**, a significant morning heat load peak of 10,000 kWh (space heating + DHW) is served using the BTES. The maximum hourly thermal output by STC is about 8,000 kWh, whereas the maximum heat charged to BTES reaches a peak of about 6,000 kW.

DISCUSSION AND CONCLUDING REMARKS

This paper presents a methodology developed to optimize the mixed of energy resources, within a neighborhood, to achieve net-zero energy status. The energy resources include PV systems, solar thermal collectors, wind turbines, waste to energy and thermal storage. The methodology prioritizes the implementation of PV and wind turbines to satisfy the electric load, subsequently, if the electrical requirement is not fulfilled, it estimates waste based energy needed to meet the electric load. For scenarios where DHW and/or space heating are non-electric, STC and BTES are exploited and sized to meet the thermal load of the neighborhood. STC and PV are assumed to share the south facing available roof areas, in all neighborhood buildings. The developed methodology allows to identify days with maximum peak electric and thermal loads, and interaction between various technologies and the conventional electric grid.

The methodology is applied to a sample mixed use neighborhood, with three scenarios of energy operations: SC1-all electric, SC2-all-electric except for DHW, and SC3-both DHW and space heating are non-electric. For all electric scenario PV systems, implemented in all available south facing roof areas together with a limited number of wind turbines can achieve NZE status. Different combinations of these two technologies yield relatively similar results. For the other two scenarios SC2 and SC3, STC and BTES need to be considered to fulfill the partial or total thermal loads, allowing significant size reduction of the PV system and number of wind turbines (WT). The area employed for PV is reduced by 25% for SC2, and 48% for SC3, whereas WT installation is cut by up to 100% for both SC2 and SC3. The remaining areas of the roofs are then employed to integrate the STC systems.

Although in all cases of the considered scenarios WtE is not required, it can be used to shave peak electrical load, reducing the stress on the grid. This methodology can be employed for the design of an integrated urban energy system, in different neighborhood configurations.

CONCLUDING REMARKS

The optimization methodology presented in this paper is applied to a hypothetical high energy performance neighborhood, designed under a Northern, mid-latitude climatic zone. This methodology can be however applied to existing and new neighborhoods, in different climatic zones, and with different geographic and energy characteristics.

This work concentrates on the technical aspects of energy resources and their theoretical feasibility within the proposed hypothetical neighborhood. Other aspects related to governance and regulatory challenges may play an important role in the application of such urban energy mix into actual neighborhoods and can be considered in future studies. Gaining insight into optimal mix of urban energy systems and their feasibility can assist many sectors including public and private stakeholders in their efforts to increase resilience and sustainability of urban areas.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

AUTHOR CONTRIBUTIONS

All authors listed have made a substantial, direct and intellectual contribution to the work, and approved it for publication.

REFERENCES

Cabeza, L. F. (2014). *Advances in Thermal Energy Storage Systems: Methods and Applications*. Cambridge: Elsevier Science.

Catalogue of WtE Facilities in the Sweden (2015). Available online at: https://research.gsd.harvard.edu/wte/files/2017/01/160602CatalogueSweden2.pdf (accessed February 2020).

Falke, T., Krengel, S., Meinerzhagen, A. K., and Schnettler, A. (2016). Multi-objective optimization and simulation model for the design of distributed energy systems. *Appl. Energy* 184, 1508–1516. doi: 10.1016/j.apenergy.2016.03.044

Fonseca, J. A., Nguyen, T. A., Schlueter, A., and Marechal, F. (2016). City energy analyst (CEA): integrated framework for analysis and optimization of building energy systems in neighborhoods and city districts. *Energy Build.* 113, 202–226. doi: 10.1016/j.enbuild.2015.11.055

Hachem, C. (2016). Impact of neighborhood design on energy performance and GHG emissions. *Appl. Energy* 177, 422–434. doi: 10.1016/j.apenergy.2016.05.117

Hachem, C., Cubi, E., and Bergerson, J. (2016). Energy performance of a solar mixed-use community. *Sustain. Cities Soc.* 27, 145–151. doi: 10.1016/j.scs.2015.08.002

Hachem, C., and Grewal, K. S. (2019). Investigation of the impact of residential mixture on energy and environmental performance of mixed use neighborhoods. *Appl. Energy* 241, 362–379. doi: 10.1016/j.apenergy.2019.03.030

Hachem-Vermette, C., and Singh, K. (2020). Developing an optimization methodology for urban energy resources mix. *Appl. Energy* 269:115066. doi: 10.1016/j.apenergy.2020.115066

Harley, R. G., and Infrastructure, X. (2012). *Waste-to-Energy*. Available online at: http://web-resol.org/textos/09_st_01_xicon_waste-2-energy.pdf

Hezaveh, S. H., Bou-Zeid, E., Dabiri, J., Kinzel, M., Cortina, G., and Martinelli, L. (2018). Increasing the power production of vertical-axis wind-turbine farms using synergistic clustering. *Bound. Layer Meteorol.* 169, 275–296. doi: 10.1007/s10546-018-0368-0

International Solid Waste Association (ISWA) (2013). *Guidelines: Waste to Energy in Low and Middle Income Countries.* International Solid Waste Association (ISWA).

Jing, R., Wang, M., Liang, H., Wang, X., Li, N., Shah, N., et al. (2018). Multi-objective optimization of a neighborhood-level urban energy network: considering game-theory inspired multi-benefit allocation constraints. *Appl. Energy* 231, 534–548. doi: 10.1016/j.apenergy.2018.09.151

La Scala, M., Vaccaro, A., and Zobaa, A. F. (2014). A goal programming methodology for multiobjective optimization of distributed energy hubs operation. *Appl. Therm. Eng.* 71, 658–666. doi: 10.1016/j.applthermaleng.2013.10.031

Li, L., Mu, H., Li, N., and Li, M. (2016). Economic and environmental optimization for distributed energy resource systems coupled with district energy networks. *Energy* 109, 947–960. doi: 10.1016/j.energy.2016.05.026

Llanes, J. L., and Kalogirou, E. (2019). Waste-to-energy conversion in Havana: technical and economic analysis. *Soc. Sci.* 8:119. doi: 10.3390/socsci8040119

Loonen, R. C. G. M., Trčka, M., Cóstola, D., and Hensen, J. L. M. (2013). Climate adaptive building shells: state-of-the-art and future challenges. *Renew. Sustain. Energy Rev.* 25, 483–493. doi: 10.1016/j.rser.2013.04.016

Math Works (2020a). *Declare Function Name, Inputs, and Outputs–MATLAB function*. Available online at: https://www.mathworks.com/help/matlab/ref/function.html (accessed April 27, 2021).

Math Works (2020b). *Genetic Algorithm–MATLAB and Simulink–MathWorks*. Available online at: https://www.mathworks.com/help/gads/genetic-algorithm.html (accessed April 27, 2021).

Murray, P., Orehounig, K., Grosspietsch, D., and Carmeliet, J. (2018). A comparison of storage systems in neighbourhood decentralized energy system applications from 2015 to 2050. *Appl. Energy* 231, 1285–1306. doi: 10.1016/j.apenergy.2018.08.106

National Renewable Energy Laboratory (NREL) (2016). *EnergyPlus*. Available online at: https://energyplus.net/ (accessed November 28, 2018).

Parra, D., Norman, S. A., Walker, G. S., and Gillott, M. (2017). Optimum community energy storage for renewable energy and demand load management. *Appl. Energy* 200, 358–369. doi: 10.1016/j.apenergy.2017.05.048

Sikder, S., Eanes, F., Asmelash, H., Kar, S., and Koetter, T. (2016). The contribution of energy-optimized urban planning to efficient resource use–a case study on residential settlement development in Dhaka City, Bangladesh. *Sustainability*. 8:119. doi: 10.3390/su8020119

Singh, K., and Hachem-Vermette, C. (2019). Impact of commercial land mixture on energy and environmental performance of mixed use neighbourhoods. *Build. Environ.* 154, 182–199. doi: 10.1016/j.buildenv.2019.03.016

Singh, K., and Hachem-vermette, C. (2021). Economical energy resource planning to promote sustainable urban design. *Renew. Sustain. Energy Rev.* 137:110619. doi: 10.1016/j.rser.2020.110619

Tsai, W. T. (2019). An analysis of operational efficiencies in the waste-to-energy (WTE) plants of Kaohsiung municipality (Taiwan). *Resources* 8:125. doi: 10.3390/resources8030125

University of Wisconsin Solar Energy Lab (1990). *TRNSYS: A Transient System Simulation Program*. University of Wisconsin. Available online at: https://books.google.ca/books?id=f3oSPQAACAAJ (accessed March, 2020).

Wang, L., Zhang, B., Li, Q., Song, W., and Li, G. (2019). Robust distributed optimization for energy dispatch of multi-stakeholder multiple microgrids under uncertainty. *Appl. Energy* 255:113845. doi: 10.1016/j.apenergy.2019.113845

Windspire (2019). *5kW Vertical Axis Wind Turbine*.

Yin, S., Xia, J., and Jiang, Y. (2020). Characteristics analysis of the heat-to-power ratio from the supply and demand sides of cities in northern China. *Energies* 13:242. doi: 10.3390/en13010242

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Integrated Transportation, Building, and Electricity System Models to Explore Decarbonization Pathways in Regina, Saskatchewan

Madeleine Seatle, Lauren Stanislaw, Robert Xu and Madeleine McPherson*

Department of Civil Engineering, Institute for Integrated Energy Systems, University of Victoria, Victoria, BC, Canada

In Canada, the majority of urban energy demand services the transportation or building sectors, primarily with non-renewable energy sources including gasoline and natural gas. As a result, these two sectors account for 70% of urban greenhouse gas (GHG) emissions. The objective of this paper is to explore the potential for co-benefits when simultaneously electrifying transportation and building demand sectors while expanding variable renewable energy (VRE) production. The investigation uses a novel integrated framework of the transportation, building, and electricity sectors to represent the operational implications of demand side flexibility on both the demand and supply side of the energy system. This original approach allows for very fine temporal and spatial resolution within models, while still performing a multi-sector analysis. First, the activity-based transportation model produces passenger travel demand profiles, allowing for investigation of potential electricity demand and demand response from electric vehicles with high spatial and temporal resolution. Second, the archetype-based building model predicts electricity demand of the residential building sector, allowing for investigation into demand-side management strategies such as load-shifting, building retrofits, and changes in appliance technology. Third, the electricity system production cost dispatch model is used to model the operations of Regina's electricity grid and has a spatial resolution capable of assessing individual and connected positive energy districts as well as VRE integration. Through linking of these three models, the effects of consumer flexibility in transportation and building energy demand are explored, especially in the context of introducing much needed flexibility for large-scale VRE integration. A utility-controlled demand response (DR) strategy is explored as means for Regina to reach their renewable target, along with battery storage. Various pathways to Regina's target are considered, based on the various proposed scopes of the target. The results show that Regina can meet their renewable target with large-scale rooftop solar and wind capacity. DR strategies are marginally effective in aiding toward the renewable target, but, when implemented in conjunction with battery storage, is able to get Regina to within 1% of their renewable target.

Keywords: decarbonization, city-scale modeling, integrated energy modeling, variable renewable energy integration, electrification, demand response, storage

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Matthias Haase,
Zurich University of Applied Sciences, Switzerland

Reviewed by:
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Salesian Polytechnic University, Ecuador
Genku Kayo,
Tokyo City University, Japan
Francesco Guarino,
University of Palermo, Italy

****Correspondence:***
Madeleine Seatle
mseatle@uvic.ca

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INTRODUCTION

In Canada, end-use energy demand in the transportation and building sectors relies heavily on carbon-intensive sources. These sectors, which are collectively responsible for ∼40% of Canada's greenhouse gas (GHG) emissions, mainly use motor gasoline and natural gas for fuel and heating (Natural Resources Canada, 2019). Some cities in North America have recognized this and committed to becoming renewable cities (Zuehlke, 2017; Eaton and Enoch, 2020). In 2018, the City Council of Regina, Saskatchewan made this decision as well, committing to using 100% renewable energy by 2050 (Tink and Folk, 2019). Though the decision was unanimous, City Council lacked clarity on the scope of the commitment, as well as an official plan for how to achieve it. More recently, three novel definitions of scope have been suggested by Bardutz and Dolter (2020):

- Scope 1 would encompass electricity used only by City owned buildings and operations;
- Scope 2 would encompass all electricity used by the City of Regina, including private residents; and
- Scope 3 would encompass all energy used by the City of Regina.

City Council has not yet finalized the scope of the commitment (Peterson, 2020). However, in October 2020, Regina City Council decided to move forwards with the development of an Energy and Sustainability Framework and Action Plan. This would include "details on how City and municipal wide action plans, with specific and aggressive timelines, could forward the commitment of a transition toward a 100% community-wide renewable Regina by 2050." This suggests the city is interested in investigating pathways to reaching the Scope 3 target (Regina City Council, 2020). Meeting Regina's target would require increased use of renewable energy, likely including variable renewable energy (VRE) such as wind and solar. When introducing uncertainty and variability inherent to VRE generation on the supply side, flexibility on the demand side becomes a necessary ingredient to maintaining cost-effective grid reliability. Without demand side flexibility, integration of large-scale VRE generation can be challenging and result in undesirable outcomes, such as inability to meet demand and high curtailment rates (McPherson et al., 2018). Electrification, or a shift away from traditional fuel sources toward electricity powered technologies, can provide demand side flexibility when combined with management strategies (Mathiesen et al., 2015). With proper load management, technologies such as electric vehicles (EVs), electric space heating, and other electric appliances are able to time-shift their demand to match spikes in VRE generation (Dennis, 2015). If carefully designed and managed, there could be a positive feedback loop when electrification and VRE integration are implemented together: low-carbon on the supply side could power the decarbonization of demand sectors, while responsive loads could provide much needed flexibility to facilitate VRE integration.

Demand response (DR) programs can operationalize this positive feedback loop by changing consumers' electricity consumption patterns (McPherson and Stoll, 2020). This can be done through user-controlled electricity reduction, typically for industrial-scale electricity consumers (Alberta Electric System Operator, 2019; SaskPower, 2019; Hydro-Québec, 2020); time-of-use electricity pricing (Ontario Energy Board, 2021); or grid control of appliances, typically with financial incentives (Holy Cross Energy, 2016).

Regina is an ideal candidate for coupling electrification with VRE integration for several reasons: it currently relies on carbon-intensive electricity generation but has immense potential for electrification and exceptional renewable resources. Saskatchewan has the second-highest emitting electricity grid in Canada, due to its reliance on coal generation (Canada Energy Regulator, 2020a,b). Meanwhile, the EV penetration in Saskatchewan is near zero, while electric space and water heating are used in <10% of households (Natural Resources Canada, 2020). Electrification of the transportation and building sectors powered by renewable generation is possible due to Regina's location in one of the highest solar (**Figure 1A**) and wind (**Figure 1B**) potential areas in Canada (Canada Energy Regulator, 2020a).

To investigate how a city such as Regina might meet an energy target such as their goal to be 100% renewable by 2050, it was necessary to have control over the types and scopes of policies that are able to be modeled; this is done by employing a novel integrated modeling paradigm. Energy transition models in Canada typically take a macroeconomic approach (Vaillancourt et al., 2014), which have simplistic specifications for energy demand, as well as being spatially and temporally aggregate. A general tendency within the formulation of macroeconomic models is the focus on the decision-making process of individual actors, thus the trade-off in the detail of energy, spatial, and temporal data. However, these simplifications and aggregations mean that highly variable, spatially, or temporally, constraints are not able to be assessed at the level of detail needed. Within city-scale energy modeling, there are models that are able to represent a city at a high spatial resolution, but do not provide the temporal resolution necessary to accurately model an electricity system with high VRE integration (Zuehlke, 2017; Crockett et al., 2019). There are also load models, which can model at the adequate temporal resolution for electricity systems but lack the ability to model the electricity system at the same spatial resolution (Salama et al., 2019). On the other end of the spectrum are micro-grid models (HOMER Energy, 2021), which are typically restricted in the size of the system they can model, thus making them unable to model the electricity grid for an entire city.

To capitalize on the strengths of multiple models, model linkage is a common practice, especially between load models and operational models. Within this space, there have been studies showing the value in model linkage between two sectors. Szinai et al. (2020) found that the linkage of a transportation model and an electricity system model was able to provide insights on the operational implications of the increased EV penetration and VRE utilization. It was found that on a solar dominant electricity grid, "smart" charging (DR program used to control charging time to provide the grid the most benefit) can reduce VRE curtailment and reduce grid operating costs (compared

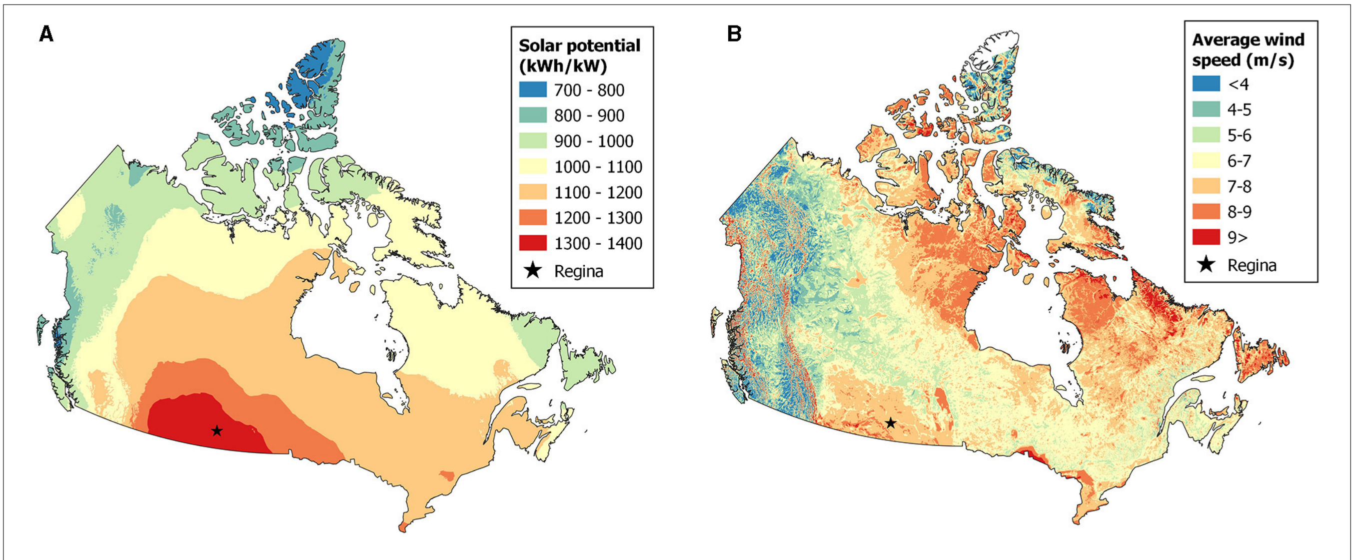

FIGURE 1 | (A) Solar potential map (Government of Canada et al., 2020) (left) and **(B)** wind potential map (Global Wind Atlas, 2019) (right).

to unmanaged EV charging). Additionally, Deane et al. (2015) found that the linkage of a building model and an electricity system model can more accurately measure the capabilities of an electricity system to manage a more highly electrified load. The linking of the models was proven to leverage the strength of each model and provide complimentary insights that would not have been seen otherwise. However, even with the proven benefit of mode linkage between two sectors, there has yet to be a model that links the transportation, building, *and* electricity sectors at a high enough resolution to fully assess the co-benefits of electrification and VRE integration. As all three sectors are key in meeting Regina's energy target and, more generally, Canada's deep decarbonization goals, a linkage of models between these sectors is a current gap in the research field.

This paper combines the strengths of multiple approaches via a novel integrated model of the transportation, building, and electricity sectors, with a bidirectional linkage allowing DR strategies to be modeled at high degree of temporal and spatial resolution. SILVER, an electricity system model, currently operates at a high temporal resolution and has the ability to model highly granular spatial boundaries; however, linkages with individual transportation and building models can allow for further spatial granularity while keeping SILVER's computation time reasonable.

METHODS

With Regina's potential for additional VRE generation and demand side electrification, there is a broad exploration space for future configurations of its energy system. Uncertainty can be explored by changing variables such as the electrification level, VRE capacity, storage, and DR. With the novel linkage between transportation, building, and electricity system models, these variables can be explored at a high temporal and spatial resolution.

Integrated Model Formulation

Reducing emissions related to energy use is a main objective behind Regina's renewable energy goal. Evaluating the effect of demand side electrification on emissions requires the demand side models to pass information to the electricity system model. Investigating DR based on VRE generation requires information to be passed from the electricity system model to the demand side models. VRE curtailment is an indicator of system efficiency and design because lower curtailment indicates more demand is being met by VRE. Since VRE is non-polluting, bidirectional linkage is implemented by using curtailment reduction as a proxy for emissions reduction.

Figure 2 illustrates the novel linkage process; the solid arrows represent the linkage from the building and transportation sector models to the electricity system model, while the dashed arrows represent the linkage from the electricity system model to the demand side models. Once a scenario is selected, the building and transportation models—outlined in detail in the following sections—are run concurrently and output demand load curves. These are combined with a baseline demand to represent the total electrical load for Regina, which is then input directly into the electricity model. Although these models interact with each other while running a scenario, they are decoupled and individual insights are able to be drawn from each model individually, as well as from the linked outputs.

After the electricity model is run, the amount of VRE curtailment is assessed. DR is modeled to occur through utility control over EV charging and building temperature setpoints, allowing the utility to time-shift loads during periods of curtailment to take full advantage of VRE generation. Constraints are placed upon utility control to minimize the disruption to the customers. For example, EVs must charge if needed to get to their next destination, even if curtailment is not occurring. Similarly, the utility can only allow the temperature within a building to drop to a certain degree before allowing the heater to turn on. It

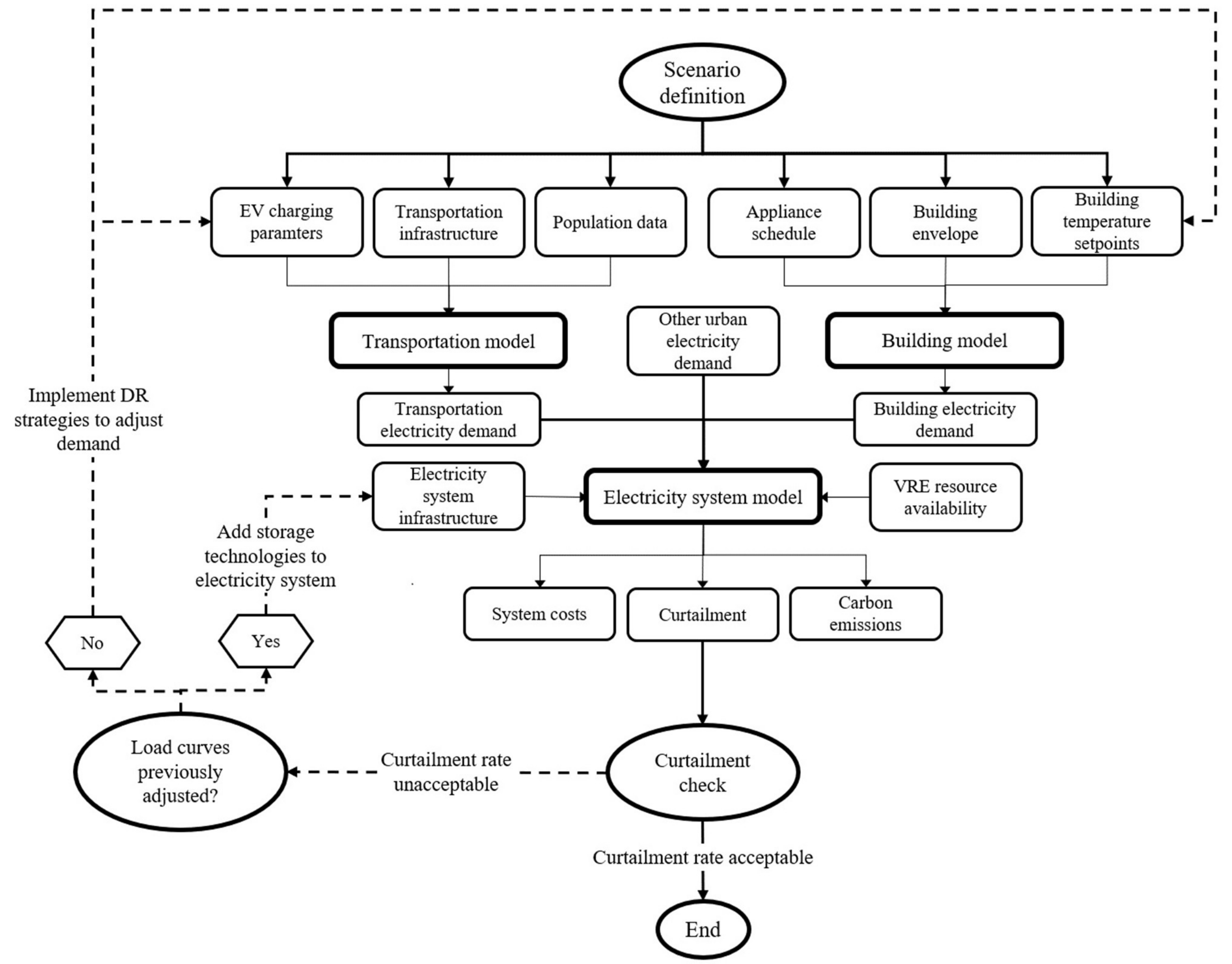

FIGURE 2 | Bidirectional model framework with key inputs and outputs.

is assumed that all electrified vehicles and buildings participate in DR.

The utility would decide how to allocate DR load to the building and transportation sectors; for simplicity, as it makes no difference to the overall system which sector uses electricity, every EV is charged until there is either no curtailment, or no remaining vehicles available to charge. The setpoints of all electrified buildings are then changed until there is either no curtailment, or all buildings have reached their maximum setpoint. This results in curtailment being minimized for that scenario. If the curtailment is still at unacceptable levels after the setpoints of all possible buildings have been changed, and the renewable target is not met, SILVER is rerun with storage technologies added.

Transportation Model

To predict EV charging, the travel and charging behavior of individual vehicles are simulated. By understanding when and where individual vehicles are traveling, the spatiotemporal distribution and flexibility of EV charging can be estimated by aggregating the charging of individual vehicles.

TASHA, an activity scheduling model developed and maintained at the University of Toronto (Miller and Roorda, 2003), is used to model vehicle schedules. It is currently being used to forecast travel patterns and test policy decisions in the Greater Toronto Area (Miller et al., 2015). Selected for its ability to consider spatiotemporal and resource constraints, such as vehicle availability, TASHA is able to use this information to predict EV demand within the integrated model platform. A complete daily travel schedule is generated for each household resident in a synthetic population, but commercial and freight transportation is not considered. This and other limitations regarding the transportation model are elaborated in the Limitations section. Detailed steps for creating and calibrating a TASHA implementation are documented by the University of Toronto Travel Modelling Group (Travel Modelling Group,

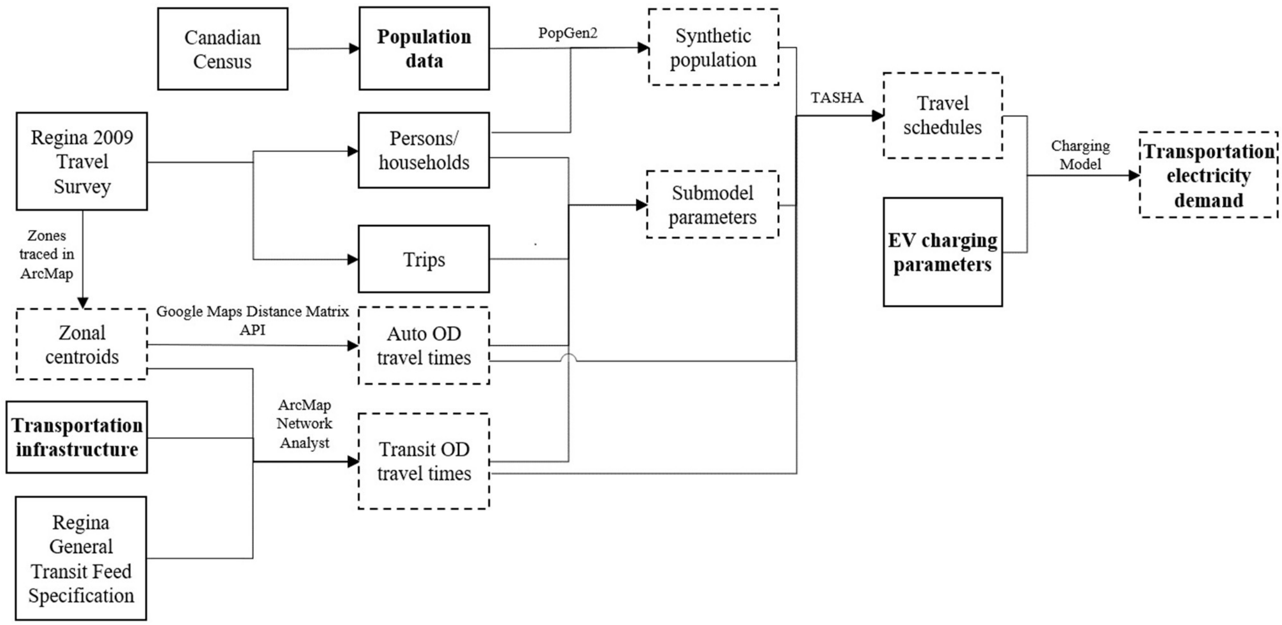

FIGURE 3 | Transportation model processes, with solid boxes representing raw data inputs and dashes boxes representing a processed output. Note that bold text represents a direct tie-in to **Figure 2**.

2020). Specific details on the development of TASHA for the Regina case study, including input preparation and model calibration, are described in the **Supplementary Information**.

The data sources and processing flows for the Regina transportation and EV charging model are shown in **Figure 3**, where the output of TASHA is used as an input into the charging model. Without DR, EVs are assumed to charge as soon as they arrive to their destination, and this strategy is modeled for scenarios without DR. Charging is modeled by processing each vehicle's trip schedule in temporal order: when a vehicle departs from an activity, its battery level is updated based on the trip distance and depletion rate following the assumptions described in the transportation model assumptions section. The equations which describe EV charging without DR are included in the **Supplementary Information**.

DR implementation is modeled for EVs as utility-controlled charging (UCC), where the utility can control the charging status of individual vehicles. When DR is modeled, it is assumed that all EVs participate in DR and are required to communicate the following with the utility: time of next trip departure, desired battery state of charge at time of departure, and charging status (i.e., vehicle plugged in, vehicle charging). With UCC, participating vehicles follow the same travel schedules as with uncontrolled charging, but modify their charging behavior. Instead of charging immediately, EVs delay charging until the last possible moment such that the total energy charged during the activity is the same that would be charged without UCC. Because of this delay, the utility can charge EVs with excess renewable energy if it occurs. As previously mentioned, the VRE curtailment output from SILVER is used to guide UCC within the charging model; specifically, the utility tries to charge as many vehicles as possible (when curtailment occurs) to minimize curtailment and maximize use of VRE. Additional details on the implementation and modeling of UCC are included in the **Supplementary Information**.

Building Model

A detailed representation of the relationship between building characteristics and the resulting energy usage is needed to investigate the effects of retrofit policies on building energy use. However, it is also necessary to keep data and computational requirements to a manageable level. Therefore, electrification of the residential building sector is modeled using an archetype-based engineering model, similar to that employed by Ballarini et al. (2014).

Under this modeling framework, heat exchange between individual buildings and their environment is calculated using EnergyPlus, a detailed thermodynamics simulator. For this, building properties relevant to heat transfer are specified, which include building shape, building size, construction materials, size and location of windows, and the living patterns of occupants (Swan and Ugursal, 2009). A large population of varied buildings are modeled by specifying these characteristics for a small number of archetypes, whose properties are representative of the population as a whole (Reinhart and Davila, 2019). Building policies are then simulated by changing specific details in each of the archetypes. For example, insulation retrofits in houses built before a specified date are modeled by changing the construction materials of the relevant archetype within the EnergyPlus simulation.

The process flows and data sources used within Regina specifically can be seen in **Figure 4**. Archetypes were defined

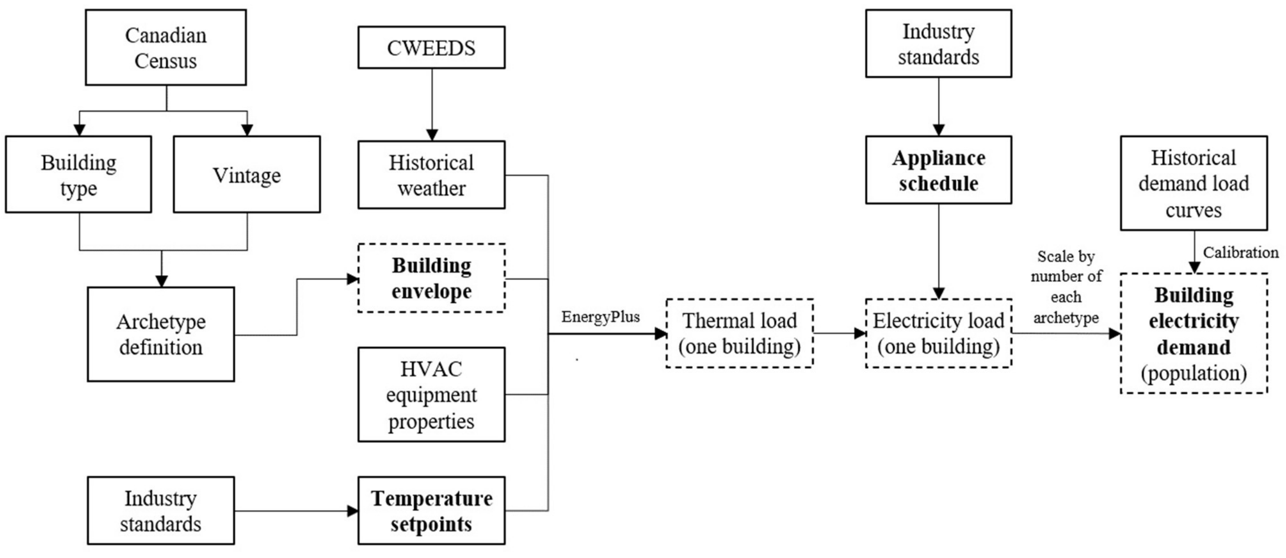

FIGURE 4 | Building model processes, with solid boxes representing raw data inputs and dashes boxes representing a processed output. Note that bold text represents a direct tie-in to **Figure 2**.

based on census data for the city, and archetype annual load curves were aggregated up to a city scale by multiplying by the number of houses represented by each archetype. The simulation was then verified by visual comparison to historical load curve data. Further details on the development of the building model specifically for the Regina case study, including data sources used, specifications of each selected archetype, and technical details of the simulation, is described in the **Supplementary Information**.

DR was implemented in the model by manipulating the building setpoints for each hour based on whether VRE curtailment was occurring in that period. When the model is run without DR, all buildings are kept at a constant setpoint of 19°C for heating and 27°C for cooling, as per (SOURCE). In contrast, when DR is applied, building setpoints vary depending on if there is curtailment occurring, so that the buildings can be used as heat storage for the otherwise curtailed electricity. When curtailment is *not* occurring, setpoints relax to 18°C for heating and 28°C for cooling (i.e., lessening the electricity demand). During periods of curtailment, the heating and cooling setpoints change to the more restrictive values of 21°C and 26°C, respectively (i.e. increasing the electricity demand).

Electricity System Model

To effectively model a renewable city, it is crucial to develop a city-scale electricity system model. SILVER, a production-cost model (McPherson and Karney, 2017), was chosen as the electricity system model for the following reasons. First, though originally developed for analyses at the provincial level, it can also be applied at a city-scale (McPherson et al., 2018). Second, SILVER models an electricity system as defined by the user, including generation and transmission assets; generation operational constraints, costs, and carbon-intensity; VRE characteristics; and electricity demand. These inputs are then validated through transmission congestion checks, generation capacity checks, and flexibility checks before proceeding to the optimization module, which determines the least-cost dispatch of the electricity system (generation and transmission assets) needed to satisfy demand at every node and each timestep of the simulation (McPherson and Karney, 2017). Third, SILVER is conducive to DR implementation within the model linkage by synthesizing multiple load curves into one overall demand load and quantifying curtailment.

An overview of the data sources and model processes can be seen in **Figure 5**. In summary, the available electricity demand data came from SaskPower, the electricity distributor for most of the province of Saskatchewan; census population data came from the Canadian Census (Statistics Canada, 2017), and neighborhood boundary data came from the City of Regina (City of Regina, 2017). Boundary resolution and VRE resource analysis are discussed in detail in the **Supplementary Information**, while the processes within SILVER are outlined in more detail by McPherson and Karney (2017).

For city-scale analysis, resolving spatial boundaries across data sources is a key priority; the high spatial resolution inherent to SILVER makes this especially important. As city-scale data is typically adopted from larger-scale data collection, there are discrepancies in spatial boundaries between data sets, as well as between the transportation and building model spatial boundaries. A detailed description of the assumption made within boundary resolution for Regina can be found in the **Supplementary Information**.

Due to Regina's high solar and wind potential, this analysis considers rooftop solar and wind. The hourly generation profiles are derived on a nodal level through capacity factor values. The wind capacity factor values were taken from the Global Renewable Energy Timeseries and Analysis (GRETA) online

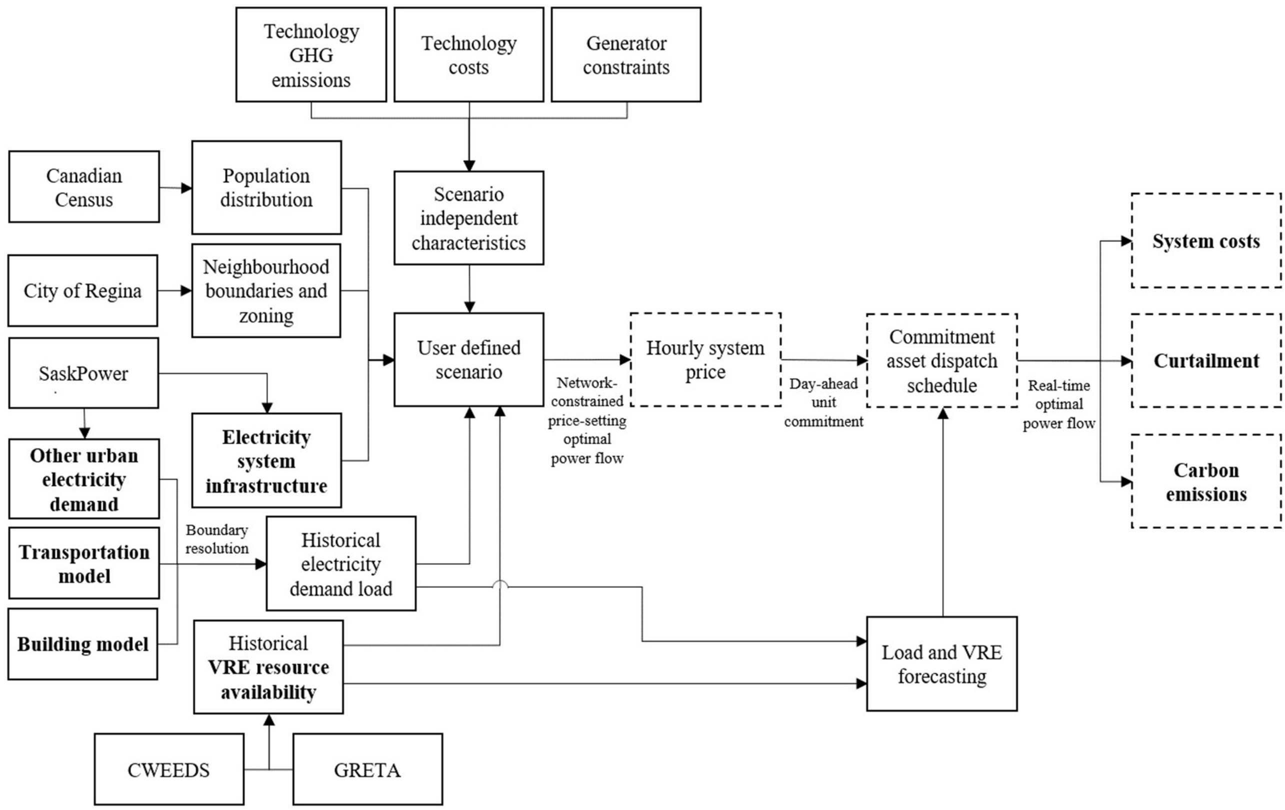

FIGURE 5 | Electricity model processes, with solid boxes representing raw data inputs and dashes boxes representing a processed output. Note that bold text represents a direct tie-in to **Figure 2**.

tool (McPherson et al., 2017). Due to the intricacies of solar capacity factor calculations in relation to rooftop solar and shading variabilities, the calculations were done based on local weather station data and the capacity factor procedure outlined by Masters (2004) and the GIS-work procedure outlined by Latif et al. (2012). Additionally, seasonal changes in sun position and rooftop slopes are accounted for by average annual rooftop shading factors. The related weather data came from the Canadian Weather Energy and Engineering Datasets (CWEEDS) (Environment and Climate Change Canada, 2015), while applicable GIS surface cover data came from various sources (City of Regina, 2017; Natural Resources Canada, 2020).

Scenario Development

Regina currently draws its power entirely from the SaskPower grid, which is heavily dependent on coal (30% of generation capacity) and natural gas (43% of generation capacity) (SaskPower, 2021). The electricity demand on the grid is primarily commercial, industrial, and residential plug-load, with very little residential heating being electrified, nor significant EV load. With the current grid composition, electrifying residential building and transportation loads would lead to an increase in overall emissions. However, with an increasing share of VRE generation, the effects of electrification would allow for an overall reduction in city-wide emissions.

Utilizing the novel methodology to explore the simultaneous implementation of VRE integration and electrification is explored. In order to assess the feasibility of Regina's energy target, 10 different scenarios were developed (**Table 1**). Each scenario is run in three stages, where curtailment and system cost are evaluated at each stage: Stage A models the naive load curve as a result of the transportation and building electrification scenarios with renewable generation infrastructure added; Stage B adjusts the transportation and building demand by enacting DR strategies when renewable energy would otherwise be curtailed; and Stage C adds storage technologies, reducing curtailment while still maintaining high VRE implementation on the grid. Note that Stage B has the same parameters as Stage A, but a different model architecture.

As future electrification rates are highly uncertain, electrification levels were chosen to explore as broad a space as possible to align with Regina's ambitious decarbonization goal. Levels of 50 and 100% electrification balance the computational burden of running multiple scenarios with representing pathways to Regina's target.

Electrification of the transportation sector focuses on the switch from combustion engines to battery EVs, which run exclusively on electricity. It should be noted that electrification of the building sector refers to both replacing natural gas-powered furnaces with electric ground source heat pumps (GSHPs), and

TABLE 1 | Scenario parameters.

	Stage A/B			Stage C
Scenario number	**Electrification level**	**Rooftop solar capacity (MW)/Share of viable rooftops covered**	**Wind farm size (MW)**	**Maximum storage size (MW)/Maximum storage capacity (MWh)**
Current system	Transportation: 0%; Buildings: 10%	0/0%	0	0/0
1	50%	353/25%	0	0/0
2	100%			0/0
3	50%	705/50%	0	0/0
4	100%			0/0
5	50%	1,410/100%	0	225/900
6	100%			200/800
7	50%	1,410/100%	100	250/1,000
8	100%			250/1,000
9	50	1,410/100%	200	325/1,300
10	100%			325/1,300

upgrading window, wall, and roof insulation levels to match the highest tier of the BC Step Code (Robinson, 2018). The insulation upgrades support electrification by reducing the energy demand of affected buildings, making it more feasible for electrification to be powered by renewable sources.

Within the scenarios, transportation and building electrification levels are assumed to change concurrently[1]; an electrification level of 50%, as in Scenario 1, means that 50% of households use exclusively EVs, 50% of households switch to GSHP, and 50% of households increase their level of insulation. For simplicity, it is assumed that policies for these variables would be implemented at similar times, resulting in similar electrification levels across sectors. This allows for a greater focus on how electrification as a whole will affect the electricity grid, rather than the effect of specific sectors.

Regardless of the adoption level, there are several assumptions in the EV charging model which remain constant across scenarios:

- EVs charge at every destination (home, work, shopping, and other activities) and have a battery capacity of 40 kWh;
- EV adoption occurs uniformly distributed across Regina households;
- Charging occurs with a power of 2 kW and the battery depletion rate is a function of external temperature;
- Temperature is sampled monthly using average temperatures from (Environment Canada, 2020); and
- Battery depletion rate was estimated using the online tool provided by Geotab (2021), where a 2019 Nissan Leaf with a 40 kWh battery is assumed.

Building model parameters varied slightly based on the adoption level. For the fully electrified scenario, all homes were assumed to receive both GSHP and insulation upgrades. For the 50% electrification scenario, all buildings received one of the two upgrades, and each upgrade was performed on exactly half of the building stock. Upgrades were strategically distributed to reduce energy consumption as much as possible, resulting in the following distribution among the types of buildings modeled:

- Buildings constructed before 1975, and a portion of those constructed in 1975, received insulation upgrades, as they are assumed to have poorer insulation.
- Buildings constructed after 1975, and the remaining portion of those constructed in 1975, received GSHP, as they are assumed to consume more energy due to their larger floor area.

Rooftop solar integration is reflective of both residential and commercial implementation and is based on the percentage of usable[2] rooftop space covered with photovoltaic (PV) panels. Rooftop solar integration levels were taken based on recent residential opinion survey conducted in Regina (Bardutz and Dolter, 2020):

- Twenty five percent of residents are willing and able to install rooftop solar without any financial incentives;
- Fifty percent of residents are willing and able to install rooftop solar with financial incentives;
- And 100% rooftop solar integration, though not directly taken from the survey data, relates to a best-case scenario of residents willing and able to install rooftop solar.

Though this data reflects only residential interest in rooftop solar, it is assumed to be consistent across commercial and industrial building owners as well.

Wind farms are assumed to be installed outside city limits, for which there is significant support (Bardutz and Dolter, 2020). A wind farm is assumed to be introduced into the generation mix in conjunction with 100% rooftop solar implementation

[1]Unless otherwise indicated, i.e., Current system scenario.

[2]Usable rooftop space is defined as an area where the average annual solar capacity factor is at least 10% for a minimum of 25.5 m^2, which is equivalent to a 5 kW PV array (Solar Calculator, 2020).

scenarios. This was done so that scenarios with a wind farm could be directly compared. Currently, the largest wind farm in Saskatchewan[3] is 200 MW, which was taken as the upper bound for the modeled wind farm. To explore the space further, scenarios were also modeled with a 100 MW wind farm.

Storage was introduced to six scenarios (Scenarios 5 through 10) that were identified as having the potential to meet the renewable target if curtailment was decreased further than found in the previous stage. This was based on the amount of curtailment and progress toward the target renewable usage after the DR strategy was implemented (further discussion can be found in discussion). The storage technology was assumed to be lithium-ion batteries with a 4-h discharge duration. The maximum capacity of the storage technology (equivalent to the storage size multiplied by the duration of the battery) was assumed to equal the maximum curtailment within each scenario.

RESULTS

Electrification of private vehicles and building heating, DR, and storage each have different effects on system cost, VRE curtailment, and the ability of Regina to meet its renewable energy target. In this section, detailed results from all three stages are discussed. Figures that are referred to across subsections are various generation mixes (**Figure 6**) and a comparison of annual average curtailment levels for each scenario in each stage (**Figure 7**).

Scenarios are evaluated on two key criteria: levelized cost of electricity (LCOE) (International Renewable Energy Agency, 2020; Lazard, 2020) and ability to meet Regina's renewable target (**Figure 8**). Additionally, as these scenarios are looking ahead to 2050, when Regina's target is set to be achieved, the cost is also evaluated based on a carbon tax of 170 CAD, as per the federal carbon tax guidelines (Canada Energy Regulator, 2020b; Tasker, 2020). It should be noted that LCOE is only reflective of the cost of electricity and future analysis should include comparison to the cost of other energy sources. The costs reported here may not be representative of overall energy costs in any given scenario, as discussed further in current limitations.

Stage A: Electrification Impact

Electrification increases the annual peak demand by almost 50%, though the effects on overall electricity consumption varies by electrification level. An electrification level of 50%, along with building retrofits to make consumption more efficient, was found to decrease consumption by almost 18%, while an electrification level of 100% was found to increase consumption by 15% (**Table 2**). Buildings were shown to be the more significant source of the changes in consumption, with transportation contributing under 5% of the total for both 50 and 100% EV penetrations.

The addition of rooftop solar allows Regina to be powered entirely by solar generation for periods in the summer (comparing **Figure 6**: Current system to **Figure 6**: Scenario 6A). Further, the deployment of wind allows for renewables to contribute to the generation mix at night (**Figure 6**: Scenario 10A), which is especially important in the winter electrification contributes significantly to overnight demand.

However, without DR or storage, Regina is unable to meet their target of 100% renewable energy across for the entire energy system. Only 65% of the energy demand is sourced from renewable energy, even when 100% of roofs are covered with solar PV (1,410 MW) and 200 MW of wind is installed, when DR and storage do not contribute to the grid balancing. In this scenario, 60% of the renewable energy is curtailed, which not only impedes reaching the target, but also indicates that the system is being operated inefficiently. Compared with the current system (composed of primarily not electrified loads), electrification of private vehicles and building heating and cooling results in a 7–33% higher LCOE (**Figure 8**). Assuming an LCOE of $40/MWh for wind and $126.5/MWh for rooftop solar, the addition of a wind farm tends to decrease the overall LCOE, as seen in the clustering of Scenarios 7A, 8A, 9A, and 10A in **Figure 8**.

As expected, curtailment in Stage A scenarios, when DR and storage are excluded from the system mix, is the highest. Curtailment peaks at almost 70% in Scenario 5A (refer to **Figure 7**) when there is 50% electrification and 100% rooftop solar penetration. In general, since electricity demand is higher in 100% electrification than 50% electrification scenarios, curtailment decreases between 9 and 15%, across all VRE penetrations. Without DR, EV charging demand follows a similar pattern day to day, when holding temperature constant. Lower efficiency in the winter results in longer charging events—because EVs arrive at their destinations with more depleted batteries than in the summer—and therefore a larger peak demand, as shown in **Figure 9A**. Temperature dependent efficiency was the only seasonal variation accounted for, but different seasonal travel patterns may also affect charging patterns and were not investigated. By disaggregating the EV charging curve by load type, it is seen that charging at work and home charging are responsible for the two peaks observed in EV charging (**Figure 9B**). However, it was assumed in this work that EV charging could take place at any location (i.e., work, home, shopping areas, etc.)—which would require widespread charging availability throughout the network. Such a scenario would result in infrastructure costs that were not quantified in this work.

The building model also uses markedly more energy in the winter than the summer. As seen by comparing **Figures 10A,B**, winter peak loads are almost three times higher than summer peaks, while winter troughs are approximately equal to summer peaks. The magnitude of this seasonal variation underscores that Regina's climate is heavily heating-dominated, and that it is important to choose envelope retrofits that help retain heat and HVAC systems that are optimized for efficient heating.

Comparison between winter load curves in the 50% penetration scenario and the 100% penetration scenario (**Figure 10A**) shows that the two display a different temporal shape. In the 50% scenario, some of the electrified homes are powered by less-efficient electric heating systems, which are left over from the current system. This results in the 100% penetration scenario only using 20% more electricity

[3]Golden South Wind Project is currently in the progress of being constructed and should be operational by 2021 (SaskPower, 2018).

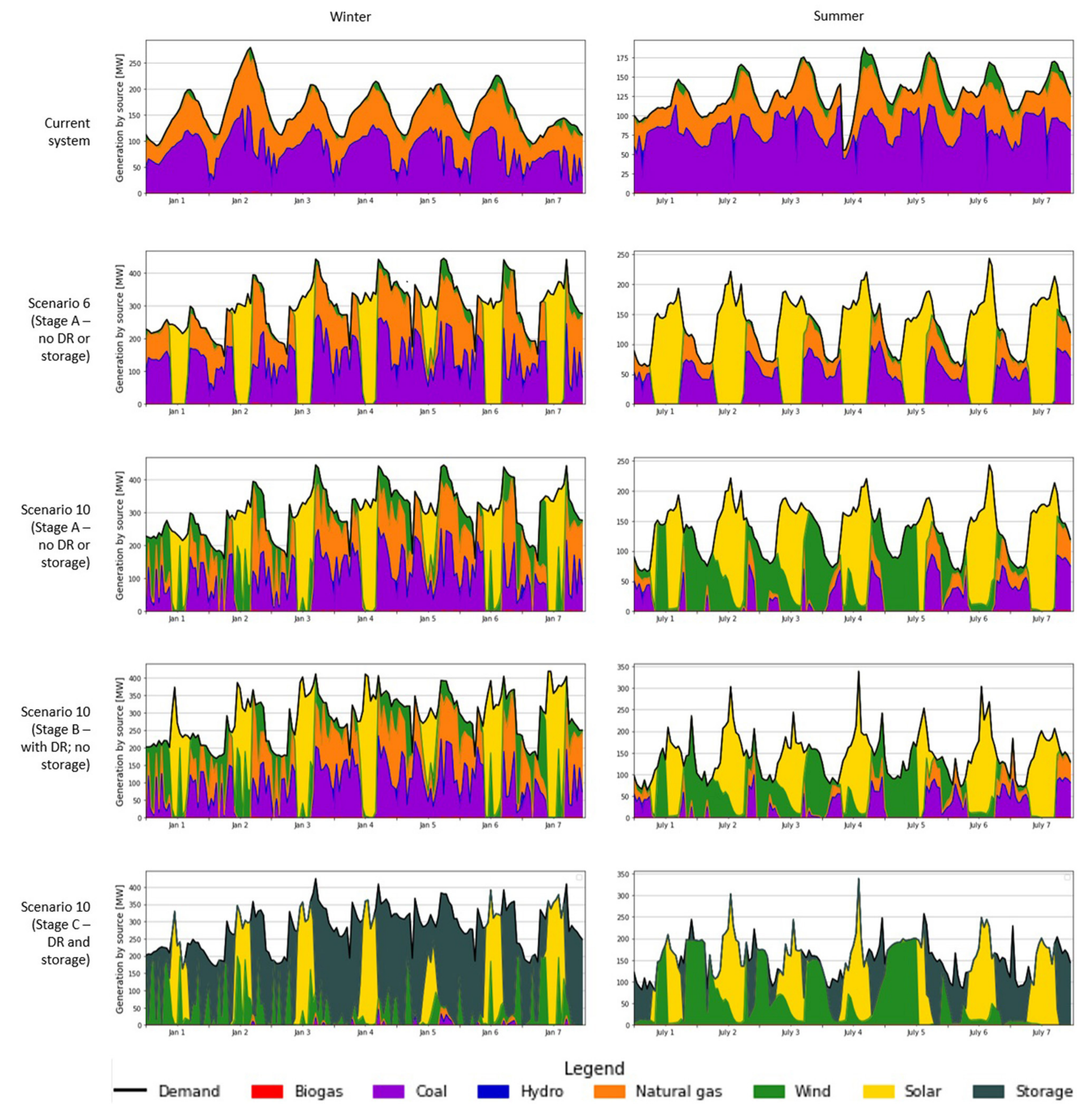

FIGURE 6 | Generation mixes of various scenarios. Winter generation is seen from January 1–7 (left column) while summer generation is seen from July 1–7 (right column). As previously outlined, Scenario 6 has added rooftop solar capacity, and Scenario 10 has added rooftop solar and wind capacity.

over the course of the year, despite having twice as many homes contributing to the thermal load curve. From that, it can be seen that replacing gas-powered HVAC systems with more efficient systems can have a significant impact in terms of energy savings.

Stage B: DR Impact

Implementing DR had a noticeable but small effect on VRE curtailment, which allowed for an increase in the percent of load serviced by renewable energy, as shown in **Figure 8**. Seen in **Figure 7**, the DR results in only a 1–3% reduction in curtailment.

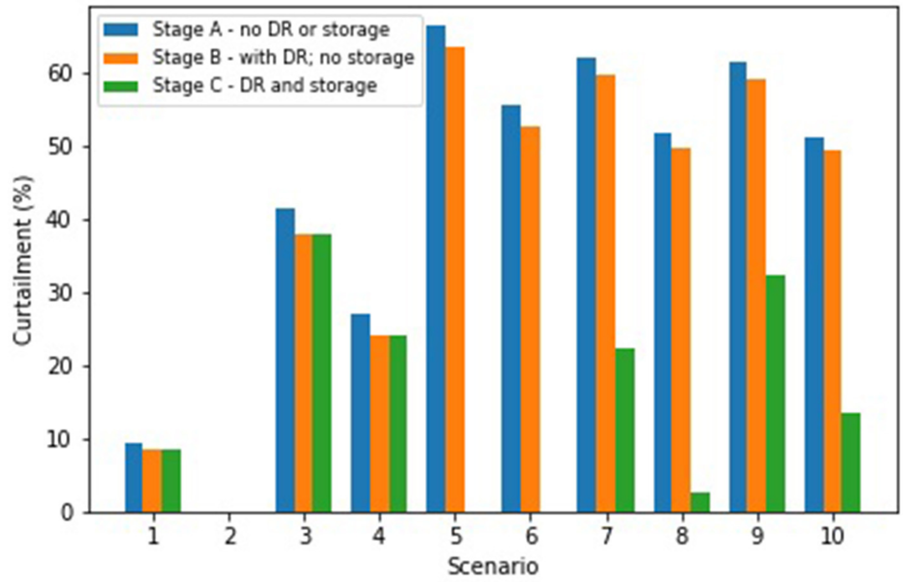

FIGURE 7 | Annual average curtailment value across all scenarios and stages. Curtailment in Stage C of Scenarios 1 through 4 is identical to Stage B, as there is no storage capacity added to the system. Note that if scenarios appear to not have values for a particular stage it is due to that value being zero or near zero.

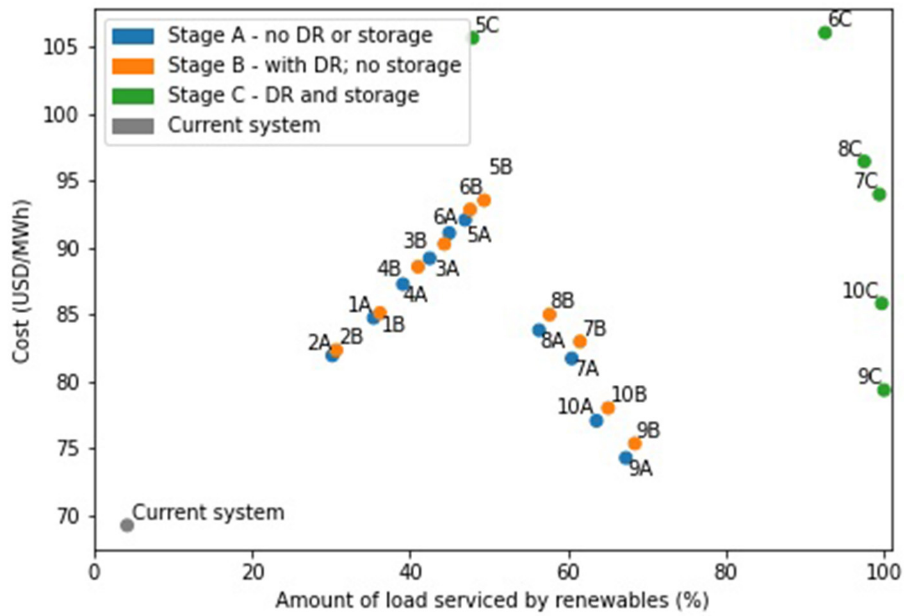

FIGURE 8 | Modeled cost of electricity system per unit energy compared to ability to meet Regina's renewable target with a carbon tax of 170 CAD. As previously outlined, odd numbered scenarios have 50% electrification levels; even numbered scenarios have 100% electrification levels; and Scenarios 7 through 10 have additional wind capacity along with rooftop solar.

This is largely due to the dual effect of decreased energy requirements and increased solar generation in the summer overwhelming the ability for DR to meaningfully decrease VRE curtailment. Additionally, the implementation of DR continued to see scenarios with 50% electrification having consistently more curtailment than those with 100% electrification, as seen in Stage B scenarios in **Figure 7**.

As the LCOE of rooftop solar is higher than non-renewable generation, DR results in a marginal increase of overall LCOE. However, even in the best-case scenario (Scenario 9B with

TABLE 2 | Modeled annual electricity consumption by sector based on electrified share of personal vehicles and residential building heating.

	BAU electricity consumption (GWh)/Contribution to total consumption	50% electrified electricity consumption (GWh)/Contribution to total consumption	100% electrified electricity consumption (GWh)/Contribution to total consumption
Transportation	0/0%	29/2%	58/3%
Building	921/49%	562/37%	1,157/54%
Other urban loads	947/51%	947/62%	947/44%

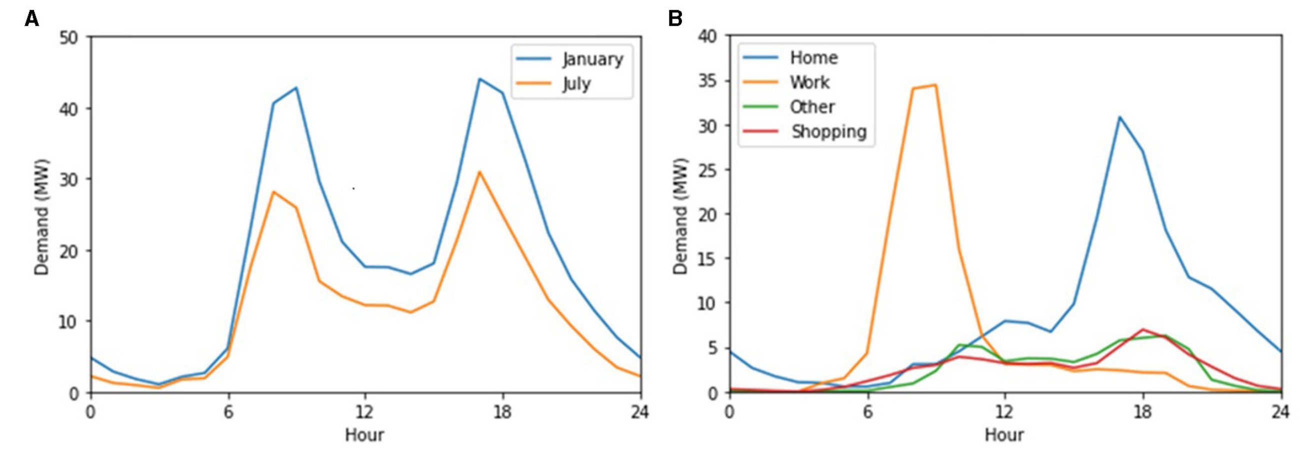

FIGURE 9 | (A) EV charging demand load at 50% EV penetration compared seasonally (left) and **(B)** winter EV charging demand load for 50% EV penetration disaggregated by trip activity (right).

50% electrification, 100% rooftop solar, and 200 MW wind farm), curtailment rate was 60%, impeding the contribution that renewables could make. Though 70% of the load was serviced with renewable energy; this is only marginally better than that achieved without DR (Scenario 9A).

Though it was seen that 50% electrification scenarios are better able to service their electricity demand from renewables (**Figure 8**), this is mainly due to the overall lower electricity demand when compared to 100% electrification scenarios. It should be noted that 50% electrification scenarios may be representing a different pathway to meeting the renewable target than 100% electrification scenarios, as other renewable energy needed to meet Scope 3 are not accounted for in this modeling work. To meet Regina's Scope 3 target, the 50% electrification scenarios must be implemented in conjunction with additional decarbonization strategies for the remaining energy sources.

Implementing DR on the demand-side transportation model causes EV charging demand to shift toward the beginning of the curtailment period. A visual comparison of EV demand and VRE curtailment shown in **Figure 10** shows that no matter how DR is implemented, the amount of curtailment may be so large that fulfilling 100% of EV charging with excess VRE would still result in curtailment. This is shown in **Figure 11** for Scenario 3B (50% rooftop solar penetration) in the winter and summer.

As an EV is simulated to charge to its maximum capacity before every departure, there is charging occurring at times when there is no curtailment. As a result, not all EV charging is fulfilled by VRE generation (**Figure 12**). Alternative charging strategies, such as those where a vehicle is not charged until it reaches a certain battery level, could potentially be used to further shift EV charging and utilize more excess VRE. As the focus of this work was on electrification, space of EV charging behavior was not explored. Implementing DR successfully for EVs also requires that the infrastructure for DR exists where vehicles are during curtailment times. This can be seen in **Figure 12**, which shows EV charging load in Scenario 3B for select days in the winter, disaggregated by activity. Work related charging experiences the greatest increase during curtailment times, suggesting that most vehicles are parked at work when curtailment occurs.

Similarly, the underwhelming effect of DR on building load shifting, as seen by the proximity of the curves in **Figure 13**, can be explained by the nature of the DR strategies investigated. Even in the winter (**Figure 13A**) when the thermal load is much higher, additional activities such as lighting, appliance usage, and water heaters contribute to the total electric load of buildings. Effective load-shifting on the building side therefore requires comprehensive DR programs that include as many electricity-consuming activities as possible. It is also worthwhile to investigate the inclusion of industrial and commercial buildings in these programs.

Stage C: Storage Impact

As seen in **Figure 6**: Scenario 10C, the introduction of VRE storage changes the generation mix significantly. The ability to store renewable generation leads to a decrease in curtailment in all scenarios (**Figure 7**). Notably, adding storage to scenarios

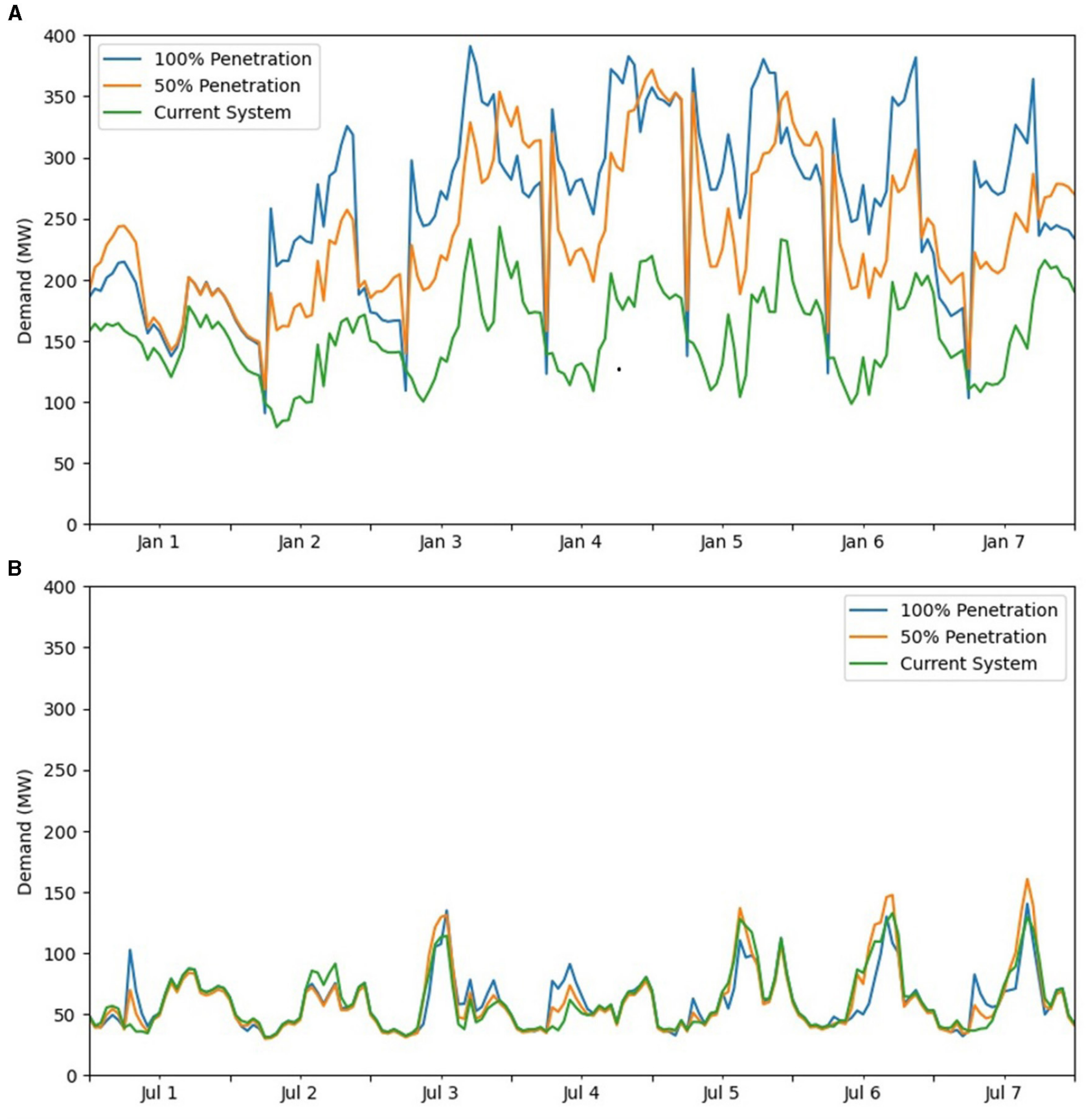

FIGURE 10 | Building demand load in 50% and 100% penetration scenarios in **(A)** winter (top) and **(B)** summer (bottom).

with 100% rooftop solar penetration but no added wind capacity (i.e., Scenarios 5C and 6C) reduce their curtailment to near zero. Though there is still curtailment within some of these scenarios (ex. Scenario 9C), the level falls within an acceptable range considering the amount of demand being met by renewables.

As seen in **Figure 7**, adding storage technology to the grid is the most successful strategy in reducing curtailment. Overall, reducing curtailment directly correlates to Regina's ability to meet their target, but there are scenarios that have significant curtailment even when the target has been met (i.e., Scenario 9C). This indicates that there is excess renewable generation within this scenario, meaning increasing storage capacity would not necessarily increase Regina's ability to meet their target. In this situation, excess VRE generation unable to be stored can be exported to the provincial grid and potentially used as a renewable credit toward the renewable target, which is discussed further in the discussion.

As can be seen comparing **Figure 8**, the current system will continue to be the least expensive option in terms of LCOE due to the relative low cost of carbon intensive generations, though it is comparable to scenarios that have 100% rooftop solar penetration and a 200 MW wind farm (i.e., Scenarios 9C and 10C) are able to meet over 99% of their demand load with renewables. However, there is potential for cost reduction in the method of renewable penetration chosen; rooftop solar had a significantly higher LCOE than utility scale solar or wind, the latter of which can be seen in the cost difference between Scenarios 6C and 10C.

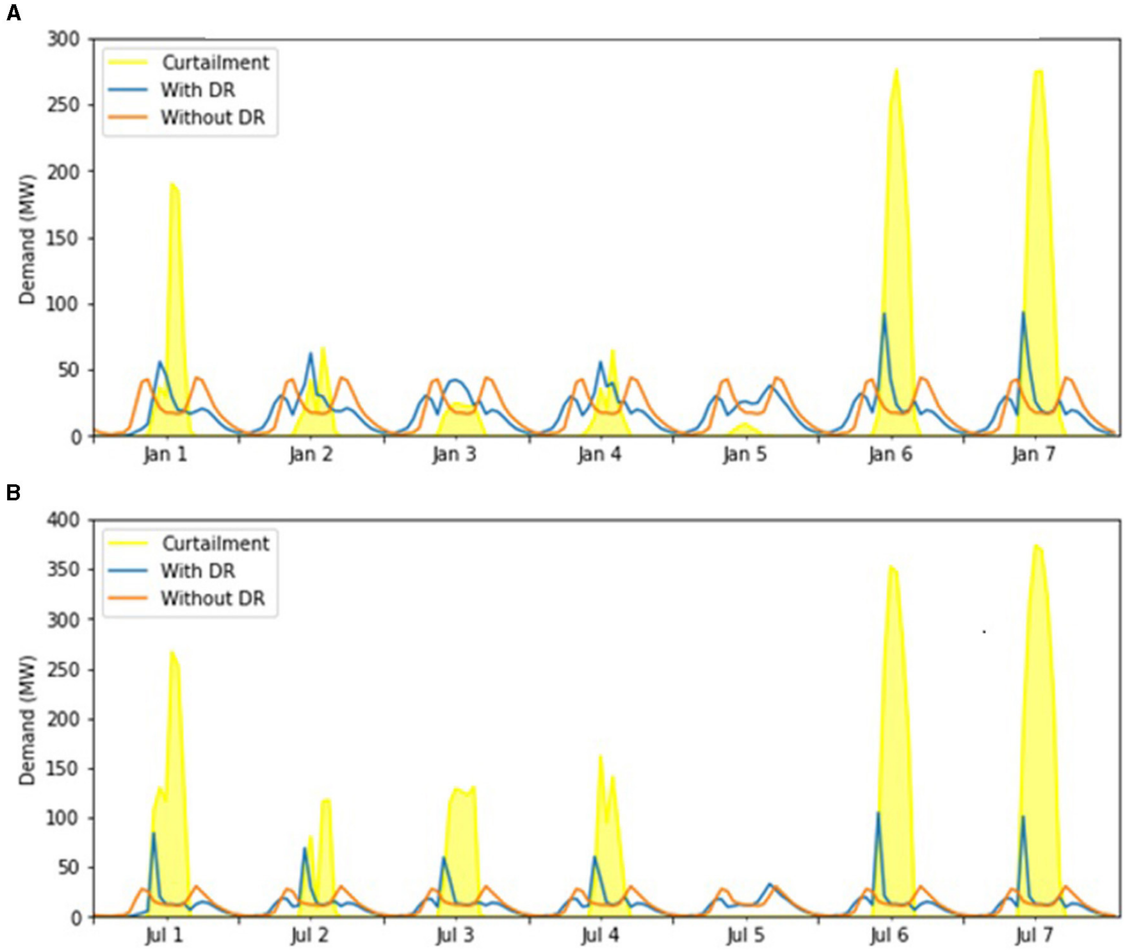

FIGURE 11 | Time-shifting of EV demand load due to curtailment within Scenario 3B in the **(A)** winter (top) and **(B)** summer (bottom).

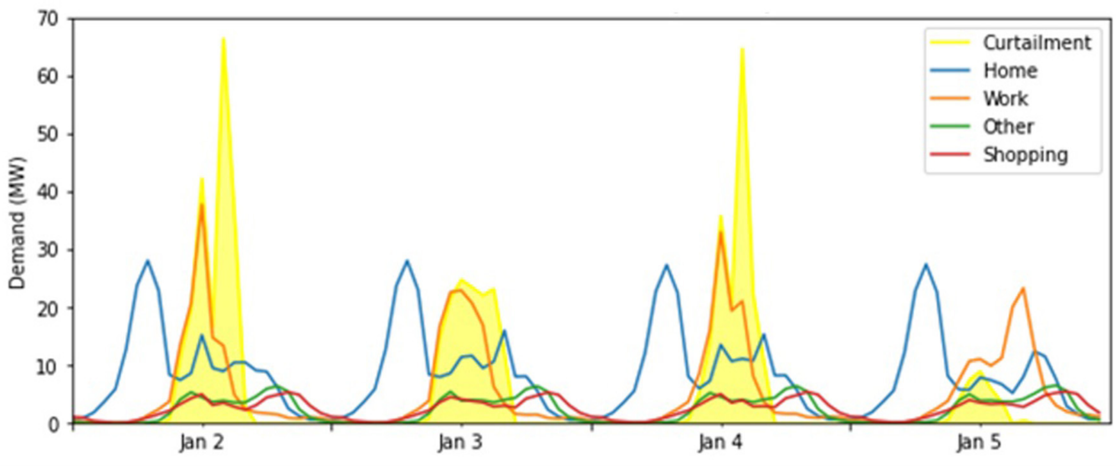

FIGURE 12 | Time-shifting of EV demand load due to curtailment within Scenario 3B disaggregated by trip activity for select dates with low curtailment in the winter.

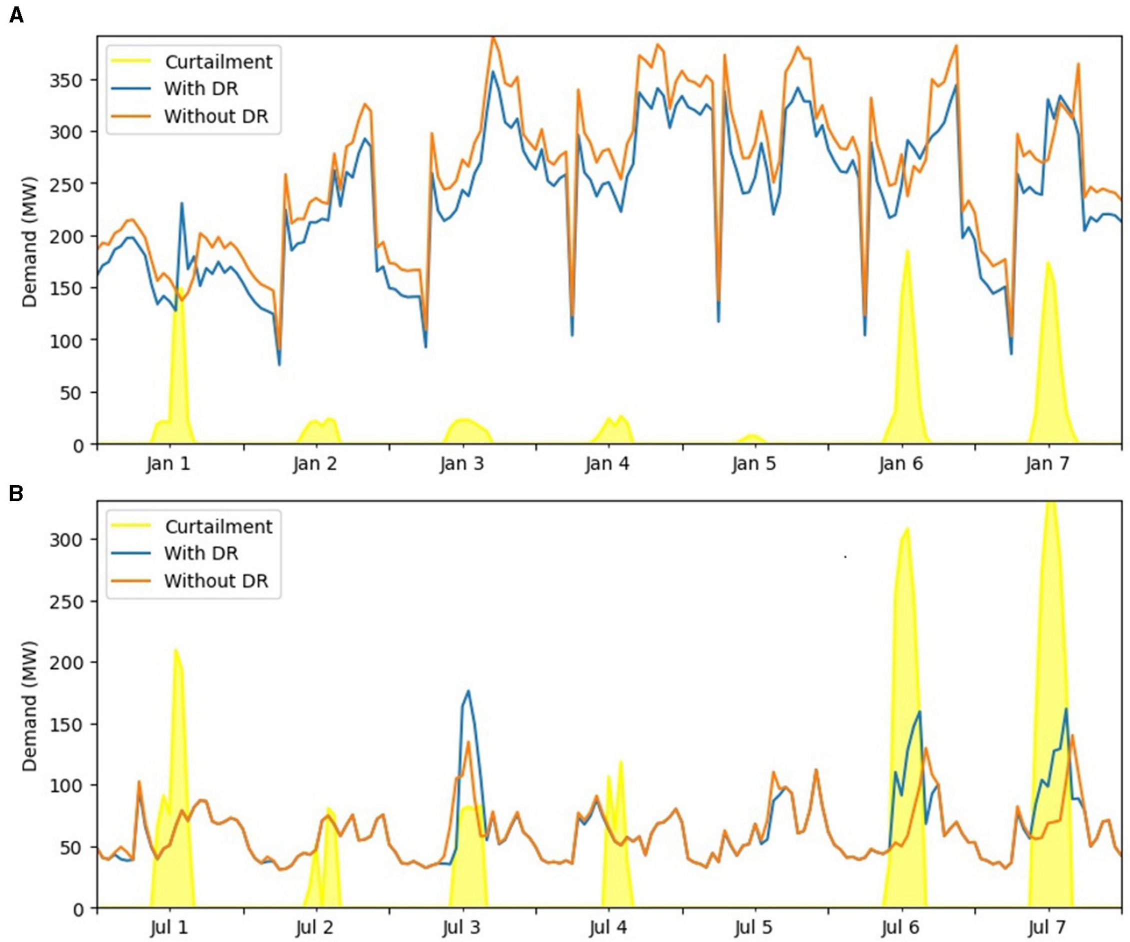

FIGURE 13 | Time-shifting of building demand load due to curtailment within Scenario 3B in the **(A)** winter (top) and **(B)** summer (bottom).

Both these options would be viable and realistic ways to decrease the cost of integrating large-scale renewables.

DISCUSSION

The integrated model platform developed was used to investigate the feasibility of electrifying private vehicles and homes to run on renewable energy from a system operation perspective. With the high spatial and temporal resolution of the operational perspective, the feasibility of future planning decisions can be evaluated, and insights from the operational model can be used to inform planning in the building, transportation, and electricity sectors.

Though it was shown that DR within the transportation and residential buildings sectors only slightly reduces curtailment levels (1–3%), they are comparable to results within other literature. On the transportation side, though it was not quantified, Wolinetz et al. (2018) found that utility-controlled charging of EVs alone may not be effective for integrating additional VRE into the generation mix. However, the authors only simulated capacity additions to the electricity system that would not result in excess VRE generation, while this analysis assumed fixed VRE capacity. In the building sector, Pedersen et al. (2017) noted that thermal DR strategies could shift roughly 30–47% of peak residential building load in a cold climate. This is consistent with the Stage B results showing 11–60% of peak load was reduced in winter curtailment events.

This analysis found that electrification and renewable energy integration could not meet Regina's target without adding a significant amount of energy storage. Two hundred and fifty MW could fully power Regina with renewable energy in the fully electrified scenario. While this level of storage is technically feasible, the scale is more consistent with utility-scale energy storage projects such as Sir Adam Beck Pump Generating Station (174 MW) (OPG, 2021) and Hornsdale Power Reserve (150 MW) (Hornsdale Power Reserve, 2021). These projects serve entire provinces, which may raise the question of whether such a large-scale storage system is reasonable for a single city. Nonetheless, Solomon et al. (2017) found that to integrate large-scale VRE into an electricity system, the optimal storage size is roughly equivalent to the daily average demand. Comparing storage size found within the scenarios to winter daily average demand shows that storage sizing is in line with these results, though it is over-sized in relation to summer demand.

Though no possible with battery storage alone, the fact that there are higher curtailment levels in the summer, paired with higher electrified demand loads in the winter, indicate that long-duration electricity storage may be beneficial in creating more reasonably sized storage systems (Albertus et al., 2020; Dowling et al., 2020). However, the logistics of this would prove complicated in regards to Regina specifically; the traditional long-duration electricity storage system is pumped hydro storage (PHS) (Albertus et al., 2020), though Regina is not located close enough to a major waterway to feasibly utilize PHS. This means that other long-duration electricity storage options would need to be considered [such as power-to-gas-to-power (Dowling et al., 2020)], or construct it where SaskPower grid resources would be needed to reach it. As SaskPower currently does not have any utility-scale storage technology on its grid (SaskPower, 2021), this option may not be feasible for Regina in the near future, though should be kept in mind for a time when long-duration storage plants are more accessible.

A possible alternative or complement to energy storage is exporting excess VRE to the provincial grid; this would allow for the City of Regina to act as a net generator at specific times of the day and create a revenue stream through the sale of excess electricity. This could contribute to Regina's target as a "renewable credit" to offset any non-renewable generation utilized. This option may be necessary if Regina's renewable target is at odds with the provincial utility grid's capacity expansion plan, resulting in Regina's generation mix being less carbon-intensive than the provincial mix. Adding capacity at a provincial-scale would be less expensive due to economies of scale but adding them at a city-scale may be required if the province and city have opposing views on renewable generation. Other options such as the use of renewable natural gas in the building sector and clean fuel standards in the transport sector may play a role in the energy future of Regina (Government of Canada, 2017). The latter is explored in more detail in the suggested further research.

Current Limitations

This study has limitations within the results presented, the linkage architecture, as well as in the individual models. Firstly, LCOE results are only indicative of electricity and do not consider the cost benefits of offsetting gasoline and natural gas use in transportation and building sectors. Excluding these cost benefits would have over-reported the relative costs of meeting Regina's renewable target.

Currently the integrated model platform is unable to model either the electrified load or the DR capabilities of commercial and industrial sectors. This may have resulted in an under-representation of the effectiveness of DR. However, an area of inconsistency is that rooftop solar was assumed to be installed on commercial and industrial buildings in addition to residential.

Based on how the curtailment values are passed to the building and transportation models, the time-shifting of loads in DR adjustments may, with certain configurations, create new periods of curtailment. Though this did not occur within the scenarios analyzed, it can be addressed in future scenario configurations by changing the types of data passed from the electricity system model to the transportation and building models.

Finally, a limitation to the scenarios considered was that that they do not aim to capture the long-term planning and evolution of any of the systems modeled. Instead, the scenarios aimed to capture a snapshot of the system as it could optimally operate. This means that the degradation and replacement of equipment (EV batteries, HVAC equipment, etc.) was not considered within any costs or associated emissions.

A limitation of the transportation model is that it does not include a traffic assignment step. This may have affected the accuracy of travel and activity scheduling, resulting in different EV charging patterns. Similarly, the assumption that travel patterns of EV drivers are the same as non-EV drivers may limit accuracy of results. Further exploration of different charging strategies, including not charging at every activity, could improve the potential for utility-controlled charging to improve the use of VRE in EV charging.

As previously discussed, the archetype-based approach to constructing the building model under-represents the diversity actually seen in the building stock, which may lead to the model predicting higher peaks, lower troughs, and more fluctuations in the building load than would be observed in real life.

The electricity system model is assumed to import electricity from the provincial grid when it is unable to meet demand from local generation assets, but the hourly generation mix of the provincial grid may change if Regina is able to supply a significant amount of their peak demand. A linkage between a provincial electricity system model and a city-scale electricity system model would allow for these changes to be explored in more detail.

Suggested Further Research

This study developed a baseline for evaluating Regina's ability to meet their Scope 3 renewable target through various pathways, but there is still potential for future research. Some suggestions can be seen below:

- As previously mentioned, the exploration of meeting the Scope 3 renewable target through renewable energy sources other than electrification can be done in conjunction with the 50% electrification scenarios evaluated. This may include increased demand side management strategies to reduce overall energy usage, as well as the introduction of renewable fuels into the transportation and building sectors.
- Further analyzing the ability of Regina to meet the Scope 3 renewable target may involve electrifying commercial and industrial buildings, as well as electrification of commercial transportation.
- As mentioned, the system was analyzed as it currently exists. Connecting this work to a capacity expansion model would give the justification to explore scenarios that have drastically different system configurations to meet energy targets.
- Finally, on the economic side, there are several avenues to be explored pertaining to rooftop solar panels or wind farm ownership. This may include, but not be limited to, city

ownership; resident ownership (referring to rooftop solar panels) with or without net metering; or a combination of the two.

CONCLUSIONS

Several conclusions can be drawn from this exploration of the feasibility of Regina's energy target, ranging from immediately actionable results, to results that indicate further research is needed to fully understand what the impacts will be on the electricity system. The impacts of this study have a wide-range of applications within Regina, as well as the potential to be leveraged by other cities with similar VRE resources and/or are currently drawing electricity from a high-emitting grid.

It is feasible for Regina to meet Scope 3 of their renewable energy target, by considering electrification of private vehicles and households and integrating VRE.

Results from the integrated model platform show that Scope 3 of Regina's renewable energy target can be achieved through large-scale implementation of VRE capacity and storage technology. By adding 100% rooftop solar on residential, commercial, and industrial rooftops (equal to 1,410 MW of solar capacity), 100 MW of wind capacity, and 250 MW of storage, 95% of Regina's electricity demand could be met with renewable energy, even with 100% electrification of private vehicles and thermal residential building load.

Meeting the renewable target will slightly increase LCOE, but this does not capture savings from fuel switching.

Though some scenarios have comparable costs to the current system, there would still be an overall increase (15–50% cost increase across Stage C results) in the net cost of operating the electricity system. That given, scenarios with higher VRE and storage implementation had lower costs than those with lower VRE integration, indicating that it is more economical to commit to large-scale penetration strategies. Additionally, there is significant potential for further reduction in costs of scenarios that can meet Regina's renewable target through switching from rooftop solar to utility-scale solar, as well as increasing the wind capacity.

The addition of storage capacity was necessary when utilizing utility-controlled DR to reduce curtailment.

In lower VRE penetration scenarios, DR can help reduce curtailment to acceptable amounts, though this is due to the lower initial curtailment values (27 to 24% in Scenario 4). In higher VRE penetration scenarios, DR does not meaningfully reduce curtailment, making energy storage necessary to reduce curtailment and meet Regina's target. As the current demand trends exist within the building and transportation sectors, it is unlikely that the implementation of DR strategies alone would allow Regina to meet their target.

Implementing DR for EVs hinges on adequate charging infrastructure at work locations.

Particularly in scenarios with a significant amount of solar energy, charging at work is found to experience the greatest shift when DR is implemented. This indicates that many vehicles in Regina are parked at work when solar curtailment occurs. DR with large amounts of wind energy, which is less predictable, could potentially be implemented through charging infrastructure at home.

For buildings, utility-controlled thermal load shifting does not have a large impact on overall curtailment reduction.

Building thermal DR is found to be largely ineffective in the summer due to the low cooling load of Regina. In the winter, although clear differences can be seen before and after the implementation of DR, these changes are small compared to the total building load. This indicates a need for more comprehensive DR strategies that include additional loads such as water heating, appliances, or lighting.

DATA AVAILABILITY STATEMENT

The datasets presented in this article are not readily available. Most data is available upon request, but electricity demand data was acquired with an NDA and is unable to be distributed. Requests to access the datasets should be directed to SaskPower.

AUTHOR CONTRIBUTIONS

MS, LS, and RX completed the modeling work and wrote the first draft of the manuscript. MS performed final analysis of results. MM revised the manuscript. All authors contributed to conception and design of the study, and read and approved the submitted version.

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/frsc.2021.674848/full#supplementary-material

REFERENCES

Alberta Electric System Operator (2019). *AESO Operating Reserves Program*. Available online at: https://www.enelx.com/n-a/en/faq/eindustry/aeso-operating-reserves-program (accessed January 13, 2021).

Albertus, P., Manser, J. S., and Litzelman, S. (2020). Long-duration electricity storage applications, economics, and technologies. *Joule* 4, 21–32. doi: 10.1016/j.joule.2019.11.009

Ballarini, I., Corgnati, S. P., and Corrado, V. (2014). Use of reference buildings to assess the energy saving potentials of the residential building stock: the experience of TABULA project. *Energy Policy* 68, 273–284. doi: 10.1016/j.enpol.2014.01.027

Bardutz, E., and Dolter, B. (2020). *Regina's 100% Renewable Energy Target: Survey Results Measuring Support for the Target and Related Actions. Technical Report*. University of Regina.

Canada Energy Regulator (2020a). *CER Provincial and Territorial Energy Profiles - Saskatchewan*. Available online at: https://www.cer-rec.gc.ca/en/data-analysis/energy-markets/provincial-territorial-energy-profiles/provincial-territorial-energy-profiles-saskatchewan.html (accessed March 17, 2021).

Canada Energy Regulator (2020b). *NEB Canadas Renewable Power Landscape 2017 Energy Market Analysis*. Available online at: https://www.cer-rec.gc.ca/en/data-analysis/energy-commodities/electricity/report/2017-canadian-renewable-power/canadas-renewable-power-landscape-2017-energy-market-analysis-ghg-emission.html (accessed September 29, 2020).

City of Regina (2017). *Transit Network*. Available online at: http://open.regina.ca/dataset/transit-network (accessed May 4, 2017).

Crockett, D., Herbert, Y., de Jager, M., Hoffman, M., Hoffman, R., Murphy, J., et al. (2019). *Modelling Urban Climate Mitigation in Canadian Municipalities*.

Deane, J. P., Gracceva, F., Chiodi, A., Gargiulo, M., and Gallachir, B. (2015). "Soft-linking exercises between TIMES, power system models and housing stock models," in *Informing Energy and Climate Policies Using Energy Systems Models: Insights from Scenario Analysis Increasing the Evidence Base, Lecture Notes in Energy*, eds G. Giannakidis, M. Labriet, B. Gallachir, and G. Tosato (Cham: Springer International Publishing), 315–331. doi: 10.1007/978-3-319-16540-0_18

Dennis, K. (2015). Environmentally beneficial electrification: electricity as the end-use option. *Electricity J.* 28, 100–112. doi: 10.1016/j.tej.2015.09.019

Dowling, J. A., Rinaldi, K. Z., Ruggles, T. H., Davis, S. J., Yuan, M., Tong, F., et al. (2020). Role of long-duration energy storage in variable renewable electricity systems. *Joule* 4, 1907–1928. doi: 10.1016/j.joule.2020.07.007

Eaton, E., and Enoch, S. (2020). *Renewable Regina Putting Equity into Action. Technical Report*. Available online at: https://www.policyalternatives.ca/sites/default/files/uploads/publications/Saskatchewan%20Office/2020/09/Renewable%20Regina%20Report.pdf

Environment Canada (2020). *Regina, SK - 7 Day Forecast - Environment Canada*. Available online at: https://weather.gc.ca/city/pages/sk-32_metric_e.html (accessed February 10, 2021).

Environment and Climate Change Canada (2015). *Canadian Weather Energy and Engineering Datasets (CWEEDS) v_2016*.

Geotab (2021). *Temperature Tool for EV Range*. Available online at: https://www.geotab.com/fleet-management-solutions/ev-temperature-tool/ (accessed January 28, 2021).

Global Wind Atlas (2019). Canada Wind Speed at 100 meters. Available online at: https://globalwindatlas.info (accessed February 8, 2021).

Government of Canada (2017). *National Energy Use Database*. Available online at: https://oee.nrcan.gc.ca/corporate/statistics/neud/dpa/data_e/databases.cfm#wb-info (accessed April 12, 2015).

Government of Canada, Natural Resources Canada, and Federal Geospatial Platform (2020). *Photovoltaic Potential and Solar Resource Maps of Canada*. Natural Resources Canada.

Holy Cross Energy (2016). *Distribution Flexibility Program*. Availablee online at: http://www.holycross.com/programs-overview/ (accessed January 13, 2021).

HOMER Energy (2021). *HOMER - Hybrid Renewable and Distributed Generation System Design Software*. Available online at: https://www.homerenergy.com/index.html (accessed January 22, 2021).

Hornsdale Power Reserve (2021). *Hornsdale Power Reserve | South Australia's Big Battery*. Available online at: https://hornsdalepowerreserve.com.au/ (accessed February 27, 2021).

Hydro-Québec (2020). *Addenda: Electricity Rates 2019*. Available online at: https://www.hydroquebec.com/data/documents-donnees/pdf/addenda-tarifs-electricite-decembre-2020-en.pdf (accessed February 28, 2021).

International Renewable Energy Agency (2020). *Hydropower*. Available online at: https://www.irena.org/costs/Power-Generation-Costs/Hydropower (accessed February 19, 2021).

Latif, Z. A., Zaki, N. A. M., and Salleh, S. A. (2012). "GIS-based estimation of rooftop solar photovoltaic potential using LiDAR," in *2012 IEEE 8th International Colloquium on Signal Processing and its Applications* (Malacca: IEEE), 388–392. doi: 10.1109/CSPA.2012.6194755

Lazard (2020). *Levelized Cost of Energy and of Storage*.

Masters, G. M. (2004). *Renewable and Efficient Electric Power Systems*. Hoboken, NJ: John Wiley & Sons. doi: 10.1002/0471668826

Mathiesen, B. V., Lund, H., Connolly, D., Wenzel, H., Stergaard, P. A., Mller, B., et al. (2015). Smart energy systems for coherent 100% renewable energy and transport solutions. *Appl. Energy* 145, 139–154. doi: 10.1016/j.apenergy.2015.01.075

McPherson, M., Ismail, M., Hoornweg, D., and Metcalfe, M. (2018). Planning for variable renewable energy and electric vehicle integration under varying degrees of decentralization: a case study in Lusaka, Zambia. *Energy* 151, 332–346. doi: 10.1016/j.energy.2018.03.073

McPherson, M., and Karney, B. (2017). A scenario based approach to designing electricity grids with high variable renewable energy penetrations in Ontario, Canada: development and application of the SILVER model. *Energy* 138, 185–196. doi: 10.1016/j.energy.2017.07.027

McPherson, M., Sotiropoulos-Michalakakos, T., Harvey, L., and Karney, B. (2017). An open-access web-based tool to access global, hourly wind and solar PV generation time-series derived from the MERRA reanalysis dataset. *Energies* 10:1007. doi: 10.3390/en10071007

McPherson, M., and Stoll, B. (2020). Demand response for variable renewable energy integration: a proposed approach and its impacts. *Energy* 197:117205. doi: 10.1016/j.energy.2020.117205

Miller, E. J., and Roorda, M. J. (2003). Prototype model of household activity-travel scheduling. *Transport. Res. Record* 1831, 114–121. doi: 10.3141/1831-13

Miller, E. J., Vaughan, J., King, D., and Austin, M. (2015). "Implementation of a next generation activity-based travel demand model: the Toronto case," in *2015 Conference of the Transportation Association of Canada* (Charlottetown).

Natural Resources Canada (2019). *Energy Fact Book 2019 - 2020*. Available online at: https://www.nrcan.gc.ca/sites/www.nrcan.gc.ca/files/energy/pdf/EnergyFactBook_2019_2020_web-resolution.pdf

Natural Resources Canada (2020). *High Resolution Digital Elevation Model (HRDEM) - CanElevation Series - Open Government Portal*. Available online at: https://open.canada.ca/data/en/dataset/957782bf-847c-4644-a757-e383c0057995 (accessed January 2, 2021).

Ontario Energy Board (2021). *Managing Costs With Time-of-Use Rates*. Available online at: https://www.oeb.ca/rates-and-your-bill/electricity-rates/managing-costs-time-use-rates (accessed January 13, 2021).

OPG (2021). *Niagara Pump Generating Station Reservoir*. Available online at: https://www.opg.com/strengthening-the-economy/our-projects/niagara-pump-reservoir/

Pedersen, T. H., Hedegaard, R. E., and Petersen, S. (2017). Space heating demand response potential of retrofitted residential apartment blocks. *Energy Build.* 141, 158–166. doi: 10.1016/j.enbuild.2017.02.035

Peterson, J. (2020). Regina administration to revisit renewable energy plan once more in September. *CBC News*.

Regina City Council (2020). *CITY COUNCIL*. Available online at: http://reginask.iqm2.com/Citizens/FileOpen.aspx?Type=1&ID=4136&Inline=True (accessed February 10, 2021).

Reinhart, C., and Davila, C. C. (2019). Urban building energy modeling. *Build. Perform. Simul. Des. Opera.* 696–722.

Robinson, S. (2018). *British Columbia Building Code*. Available online at: https://energystepcode.ca/ (accessed October 1, 2021).

Salama, M., Gaouda, A., and Nassar, M. E. (2019). *A Cluster-Based load Model for a Resilient and Sustainable Community. Technical Report* (QualSys Engco Inc.)

SaskPower (2018). *Potentia Renewables to Build 200 Megawatt Wind Power Facility Near Assiniboia*. Available online at: https://www.saskpower.com/about-us/media-information/news-releases/potentia-renewables-to-build-200-megawatt-wind-power-facility-near-assiniboia (accessed January 4, 2021).

SaskPower (2019). *Demand Response Program*. Available online at: https://www.saskpower.com/efficiency-programs-and-tips/saving-power-at-work/savings-programs/business-programs/demand-response-program

SaskPower (2021). *System Map*. Available online at: https://www.saskpower.com/Our-Power-Future/Our-Electricity/Electrical-System/System-Map (accessed February 28, 2021).

Solar Calculator (2020). *Solar Panel System Size Calculator*. Available online at: https://solarcalculator.com.au/solar-system-size/ (accessed January 4, 2021).

Solomon, A. A., Child, M., Caldera, U., and Breyer, C. (2017). How much energy storage is needed to incorporate very large intermittent renewables? *Energy Procedia* 135, 283–293. doi: 10.1016/j.egypro.2017.09.520

Statistics Canada (2017). *Census Profile, 2016 Census - Toronto [Census metropolitan area], Ontario and Regina, City [Census subdivision], Saskatchewan*. Available online at: https://www12.statcan.gc.ca/census-recensement/2016/dp-pd/prof/details/page.cfm?Lang=E&Geo1=CMACA&Code1=705&Geo2=PR&Code2=47&Data=Count&SearchText=Regina&SearchType=Begins&SearchPR=01&B1=All (accessed June 18, 2019).

Swan, L. G., and Ugursal, V. I. (2009). Modeling of end-use energy consumption in the residential sector: A review of modeling techniques. *Renew. Sustain. Energy Rev.* 13, 1819–1835. doi: 10.1016/j.rser.2008.09.033

Szinai, J., Sheppard, C., Abhyankar, N., and Gopal, A. (2020). Reduced grid operating costs and renewable energy curtailment with electric vehicle charge management. *Energy Policy* 136:111051. doi: 10.1016/j.enpol.2019.111051

Tasker, J. P. (2020). Ottawa to hike federal carbon tax to $170 a tonne by 2030. *CBC News*. Available online at: https://www.cbc.ca/news/politics/carbon-tax-hike-new-climate-plan-1.5837709 (accessed December 12, 2020).

Tink, C., and Folk, L. (2019). *PPC19-4 Energy and Sustainability Framework - City of Regina, Saskatchewan CA*. Available online at: http://reginask.iqm2.com/Citizens/Detail_LegiFile.aspx?Frame=&MeetingID=4593&MediaPosition=&ID=4218&CssClass= (accessed January 2, 2021).

Travel Modelling Group (2020). *GTAModel V4.0 Introduction*. Available online at: https://tmg.utoronto.ca/doc/1.4/gtamodel/index.html (accessed February 28, 2021).

Vaillancourt, K., Alcocer, Y., Bahn, O., Fertel, C., Frenette, E., Garbouj, H., et al. (2014). A Canadian 2050 energy outlook: analysis with the multi-regional model TIMES-Canada. *Appl. Energy* 132, 56–65. doi: 10.1016/j.apenergy.2014.06.072

Wolinetz, M., Axsen, J., Peters, J., and Crawford, C. (2018). Simulating the value of electric-vehiclegrid integration using a behaviourally realistic model. *Nat. Energy* 3, 132–139. doi: 10.1038/s41560-017-0077-9

Zuehlke, B. (2017). *Vancouver's Renewable City Strategy: Economic and Policy Analysis*. 98.

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