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Co-creating innovative climate policy frameworks for urban decarbonization: high school engagement in carbon pricing

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Introduction: Urban energy transition requires innovative approaches that make key climate policy tools, such as carbon pricing, actionable and understandable for younger populations and local communities. This study addresses how the co-development of carbon pricing processes in secondary schools can promote CO₂ emissions reduction and students' awareness of their role as agents of change in the community.

Methods: An action research-based case study conducted in a Portuguese public high school with a group of 10th and 11th-grade students, combining a participatory and experiential learning methodology. A participatory action research methodology was applied as the analytical framework. Data collection included quantitative and qualitative surveys and digital logs.

Results: Within the group, 31% lowered emissions and 7% reported zero emissions by walking, while co-developing a simulation of a carbon pricing mechanism. Students collaborated in assigning an economic value by finding a cost factor based on their experiential learning for the avoided emissions achieved.

Discussion: The approach fostered students' understanding of carbon pricing while driving measurable reductions in behavior change through commuting-related emission: The students co-created a simplified, context-based model of carbon pricing, reinforcing pro-environmental behavior and offering a model that can inform local climate policy and sustainability goals. The method provides a potential transferable framework for integrating advanced climate policy tools into educational practice.

KEYWORDS

climate policy, urban decarbonization, high school, carbon pricing, climate change education, local community, school commuting

1 Introduction

Climate change education or climate action education, as its evolving action-focused expression (Alméstær et al., 2022) is increasingly recognized as a critical factor in schooling that addresses the impacts of climate change and engages students and teachers as agents of social change through behavioral change, mitigation, adaptation, and collective action, focusing on preparing young people to respond to climate crisis (Lenton et al., 2022; Otto et al., 2020).

The notable contribution of (Otto et al., 2020) research on social tipping dynamics and actionable concepts for climate action identifies the education system as one of six areas of the planetary socioeconomic system with unique potential to accelerate social and technological transformation toward a carbon-neutral global society by 2050, including energy production systems, cities, financial markets, norm systems, and information transparency. Within the education system, the intervention identified was “strengthening climate education and engagement”.

Milkoreit et al. (2018) define social tipping point as where a small quantitative shift in a social-ecological system triggers, through positive feedback mechanisms, a nonlinear and often irreversible shift in the social part of the system, leading it to a qualitatively different state.

Article 6 of the 1992 United Nations Framework Convention on Climate Change (UNFCCC), the 2009 Climate Change Initiative of the United Nations Educational, Scientific and Cultural Organization (UNESCO) and its most recent policy documents (UNESCO, 2022), the 2015 Paris Agreement, the 2030 Sustainable Development Goals (SDG) Agenda, and the World Bank (Sabarwal et al., 2024; Teixeira and Crawford, 2022) emphasize the growing importance of climate change education. Emerging from education for sustainable development, climate change education promotes innovative perspectives on climate action adapted to local needs across all education levels and integrated into their very diverse curricula (R. B. Stevenson et al., 2017).

Experiential learning is an important approach in climate education, especially in science education and sustainability (Gaffney and O’Neil, 2019; Zhang et al., 2023). Hands-on experience and real-world applications enhance students’ understanding of climate change concepts and promote environmental awareness (Guerra et al., 2022; Ridwan et al., 2023; Sharma, 2017; Siegner, 2018). Various studies have shown that experiential learning can successfully develop awareness and encourage critical thinking regarding climate change.

However, progress in national governments’ attention toward education for climate remains slow (Sabarwal et al., 2024; UNESCO, 2021). The Nationally Determined Contributions (NDC), which represent each country commitments under the Paris Agreement, still do not fully reflect the importance of climate change education in terms of awareness, inclusion, climate justice, system strengthening, and quality, despite the political importance given to youth.

Internal policies have also failed to highlight this issue, and progress in adopting national laws or strategies for climate change education has been slow (Antoninis et al., 2020). In other words, climate change education has not yet become a political priority (McKenzie et al., 2024; UN, 2022). Meanwhile, young people are staging climate strikes, demanding carbon taxes on greenhouse gas emissions and suing governments and corporations. Therefore, a gap exists between school learning outcomes and young people’s expectations and needs.

Carbon pricing, which includes carbon taxes and other instruments such as emissions trading systems, is considered a central tool in policy for reducing GHG emissions and achieving climate goals (Baranzini et al., 2017). The carbon market, as a credit mechanism derived from sustainable investment, whether

governmental or not, must meet a set of criteria to generate market tradable credits.

Traditional climate policy focuses on system-level changes and technological solutions based on the polluter-pays principle, while paying less attention to the micro-level mechanisms of behavioral change. However, collaborative processes in urban environments and community-based can create new practices that allow for greater flexibility of the rules and institutional rigidity (Alméstár et al., 2025; Alméstár, Romero-Muñoz, et al., 2025).

In theory, carbon pricing is an effective tool for reducing GHG emissions and meeting climate goals. In practice, its global adoption falls short of the Paris Agreement targets for both coverage and pricing (World Bank, 2024). Governments prioritize the industrial, energy, transport, and building sectors, directly shaping corporate behavior, and in turn, consumers.

Research on the measurable effects of carbon pricing on reducing greenhouse gas emissions has mostly used macrodata aggregation, producing varied results (Döbbling-Hildebrandt et al., 2024; Green, 2021; Rafaty et al., 2020; Vrolijk and Sato, 2023). Household consumption and behavior are comparatively understudied (Clarke, 2023; Erutku and Hildebrand, 2018). Carbon pricing directly impacts families through fuel consumption and energy sources and indirectly through non-energy goods and services. Emission reductions from demand responses are moderate and driven more by substitution than by decreased consumption.

Carbon pricing is too complex to understand and test across diverse climate-policy frontiers for energy transition (Stoll and Mehling, 2021). We argue that understanding its mechanics is crucial for preparing future climate leaders, as it is important to develop fair carbon pricing solutions that citizens can accept politically (Klenert et al., 2018; Valencia et al., 2024) and school plays a critical role for that.

Schools serve the foundation of education and knowledge dissemination for current and future generations rooted in their local context. They uniquely equipped students with the knowledge and experimentation needed to tackle climate change.

A school is also a community hub as it connects and attracts other communities, including parents, educational and community services, and cross-sector partnerships (Cleveland, 2023; Cleveland et al., 2023). As local community, there is an increasing need for sustainable urban energy transition as climate risk and opportunities to take urgent climate action are concentrated in cities.

Decarbonization is a multifaceted concept for achieving net zero CO₂ emissions and focuses on transforming energy systems, addressing technological issues in industries and sectors, and addressing social issues in multiple dimensions of analysis and intervention. This has become a key concept in social science research on energy transition, with an increasing number of interdisciplinary studies (Rizzoli et al., 2021; Wimbadi and Djalante, 2020).

Carbon economics, which combines economics and environmental science, plays a critical role in providing mechanisms for reducing greenhouse gas emissions and transitioning toward a low-carbon future. While universities have included carbon pricing in their climate change education programs and operations, secondary education has seldom addressed this topic over the past decade. Making carbon economics more

understandable and accessible to secondary school students, who are already advocating carbon taxes, could greatly enhance education and foster informed citizens and decision-makers (Osborne and Pimentel, 2023).

Although research has emphasized the role of schools in tackling climate change and promoting sustainability, there have been limited investigations into how schools can make education in carbon economics more actionable. This study addresses this gap in climate education research by analyzing a secondary school intervention in which students collaboratively designed a carbon pricing mechanism simulation as a hands-on solution, linking the school to the city's climate action. Initiatives that introduce climate-economic mechanisms into educational settings serve as laboratories to enhance learning, engagement, and participation. To the best of our knowledge, this is the first study to apply carbon economics concepts to climate change education at the secondary level by integrating theory and practice.

This approach provides an opportunity to study key aspects of energy transition, facilitate effective climate change education action, and serve as a tool to assess the complexities of climate change while accelerating decarbonization at the local community level.

The paper is guided by the research question:

“How can the co-development of carbon pricing processes in secondary schools promote CO₂ emissions reduction while fostering students' awareness of their roles as community agents contributing to low-carbon cities?”

This study introduces a co-development model for a carbon-pricing mechanism aimed at reducing carbon emissions from secondary school commutes. It serves as an educational tool for climate empowerment and facilitates community engagement in the city's climate. The initiative took place between November 2022 and November 2023 at João Gonçalves Zarco Public Secondary School in Matosinhos, Portugal. A group of 69 students and three teachers collaborated to develop a carbon pricing initiative to encourage CO₂ emissions reduction among students and staff.

Section 2 presents a thematic literature review to provide the context and the rationale for the research, followed in Section 3 by the description of materials and methods applied. The results and discussion are presented in Section 4, and the conclusions in Section 5.

In this article CO₂, carbon and GHG (greenhouse gases) are used interchangeably, with all terms referring to greenhouse gases.

2 Thematic literature review

2.1 Climate change education

Climate change education is a relatively new field compared to established areas such as education for sustainable development, environmental education, and science education. It primarily utilizes empirical methods to deepen understanding (Bhattacharya et al., 2021a; 2021b; Kumar et al., 2023; Nepraš et al., 2022). However, theoretical research on climate change education remains insufficient (Rousell and Cutter-Mackenzie-

Knowles, 2019; Sato and Kitamura, 2023). There is also a lack of representation of low-income countries and those most affected by climate change, which are often marginalized in this research (Apollo and Mbah, 2021; Guerra et al., 2023; Rousell & Cutter-Mackenzie-Knowles, 2019).

Bhattacharya et al. (2021b); Jorgenson et al. (2019) and Monroe et al. (2017) found frequent ineffectiveness in the climate change education models used, which tended to focus heavily on scientific knowledge of climate change. Multidimensional and participatory approaches are required to integrate (Schmidt et al., 2011; Wals, 2011) bottom-up, top-down, and scientific dimensions with the social, ethical, political, and economic dimensions of global climate change.

Monroe et al. (2017) found that effective climate change education strategies focused on personally relevant and meaningful information. They use active and engaging teaching methods, such as experiential learning, and emphasize the need for deliberative discussions, interaction with scientists, addressing misconceptions, and implementing school or community projects, regardless of the intervention's duration or context. Successful interventions often consider the local impacts of climate change on community life (Cincera et al., 2019; Hu and Chen, 2016; Kagawa and Selby, 2010; Khadka et al., 2021). Students deepen their understanding of climate change when they use evidence and data-driven models to conduct experiments (Schmidt et al., 2014).

Moreover, both teachers and students can have a good understanding of climate change and be aware that human action is a significant contributing factor (K. J. Ahmed et al., 2021). School and community projects allow learners to engage with issues on a manageable scale, enabling them to discuss and take action (J. J. Lee et al., 2013; Pruneau et al., 2003).

In addition to the need for a systemic and comprehensive evaluation of all aspects of climate change education programs, the practical and solution-oriented nature of climate change education makes behavior central. Various studies have shown that knowledge is important but not sufficient for behavioral change (Hohenhaus et al., 2023; Kranz et al., 2022; Rousell and Cutter-Mackenzie-Knowles, 2019; Stern, 2000; K. T. Stevenson et al., 2018) and effective climate change education should aim to bridge the attitude-behavior gap (Howard-Jones et al., 2023; Tang, 2022; Wynes and Nicholas, 2017), 2023; Tang, 2022; Wynes and Nicholas, 2017).

Hohenhaus et al.'s (2023) review of 48 articles identified several factors that contribute to successful behavioral change in youth beyond knowledge, such as social environment, location, leadership development, goal setting, identity agency, action competence, systems thinking, and internal factors of self-efficacy.

Bandura (1986) pioneer research on internal factors of self-efficacy, also on education and youth, identified four factors as the individual's belief in his own performing capability: mastery experiences (previous task successes), observational learning (social modeling), verbal persuasion (social encouragement), and physiological and emotional states (such as stress and anxiety).

While all educational levels are important in climate change education, the learning characteristics of upper secondary school students respond significantly to experiential climate change education initiatives (Lausselet and Zosso, 2022). identified

reflexivity, commitment, environmental communication, and networking with societal actors regarding environment, agency, and performative bonds. Recent research increasingly focuses on the relationship between secondary school students and climate and environmental issues, examining the evolution of their knowledge, attitudes and behaviors (Olsson et al., 2019) and the creation of advanced tools for an integrated investigation perspective (Gao and Jiang, 2024).

Climate action education is a concept emerging from recent research on practical strategies for scaling up climate action education programs and strengthening the collective efficacy of processes, through which schools and their environments can serve as facilitators of sustainable urban transformation (Alm  star et al., 2022).

The current push for effective climate education is still rooted in John Dewey's pragmatism (Dewey, 1963) which emphasizes the importance of real-life experiences, experimentation, and active student participation in learning. Dewey believed that schools should provide meaningful experiences that engage students' interests and emotions, encouraging them to reflect, analyze, and interpret to adapt their habits.

2.2 School as a community

The school community serves diverse functions that uniquely connect it to the city, with its carbon footprint originating from commuting, food consumption, energy use (heating and power), waste, and building infrastructure, all of which influence the city's decarbonization efforts.

Schools function as community hubs that engage various stakeholders including parents, educational institutions, community services, and cross-sector partnerships (Cleveland, 2023; Cleveland, Backhouse, et al., 2023). This challenges them to extend their roles beyond traditional academic functions and to be "more than a school" (Cleveland, Backhouse, et al., 2023). Dewey (1915), Dewey (1963) argued for an intrinsic link between schools and active community life, emphasizing that schools play a central role in helping young people understand the world, prepare for citizenship, promote connections between school homes, and provide experiential and interdisciplinary education (Miles et al., 2023). That is, being real "sustainability laboratories" (Schmidt et al., 2011).

School-community partnerships, which are collaborative arrangements among schools, families, and communities, typically focus on enhancing students' success by promoting intellectual, social, and emotional development. Research over recent decades indicates that these partnerships tend to be mutually beneficial, regardless of their model, which combines six key involvement practices: parenting, communication, volunteering, learning at home, decision-making, and community collaboration (Epstein, 1995; Epstein, 1987; Epstein and Connors, 1992; Sanders and Epstein, 2000).

As noted by Valli et al. (2016) school-community partnerships evolve into a typology of four categories. These range from school-centric models to sustainable models that promote parental and community engagement in a local context. These include (i) family and interagency collaboration, which involves coordinating services

and an expanded version of (ii) full-service schools. (iii) Full-service community schools encompass partnerships in which families and communities have a voice in decision-making. More ambitiously, (iv) community development involves transforming the relationship between schools and communities, which leads to interdependence. This transformation impacts both the school and the broader community as well as the interconnectedness of schools within the larger network of community infrastructure (Miles et al., 2023) as reflected in the increased use of cars on school trips and its impact on GHG emissions (Ergler and Smith, 2023).

School-community partnerships traditionally focus on enhancing student development; however, in the context of climate change, these partnerships can be redefined to include school engagement in the city, potentially benefiting both the school and the community.

The pressure on schools and for school-community partnerships to involve stakeholders in addressing real-world challenges within the local context (Bouillion and Gomez, 2001) offers an opportunity to explore how schools can extend transformative school-community partnerships and contribute to urban governance on climate change mitigation and adaptation (Capon et al., 2009; Ruiz-Mall  n et al., 2022; R. B. Stevenson et al., 2017).

Emissions from student commutes and school buildings contribute significantly to the carbon footprint of educational institutions (Fenner et al., 2020; Odell et al., 2020; Singleton, 2014). In this study, school communities were associated with a notable share of the city's commuting mobility and energy consumption (Pierce et al., 2024).

The urgent need to reduce GHG emissions by 2050 (Pathak et al., 2022) requires collaboration between local governments, communities, and stakeholders. Cities are increasingly transitioning from contributing to emissions to leaders in deploying solutions (Linton et al., 2022; Salvador Costa et al., 2022). Encouraging and involving local communities in cooperative processes through community-based initiatives can transform them into agents of change toward urban decarbonization (Urrutia-Azcona et al., 2020).

Recent research on holistic approach to climate change in schools converges with the priorities of Otto et al.'s (2020) social tipping dynamics by advocating for the integration of climate education throughout the education system to empower students for climate (Leite, 2024; Soubhari et al., 2024; Szczepankiewicz et al., 2021) with an interdisciplinary curriculum (Alexandru et al., 2013) combined with transformative learning (Leite, 2024) and experiential learning (Wilson, 2012) for engagement with real-life problems, community-based learning methods (Kroufek and Nepra  , 2023), mental health and wellbeing strategies (Newberry Le Vay et al., 2023), and nature-based solutions implemented in school settings (Ruiz-Mall  n et al., 2023)

2.3 Schools' carbon footprint

Early research on schools' carbon footprints, such as the UK's Strategic Approach to Schools' Footprint (Sustainable Development Commission, 2008) highlighted their impact on local communities as hubs.

The literature on schools' carbon footprint has essentially focused on case studies and frequently related with education for sustainable development programs. Engaged carbon footprint measurement, students develop the characteristics of change agents through knowledge acquisition to perform more informed choices and action and agency skills. They also identify transformations in learning environments using a whole-institution approach (Leicht and Heiss, 2018) and new tools (Bramley et al., 2011; Wagner et al., 2021).

Schools are also capable of accelerating sustainable solutions at the local level, stimulating research, innovation, and collaboration that leads to deliberate and consciously sustainable development paths (Pesanayi and Lupele, 2018). Valderrama agrees that the introduction of tools based on co-creation and co-implementation processes contributes to more sustainable schools and student skill acquisition (Marques-Valderrama et al., 2023).

Carbon footprint reduction also enables schools to achieve substantial gains in reducing carbon emissions and operating costs, at zero or low cost (Odell et al., 2020).

2.4 Attributing an economic value to carbon emissions

Local governments are increasingly adopting carbon pricing mechanisms as part of the "localization" of carbon costs, recognizing the importance of local climate action in the global context (Barrett et al., 2024; Cruz and Rossi-Hansberg, 2022; Gomi et al., 2010; Khanna et al., 2014; Kornek et al., 2021; Warbroek and Hoppe, 2017).

The Conference of the Parties to the United Nations Framework Convention on Climate Change recognized and encouraged the 'localization' (UNFCCC, 2015) of climate action by governments and communities, emphasizing the integration of new local governance and climate change strategies. The European Union Mission for Smart and Climate-Neutral Cities (EU, 2021) emphasizes citizen participation and community engagement to achieve climate neutrality in 100 European cities by 2030, selected as hubs for urban and social experimentation and innovation.

European cities with ambitious decarbonization goals for 2030 have multi-sector priorities in their local climate action plans (Rivas et al., 2021), including transport and mobility, which remain some of their biggest challenges. This involves exploring new policy instruments and actively engaging local communities (Linton et al., 2022; Urrutia-Azcona et al., 2020).

The transportation sector, as one critical issue for climate policies (Peng et al., 2025), it is frequently reviewed in climate change education actions aimed at encouraging sustainable transportation modes. It allows students to analyze the environmental impact of their own habits (Kranz et al., 2022; Radzi et al., 2022). However, they may be ineffective, depending on climate change knowledge and educational approaches (Chang et al., 2012; Kranz et al., 2022; Radzi et al., 2022; Whitmarsh et al., 2011).

However, aspects of complexity, subjectivity, uncertainty, and limitations in aggregated approaches at the national and regional levels become barriers when applied at smaller scales (Aldy and Stavins, 2012; Van den Bijgaart et al., 2016). The challenge lies in

developing innovative, locally relevant solutions that contribute to urban decarbonization.

Universities are increasingly adopting carbon pricing to enhance their operational sustainability (Gillingham et al., 2017; Guerrieri et al., 2019; S. Lee and Lee, 2021; Lee and Lee, 2022). This includes implementing internal carbon pricing as a "tax" on negative externalities, influencing cost structures (Barron et al., 2020). As an educational tool, some universities are exploring innovative approaches such as environmental credit schemes to avoid CO₂ emissions (Cirrincione et al., 2022) and convert monetized savings into tokens.

The real-world mechanisms are based on an economic value that should inform the formulation of a price. It can use either the social cost of carbon (damage cost of each additional ton of CO₂) or the marginal abatement cost (marginal cost of reducing one more unit of CO₂) reflected in taxes and market mechanisms to promote sustainable consumption and investment.

Extensive research shows a significant variability in the social cost of carbon (SCC), reflecting the complexity of carbon economics mechanics. The average value of SCC was between €160 and €240 in 2023, in the year of the study, but authors such as Wang et al. (2018) calculated values that reach €2,386/tCO₂. Practice differs substantially from theory. In 2023, the year the study was conducted, the social cost of carbon in the US applied to regulatory impact analysis was close to half the average cost in the European Union Emissions Trading System (EU-ETS), ranging from €43/tCO₂ to €83/tCO₂.

In secondary education, climate change education programs tend to promote awareness-raising projects, while the economic impact of climate-change initiatives remains a minority focus (Bhattacharya et al., 2021a).

Despite its potential to drive climate action, carbon pricing is still not sufficiently adopted and scaled in educational institutions (Rousell & Cutter-Mackenzie-Knowles, 2019), especially given the significant impact of climate change on children. Programs addressing the economic aspects of climate change remain a minority (Bhattacharya et al., 2021b; Herman et al., 2017) and tend not to focus on carbon pricing. This gap highlights the need to make carbon economics more accessible and tangible in education.

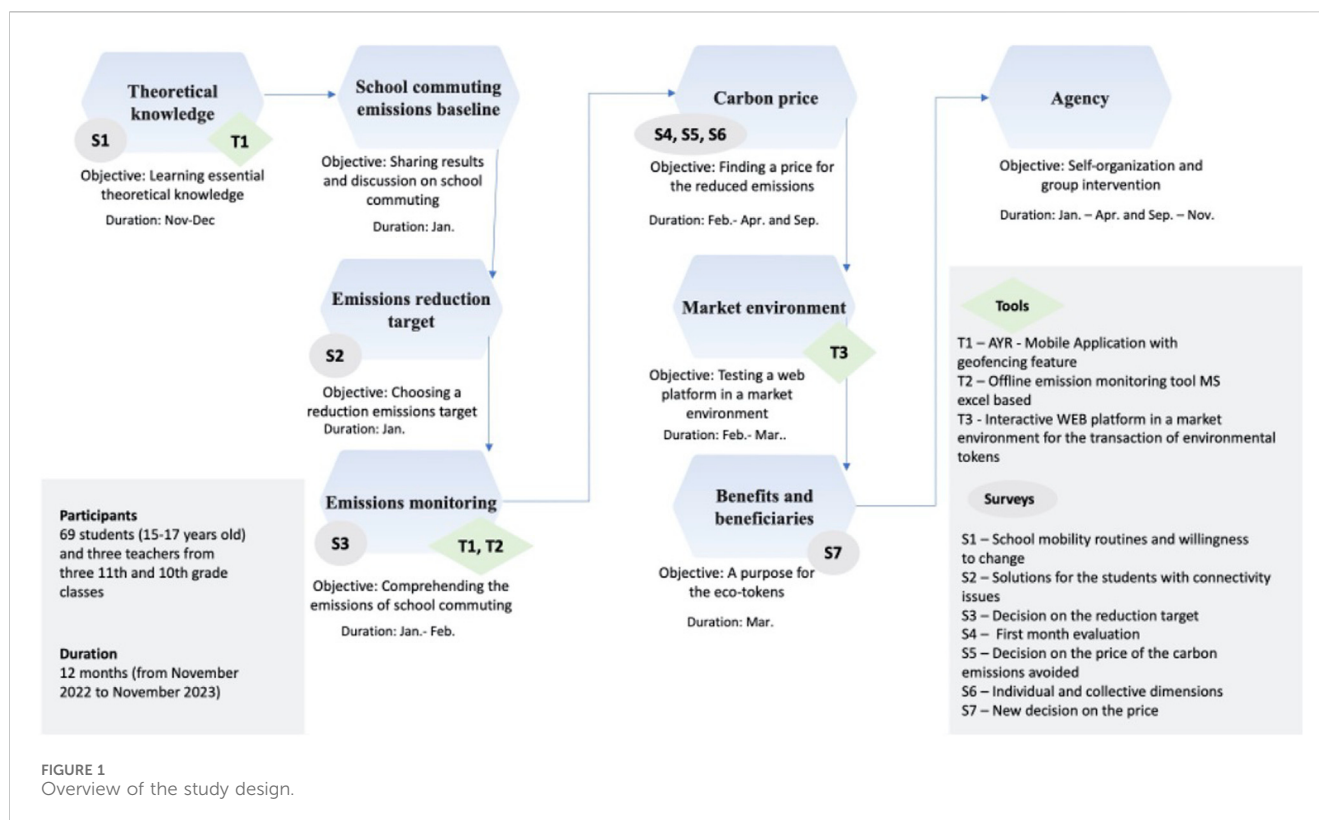
In the current climate emergency, these tools must be adapted for younger learners, aligned with their learning characteristics, and designed to encourage knowledge and action.

Local climate policies focus on the importance of mobility in achieving sustainability goals through technological solutions and low-carbon behavior (Aboagye and Sharifi, 2023; Barrett et al., 2024; Brozynski and Leibowicz, 2018; Christidis et al., 2024).

3 Materials and methods

3.1 Study design

This subsection presents an overview of the study design and a practical perspective with the aim of facilitating future replication. A group of students from secondary education (Figure 1) participated in the study designed with eight stages. These include theory basics, finding school commuting baseline, defining an emissions reduction



target, emissions monitoring, attributing a “price” to carbon, exploring market environment, choosing benefits and beneficiaries, and agency. It took place within the context of Citizenship and Development classes and open sessions. Participants used a digital application on the school journey to monitor the avoided emissions. Some phases occurred simultaneously, either partially or completely. Seven surveys (S1 to S7) were conducted, and three digital tools were included: the AYR application (T1), MS Excel-based offline software (T2), and the web platform market environment (T3).

A detailed description of each stage is provided in [Supplementary Material](#).

3.2 Analytical framework

The case study adopts the precepts of participatory action research methodology as the analytical framework.

The case study approach is appropriate as an empirical inquiry to investigate a real life-problem/phenomenon in its real-life context (Yin, 2009) which is the practice of school commuting in the city, strongly influenced by and influencing the local context.

Although the evolution of the conceptual and theoretical field of action research, especially since the second half of the 20th century, with the seminal work of Kurt Lewin, (1946) and Freire, (1968), participatory action research continues to emphasize its core participatory methodology of inquiry that is made of collective and decision-making involvement in the research and change of social practices (Kemmis and McTaggart, 2014) such as educational

ones, in which participants collectively self-reflect on their own actions and contexts to promote informed and just change, aiming to improve of the practice through a “systematic oscillation” acting and inquiring into it (Tripp, 2005).

This approach allows to identify iterative cycles of planning, action, observation and reflection of action research, of collective co-construction of knowledge, of democratic and practical participation, and thus respond to specific context conditions in the design of a “collaborative commitment” process (McNiff, 2013).

In the intervention, students received background knowledge (based on facts, data and theories) and experiential knowledge (based on practice) triggered successive iterations linked to the real-life problem (Perrett, 2003; Wallace, 1991). The real-life problem is the impact of the social practice on school commuting choices in terms of carbon emissions and the response that young people from the school community find linked to their city.

For the whole process of iterative cycles that constitute the research action cycle, the authors adopt the concept of “epicycles” of Tripp (2005) as the “many cycles of action-research when acting in each phase of the action research cycle”. This option allows for a detailed view of each cycle within the implementation phase.

The analytical framework (Table 1) adapts Tripp’s field representation of the action research cycle through the action sequence and the action taken in the practice and inquiry. This adaptation focuses on the co-decision points involved in the action sequence, the evaluation metrics and constructs for each activity, data gathering, and observation as the intervention progressed.

TABLE 1 Analytical framework.

Corresponding study design stages	Action sequence	Practice			Inquiry		
	Phase/Iteration	Co-decision points	Participants decision	Activity	Evaluation metrics /constructs	Data	Evaluation of results
Plan							
	May/June	Contacting school and parents					
Implementation							
1.Theoretical knowledge	i) November	i) Attending classes of theoretical background	Participants decision	Activity	Evaluation metrics /Constructs	Data	Evaluation of results
2. School commuting emissions baseline	ii) January; iii) January; iv) January	ii) Deciding to monitor emissions after sharing carbon footprint baseline; iii) decision on co-decision method; iv) Deciding group’s data access					
3. Emissions reduction target	v) January	v) Confirming emission reduction target					
4. Emissions monitoring	vi) January; vii) February	vi) Addressing connectivity issues; vii) Sharing one-month mobility data					
5. Carbon price	viii) February; ix) February; xv) September	viii) and ix) Deciding a next phase offered by the eco-tokens accumulated by the group (factors and metrics); xv) Confirming the economic value of the emissions avoided					
6. Market Environment	x) February	x) Proposing a carbon market environment platform					
7. Benefits/Beneficiaries	xii) March	xii) Deciding the destination of the eco-tokens					
8. Agency	xi) March; xiii) March; xiv) May	xi) All-school one-day presentation; xiii) Group’s openness to communicate to the public; xiv) Proposal to the City Council					
Evaluation							
	Participants assessment		Participants decision	Activity	Evaluation metrics /Constructs	Data	Evaluation of results

Adapted from Tripp (2005).

Given the extensive nature of the analytical framework (Table 1) it is provided in [Supplementary Material](#).

The study corresponded to a complete cycle of participatory action research, including its planning, implementation, and evaluation phases, whose sequence of actions includes a practical component and an investigative component. The practical component coincided with an iteration in the planning and evaluation phases, while the implementation phase developed over 15 iterations of group of which 13 generated a collaborative decision (by voting), based on discussion, data sharing, or topic exploration, which shaped the intervention's progress and direction.

The planning and networking phase corresponded to (i) preparatory contacts with the school and meeting with the parents, (ii) planning theoretical classes, (iii) defining key metrics and data collection.

The first step of the implementation phase consisted of classes on theoretical scientific, political, social, and economic background aspects of climate change, followed by the group's first co-decision-making session. From there, the researchers had some guidelines for co-decision-making moments until the end of the action research cycle.

The 15 iterations of the implementation phase represent the sequence of co-decision points and the respective outcome. They included contacting the school and parents to assess interest; presenting to students to encourage their participation, given that it is a voluntary approach; self-monitoring avoided emissions during school transportation; choosing the co-decision-making method and continuing the intervention; determining how to access the data progressively collected; reviewing emissions reduction targets; addressing digital access issues; exploring ways to make avoided emissions tangible (converted into eco-tokens) and the metrics to assign them economic value; the introduction of a market-based platform; the sharing of a month of mobility; the preparation and execution by students of a day-long presentation of the project involving the three classes to the entire school; the selection of a destination for the eco-tokens' benefit; the proposal to the City Council to implement this destination; and the reformulation of the economic value attributed to avoided emissions.

Decision points are the subject of co-decision by participants and corresponding to the activity, mostly through discussion and voting in class. Stages included evaluation metrics for analyzing the constructs involved, data collection, and the evaluation of results.

The implementation stage concluded with the review of the economic value of avoided emissions, when the group showed the ability to use a new metrics and reviewing the previous values.

In the reflective phase, corresponding to the intervention's concluding activity, the only group's decision point was for evaluating participation.

Data collection included the following tools:

- i. Seven (7) quantitative and qualitative surveys were conducted using Forms with closed and open-ended answers, including 5-point Likert scales, collected in iterations of the implementation phase to capture individual and collective school mobility habits, the willingness to develop pro-environmental behavior, digital access issues, the interest in the experiential learning of new concepts and their use by participants.
- ii. App logs monitoring the carbon footprint of individual school commuting habits were used to evaluate the changes in one-month mobility and develop the concept of the economic value of avoided emissions.
- iii. Platform logs used to test the group's interest in exploring a digital market environment.
- iv. Offline MS Excel was used temporarily during the monitoring period for students with difficulties accessing digital resources online.
- v. Open coding was used for open-ended answers, and no pre-testing was performed before administering the surveys.
- vi. Individual and group carbon footprint baseline, focused on the local dimension of school mobility practices, was estimated based on several sources namely: the local bus operator STCP 2020 sustainability report, the 2021 light-train/tram - Metro do Porto Sustainability Report, the Portuguese vehicle tax database taking the most common internal combustion engine diesel and gasoline light passenger vehicle models in the Portuguese market, the IEA Global EV Outlook 2020 for electric vehicles, the Matosinhos pilot for electric bikes and electric scooters, and the energy mix of electricity production as of 30.12.22 to derive the emission factor during charging (Details in [Supplementary Material](#)).

No ethics committee approval was required as the study was integrated into educational activities in Citizenship and Development classes, for which the school holds legal competence under national law, ensuring the provision of legally required information and obtaining informed consent from students or their guardians.

The study has a dual aim of learning the mechanics of carbon pricing and encouraging pro-environmental behavior.

3.3 Context

The intervention involved a collaboration between the João Gonçalves Zarco public secondary school in Matosinhos, the nonprofit Center for Engineering and Product Development (CEiiA) for mobility and aerospace, and the municipality of Matosinhos.

Matosinhos is located at the north of Portugal with 172 thousand residents, being 17.2% of young people (≤ 18 -year-old) (INE, 2021). The municipality is part of the densely populated Porto metropolitan area and aims to become carbon neutral by 2030 (CMM, 2023). The transport and mobility sectors contribute 23.5% of the total municipality's GHG emissions (APA, 2020). Matosinhos has one of the highest mobile population rates in the country of 83.0% (INE, 2018).

Daily travel patterns such as home-school commuting contribute to the city's CO₂ footprint and provide an opportunity to contribute to the energy transition in Matosinhos. The high school community in Matosinhos municipality totals 2,300 students in six schools, of which João Gonçalves Zarco public secondary school has approximately 500 students enrolled and employs 171 teachers and 46 non-teaching staff members (ME, 2024).

The study took place as there were public expectations for the municipality to create a school corridor in the city to provide the

local school community with safer and more sustainable road circulation infrastructure, especially for public transport and bikes, nearby the school. Zarco school locates in a central avenue of Matosinhos, which is short on bike lanes and parking.

The school expressed interest in voluntarily participating in a co-development process that would promote the school corridor for students. Three classes were selected as students are from different scientific domains, being a group of 69 students (aged 15–17) and three teachers from the 10th and 11th grades in Science and Technology and Socioeconomic Sciences. The study was conducted within Citizenship and Development classes and open sessions as well between November 2022 and December 2023.

The study on climate change education involves the school community in making their school commute impacts tangible. The study combined elements of participatory approach and experiential climate change education, with mechanisms of group collaborative decision-making on the continuity of the initiative and method.

A pricing scheme was collaboratively created to convert avoided emissions into “eco-tokens” due to more sustainable mobility options. “Eco-tokens” were used as a pedagogical proxy based on the carbon pricing tool, to incentivize emissions reduction based on real-life concepts and observation and measurability suitable to an experiential learning process (Coe et al., 2014).

Students and teachers used personal digital tools to estimate the carbon avoided emissions by adopting different modes of transport, thus making the impact of individual behavioral changes understandable. Students’ participation was voluntary and of co-decision throughout the process, both in generating data through their means of transport using an application and in each group’s decision-making for the next stage.

Students were encouraged to talk to their parents about changing their modes of school transportation during the intervention. In addition, the school provided parents with information to raise their awareness of the project and their participation. However, no further active parental involvement was observed, although they authorized their children’s participation. They reportedly observed the process from a domestic perspective.

4 Results and discussion

This section presents the main findings of the experiential learning case based on the principles of the action research methodology, specifying the sequence of co-decision-making observed throughout an entire cycle.

For more accessible and structured reading, the main results from iterations in implementation phase were grouped into six thematic categories, that emerged from the multiple iterations succession.

In the planning phase, the main results came from the two preparatory meetings with parents, organized by the school and subsequent information, showing a substantial difference in parent availability in participating in the intervention. Almost 70% of the parents from one class participated in the first meeting, while less than 40% participated regarding the other two classes. Parents

authorized their children did not provide further feedback, despite the initial outreach.

These differences in parents’ interest or availability may be related to socioeconomic factors that influence parents’ ability or willingness to engage (Ferreira and Liu, 2023). This result highlights the need for specific strategies to increase engagement and reduce barriers to participation.

Among the three teachers involved, one actively participated, while the other was instrumental in organizing school-wide sessions.

In the implementation phase, the intervention progressed along 15 iterations, of which 13 were based on co-decision. Major achievements were reached through co-decision. The group decided the continuation of the intervention after the theoretical lessons and chose the surveys as a voting process. The group opted for the group-wide access to all data and preferred to review the emissions reduction target to make it more realistic. The group decided the need for consultation of colleagues affected by digital access limitations and the development of alternatives. They expressed the disinterest in exploring a market environment platform but favored the exploration of mechanisms to make the economic value of emissions tangible with a social purpose. They co-organized the holding of a presentation day for the entire school and the participation in public events to share the experience, namely the meeting with the city council for the recognition of a municipal eco-token system.

The group started with a participation rate in the first survey of 69% and a moderate willingness to change school commuting choices, standing at 2.66 on the Likert scale. However, in average, 84% of the group responded to all surveys through the intervention.

As almost all surveys included one or more points for co-decision, 36.2% engaged partially by answering surveys but did not monitor daily mobility avoided emissions based on the app, and 18% did not participate, likely to consist of students reliant on cars for their commute. None of the participants relied solely on monitoring mobility. Those who completed both tasks were the most engaged, providing 70% of the questionnaire responses, and actively proposing improvements for the app’s future use.

4.1 Knowing the carbon footprint

The students started to learn how to convert their daily commuting patterns into individual and community CO₂ footprint baselines. The result is an average daily carbon footprint of 1.5 kg CO₂ per student and 108.6 kg CO₂ for the group.

Car usage dominated morning journeys (59.6%), and public transport was more common for return trips (23%). The data revealed a notable group that consistently used sustainable transportation for both trips (29%), those relying on cars for both trips (21%), and those driven by parents in the morning but using public transport homes (21%).

After the baseline defined, trips tracked by the app over 21 school days in January and February corresponded to 129 validated trips across bus, walking, and cycling modes. The students that connected to the app reached less than half (45.8%), suggesting modest involvement in the experiential part of the intervention. However, those who used it responded to all the surveys.

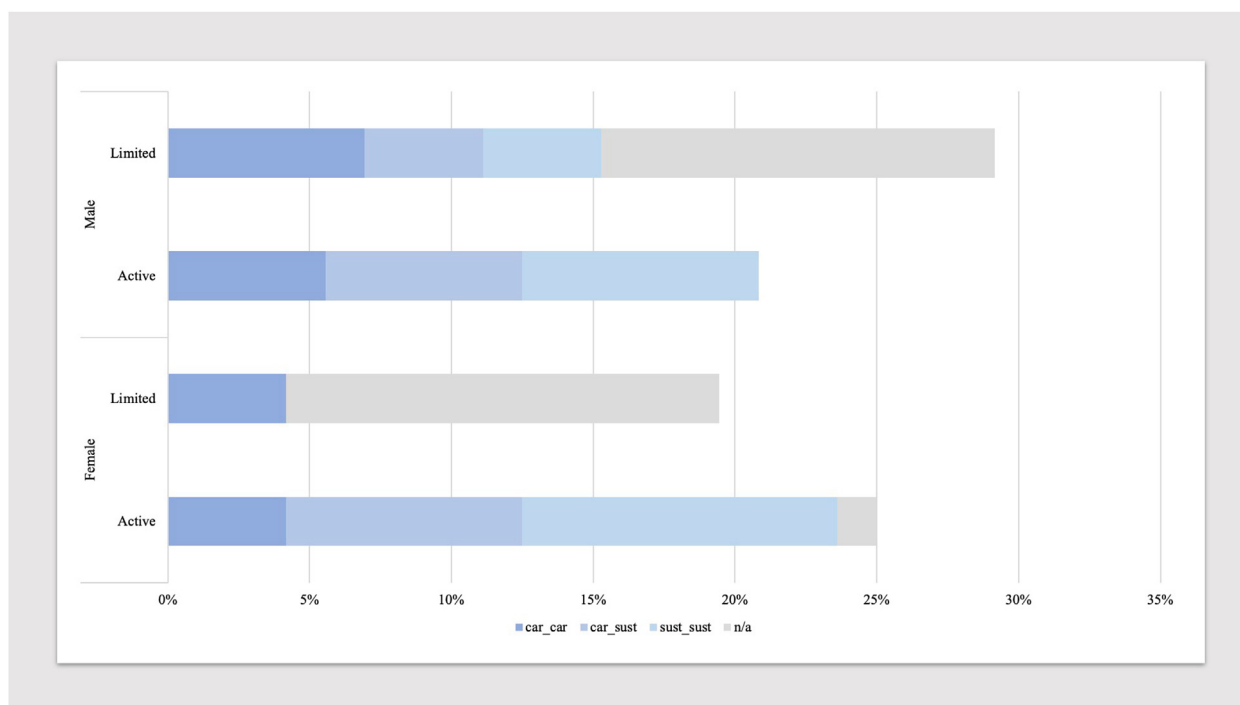


FIGURE 2
Participants characterization by gender, modes used in round-trip and engagement level.

Although boys constituted the majority of student participants (53.6%), girls were the most active, tracking more sustainable trips and saving more CO₂ emissions (64.2% of the group). We defined active participation as students who both responded to the surveys and used the application, whereas limited participation referred to those who only completed the surveys (Figure 2).

This finding aligns with studies on the gender gap in pro-environmental behavior and its determinants, which state that women tend to take more pro-environmental actions (Egan and Mullin, 2017; Eisler et al., 2003; McCright and Dunlap, 2011; Rätty and Carlsson-Kanyama, 2010; Truninger et al., 2022; Zelezny et al., 2000). Conversely, some studies suggest that men possess greater knowledge of environmental issues (Eisler et al., 2003; Vicente-Molina et al., 2018), while others report mixed results regarding gender differences in environmental concerns (Hayes, 2001; Vicente-Molina et al., 2018; Xiao and Hong, 2010).

During tracked school trips, we observed students (i) predominantly used cars for both trips (car_car), (ii) traveled by car to school but returned via a sustainable mode (car_sust), (iii) exclusively utilized sustainable modes in both ways (sust_sust), or (iv) had unrecorded transport modes (n/a). The sustainable mode included just two trips by bike due to unfavorable circulation conditions.

4.2 The group governance

The classes were unanimous in choosing surveys as voting mechanism and shared access to all data. Despite a moderate interest in the project, the classes were cohesive regarding

decision method. The high level of favoring transparency of information suggests self-perception of a trusting environment.

Also, the results suggest strong level of group cohesion and collaborative sense, as the group expressed unanimous support for consulting colleagues with digital access issues that impeded equitable access.

Nine students (12.5% of the group) reported technical difficulties and all but one were in favor of a temporary offline alternative.

The offline alternative tool was used for less than 3 weeks, with the last of its four users ceasing to submit daily notes. One user switched from taking the subway (owing to a weak internet signal) to the bus, two others resolved smartphone connectivity issues, and the fourth ceased participation altogether. Although the tool was inclusive, additional time was required to input the routes at the end of the day.

At this stage the group was also able to critically think and revise the emissions target reduction, as the initial target was found to high, therefore compromising the interest in participating. 93% of the group voted for an emission reduction target from 15% to 10%.

To reduce their commuting carbon footprint, the group initially aimed for a 15% emissions reduction based on the suggested changes in transportation modes. However, concerns regarding feasibility led to a second survey that offered 15%, 10%, and 8% reduction options. Ultimately, 40% of the respondents favored a 10% reduction, which was the most voted choice. This slightly lower target suggests a learning gain, reducing a knowledge-action gap.

The findings show that aspects of the knowledge-action gap on climate change became apparent early on as fewer students fully participated than those who expressed a willingness to change. This

aligns with previous research on the disconnect between attitudes and actions regarding climate change, especially among young people who are concerned but struggle to translate them into action. In pro-environmental behavior, the intentional behavior gap is critical (De Bruin et al., 2012; Gollwitzer and Sheeran, 2006; Moser and Kleinhüchelkotten, 2018; H. Wang and Mangmeechai, 2021).

4.3 Monitoring mobility data

The 129 students recorded trips were 70.3% on foot, 29.69% by bus, and 0.78% by bicycle. Bus users, who traveled longer distances, emitted fewer emissions and thus accrued more “eco-tokens.” During the emissions monitoring period, adjustments, rather than changes, to daily school transportation practices emerged. 31% of the group lowered emissions; 7% achieved zero emissions by walking and just 3% partially changed to public transport for one leg of the journey instead of a car. The global reduction was 1.5% in school commuting over the month of monitoring, with none of the actively engaged students fully switching their commuting modes.

Although the reduction was observed, this minor change did not reach statistical significance and may partly reflect natural fluctuations in mobility patterns, as well as the direct influence of the project. This direct influence refers to the concrete behavioral changes observed among participants, such as closely monitoring their journeys and adopting more sustainable travel modes, changes that, according to our assessment, would likely not have occurred without the project intervention.

For example, one student said, “I now take the bus home, but still commute to school in my sister’s car because her trip would happen anyway.” Another 12% reduced their car usage and included walking as part of their daily routines. Students who already used public transport strengthened their practice by integrating additional walking. One participant stated, “I started taking the bus to the subway instead of relying on my parents for the entire trip.”

In general, students reported increased use of buses and walking, and those who had already walked continued to do so. The distances recorded by the app indicate that more students introduced sustainable modes for parts of their commutes, although not all trips, such as those involving the subway, were captured by the app. It was assumed that students who did not use the app and who primarily relied on cars continued to do so.

The application highlighted these behavioral adjustments. The use of the application as a supportive technology enabled the valuation of sustainable behavior change, as digital tools to support urban decarbonization can reinforce participatory processes and impact attitudes and behaviors (Collins et al., 2020; Lin, 2016; Obracht-Prondzyńska et al., 2023).

Participants were surprised with the small change and statistically irrelevant result that reflected the shortest month of the year that includes some Carnival holidays, as they expected a higher value, though only a minority contributed to emissions reduction through relatively minor changes.

Although a reduction in CO₂ emissions was observed, this minor change did not reach statistical significance and may partly reflect natural fluctuations in mobility patterns, as well as

the direct influence of the project. This direct influence refers to the concrete behavioral changes observed among participants, such as closely monitoring their journeys and adopting more sustainable travel modes, changes that, according to our assessment, would likely not have occurred without the project intervention.

This perception provided the group with the opportunity to confront a real-life problem, highlighting a low behavioral and sustainable engagement in changing modes.

Fewer than 40% of the students contributed to this reduction, with 31% lowering their emissions and 7% achieving zero emissions by walking. Those who did not contribute maintained their current emission levels, were unable to track their trips, or continued to rely exclusively on cars. The proportion of students who contributed to emissions reduction are 57% of those who said they were willing to change.

In longer time frames and statistically relevant studies, results converge into the challenge of changing behavior. (Feldbacher et al., 2024) found a disconnect between participants’ perceptions, actions, and climate impact. Research on voluntary climate change programs tend to have lower participation rates than mandatory regulations; however, their effectiveness can vary widely (Ramaswami et al., 2012). For instance, one study found that participants in a 3-year intervention altered approximately half of the household behaviors examined (Staats et al., 2004) while a school-based intervention saw 77% of participants switch to cleaner routes (S. Ahmed et al., 2020).

Additionally, Gaus and Mueller (2011) research on large-scale consumer climate education programs has highlighted that while such programs positively influenced participants’ intentions to seek further information and adopt climate-friendly behaviors, they often fell short of concrete action. This underscores the challenge of translating awareness and intention into tangible behavioral changes.

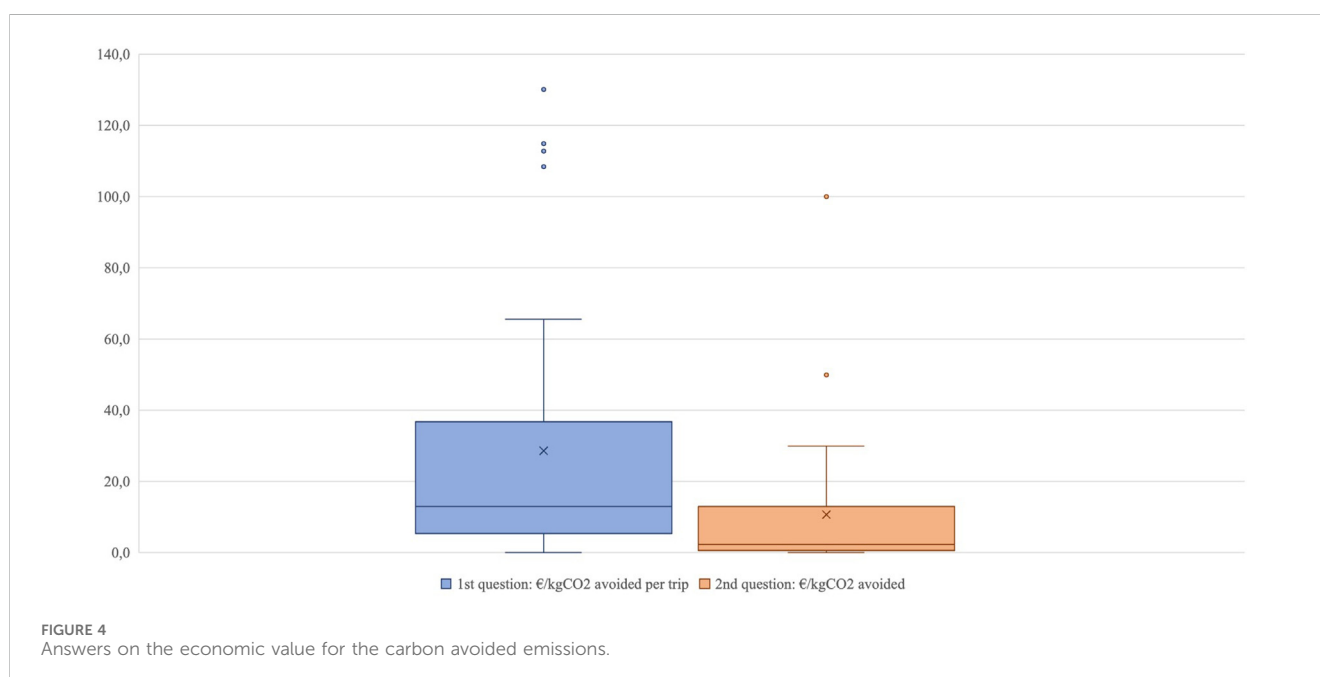
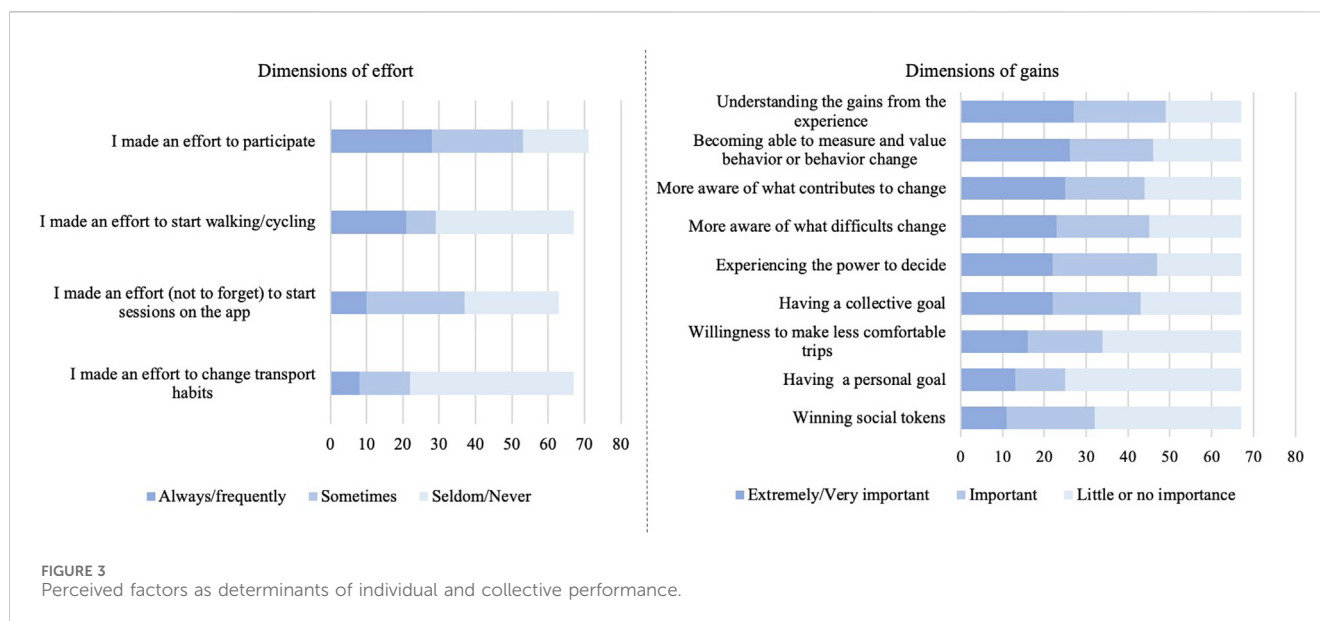
4.4 Calculating an economic value for the avoided emissions

The most positive engagement results were observed when the group co-decided on what to do with the avoided emissions accumulated and converted into eco-tokens, with 93% participation. This stage condensed experiential learning loops on the concept of carbon pricing and avoided emissions.

This intervention emphasizes experiential learning as a means for participants to grasp the underlying logic of the mechanism and subsequently engage in co-designing a version adapted to their needs and context. The motivation was co-designing a new mechanism for climate change education within local climate policy, as pedagogical proxy, rather than monetary rewarding.

The group recognized the need to establish a metric for quantifying the economic value of avoided CO₂, even being a small reduction. The concept of the social cost of carbon was unfamiliar to the students and did not generate a discussion. The group had asked for a reference point and was given the monthly public transport pass (€30) as the most comprehensive and practical benchmark.

The group made the economic value tangible for carbon avoided emissions based on individual factors involved—by identifying their



determinants (Figure 3), and to “measure” the economic value for carbon avoided emissions based on those factors per trip; 93% of the group participated of which 97% indicated a value.

Thirteen (13) personal factors were identified as gains and effort (Figure 3). A slightly higher score (3.2 on Likert scale) was given to gains. Participants identified the most significant benefits as “understanding the gains” from their own experiences, “knowing how to measure and value” pro-environmental behaviors, and “having the capacity to make decisions.” They also highlighted the importance of “becoming aware of factors that facilitate change” and “having a collective goal,” which outweighed

considerations such as “obstacles to change,” “individual participation,” and “earning eco-tokens.” The phrases suggest that the student’s self-efficacy is strengthened as they evaluated their positive experiences as evidence of competence, according to Bandura, who also highlighted that collective efficacy is rooted in self-efficacy.

Effort factors were the least valued (2.5 on Likert scale) as the most frequently mentioned types of effort included “starting to walk or cycle,” “remembering to log into the application,” “the effort to participate,” which was the most cited, and “changing transport habits.” The least mentioned was “having to change transportation

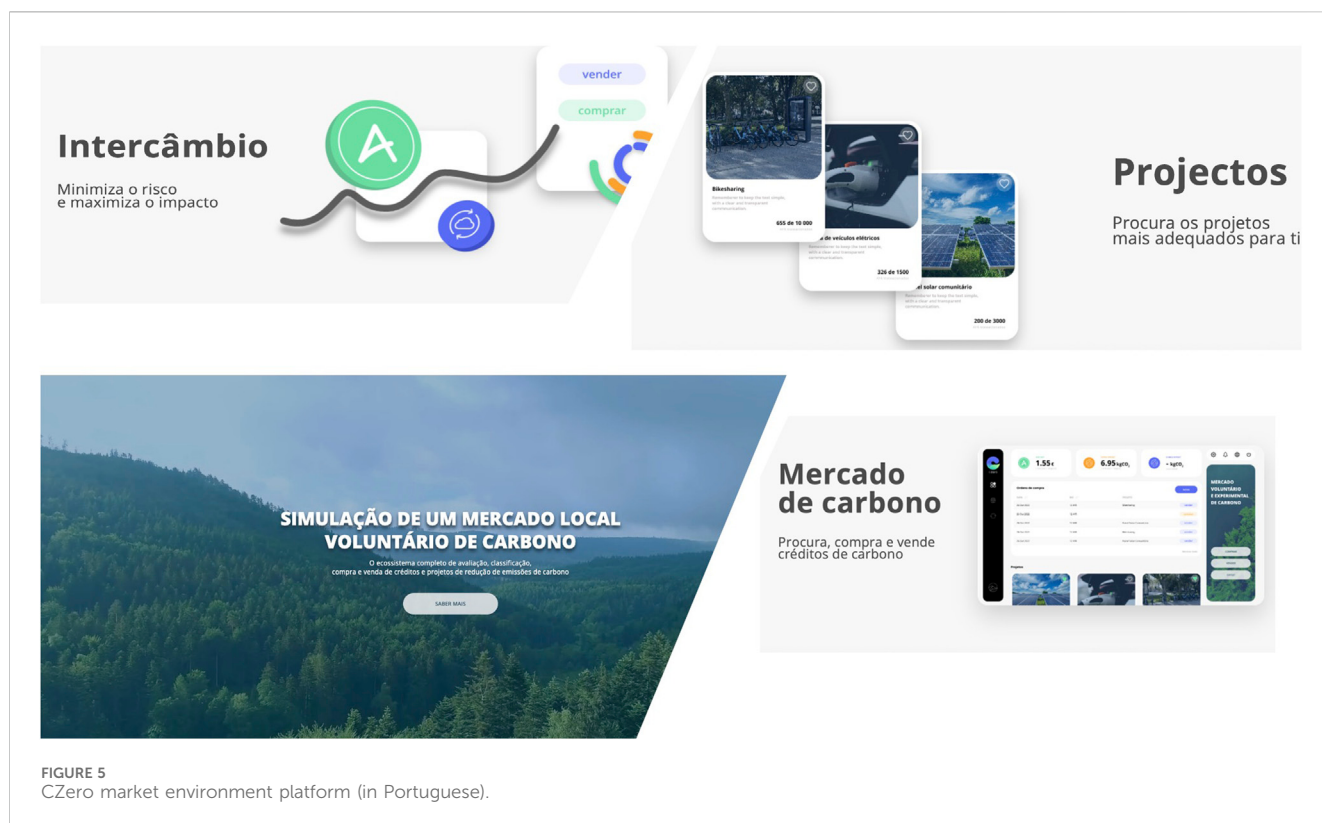


FIGURE 5
CZero market environment platform (in Portuguese).

habits,” which aligned with students who already used sustainable modes like walking or public transport or had no alternative to car use.

Figure 4 presents the responses to the initial question regarding the individual economic value assigned to carbon avoided emissions during school travel. The results show how “pricing” generated a wide range extending into three-digit values. One student assumption for his calculation: “Reductions in carbon dioxide emissions are quite valuable, and my bus trips are typically 1h30 m long.”

Students expressed discomfort with using a metric measured as €/kgCO₂, which led the group to base the average value on the avoided emissions per trip. This was converted to €/kg CO₂ per trip), resulting in an estimated value of €28.6 per kilogram of CO₂ avoided.

The result of the students’ first action to make tangible an economic value for the avoided CO₂ is 280 times higher than the moderate values of Social Cost of Carbon, although they are not comparable, including methodologically, at this stage. The approach intentionally subjective emphasized students’ engagement in co-creating solutions while freely adapting the fundamental concepts of the carbon economy to their context, rather than focusing on the price. A longer period of study would enable students to explore the parameters of the social cost of carbon, to test their ability to relate it to the value of avoided emissions.

The group raised 342 eco-tokens, equivalent to €979, during the emissions monitoring month. If the rate were sustained throughout the entire school year, the group would raise 2934 eco-tokens, worth €8391.2, while the school could potentially generate 20,375 eco-tokens worth €58,272 based on the group’s criteria.

Five months later, by September 2023, the group was proposed again to assign an economic value to each kilogram of reduced CO₂ emissions, and a significant shift of perception over the 5-month period occurred. The new average value was €10.6 per kg CO₂ avoided, with the median dropping from €12.5 kg to €2 kg of CO₂ reduced. This significant reduction from the first assignment indicates that the time passed between the two responses allowed for a substantial change of the group’s perception.

Exploring metrics and values to find a “price” for the avoided emissions outcome show group’s willingness to explore its ability to innovate and respond to a real-life problem with everyday own city life experience and suggest the intervention’s impact on the process. This may reflect an improvement in students’ capacity for abstract thinking and a more nuanced understanding of emission reduction beyond their initial experience. However, both sets of values still are considerably higher than the social cost of carbon estimates or the commonly accepted reduction costs in the literature.

These results align with two well-documented challenges that are the difficulty young people face in grasping abstract concepts, such as in carbon economics, and the need for climate change education to be more relevant to them by addressing knowledge gaps in critical mitigation measures (Baldwin et al., 2023; Thomas et al., 2022; Trott, 2021; Wynes and Nicholas, 2017).

The proposal to test a gamified market-based environment platform (Figure 5), was ultimately rejected by 83% of the group, as only four students just logged in without further engagement, while two others indicated it was “too early” to participate, evidencing that monetary reward was not a motivation. A high percentage (45%) also did not show any interest in doing it in the

future. 69% of respondents were willing to exchange their eco-tokens, but not commercially.

Research indicates that gamification and nudging do not ensure success and that their effectiveness is influenced by cultural context and motivation (AlMarshedi et al., 2017; Byrne et al., 2022). The students' limited motivation may be attributed to the brief duration of the intervention, suggesting the need for more comprehensive training in environmental service markets.

However, the group's refusal also suggests that the intervention is capable of generating a high level of autonomy and ownership while learning.

4.5 Benefits and beneficiaries

Although 93% of the group voted to co-design a local ecosystem of community-generated eco-tokens convergent with a local climate policy, the results showed it was divided. 35.8% advocated a more sustainable public transport system, suggesting improved school routes and incentives for e-bike use alongside the existing free pass. 30.9% preferred an option for individual benefit, by exchanging eco-tokens for access to local municipal services and products, and 21% did not answer.

Ultimately, the group agreed to symbolically exchange the eco-tokens for an e-bike for the school enhancing sustainability for city trips related to school needs and benefiting students, teachers, and staff. Notably, more students expressed a desire to benefit the entire school community rather than seek individual compensation.

These results suggest that more effective planning could have enabled a clear understanding of whether this stage had the potential for building a shared vision or whether it was a persistent opinion autonomy that no planning could change.

4.6 Agency

The group's openness to communicate to public and receiving prior training, after all-school one-day presentation, and the meeting with the City Council, suggests the impact of the intervention on agency and ownership.

Teachers and students collaboratively chose a "delegation" of students representing the three classes, consisting of six students. The communication training included the preparation of PowerPoint presentations. This initiative suggests that the intervention contributed to a greater level of ownership and self-awareness of the capabilities and needs of an effective communicator, as well as to the learning gains resulting from the training request.

A delegation of six students presented the project to the City Council, which was part of the collaborative initiative, and proposed the idea of "exchanging" the accumulated eco-tokens for an environmental benefit for the school. The municipality acknowledged the youth proposal as innovative. In a similar council initiative in 2024, students were invited by the municipality to contribute to a participatory budgeting mechanism debate, an open governance tool that municipalities are familiar with.

The intervention likely contributed to the group's ability to develop a concept and transform it into concrete and collectively important action, in a feedback loop of new experiential learning. The initiative for a model that publicly recognizes and values climate action, such as a school community eco-token system, demonstrates a strong sense of agency, self-organization and intervention, responding as a community in a cooperative process with the city (Urrutia-Azcona et al., 2020).

Nearly 90% of the group recognized the crucial role of the City Council in reducing CO₂ emissions.

The group that felt more prepared to discuss and act (J. J. Lee et al., 2013; Pruneau et al., 2003) comprised of those who responded to the surveys and used the app, maintaining an average participation rate of over 80%.

These findings support previous research (Jans, 2021; Jugert et al., 2016) on that it is in collective efficacy that each person finds pro-environmental efficacy that they do not possess individually, particularly individual actions against climate crises. The community-based approach emphasizes the effectiveness of collective strategies in promoting climate change (De Meyer et al., 2021; Trott, 2019).

A large proportion of the group perceived the relevance of the project - 86% of the group responded, of which a highly 82% said the experience had been "important". The group focused on learning awareness of community work regarding individual participation, an applied self-awareness development due to acquiring practical and methodological tools, agency, and a reflective maturity consistent with the iterative action research. More frequent opinions are "It gave me the tools to get a sense of what I actually save and emit", "I could work on a common objective", "I became aware of the difficulties some of my classmates face in being able to come to school more sustainably", and "the most important was incentivizing people to reduce pollution in the city".

Results suggest the contribution of the study to reinforcing participants' capacity for critical analysis of experiences and application of conceptualization skills, with self-experiential learning loops, collaboration, co-construction of knowledge, autonomy, and agency to decide and influence, enhancing internal factors of self-efficacy.

Also, a group dynamics challenge emerged throughout the intervention: a highly behavioral engagement in the surveys and class attendance, which had a strong component of self-governance development, comparing to a low motivation for new mobility practices engagement toward more sustainable modes. This dynamic derives from the dual aim study itself, of learning the mechanics of carbon pricing and encouraging pro-environmental behavior.

The intervention demonstrates the effectiveness of experiential learning about the mechanics of carbon economics but was less effective in encouraging change in school commuting practice, limited by a short time frame. The dual objective influenced and divided participants' attention.

4.7 Limitations

The main limitation found in the research is related to the study's short time frame, which limits the ability to capture changes and effects that require a longer time frame.

The small sample size of validated app-based trips may limit the possibility of generalization, but it proved sufficient to validate the objective of this sociological study of an exploratory and qualitative nature.

The evaluation of “eco-tokens” well above the average ranges of the social cost of carbon is justified by the subjective and exploratory approach of the study on the co-development of a pedagogical tool.

Local specificity constitutes a contextual limitation that stems from an inherent characteristic of this study, which aims to explore climate mitigation and adaptation strategies at the local level and the practice of school commuting, strongly influenced by and influencing the local context.

Parents did not participate in the implementation nor in the evaluation phase of the intervention, which may introduce a participation bias. However, they played a fundamental role in the planning phase by allowing their children to participate, and they will have followed it within family settings, without direct and active participation.

Given the voluntary nature of participation, the authors were aware that could introduce a self-selection bias. However, this did not condition the study, as the qualitative and exploratory purpose was to co-develop and explore carbon economics mechanisms within school community.

5 Conclusion

This study aimed to explore how the co-development of carbon pricing processes in secondary schools can promote CO₂ emissions reduction while fostering students’ awareness of their roles as community agents contributing to low-carbon cities. using an action research-based analytical framework for an experiential learning climate change education approach to carbon pricing.

Specifically, the study sought to make school commuting and the rationale for carbon pricing tangible for students by using digital tools to estimate avoided carbon emissions from various transportation modes and to illustrate the impact of both individual and community behavioral change. The experiment emphasized experiential learning as a means for participants to grasp the underlying logic of the mechanism and subsequently engage in co-designing a version adapted to their needs and context.

A main outcome of the study is that secondary school students are able to collaboratively co-create a carbon pricing mechanism by experiential learning, reduce school mobility emissions, co-develop measurable indicators, and assign value to reduced carbon emissions from school commuting, converting avoided emissions into ‘eco-tokens,’ and brought them to municipal consideration.

Carbon pricing can evolve from a complex climate-policy instrument to serve as an educational tool for secondary school students.

The analytical framework allowed to identify opportunities for future planning improvements in four main areas, two of which relate to mobility. In a future dual aim intervention, greater attention to pro-environmental behavior is needed for more sustainable school mobility practices. Focus groups and group discussions on performance beyond the “monitoring month” would provide a deeper analysis of this topic. For more robust results, especially in mobility, improvement lies in planning a longer intervention

period, and in encouraging the group to also conduct a longer-term follow-up evaluation.

Also, for more comprehensive involvement of the school community, creative planning for parental participation will be necessary, to anticipate barriers to their participation and are engaging. In technical challenges such as using the market environment platform, a longer-term study will allow young people time to develop their reflexivity and experience potential returning to the challenge at a later stage to assess potential differences.

This study provides a detailed method and a structured design, enabling its transferability for integrating climate policy tools into educational practice. It presents as portable elements the eight-phase model, the survey prompts, the school-city engagement steps, the digital tool, and the minimum data infrastructure.

The study underscores the need for collaboratively developed approaches that enable school communities to actively participate in the city’s sustainable energy transition, bridging the gap between climate action, local policy development, and young people lived experiences toward an active citizenship for climate.

Students demonstrated understanding of the problem and its current and future potential in local climate transition processes. This approach can integrate a local climate strategy while also serving as climate empowerment for youth.

Furthermore, the findings highlight the need for local policymakers to recognize the innovative contributions of younger generations, urgently rethinking the transition from traditional climate governance to more broadly participatory governance that integrates new tools and instruments that young people can collaboratively design and develop.

Future research should further extend the study time frame, as it could advance practical understanding of carbon economics concepts and tools, particularly the social cost of carbon and the marginal abatement cost, while enabling the assessment of the impact of collective actions at community and municipal levels.

Data availability statement

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

Ethics statement

The studies involving humans were approved by The Board of Escola Secundária João Gonçalves Zarco, as the entity responsible for processing students’ personal data for the purposes of developing educational activities and providing teaching services, processing which has a legal basis in the execution of educational services and in compliance with the school’s legal obligations, ensures the provision of legally required information and, where applicable, the collection of informed consent from students or their guardians regarding personal data processing activities. The participation of Lurdes de Jesus Fernandes Ferreira, a researcher at the Center for Engineering and Development (CEiiA) and the Institute of Social Sciences of the University of Lisbon, in the Citizenship and Development classes, as part of academic research on the role of the school community in

sustainable mobility in the city, for which she is responsible, and, likewise, the carrying out of such research, do not involve any other form of processing of students' personal data (without any collection of sound, image and personal information or information relating to identified or identifiable students), therefore falling within the academic activities and processing of personal data for which the school is legally competent, and consequently does not require the collection of any additional consent or authorization from the participating students and/or their guardians, either by the researcher or by the aforementioned institutions.

Author contributions

LF: Investigation, Data curation, Visualization, Conceptualization, Validation, Methodology, Formal Analysis, Writing – original draft, Writing – review and editing. LD: Formal Analysis, Methodology, Validation, Conceptualization, Writing – original draft, Writing – review and editing, Investigation, Visualization. JS: Writing – review and editing, Conceptualization, Validation. LS: Validation, Writing – review and editing, Conceptualization.

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