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Regionalized acceptance analysis of an agricultural energy management system in Germany

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In view of rising demand, energy is becoming a significant production and cost factor in industry and the economy. In addition to the consequences of climate change, the energy markets are tense and volatile due to inflation, war and higher borrowing costs. As a result of society's desire to phase out the use of fossil fuels, the focus is shifting to renewable energies as an alternative worldwide, but especially in Germany. In addition to industry, rural areas and agriculture, especially energy-intensive livestock farms, are also affected by this development and face additional economic challenges. Additional energy can be generated through the use of photovoltaic systems on the roofs of agricultural buildings or the operation of biogas plants. However, in order to be able to use the potential for renewable energy generation efficiently at all, intelligent electricity storage concepts and a globally unique energy management system (EMS) are absolutely essential in order to coordinate both inter-farm production processes and the varying energy demand in the electricity grid with the supply. As farms differ greatly both in terms of equipment and in terms of region, the question of a comprehensive market launch arises. The success or failure of this will depend to a large extent on user acceptance and application. The aim of this study is to use the web-based software tool ADOPT to forecast and predict the level of acceptance and the duration of the future market launch of the EMS innovation. Different regions in Germany (Bavaria, North Rhine-Westphalia, Mecklenburg-Western Pomerania) were selected in order to compare possible operational and region-specific differences. A very positive forecast result of 97%–98% after a market introduction period of around 8 years shows an optimistic trend. However, the ADOPT tool analyzes various influencing factors in parallel in a sensitivity analysis, which serve as strong signal generators for a later marketing concept. This shows that the economic efficiency and the existing equipment (electricity production, electricity consumption, storage) are the most important barriers to market introduction across regions and therefore critically reflect the overall result. However, various recommendations for action can be derived.

KEYWORDS

decentralized energy supply, agricultural energy management systems, renewable energies, market introduction, innovation, regionalized acceptance

1 Introduction

1.1 Background on global energy demand and climate change

Global demand for the resource "energy" has risen sharply in recent years (Energy Institute, 2024). The burning of fossil fuels in particular has a significant impact on global warming (Bundesministerium für wirtschaftliche Zusammenarbeit und Entwicklung (BMZ), 2022). In addition to their scientific significance, the consequences of climate change are increasingly forcing their way onto the agendas of politics and society (Charlotte Unger und Daniel Oppold. Bundeszentrale für politische Bildung, 2021), with some of the events extending into the health sector (Lehmkuhl, 2019). Due to the armed conflict between Russia and Ukraine, energy products are for the most part significantly more expensive, with producer prices for natural gas, for example, 50.7% higher in January 2023 than in January 2022 (Statistisches Bundesamt, 2023).

The socio-political transformation from fossil and nuclear energy generation to renewable energy sources is increasingly focusing on biomass, solar energy, geothermal energy and wind energy in Germany (Gawel et al., 2017). The rapid rise in the cost of natural gas is leading to higher electricity prices and an increase in costs for all consumer groups (Statistisches Bundesamt, 2022). According to estimates by the IEA (International Energy Agency), the peak in the use of fossil fuels will be reached before 2030, before there is a downward trend in fossil energy generation towards an effective transition to renewable energy sources (IEA, 2023). In 2020, the Federal Republic of Germany committed to increasing the share of renewables in "gross final energy consumption" to 30% by 2030 through the "National Energy and Climate Plan" (NECP) (Klaus et al., 2010). In addition, the European Union has decided to become the first climate-neutral continent by 2050 by establishing the "European Green Deal". This also means that the proportion of electricity from renewable sources is to increase to 42.5% by 2030 (Guillot, 2023).

The consequence of this transformation is also a change from centrally controlled and permanent grid stability, e.g., through nuclear power, to decentralized regulation of electricity generation from photovoltaics and wind power in the future (Höwer et al., 2019). The differences in regionalized energy production are thus set against the electricity demand from industry and households, which will lead to a change in supply and demand on the electricity market that needs to be balanced (Spiecker and Weber, 2014). The discussion about increasingly scarce fossil energy resources, the goal of a sustainable energy transition (Bartholdsen et al., 2019) and the need for regional grid regulation have recently led to an increasing focus on intelligent energy management systems (EMS) (Lachmann et al., 2020). This can be seen, for example, in the growing incentive to introduce EMSs in accordance with DIN EN ISO 50001 in the German economy (Marimon and Casadesús, 2017). In practice, however, the legal requirements for the envisaged energy regulation are often lacking (Gonçalves and Mil-Homens dos Santos, 2019).

1.2 Background to the "CowEnergySystem" project

Since 2013, the "Stable 4.0" research initiative has been working on the practical development of system-specific principles for the implementation of an operational energy management system (EMS) for agricultural dairy barns. In cooperation with three project partners from industry and with the support of the Federal Ministry of Food and Agriculture (BMEL), the group is working on a multi-stage research program with defined project phases and has already been able to gain practical and meaningful insights into the necessary requirements for such an operational energy management system on two pilot farms (Stumpenhausen and Bernhardt, 2016; Stumpenhausen and Bernhardt 2022). The EMS was implemented in a practical hardware and software solution (Bernhardt et al., 2021) and has now reached market maturity. Parallel to the growing degree of automation in the form of autonomous agricultural machinery and field robots in agriculture and horticulture (Gaus et al., 2017), indoor farming is also developing towards integrated dairy and energy production (integrated dairy farming) with a high degree of automation and sensor-controlled production monitoring (Lokhorst, 2018; Tedeschi et al., 2021). Due to the cross-production requirements for human-animal-technology interaction, further test farms will be included in the project program to gain further scientific knowledge and new foundations for the intelligent networking of relevant system elements and thus develop a complex communication structure for farm-specific load management (Höld et al., 2015; Höhendinger et al., 2023) even outside the production direction of milk production. The structural facilities required for animal husbandry (barn and storage buildings) offer the possibility of independent decentralized energy generation (photovoltaics, biogas, wind power) on site (Bernhardt et al., 2021). The holistic system view shows a realistic opportunity for a more efficient and sustainable use of existing resources in the field of renewable energies.

Figure 1 shows the complex structures of the integrated system with the most diverse areas of influence. In contrast to field management, there are no standardized data interfaces for the EMS, such as the ISOBUS standard in agricultural machinery technology. For this reason, separate actuators had to be developed for each system element to provide optimized internal network and communication technology. These actuators are electronic modules that interact as components of the technical barn system between the EMS and the individual energy consumers, thus ensuring an adaptable system installation. This proprietary sensor network makes it possible to store all important information via a cloud system and forward it accordingly. With the help of the EMS, it is thus possible to flexibilize both the times of use and the duration of use of the individual appliances during the day by coordinating energy generation, storage and energy consumption. The EMS uses other process-relevant production data, such as milk yield, current weather forecasts and barn climate data, to create real-time simulations (Höhendinger et al., 2018). From this, the system can draw conclusions about the future energy requirements of the existing barn components. If, for example, the use of an electric feed mixer wagon causes animal activity to focus on the feeding area, this is a good time to start the cleaning program of the automatic milking system (AMS). Logically, the energy required for cleaning must then

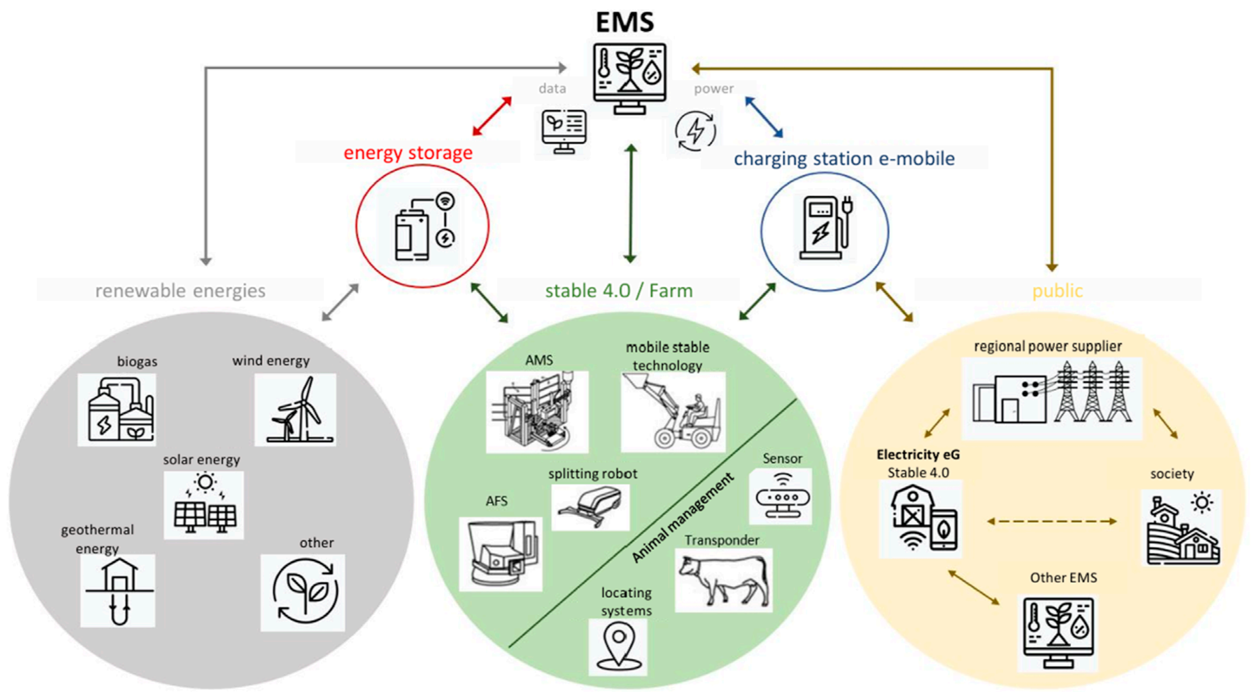

FIGURE 1
Integration of the on-farm energy management system into the production processes of an agricultural dairy farm (©TU Munich).

also be available at this time via the current energy production or already stored energy. The storage concept must therefore include a diversification of energy availability so that the EMS can take over the central control of energy flows according to supply and demand. Energy production on a farm is generally characterized by the fact that, on average, more electricity is generated than can be consumed by internal processes (Hartwig-Kuhn, 2021). This means that the remaining surplus energy can be sold into the public grid. The farm thus not only becomes energy self-sufficient, but also generates an additional source of income from existing resources and thus becomes a sustainable, decentralized energy service provider for rural areas (Bader et al., 2024).

1.3 Objective and problem definition of the "CowEnergySystem" project

Because of falling revenues due to inflation and the situation on the electricity market described above, the pressure on farmers to further reduce their production costs is also increasing. In such an environment, tensions between producers, retailers and consumers inevitably increase (Agrar-heute, 2019). As a result, the EMS presented can generate significant added value for the farms, but also for the municipalities and the population. Compared to the test farms presented, the agricultural production processes are very different both in terms of individual farm equipment and geographical location (Deutscher Bauernverband, 2017; Statistisches Bundesamt, 2021). The energy management system is a completely newly developed innovation and is the only one of its kind in the world for a specific sector. For the Free State of Bavaria, an initial survey was carried out in 2020 as part of a scientific study regarding the acceptance and market potential of an energy management system among dairy farmers (Beinert, 2020). The introduction of corresponding energy concepts is associated with extensive changes for farms and their management. Innovation research has shown that the success or failure of innovations is determined by their acceptance on the market (Wübbenhorst, 2018). In many cases, consequential problems arise in this context, ranging from internal barriers to innovation to general rejection (Möhrle and Specht, 2018) which significantly determine the spatial and temporal spread of an innovation (diffusion speed). Although the survey conducted on the use of an energy management system in Bavarian agriculture shows a positive basic acceptance, it is not yet possible to derive a more precise estimate of the market adaptation (Beinert, 2020). The necessary marketing strategies and targeted advertising measures associated with the introduction of the prototype on the market are particularly difficult to design from the survey.

This raises the question for those responsible for the "CowEnergySystem" research project as to the extent to which the industrial prototype can be marketed within the agricultural sector and which influencing factors can occur about the EMS (as an innovation) and the farmers (as users). In the present work, therefore, a more precise temporal and spatial forecast of the market adaptation for the innovative concept of the developed energy management system (EMS) is to be developed, initially for the region of Bavaria and subsequently nationwide. With the help of the web-based software tool ADOPT (Adoption and Diffusion Outcome Prediction Tool), the probable degree of adoption can be modeled, and the diffusion of this agricultural innovation can be predicted about the target group of dairy cattle farmers and analyzed on a region-specific basis.

2 Materials and methods

With the help of the web-based software tool ADOPT (Adoption and Diffusion Outcome Prediction Tool) developed by the University of South Australia, the likely degree of adoption and diffusion of an innovation for the target group of German dairy farmers can be predicted and evaluated (Kuehne et al., 2017; López-Maciel et al., 2022). In addition to predicting a possible adoption rate and maximum diffusion in practice, ADOPT provides a weighting of various factors that influence innovation diffusion. The model is flexible for the agricultural sector and uses a conceptual framework that incorporates a few variables, including questions of economics, risk, environmental impact, farm and farmer characteristics, and ease and convenience of using new technologies in practice. A consistent environment is assumed, while changes in prices or legal requirements, for example, cannot be considered. In practical comparisons, good correlations have already been found between the forecast results of ADOPT and practical data, for example, for automatic steering systems and no-till farming (CSIRO, 2018). Although ADOPT was originally designed purely for the agricultural sector, it is now also used for analyses outside of agriculture (Natcher et al., 2021; López-Maciel et al., 2023). For example, factors influencing the introduction of photovoltaic systems for water extraction in Australian sugar cane irrigation were evaluated using the ADOPT tool (Powell et al., 2021).

ADOPT is structured to look at four categories of influence (Figure 2). The ability to learn about the relative benefits of the process, which depend on the characteristics of both the management system and the potential users (farmers), plays a central role. ADOPT users responded to 22 questions on the following characteristics.

a) the application practice that influences its relative advantage,
b) the user population and its environment, which influence the perception of the relative advantage in practice,
c) the ease and speed of learning, which influence the willingness to use it in practice, and
d) the potential users, in terms of their ability to put the application into practice.

The user has the option of weighting the respective variables within various specific scales, e.g., from 1 to 5, 1 to 6 or 1 to 8, when answering. In addition to predicting the duration of dissemination in practice, the ADOPT tool also provides the option of sensitivity analyses about the factors that influence speed and maximum dissemination in particular (Kuehne et al., 2011).

The standard ADOPT model in the CSIRO version from 2018 was used to analyze the adaptation of the EMS. The innovation under investigation was defined for the federal states of Bavaria, North Rhine-Westphalia and Mecklenburg-Western Pomerania and the target population was defined as "farmers with dairy cattle farming". This selection was made on the basis of region-specific differences between the three federal states:

(a) North-south divide; based on demographic differences between the border with the east coast (Mecklenburg-Western Pomerania), the central highlands and lowlands (North Rhine-Westphalia) and the Alpine foothills and mountains (Bavaria).
b) Farm situation based on the type of management and equipment of the farms (number of animals, area, income) as illustrated in Table 1.
c) Forced electricity production (e.g., PV systems in the Alpine foothills, wind power on the coast) and the production of milk in the typical dairy regions of Germany.

The scaling and weighting of the 22 variables (Table 2) was based on an extensive literature review and the relevant arguments from the previous survey results (Beinert, 2020). In addition to a SWOT analysis, individual value drivers and the size of potential EMS users within the industry were also queried. The following is an example of the analysis of variable assignment using the example of question 4 for the federal state of Bavaria. The determination of the scaling as described in the following example was therefore carried out for all three federal states and for the respective 22 variables and analyzed in the online tool.

Analogous to the example presented, all 22 questions to be answered were scaled according to the ADOPT selection based on literature research. Since the federal states of Bavaria, North Rhine-Westphalia and Mecklenburg-Western Pomerania differ greatly both geographically and agriculturally (Table 1), it is important for the future regional marketing concept to examine these supposed differences through the ADOPT program.

The ADOPT program was then used to create a separate data analysis for each federal state. Table 2 shows the corresponding variable scaling for the three federal states of Bavaria (BY), North Rhine-Westphalia (NRW) and Mecklenburg-Western Pomerania (MV).

For the 22 variables of the three selected federal states, the following change in results (sensitivity) results about acceptance duration and acceptance level when the respective variable scaling is changed by ± 1 scale point (Table 3). If, for example, the scaling for question 2 "Environmental orientation" is lowered by one point with an initial value for NRW of 4, the level of acceptance falls by 0.075% and the duration of acceptance by 0.10 years.

3 Results

3.1 Main results

Under the defined initial situation and the associated variable assignment, the peak of market introduction is expected after 7 or 8 years for farms in Bavaria, North Rhine-Westphalia and Mecklenburg-Western Pomerania. Market penetration is expected at a maximum adaptation rate of 98% (Figure 2).

For the initial situation in North Rhine-Westphalia, market penetration can already be expected after 7 years, with the acceptance level also reaching 98% (Figure 3).

The same result was also shown in the forecast for the federal state of Mecklenburg-Vorpommern (Figure 4).

A regional comparison of the adaptation process over time is shown in Table 4 and graphically illustrated in Figure 5.

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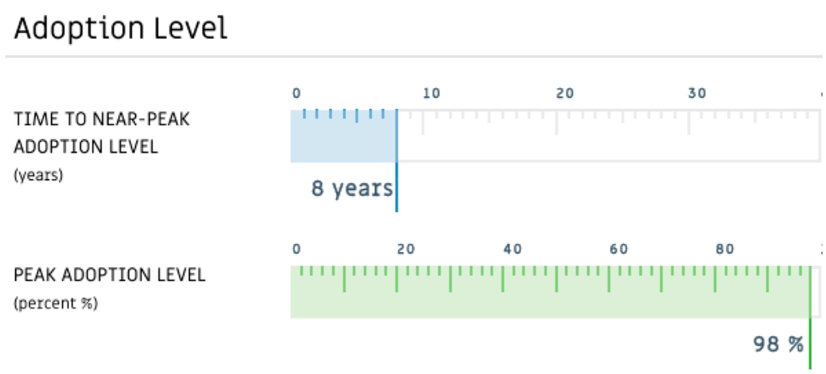

FIGURE 2
Result of the ADOPT tool forecast for the introduction of an EMS in Bavaria.

TABLE 1 Key figures for primary agricultural holdings in selected federal states 2021/22 (BMEL, 2023).

	Bavaria (BY)	North rhine Westphalia (NRW)	Mecklenburg-Vorpommern (MV)
Ø- Agricultural area (ha)	65,9	70,5	293,0
Manpower/100ha	3,0	3,5	1,0
Livestock/100ha	134,3	238,5	35,7
Operating income €/ha	5.203	7.607	2.449
Operating costs €/ha	4.106	6.291	1.974
Company profit €/ha	1.047	1.234	410
Total company profit (€)	69.039	87.009	120.159

Question 4) Enterprise scale - On what proportion of the target farms is there a major enterprise that could benefit from the innovation?
Due to the steady decline in the number of farms, there has been a significant structural change in the agricultural sector. However, this differs from region to region and in terms of socio-economic farm types (Halama, 2021). Almost half of all dairy farmers in Germany (59,925 farms - in 2019) are based in Bavaria (27,588 farms - in 2019), regardless of whether they are conventional or organic. At the same time, the number of farms with an automatic milking system (AMS) continues to grow steadily (Paulsen and Moritz, 2020). In 2021, the Landeskuratorium der Erzeugerringe für tierische Veredelung in Bayern e.V. (LKV) registered around 2.900-member farms with one or more milking boxes (Landeskuratorium der Erzeugerringe für tierische Veredelung in Bayern e. V., 2022). This in turn corresponds with the survey results of the project study at the Weihenstephan-Triesdorf University of Applied Sciences (Beinert, 2020). In the study, 48.9% of participants were already equipped with an AMS. A further 8.1% are planning to invest in an AMS in the foreseeable future (in the next 5 years). In terms of farm size, measured by livestock numbers, around 50% of the farms have livestock in the order of 50 livestock units and 125 livestock units per farm. It can therefore be assumed that, based on livestock numbers, around half of them run a medium to large farm that could be considered for the use of an EMS, especially as around 57% will work with an AMS in the medium term. This indicates a positive correlation with the use of further innovations in the field of automation (Beinert, 2020).
ADOPT assessment: "About half of the target farms have a major enterprise that could benefit"
Definition of scaling: 3 - (for selection options 1–5)

3.2 Analysis of the influence on the acceptance level

The sensitivity analysis for the maximum acceptance of innovative EMS technology clearly shows that company size (question 4 - "In what proportion of the target companies is there a larger company that could benefit from the innovation?") has the greatest influence in all federal states (Figure 6). Other decisive factors are the short-term and long-term profit expectations (questions 16 and 17), the variation of which is in the order of –0.2% (scaling –1) and +0.15% (scaling +1) respectively. Overall, the Free State of Bavaria therefore exhibits the greatest variation in influence. In contrast, the variables in the "learning characteristic" category have no influence on the level of acceptance of the innovation, neither for the innovation itself (questions 7–9) nor for the user (questions 10–13) (Figure 6).

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TABLE 2 Overview of the selected responses and the associated scaling of the ADOPT analysis for selected federal states.

Question	Variable in ADOPT	Scaling range	Scaling Bavaria (BY)	Scaling North Rhin Westphalia (NRW)e	Scaling Mecklenburg-Vorpommern (MV)
Relative Advantage for the Population					
1	Profit orientation	(1–5)	5	5	5
2	Environmental orientation	(1–5)	3	4	3
3	Risk orientation	(1–5)	4	4	4
4	Enterprise scale	(1–5)	3	3	4
5	Management horizon	(1–5)	4	4	3
6	Short term constraints	(1–5)	3	4	4
Learnability Characteristics of the Innovation					
7	Trialable	(1–5)	4	4	4
8	Innovation complexity	(1–5)	5	5	5
9	Observability	(1–5)	1	1	1
Learnability of Population					
10	Advisory support	(1–5)	3	3	3
11	Group involvement	(1–5)	4	4	3
12	Relevant existing skills and knowledge	(1–5)	3	3	3
13	Innovation awareness	(1–5)	2	2	2
Relative Advantage of the Innovation					
14	Relative upfront cost of the project	(1–5)	3	3	3
15	Reversibility of the innovation	(1–5)	2	2	2
16	Profit benefit in years that it is used	(1–8)	6	6	6
17	Future profit benefit	(1–8)	6	6	6
18	Time until any future profit benefits are likely to be realised	(1–6)	5	5	5
19	Environmental costs and benefits	(1–8)	8	8	8
20	Time to environmental benefit	(1–6)	5	5	5
21	Risk exposure	(1–8)	7	7	7
22	Ease and convenience	(1–8)	7	7	7

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TABLE 3 Overview of the influence of the variables when changing the scaling by ± 1 (sensitivity).

Question	Bavaria (BY)				North rhine-Westphalia (NRW)				Mecklenburg-Vorpommern (MV)			
	"Change inacceptance (%)"		Time to maximum acceptance (years)		"Change inacceptance (%)"		Time to maximum acceptance (years)		"Change inacceptance (%)"		Time to maximum acceptance (years)	
	Scaling down (−1)	Scaling up (+1)	Scaling down (−1)	Scaling up (+1)	Scaling down (−1)	Scaling up (+1)	Scaling down (−1)	Scaling up (+1)	Scaling down (−1)	Scaling up (+1)	Scaling down (−1)	Scaling up (+1)
Relative Advantage for the Population												
1	−0,100	0,000	0,000	0,100	−0,050	0,000	0,000	0,200	−0,010	0,000	0,000	0,200
2	−0,150	0,000	−0,200	0,200	−0,075	0,025	−0,100	0,200	−0,010	0,010	−0,200	0,200
3	−0,050	0,000	−0,100	0,000	−0,010	0,010	0,000	0,100	−0,010	0,000	−0,100	0,100
4	−0,600	0,150	−0,500	0,500	−0,375	0,050	−0,500	0,600	−0,100	0,010	−0,500	0,500
5	0,000	0,000	−0,100	0,000	−0,010	0,010	0,000	0,100	−0,010	0,010	0,000	0,100
6	0,000	0,000	−0,750	0,750	0,000	0,000	−0,750	0,800	0,000	0,000	−0,750	0,800
Learnability Characteristics of the Innovation												
7	0,000	0,000	−1,200	1,200	0,000	0,000	−1,200	1,250	0,000	0,000	−1,200	1,200
8	0,000	0,000	0,000	1,200	0,000	0,000	0,000	1,250	0,000	0,000	0,000	1,200
9	0,000	0,000	−0,600	0,000	0,000	0,000	−0,500	0,000	0,000	0,000	−0,500	0,000
Learnability of Population												
10	0,000	0,000	−0,600	0,600	0,000	0,000	−0,500	0,600	0,000	0,000	−0,600	0,600
11	0,000	0,000	−0,400	0,400	0,000	0,000	−0,350	0,400	0,000	0,000	−0,400	0,400
12	0,000	0,000	−0,900	0,900	0,000	0,000	−0,800	0,900	0,000	0,000	−1,100	1,200
13	0,000	0,000	−0,700	0,700	0,000	0,000	−0,700	0,750	0,000	0,000	−0,700	0,700
Relative Advantage of the Innovation												
14	0,000	0,000	−0,100	0,800	−0,010	0,010	0,000	0,900	−0,010	0,000	0,000	0,800
15	0,000	0,000	−0,100	0,000	−0,010	0,010	0,000	0,100	−0,010	0,000	0,000	0,100

(Continued on the following page)

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TABLE 3 (*Continued*) Overview of the influence of the variables when changing the scaling by ± 1 (sensitivity).

Question	Bavaria (BY)				North rhine-Westphalia (NRW)				Mecklenburg-Vorpommern (MV)			
	"Change inacceptance (%)"		Time to maximum acceptance (years)		"Change inacceptance (%)"		Time to maximum acceptance (years)		"Change inacceptance (%)"		Time to maximum acceptance (years)	
	Scaling down (−1)	Scaling up (+1)	Scaling down (−1)	Scaling up (+1)	Scaling down (−1)	Scaling up (+1)	Scaling down (−1)	Scaling up (+1)	Scaling down (−1)	Scaling up (+1)	Scaling down (−1)	Scaling up (+1)
16	−0,200	0,150	−0,250	0,250	−0,100	0,040	−0,250	0,250	−0,040	0,005	−0,250	0,300
17	−0,200	0,150	−0,250	0,250	−0,090	0,040	−0,200	0,250	−0,040	0,005	−0,250	0,300
18	0,000	0,000	0,000	0,000	−0,010	0,010	0,000	0,100	0,010	0,010	0,000	0,100
19	−0,150	0,000	0,000	0,200	−0,090	0,000	0,000	0,250	−0,030	0,000	0,000	0,250
20	0,000	0,000	−0,100	0,000	−0,010	0,010	0,000	0,100	0,000	0,000	0,000	0,100
21	−0,150	0,150	−0,200	0,200	−0,080	0,040	−0,200	0,250	−0,010	0,005	−0,200	0,250
22	−0,150	0,150	−0,200	0,200	−0,075	0,030	−0,200	0,200	−0,010	0,005	−0,200	0,250

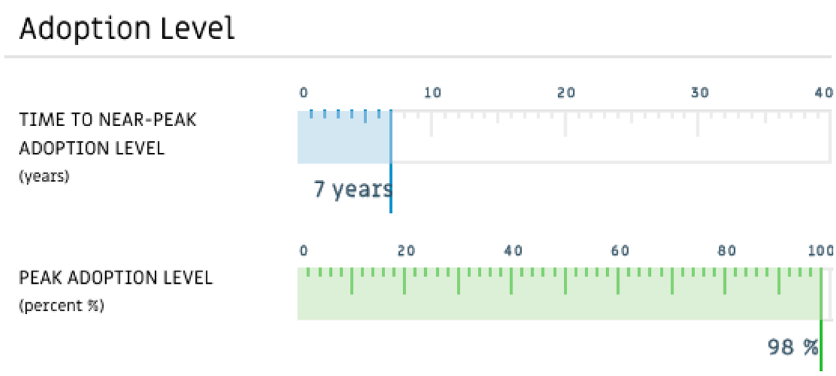

FIGURE 3
Result of the ADOPT tool forecast for the introduction of an EMS in North Rhine-Westphalia.

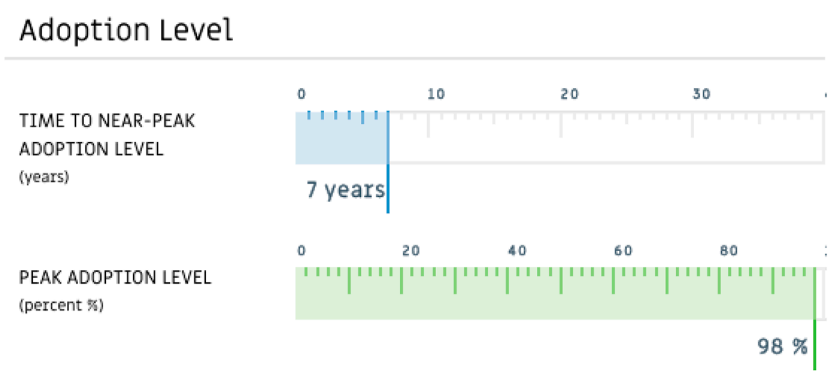

FIGURE 4
Result of the ADOPT tool forecast for the introduction of an EMS in Mecklenburg-Vorpommern.

TABLE 4 Development of the annual adoption rate in the federal states analyzed.

Year (peak adoption)	Adoption (%) bavaria (BY)	Adoption (%) north rhine Westphalia (NRW)	Adoption (%) mecklenburg-vorpommern (MV)
1	3	4	4
2	15	20	20
3	36	44	44
4	58	68	67
5	76	84	84
6	87	93	92
7	94	97	96
8	97	—	—

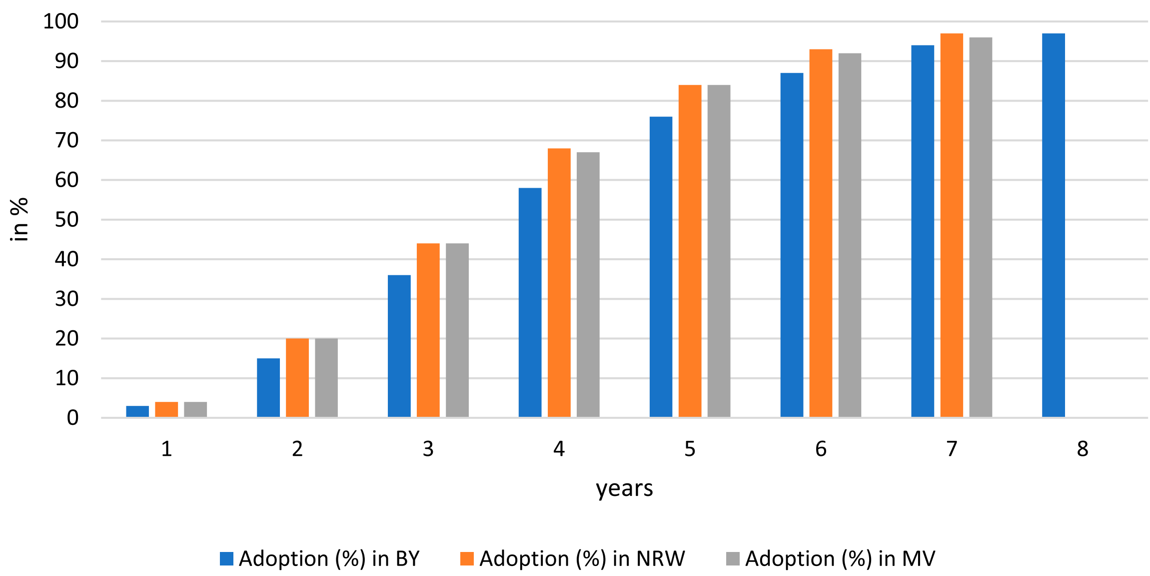

FIGURE 5
Development of the annual adoption rate in the federal states analyzed.

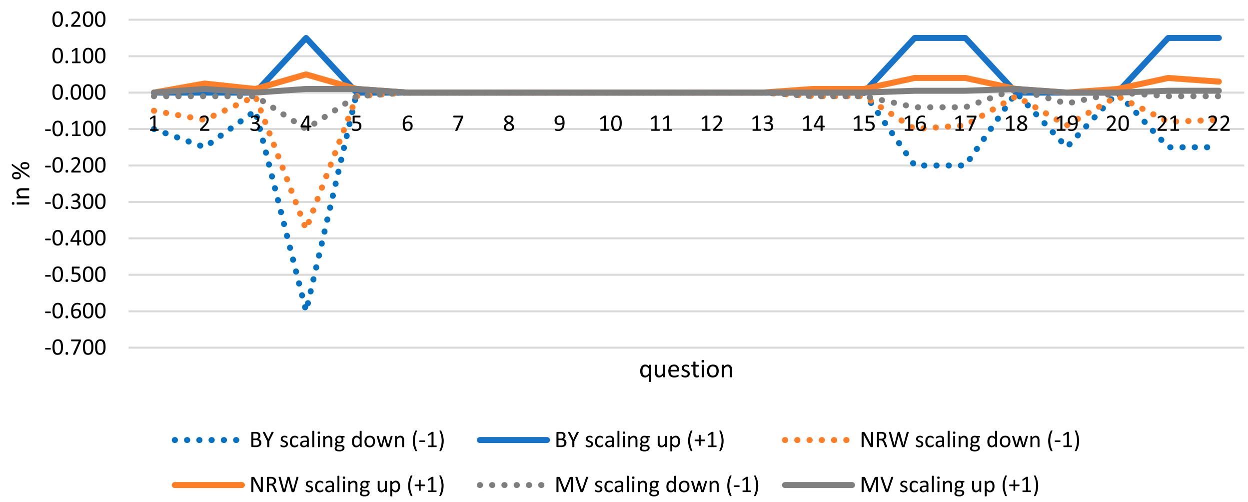

FIGURE 6
Sensitivity effects of the individual variables on the maximum acceptance level in the selected federal states.

3.3 Analysis on the influence on adoption duration

Parallel to the general acceptance, the influence of the various variables on the sensitivity of the diffusion period of the innovation was also calculated. The effects for the federal states are summarized in Figure 7. The highest rate of change is found for question 7 - "Testing of the innovation" about the duration; it amounts to +1.25 years (scaling −1) and −1.20 years (scaling +1) in the federal state of North Rhine-Westphalia, followed by Bavaria and Mecklenburg-Western Pomerania with ±1.2 years. When looking at the individual effects, all variables have an impact on the adaptation period, albeit to a very small extent in some cases (Figure 7).

4 Discussion

4.1 Discussion of the main results

The primary aim of this work was to predict how an innovative energy management system will spread in the potential market of selected German federal states with the help of the two parameters adaptation rate and the associated adaptation speed. A market penetration rate of 98% was forecast for the group of dairy farms, leading to maximum dissemination within 7 or 8 years of market launch. The ADOPT tool used thus helps to make a quantified statement on the spread of the "EMS" innovation, in contrast to a pure survey. In principle, the number of 22 variables included

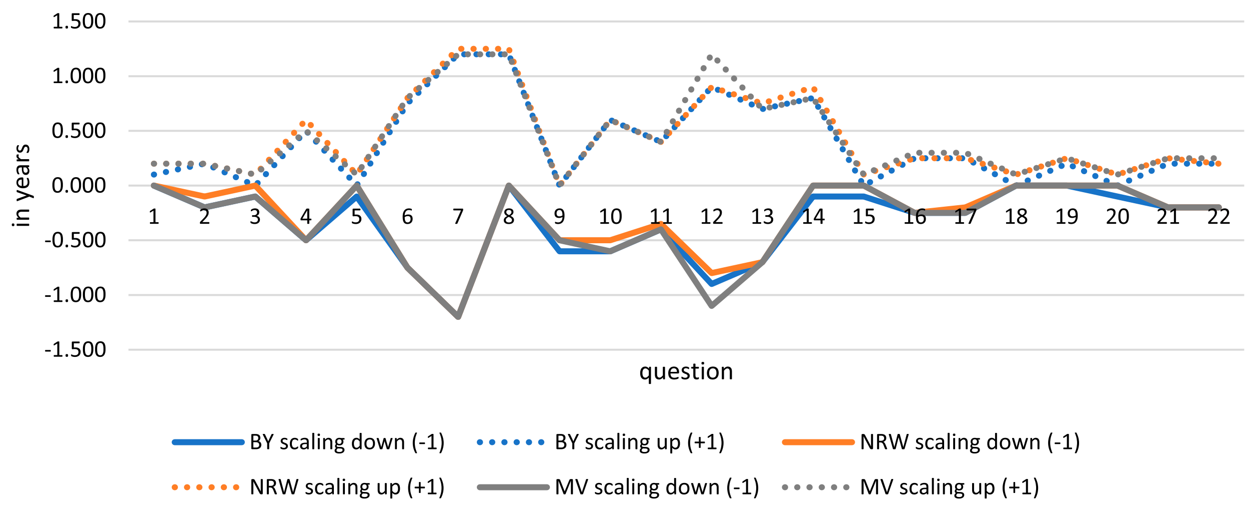

FIGURE 7
Sensitivity effects of the individual variables on the acceptance period in the selected federal states.

does justice to the complexity of the question. However, it must be critically noted that although reference relationships between the variables are shown graphically (Figure 8), there is a lack of concrete information on the calculation methodology (e.g., about variable weighting, etc.) both in the input mask and in the digital explanations (López-Maciel et al., 2022). A further weakness lies in the previous rasterization of the variables, which were specified in a range of 1-5 for 15 influencing variables (i.e., around 68%), which may represent a (too) rough classification of the respective assessment criterion. However, a test using the new PRO version of CSIRO ADOPT (with extended scaling options 1–7) did not reveal any significant changes in the results. Both the main results and the sensitivity analyses were almost identical between the standard version and the PRO version. However, a review of the results using the new PRO version of CSIRO ADOPT (with extended scaling options 1–7) did not reveal any significant changes in the results. Both the main results and the sensitivity analyses were almost identical between the CSIRO standard version and the CSIRO PRO version. This means that a more precise scaling does not have a decisive influence on the acceptance level and acceptance duration when introducing an EMS in the agricultural sector. The result of the review seems plausible, as the data basis and literature research of the variable assignment of the 22 questions to be answered remains identical. A basic positive or negative trend in the respective definition of the scaling remains in place, with only insignificant deviations to be noted.

Another point of criticism lies in the assessment of the economic benefits of innovation, which would be fundamentally necessary for a more realistic scaling of variables. This relates less to the tool and the corresponding scaling itself than to the background data required for the scaling. Especially as the innovation is currently still in the pilot phase and therefore the actual company-specific benefit cannot be stated with certainty. A penetration rate of almost 100% seems very optimistic overall. In this context, it is assumed that all technically possible elements (e.g., AMS, ice water cooling, e-vehicles, PV or biogas system) are already available on the farms, except for the EMS and additionally required energy storage systems. However, the liquidity assessment and economics change accordingly as the amount of additional technology to be purchased increases. A decrease in the benefit expectation, e.g., due to higher investments, certainly leads to a lower spread and/or correspondingly longer adaptation time.

This is also underlined by an economic evaluation of the Federal Ministry of Food, Agriculture and Forestry, which addresses the investment power of the main commercial farms in a highly variable manner according to the type of farm and location (BMEL, 2022).

4.2 Discussion of the learning properties category

The ADOPT program groups 22 restrictions (questions) to be evaluated into four categories, which can be subdivided into "learning characteristics" and "advantage/relative advantage". The tool differentiates between the innovation (the on-farm EMS) and the so-called target population (dairy farms) in the evaluation. In this context, the effects of the variables within the same category can be compared using sensitivity analysis. The analysis of the "learning characteristics" category shows that the level of acceptance did not change either for the innovation itself (questions 7–9) or for the target population (questions 10–13), despite variation of the associated variables (scaling ±1). The situation is different for the duration of adaptation, where effects were found in each case. This result seems plausible, as there are no changes in the basic acceptance of the EMS with corresponding variable variation and therefore no effective change in the adaptation rate is to be expected (Table 5).

In the case of a longer period of time required for testing or a greater need for knowledge transfer for the users, the assumed delay only affects the adaptation time for all three federal states. In the case of the variable "testing" in question 7, this would mean an extension of 1.25 or 1.20 years and, in the case of longer knowledge transfer, an increase of 0.90–1.20 years.

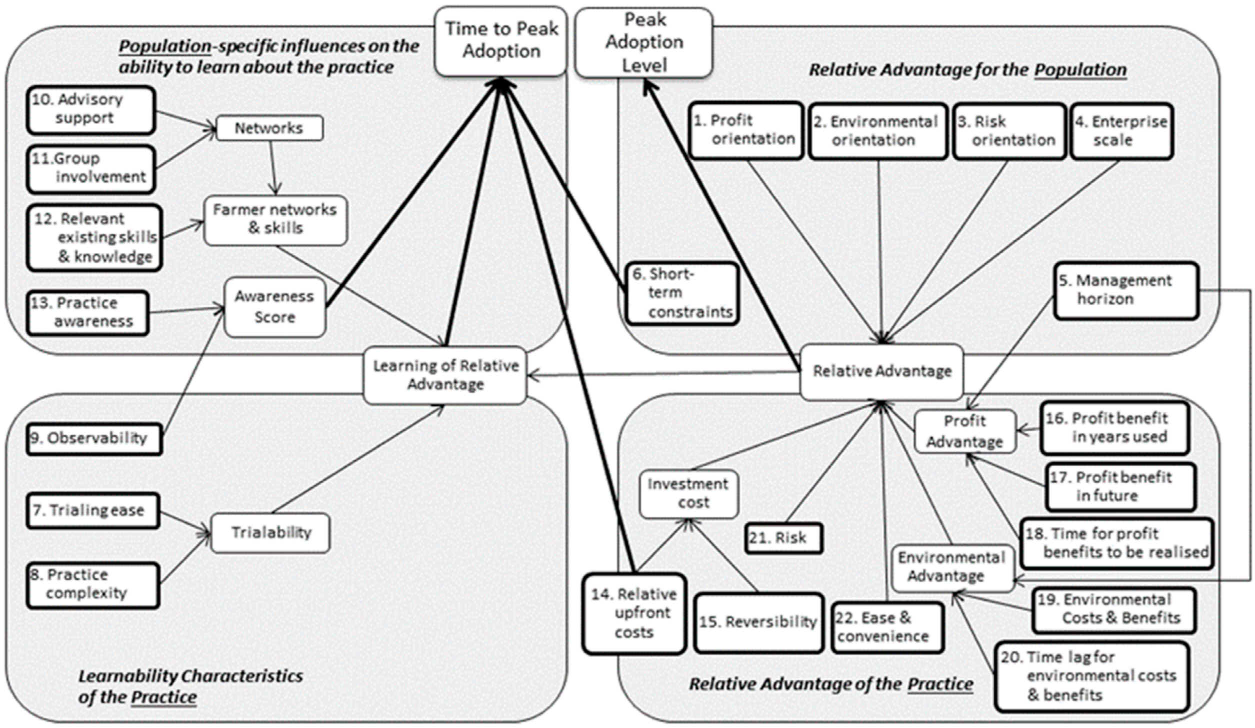

FIGURE 8
How CSIRO ADOPT's Adoption and Diffusion Outcome Prediction Tool works.

In principle, it can be said of the influence of the "learning characteristics" category that, depending on the initial position, an acceleration or delay in learning will shorten or lengthen the adaptation time accordingly, without necessarily changing the acceptance of the on-farm EMS. For the planned market launch of the EMS, it must therefore be recommended that targeted training and information measures help to shorten the time it takes to reach the peak of adaptation. In concrete terms, faster testing during the current research phase means faster adaptation and early measures for knowledge transfer in the target group, for example, through articles in specialist journals or trade fair presentations, contribute to accelerated adaptation of the EMS. The results of Beinert's survey (Beinert, 2020) support the finding that trade journals, the internet and contacts at agricultural trade fairs contribute to a stronger exchange and better knowledge transfer within the sector. It should also be mentioned that this finding from the first study for the federal state of "Bavaria" (Bader et al., 2024) was also confirmed in an extended regional comparison.

4.3 Discussion category advantageousness

If the second relevant main category "Advantages or relative advantage" is considered, the possibilities of influence are more pronounced (Figure 7). However, it is important to mention here that the level of the respective individual influence is very low. The most effective variable (question 4 - company size) is only −0.60% for Bavaria in terms of the adaptation rate (98%), −0.37% in North Rhine-Westphalia and −0.10% in Mecklenburg-Western Pomerania (scaling −1) (Table 6).

The influence of the "Advantageousness" category on the adaptation time is also very low, with an average range of +0.49 years (scaling +1) to −0.31 years (scaling −1) in the three federal states. It can also be seen that most variables within the main category "Advantageousness" have a simultaneous effect on both adaptation indicators (Figure 7; Table 6). It must be emphasized that some variables stand out in the question pool involved, for example, the size of the company (variable 4) or the investment-related, short-term financial restrictions (variable 6). It is also evident - and understandable - that the expected monetary success (variables 16 and 17) also has a decisive influence on the spread of the innovation.

In summary, this means that a corresponding marketing concept to be drawn up should specifically address these points. An investment or financing-oriented entry scenario must be developed as an aid for the innovation decision and as a basis for consultation. The economic advantages still need to be placed on a more stable data basis using reliable practical results and communicated accordingly using model calculations. It is precisely when the benefits of an EMS appear to be positive from both the ecological aspect in the form of regenerative energy generation and from an economic point of view that the decision of potential customers is increasingly steered in the direction of adopting the innovative technology (Sundrum, 2022). In addition to the purely economic aspects, risk minimization (variable 21) and easier management (variable 22) also have a significant, if only indirect, influence on the perception of added value. This finding is also confirmed in the preliminary analysis for Bavaria (Bader et al., 2024). Overall,

TABLE 5 Result of the sensitivity analysis of the category "learning property" depending on selected federal states.

Question number	Bavaria (BY)				North rhine-Westphalia (NRW)				Mecklenburg-Vorpommern (MV)			
	"Change inacceptance (%)"		Time to maximum acceptance (years)		"Change inacceptance (%)"		Time to maximum acceptance (years)		"Change inacceptance (%)"		Time to maximum acceptance (years)	
	scaling down (−1)	scaling up (+1)	scaling down (−1)	scaling up (+1)	scaling down (−1)	scaling up (+1)	scaling down (−1)	scaling up (+1)	scaling down (−1)	scaling up (+1)	scaling down (−1)	scaling up (+1)
Learning properties of the innovation												
7	0,000	0,000	−1,200	1,200	0,000	0,000	−1,200	1,250	0,000	0,000	−1,200	1,200
8	0,000	0,000	0,000	1,200	0,000	0,000	0,000	1,250	0,000	0,000	0,000	1,200
9	0,000	0,000	0,600	0,000	0,000	0,000	−0,500	0,000	0,000	0,000	−0,500	0,000
Learning properties of the population												
10	0,000	0,000	−0,600	0,600	0,000	0,000	−0,500	0,600	0,000	0,000	−0,600	0,600
11	0,000	0,000	−0,400	0,400	0,000	0,000	−0,350	0,400	0,000	0,000	−0,400	0,400
12	0,000	0,000	−0,900	0,900	0,000	0,000	−0,800	0,900	0,000	0,000	−1,100	1,200
13	0,000	0,000	−0,700	0,700	0,000	0,000	−0,700	0,750	0,000	0,000	−0,700	0,700

TABLE 6 Result of the sensitivity analysis of the category "Advantageousness" depending on selected federal states.

Question	Bavaria (BY)				North rhine-Westphalia (NRW)				Mecklenburg-Vorpommern (MV)			
	"Change inacceptance (%)"		Time to maximum acceptance (years)		"Change inacceptance (%)"		Time to maximum acceptance (years)		"Change inacceptance (%)"		Time to maximum acceptance (years)	
	Scaling down (−1)	Scaling up (+1)	Scaling down (−1)	Scaling up (+1)	Scaling down (−1)	Scaling up (+1)	Scaling down (−1)	Scaling up (+1)	Scaling down (−1)	Scaling up (+1)	Scaling down (−1)	Scaling up (+1)
Advantage for the population												
1	−0,100	0,000	0,000	0,100	−0,050	0,000	0,000	0,200	−0,010	0,000	0,000	0,200
2	−0,150	0,000	−0,200	0,200	−0,075	0,025	−0,100	0,200	−0,010	0,010	−0,200	0,200
3	−0,050	0,000	−0,100	0,000	−0,010	0,010	0,000	0,100	−0,010	0,000	−0,100	0,100
4	−0,600	0,150	−0,500	0,500	−0,375	0,050	−0,500	0,600	−0,100	0,010	−0,500	0,500
5	0,000	0,000	−0,100	0,000	−0,010	0,010	0,000	0,100	−0,010	0,010	0,000	0,100
6	0,000	0,000	−0,750	0,750	0,000	0,000	−0,750	0,800	0,000	0,000	−0,750	0,800
Relative advantage of innovation												
14	0,000	0,000	−0,100	0,800	−0,010	0,010	0,000	0,900	−0,010	0,000	0,000	0,800
15	0,000	0,000	−0,100	0,000	−0,010	0,010	0,000	0,100	−0,010	0,000	0,000	0,100
16	−0,200	0,150	−0,250	0,250	−0,100	0,040	−0,250	0,250	−0,040	0,005	−0,250	0,300
17	−0,200	0,150	−0,250	0,250	−0,090	0,040	−0,200	0,250	−0,040	0,005	−0,250	0,300
18	0,000	0,000	0,000	0,000	−0,010	0,010	0,000	0,100	0,010	0,010	0,000	0,100
19	−0,150	0,000	0,000	0,200	−0,090	0,000	0,000	0,250	−0,030	0,000	0,000	0,250
20	0,000	0,000	−0,100	0,000	−0,010	0,010	0,000	0,100	0,000	0,000	0,000	0,100
21	−0,150	0,150	−0,200	0,200	−0,080	0,040	−0,200	0,250	−0,010	0,005	−0,200	0,250
22	−0,150	0,150	−0,200	0,200	−0,075	0,030	−0,200	0,200	−0,010	0,005	−0,200	0,250

the trend in the influence of variables also shows great regional similarities.

5 Conclusion

This study investigated the question of how the central element of an energy management system (EMS) developed as part of the "Stable 4.0" concept by Bernhardt and Stumpenhausen (2013–2024) can be established across regions in German dairy farms. The basic idea of the overall concept is to combine the energy consumers of a dairy cattle barn (e.g., milk production and cooling, feeding, ventilation) with energy generation and storage (photovoltaics, biogas, hydrogen) in such a way that, on the one hand, extensive individual farm energy self-sufficiency can be achieved, but also energy networking in the form of a regional network with the integration of supply relationships with local energy supply companies in rural areas.

The project managers are interested in the extent to which the industrial prototype can be introduced within the user group and region. So far, attempts have been made to determine interest in this innovation with the help of traditional surveys and user interviews. Despite the positive response, it has not yet been possible to make a sufficiently precise indicator-based assessment of adaptation. With the help of CSIRO's ADOPT tool, the temporal and spatial market adaptation of technical innovations can be predicted using 22 scaled questions. The results for the three exemplary federal states of Bavaria, North Rhine-Westphalia and Mecklenburg-Western Pomerania are as follows:

1) A market acceptance of 97%–98% within the predefined user group was predicted for the EMS in question and the diffusion period until maximum market penetration is reached was estimated at 8 years. This was the first time that a regional comparison could be presented and valid figures on the diffusion of this innovation could be presented.
2) However, when using the ADOPT tool, it must be critically noted that some of the calculation algorithms and variable weighting in the tool are not described in a sufficiently comprehensible manner. This nevertheless casts the (comparatively very positive) overall result in a critical light. The tool also does not take into account any possible external influences (market developments, subsidies, remuneration) of a market launch. It should also be noted that the target companies are assumed to already have existing operational equipment (PV system, electricity storage and consumers, etc.).
3) In the in-depth impact analysis of the (2 × 2) influence categories used in the tool, individual main influencing variables such as "company size", but also "current and future benefit expectations", were found to be significant for the intensity of adaptation, which indicates a need for further investigation. This finding is in line with the value drivers mentioned in the survey, which can directly and extensively influence a purchase decision. It will therefore be necessary to work out the economic principles and necessary framework conditions in more detail, particularly for the added value for the business, to provide farmers with reliable information about the EMS used so that the purchase decision can be positively influenced accordingly. The question of economic viability in a region- and farm-specific analysis (BMEL, 2022) also becomes clear in the variable characteristics of the ADOPT analysis.
4) Although the ADOPT tool was originally designed purely for the agricultural sector, it is now also used for analyses outside agriculture (Natcher et al., 2021; López-Maciel et al., 2023). Good correlations have already been established between the forecast results of ADOPT and practical figures, for example, for the use of GPS autosteer steering in tractors and new perennial legumes for low-precipitation pastures (CSIRO, 2018) and for the introduction of photovoltaic systems for water pumping in Australian sugar cane irrigation systems (Powell et al., 2021).

5.1 Outlook

In the current "CowEnergySystem" project, the functionality of a newly developed energy management system is to be tested about the optimization of electricity flows in dairy farms (Stumpenhausen and Bernhardt, 2022). Supported by the planned pre-series test on ten additional farms, the aim is to confirm that the EMS can be used permanently and reliably. The functional capability should also be tested with different technical equipment in the stables and for both new buildings and existing facilities. In addition to technical and application-related investigations, a necessary component of the research project is the rapid creation of a marketing concept to be able to start an information and participant recruitment campaign that is as target group and region-oriented as possible. The internal drivers and the main category "learning characteristics of the (target) population" used in the ADOPT tool do not differ significantly about the regional-geographical location of the operations (Bader et al., 2024). Likewise, the hypothesis that differences in farm equipment and production orientation between a northern German and a southern German dairy farm in the category "advantage for the population" have an impact on the adaptation of an EMS was not confirmed. This can be explained by the fact that the statistically confirmed influence of decisive variables follows a similar course. For successful market adaptation, even more extensive economic and region-specific modeling with farm-specific data is essential. This is the only way to demonstrably achieve not only economic, but also ecological added value for the agricultural and national economy. The ADOPT tool provides well-founded key figures for this purpose, making it possible for the first time to compare them with operating figures from practice. One recommendation for the future implementation of an energy management system in the agricultural sector is for political representatives to create a feasible framework that focuses on efficient energy storage and the intelligent use of resources in addition to purely renewable electricity production. These new incentives for energy transformation through decentralized and renewable electricity storage can thus make a significant contribution to balancing the electricity demand from industry and households. As a result, the fluctuations in supply and demand on the electricity market could be regulated. By using an energy management system, unused synergies in agriculture and society can be leveraged and lead to a higher degree of self-sufficiency in energy resources.

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

CB: Conceptualization, Data curation, Formal Analysis, Methodology, Validation, Visualization, Writing – original draft, Writing – review and editing. EG: Conceptualization, Data curation, Formal Analysis, Methodology, Validation, Writing – review and editing. JS: Conceptualization, Funding acquisition, Project administration, Supervision, Writing – review and editing. TE: Data curation, Formal Analysis, Investigation, Writing – review and editing. LH: Data curation, Formal Analysis, Investigation, Writing – review and editing. HB: Conceptualization, Funding acquisition, Project administration, Supervision, Writing – review and editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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