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Pushing the Boundaries of Electric Energy Management at German Dairy Farms

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“Science may set limits to knowledge, but should not set limits to imagination.”
Bertrand Russel (1945). *A History of Western Philosophy.*

Abstract

The demand for dairy products is on the rise both due to the global population growth and an increasing per capita demand for milk products. Forecasts state that the global milk production will increase by 19 % between 2021 and 2031. This development poses a global challenge since, already in 2015, Greenhouse gas (GHG) emissions from the dairy sector accounted for around 3 % of the carbon footprint worldwide. That is why a series of countries – including Germany – strive for more environmental sustainability along the dairy supply chain. In this context, there are already trends observable that are conducive for a reduction of GHG emissions from German dairy farming – such as an increasing milk yield per cow. However, to move towards a net zero milk production, German dairy farms should pursue further carbon removal and mitigation strategies while also keeping or even improving their as-is profitability. In this context, electric energy management – i.e., the management of electricity from procurement to utilization – is one important approach impacting both a dairy farm's GHG balance and its financial balance sheet.

Against this background, this dissertation investigates selected research fields of electric energy management at German dairy farms that so far have rarely been addressed by pertinent literature. More specifically, the three embedded publications of this dissertation deal with (1) the development of energy-related revenues at German dairy farms in the next 10 years, (2) the market opportunity for offering digital energy management services (DEMSs) to German dairy farmers, and (3) the implementation of DEMSs in the context of digital agricultural (agri-) ecosystems. For this purpose, this dissertation applies a series of methods, including a survey capturing the relevance of DEMSs for German dairy farmers and a scenario analysis quantifying farm revenue trends related to electricity sales and energy data sharing.

Research article 1 shows that German dairy farms will have the chance to increase their energy-related revenues due to the rise of electricity prices in the German market since 2021 and the fact that there is often an electricity surplus at German dairy farms. Furthermore, the need for a higher transparency along the dairy supply chain, e.g., for calculating GHG footprints of milk packages, gives German dairy farmers the chance to receive additional remunerations. However, with regards to the latter, findings from research article 2 indicate that German dairy farmers have a low incentive to use a digital marketplace for sharing their energy data. Instead, they are more interested in digital services helping to optimize their electric energy management, e.g., to lower energy-related costs. Yet, the offering of such digital services is limited. That is why this dissertation suggests an inclusion of DEMSs in the product portfolio of new or existing farm management information systems (FMISs) or digital agri-ecosystems. The latter – as the most complex system class of Digital Farming solutions – deal with the

challenge of orchestrating platform content across digital service providers and platform operators. Against this background, research article 3 introduces a methodology for structuring this content orchestration process and afterwards tests this methodology with the example of DEMSs.

As a synthesis, it can be stated that the findings from this dissertation make an important contribution to the further digitalization of German dairy farms: The dissertation creates a basis for adding a not yet established group of digital services – DEMSs – to the portfolio of Digital Farming solutions. In practice, the results from this dissertation are utilized by a publicly funded project, which aims to develop a digital energy management platform (DEMP) – DairyChainEnergy – for the German dairy sector.

Zusammenfassung

Die zukünftige Nachfrage nach Milcherzeugnissen wird sowohl aufgrund des weltweiten Bevölkerungswachstums als auch wegen des zunehmenden Pro-Kopf-Verbrauchs ansteigen. Um diese wachsende Nachfrage decken zu können, wird ein Anstieg der weltweiten Milchproduktion auf 19 % zwischen 2021 und 2031 prognostiziert. Dies stellt eine globale Herausforderung dar, da die Treibhausgas (THG) – Emissionen des Milchsektors bereits im Jahr 2015 für rund 3 % der weltweiten Emissionen verantwortlich waren. Aus diesem Grund strebt eine Reihe von Ländern – darunter auch Deutschland – nach mehr ökologischer Nachhaltigkeit bei der Erzeugung von Milchprodukten. In diesem Zusammenhang gibt es bereits erste Trends, die eine Verringerung der THG-Emissionen in der deutschen Milchwirtschaft begünstigen – wie etwa eine steigende Milchleistung pro Kuh. Um sich jedoch in Richtung einer klimaneutralen Milchproduktion zu entwickeln, müssen weitere Nachhaltigkeitsstrategien verfolgt werden, wobei die derzeitige Profitabilität von Milchviehbetrieben beibehalten oder verbessert werden sollte. In diesem Zusammenhang ist das elektrische Energiemanagement – d.h., das Strommanagement von der Beschaffung bis hin zum Verbrauch – ein Ansatz, welcher sich sowohl auf die THG-Bilanz als auch auf die Finanzen eines Milchviehbetriebs auswirkt.

Vor diesem Hintergrund werden in dieser Dissertation ausgewählte Forschungsfelder des elektrischen Energiemanagements deutscher Milchviehbetriebe untersucht, welche bisher kaum in der Literatur behandelt wurden. Konkret befassen sich die drei eingebetteten Publikationen dieser Dissertation mit (1) der voraussichtlichen Entwicklung der energiebezogenen Einnahmen deutscher Milchviehbetriebe in den nächsten 10 Jahren, (2) den Marktchancen für das Angebot digitaler Energiemanagementdienste (DEMSs) für deutsche Milchviehhalter, und (3) der Implementierung von DEMSs im Kontext digitaler Agrar-Ökosysteme. Zu diesem Zweck wurde eine Reihe von Methoden angewandt, darunter eine Umfrage zur Erfassung der Relevanz von DEMSs für deutsche Milchviehhalter und eine Szenarioanalyse zur Quantifizierung der Einkommenstrends auf deutschen Milchviehbetrieben im Zusammenhang mit dem Verkauf von Strom und dem Vertrieb von Energiedaten.

Die Ergebnisse, die im Rahmen dieser Dissertation veröffentlicht wurden, zeigen, dass deutsche Milchviehbetriebe die Chance haben, ihre energiebezogenen Einnahmen zu erhöhen, da die Strompreise auf dem deutschen Markt seit 2021 gestiegen sind und auf deutschen Milchviehbetrieben häufig mehr Strom erzeugt als verbraucht wird. Darüber hinaus gibt es Bedarf nach höherer Transparenz entlang der Milchlieferkette, z.B. bei der Berechnung des THG-Fußabdrucks. Dies gibt deutschen Milchlandwirten die Möglichkeit, zusätzliche

Umsätze durch die Bereitstellung von Energiedaten zu erzielen. Im Rahmen dieser Dissertation wurde allerdings ebenfalls festgestellt, dass deutsche Milchviehhalter ein eher geringes Interesse an der Nutzung eines digitalen Marktplatzes für den Austausch von Energiedaten haben. Stattdessen sind Milchviehlandwirte eher an digitalen Diensten interessiert, die ihnen helfen, ihr elektrisches Energiemanagement zu optimieren, z.B. um energiebezogene Kosten zu senken. Das Angebot an solchen digitalen Diensten ist jedoch begrenzt, weshalb die Ergebnisse dieser Dissertation eine Aufnahme von DEMSs in das Produktportfolio neuer oder bestehender landwirtschaftlicher Management-Informationssysteme (FMISs) oder digitaler Agrar-Ökosysteme vorschlagen. Letztere werden derzeit als die komplexeste Systemklasse digitaler Agrar-Lösungen angesehen und bergen die Herausforderung der Orchestrierung von Plattforminhalten zwischen den Anbietern digitaler Dienste und den Betreibern digitaler Plattformen. Vor diesem Hintergrund wurde eine Methodik zur Strukturierung dieses Orchestrierungsprozesses vorgestellt und anschließend am Beispiel von DEMSs getestet.

Zusammenfassend kann festgehalten werden, dass die Erkenntnisse aus dieser Arbeit einen wesentlichen Beitrag zur weiteren Digitalisierung deutscher Milchviehbetriebe leisten. Es wurden Grundlagen dafür geschaffen, das Produktportfolio digitaler Lösungen für deutsche Milchviehbetriebe um eine noch nicht etablierte Gruppe von digitalen Diensten – DEMSs – zu erweitern. In der Praxis werden die Ergebnisse dieser Dissertation bereits in einem staatlich geförderten Projekt genutzt, welches die Entwicklung einer digitalen Energiemanagement-Plattform (DEMP) – DairyChainEnergy – für die deutsche Milchwirtschaft anstrebt.

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II Acknowledgments

"Make it a habit to tell people thank you. To express your appreciation, sincerely and without the expectation of anything in return." [1] Following this recommendation from RALPH MARSTON, I would like to express my honest gratitude to all the people who supported and motivated me in writing this dissertation.

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III List of Abbreviations

Abbreviation	Description
ADOPT	Adoption and Diffusion Outcome Prediction Tool
Agri	Agricultural
AMS	Automatic milking system
ASABE	American Society of Agricultural and Biological Engineers
ASF	Animal-source food
AV	Agrivoltaics
B	Billion
DEMP	Digital energy management platform
DEMS	Digital energy management service
DEP	Dairy Energy Prediction
DCFS	Digital crop farming service
DSSED	Decision Support System for Energy use in Dairy Production
e	Error margin
EEG	Erneuerbare-Energien-Gesetz (English: Renewable Energy Sources Act)
e.g.	Exempli gratia (English: for example)
Et al.	Et alii (English: and others)
EU	European Union

FADN	Farm Accountancy Data Network
FAO	Food and Agriculture Organization of the United Nations
FMIS	Farm management information system
GHG	Greenhouse gas
HIT	The German tracing and information system for animals
i.e.	Id est (English: that is)
IoT	Internet of Things
kg	Kilograms
KTBL	Kuratorium für Technik und Bauwesen in der Landwirtschaft (English: Board for Technology and Construction in Agriculture)
kWh	Kilowatt hours
kWp	Kilowatt peak
LKV	Landeskontrollverband (English: State control association)
LU	Livestock unit
M	Million
MDPI	Multidisciplinary Digital Publishing Institute
Max.	Maximum
Min.	Minimum
MVP	Minimum Viable Product
N	Population

n	Sample size
n/a	Not applicable
NAIDEA	National Artificial Intelligent Dairy Energy Application
PSF	Plant-source food
RDV	Rinderdatenverbund (English: Cattle data network)
RQ	Research question
SCEM	Supply chain energy management
StMELF	Staatsministerium für Ernährung, Landwirtschaft und Forsten (English: State ministry of food, agriculture and forestry)
T	Trend
T_4	Yearly change of electricity sales market price
THG	Treibhausgas (English: GHG)
TWh	Terrawatt hours
TUM	Technical University of Munich
USA	United States of America
VDI	Verein Deutscher Ingenieure (English: Association of German engineers)
VIT	Vereinigte Informationssysteme Tierhaltung (English: United Information Systems Animal Husbandry)

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1 Introduction

1.1 Motivation and Background

1.1.1 Future Relevance of Milk Production

According to the Food and Agriculture Organization of the United Nations (FAO), the world population is expected to grow to 9.73 billion (B) in 2050 – leading to an almost 50 % required increase in demand of food, feed, and biofuel compared to 2012 [2]. The resulting nutrition demand is to be covered with plant-source foods (PSFs) and animal-source foods (ASFs) – the latter having been accountable for around 17 % of the per capita calorie intake worldwide in 2021 [3] – comprising food items such as meat, dairy, fish, and eggs [4]. The consumption of ASFs is "[...] generally highest among urban, high-income, and educated populations, with few exceptions" [4]. An analysis by HENCHION et al., for example, shows that the ASF to PSF protein ratio in Europe amounted to 1.08 in 2017 while it was only at 0.29 in Africa and South-East Asia [5], with milk products having been accountable for around 36 % of the ASF calorie intake worldwide [3]. Looking in this context at the future development of the ASF sector, "dairy will remain the fastest expanding livestock sector over the next decade [...]" [6]. This is due to a growing demand for dairy products, which is expected to be at around 1.5 % per annum between 2023 and 2032 – attributable to the global population increase as well as to a growth of the per capita demand [6]. For 2021, the FAO estimates a yearly per capita dairy consumption of more than 200 kilogram (kg) for the following regions: Central Asia, Northern America, Europe, Australia and New Zealand [3], while highest growth rates until 2050 are expected for South-East Asia and Africa [5].

In order to meet this growing demand, the worldwide production of raw milk is forecasted to reach a volume of 1,060 million (M) tons in 2031, which means an about 19 % increase compared to levels from 2021 (see Figure 1.1) [7]. With 22 % of the total volume, India had in 2021 the largest milk production per country and is expected to expand its pole position with an above-average increase of 39 % [7]. Similar growth rates are expected for Pakistan [6,7]. This country has in relation to most other developing nations an outstanding per capita consumption of dairy products (e.g., of more than 120 kg in 2021 [3]) [8]. The European Union (EU) and the United States of America (USA), on the other hand, which are today the second and third largest milk producer [6], are about to forfeit 1-2 % respectively of their global market share (see Figure 1.1) [7].

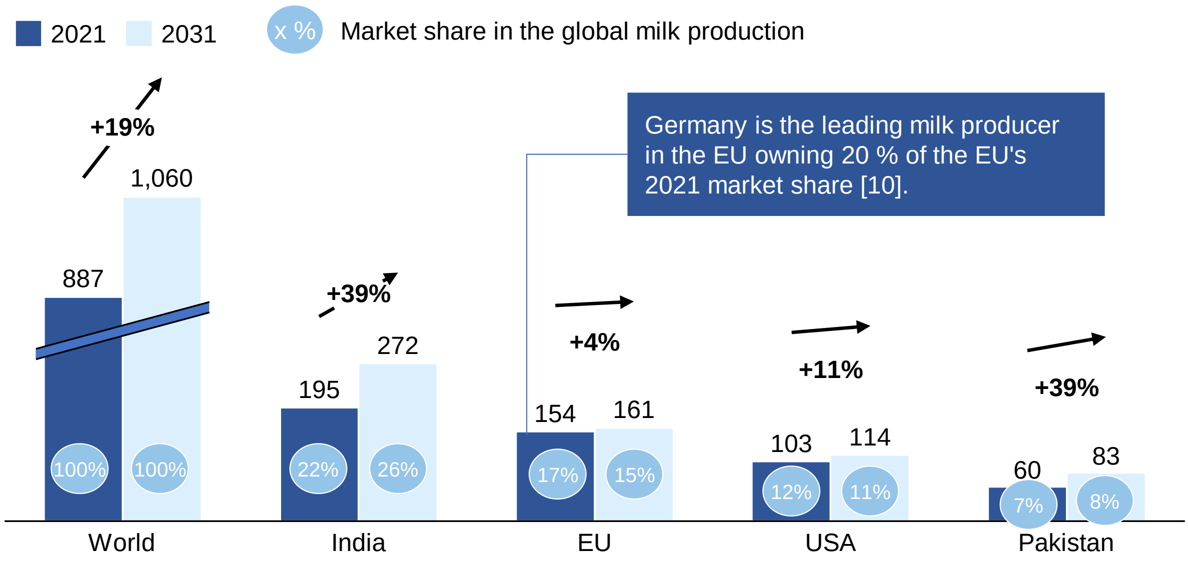

Figure 1.1 Development of the worldwide milk production – in M tons (2021 vs. 2031)[1]

While countries like India and Pakistan focus on growth, e.g., by increasing their cow inventory (proximately by 19 % and 24 % respectively between 2021 and 2031) [7], the EU increasingly supports initiatives that make its agricultural (agri-) productions more sustainable [6]. In this regard, the dairy sector plays a key role to achieve those EU sustainability goals since dairy farming is the EU's most relevant agri-production factor right before crop and pig farming [9]. Therefore, given that Germany is the number one milk producer in the EU with a market share of 20 % in 2021, Germany has to take a leading role to make dairy farming in the EU more sustainable [10].

1.1.2 Characteristics of the German Dairy Sector

When taking a closer look at the consumer demand for dairy products, it becomes apparent that "about 93% of global milk production is consumed domestically in the form of fresh, unprocessed, or lightly processed (e.g. pasteurised or fermented) dairy products" [6]. In Germany, this processing is done at 214 dairy factories[2] that export around one third of their products to other nations [9]. According to data from Eurostat, around 99.9 % of processed milk in Germany is coming from cattle farms.[3] Hence, only a very small share is produced by

[1] Figure 1.1 is an own visualization in the style of [6], showing data from [7].

[2] This number of 214 dairy factories is derived from a data gathering in 2020 and incorporates only companies with an employee count higher or equal 20 [9].

[3] In a global comparison, this figure is remarkable since cow milk constitutes 81 % of the total raw milk volume worldwide [6].

other animals like goats or sheep [10,11]. Therefore, research on the German dairy sector is predominantly looking at dairy cattle [12–15]. In this context, it is important to note that scholars are often speaking of *dairy* when actually meaning *dairy cattle* [12–15]. This research focus on dairy cattle and also the simplified wording regarding the term *dairy* shall be applied throughout the further course of this dissertation.

When looking at how the German dairy sector has managed to achieve a 15 % increase of the total cow milk volume from 2000 to 2021 [16], it becomes apparent that there was a considerable increase of the milk yield per cow while at the same time the total number of dairy cows has declined [15] (see Figure 1.2). In fact, the milk yield per German dairy cow was only at 2,480 kg in 1950, and is nowadays at more than 8,400 kg, i.e., more than three times higher [9].[4] Furthermore, the number of dairy cows has decreased since 2000 by around 800 thousand livestock units (LUs) to 3.83 M in 2021 (see Figure 1.2) [16,18]. Strikingly, while there is nowadays a lower total number of dairy cows, the average German dairy farm grew in herd size, i.e., there was an increase of the number of dairy cows per farm from 33 dairy cows in the year of 2000 to 70 in 2021 [9].[5] Consequently, the total number of German dairy farms decreased from 138.5 thousand in 2000 to around 55.8 thousand in 2021 (see Figure 1.2), which means that today around every fifth German farm is milking dairy cows [9].

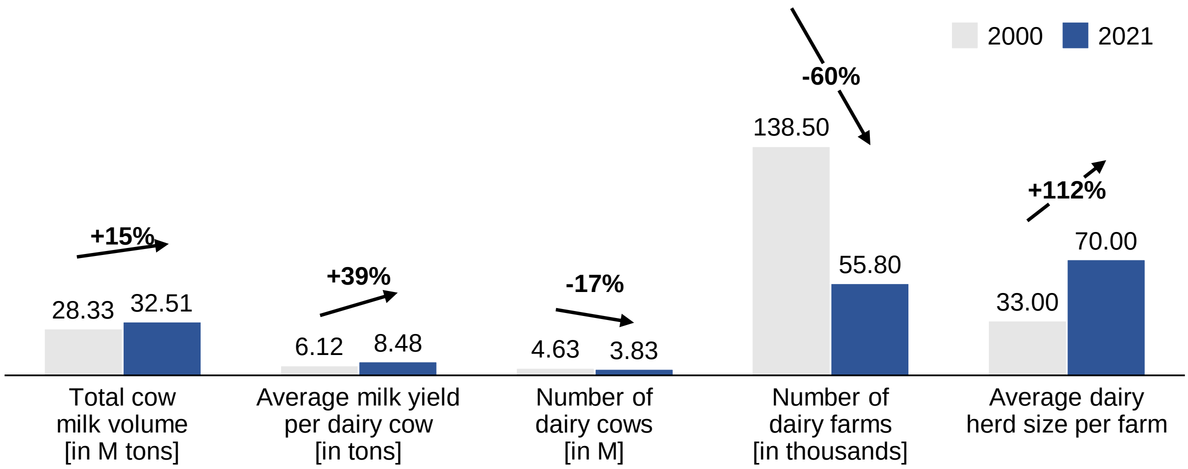

Figure 1.2 Structural changes of German dairy farming over time (2000 vs. 2021)[6]

[4] Hence, the annual milk yield per cow in Germany is nowadays higher than in most EU member states, but still is lower than in eight EU countries with Denmark and Estonia leading the list (9,973 kg*cow^{-1} and 9,657 kg*cow^{-1}) [17].

[5] Notably, there are considerable regional differences regarding the German dairy herd size in 2021 – with an average of 246 dairy cows in Mecklenburg-Western Pomerania to 43 dairy cows in Bavaria [9]

[6] Figure 1.2 is an own visualization with data from [9,16,18].

1.1.3 Digitalization and Automation at German Dairy Farms

As outlined in section 1.1.2, a bigger herd size has to be handled by one dairy farm, while at the same time the total number of employees at German farms has decreased by 13 % between 2010 and 2020 [9]. In this context, use of technology is one of the major levers that a German farm has to reduce the workload of its labor force [19], and to react to a shortage in qualification and skills [20]. In literature, those solutions enabling digitalization and automation in agriculture are summarized under the term “Digital Farming” – sometimes also referred to as Smart Farming or Agriculture 4.0 [21].

The research field of Digital Farming comprises a series of solutions, including e.g., sensors, robots, and digital platforms – each having a different level of adoption at German farms [21]. A study from GABRIEL and GANDORFER, for example, shows that automatic milking systems (AMSs) are the most frequently used Digital Farming solution at Bavarian dairy farms (15 %), while other systems such as robotic slat cleaners or robotic feed pushing systems are used less frequently (7 %) [22]. In fact, “… two out of three dairy producers now opt for an automatic milking system for a new purchase” [23].

In order to handle the high data volume generated and monitored by the rising number of sensors and robots in the dairy barn [24], Digital Farming solutions analyzing this data are also gaining in popularity [22]. In literature, it is differentiated between (1) information systems with one specialized data analysis functionality, (2) farm management information systems (FMISs) comprising a variety of digital services, (3) cyber-physical systems enabling the use of Internet of Things (IoT) applications [25], and (4) digital agri-ecosystems comprising one or more digital platforms with digital services being provided by various stakeholders [26]. [21]

Besides economic and social advantages of Digital Farming – including productivity and efficiency gains, enhanced decision-making, reduced costs, improved work conditions and higher food quality –, there is also expected a positive effect on the environment, i.e., a chance to mitigate GHG emissions from agriculture through the use of Digital Farming solutions [27,28]. Hence, the increasing application of Digital Farming solutions is conducive to the EU’s target of improving the environmental sustainability of dairy productions (see section 1.1.1).

1.1.4 GHG Emissions of the German Dairy Sector

In 2015, the dairy sector accounted for around 3 % of GHG emissions worldwide [29,30]. Considering the expected future increase of global milk production (see section 1.1.1), total GHG emissions will rise accordingly if there are no appropriate GHG mitigation strategies applied [29]. For this matter, Germany has annually tightening GHG emission goals defined until 2030 with regards to six sectors, including agriculture [31]. Against this background and since dairy goods make up around 19 % of the German agri-product value, the German dairy sector has to reduce its carbon emissions even though the GHG footprint of German raw milk is already less than half the global average [9]. In fact, a strive for making dairy supply chains net zero would provide companies along these supply chains with competitive advantages [32], and would contribute to avoiding negative economic consequences such as damages resulting from climate change [33]. With regards to the latter, actors along dairy supply chains will be effected in different ways: While dairy factories, retail stores and carriers will have to deal with food safety concerns due to increased temperature levels, dairy farmers will have to manage a higher amount of crop yield losses and heat stress symptoms of their cows [32].

In order to address these issues and increase the environmental sustainability of agri-productions, several intervention actions can be differentiated, which include – but are not limited to – water management, livestock management and energy management [28].[7] For example, MALLIAROUDAKI et al. state that 37 % of a milk package's GHG emissions are related to energy use while there are different energy management strategies applicable along the dairy supply chain. While retail stores can reduce their dairy products' environmental footprints through efficient refrigeration, dairy farms can mitigate their GHG emissions, e.g., through anaerobic digestion of manure [32]. Looking at the GHG footprint of milk, the major share of energy-related emissions (42 %) is assignable to dairy farms [32], where energy is typically used in different ways, including "[...] electricity consumption, liquid fuel use, fertilizer application, concentrate feed, and other miscellaneous energy consumption" [35]. In literature, it is differentiated between indirect and direct energy use at dairy farms – the latter comprising electricity and fuel consumption with electricity being accountable for on average 48 % of direct energy use at dairy farms according to international studies [35].

1.1.5 Electric Energy Management at German Dairy Farms

When reviewing how scholars are handling the analysis of electricity consumption at dairy farms, measured energy input is typically put in relation to the herd size or the quantity of kg milk produced [35]. The resulting figure – referred to as energy efficiency [35], energy intensity [36], or energy utilization index [37] – varies from farm to farm in dependence of "[...]

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[7] According to the VDI (Verein Deutscher Ingenieure, English: Association of German engineers) guideline 4602, energy management is defined as "[…] the forward-looking, organized and systematic coordination of the procurement, conversion, storage, distribution and utilization of energy to cover requirements for its use, taking account of ecological and economic objectives" [Verein Deutscher Ingenieure (VDI), 2016].

a number of factors including (but not limited to): type of production system (e.g. grazing, confined, conventional, organic, calving pattern, etc.), type of milking system (e.g. conventional or automatic milking system (AMS)), milking schedules, installed infrastructure, climate, etc." [35]. Looking at German dairy farms, there are indications for an increase of the electricity consumption per cow during the last decades, at least for farms with a smaller dairy herd size: While German dairy farms consumed 237-584 kilowatt hours (kWh) per cow in the 1970s [38] – when the average herd size per farm was at around 10 [39] –, farms with a similar herd size had 30 years later an average power consumption of 815.9 kWh per dairy cow [40] (see Table 1.1). This development can be attributed to the ongoing digitalization and automation trend at German dairy farms (see section 1.1.3) and hence, might even amplify in the future [14]. Nevertheless, the trend of an increasing dairy herd size at German farms (see section 1.1.2) is expected to have positively impacted the average electric energy efficiency of German dairy farms [40]. This is shown by results from NESER et al., who analyzed almost six thousand German dairy farms and found out that farms with a larger herd size tend to have a lower electricity consumption per cow [40] (see Table 1.1). Since furthermore, German dairy farms also managed to increase their milk yield per cow in the past (see section 1.1.2), additional insights can be expected from an analysis of the total electric energy use in relation to the produced milk volume. Such an analysis could be used to holistically review how the electric energy efficiency at German dairy farms has changed over time.[8] Since such a measure is, however, not to be found in literature (see Table 1.1), a projection is illustrated in Figure 1.3 based on data points on electricity consumption from [38,40,42], and data on milk volumes and cow inventories from [16]. This calculation indicates that the average electric efficiency of German dairy farms (in terms of the produced milk) has been improved over time (see Figure 1.3)[9].

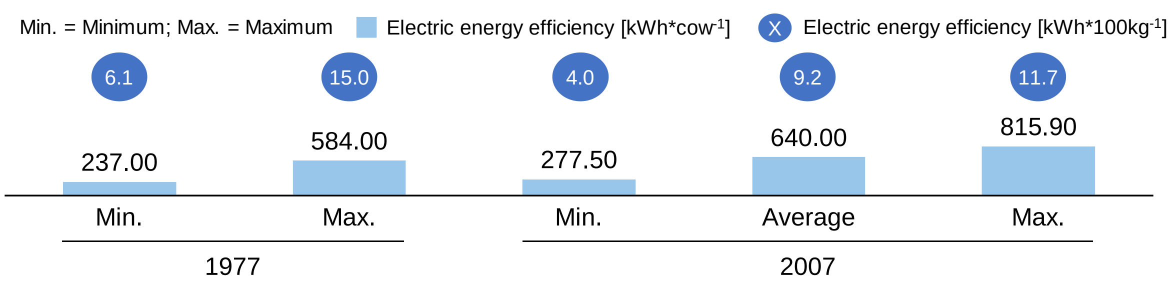

Figure 1.3 Electric energy efficiency at German dairy farms (1977 vs. 2007)

[8] This underlines the findings of EDENS et al. that the figure of electric energy use per cow might not be the best indicator for assessing the electric energy efficiency at dairy farms [41].

[9] Figure 1.3 is an own visualization with data from [16,38] and data from Table 1.1.

Table 1.1 Data points found on annual electric energy efficiency at German dairy farms (published in the 2010s onwards)

Publisher; Year of publication	Region; Count of sample dairy farms	Farm characteristics	Total		Milking		Feeding and manure		Lightning and ventilation		Others	
			[kWh* cow-1]	[kWh* 100kg-1]	[kWh* cow-1]	[kWh* 100kg-1]	[kWh* cow-1]	[kWh* 100kg-1]	[kWh* cow-1]	[kWh* 100kg-1]	[kWh* cow-1]	[kWh* 100kg-1]
Neser et al.; 2012 [40]	Bavaria; 2020	≤ 20 dairy cows	815.9	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
Neser et al.; 2012 [40]	Bavaria; 2698	21-40 dairy cows	621.9	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
Neser et al.; 2012 [40]	Bavaria; 865	41-60 dairy cows	518.4	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
Neser et al.; 2012 [40]	Bavaria; 193	61-80 dairy cows	485.5	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
Neser et al.; 2012 [40]	Bavaria; 39	81-100 dairy cows	454.2	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
Neser et al.; 2012 [40]	Bavaria; 8	≥ 101 dairy cows	277.5	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
Neser; 2014 [42]	Bavaria; 5823	n/a	640	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
Neiber and Neser; 2015 [43]	Bavaria; 6	AMS	n/a	n/a	354	4.1	n/a	n/a	n/a	n/a	n/a	n/a
Neiber and Neser; 2015 [43]	Bavaria; 4	Parlor milking	n/a	n/a	364	4.3	n/a	n/a	n/a	n/a	n/a	n/a
Neiber and Neser; 2015 [43]	Bavaria; 9	40-140 dairy cows	500	n/a	336	n/a	80.4	n/a	62.3	n/a	21.3	n/a
Bernhardt; 2023 [44]	n/a (plan data)	AMS & energy efficient barn components	450	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
Höhendinger et al.; 2023 [45]	Bavaria; 1	AMS; Photo-voltaic (PV); Battery storage	n/a	n/a	n/a	3.6	n/a	n/a	n/a	n/a	n/a	n/a

When looking in more detail at the electricity consumers at German dairy farms, it becomes apparent that the types of power consumers have not fundamentally changed during the last four decades, namely: milk withdrawal and cooling, feeding, manure removal, lighting, ventilation, and miscellaneous (e.g., cow comfort and care) (see Table 1.1) [38,40,43]. Majority of power is nowadays typically consumed for milk withdrawal and cooling [35,40,43,46]. However, actual data points on electric energy efficiency at German dairy farms are very limited – especially concerning a consumer split (see Table 1.1). This circumstance results from the fact that barn components do not have a standardized interface for data recording so that the exact electricity consumption per barn component is only recordable with the help of add-on sensors [14]. Energy management systems (EMSs), comprising such sensors as well as the related data monitoring, analysis and steering of barn components [14] are however not yet widely adopted by German dairy farms. In fact, only a handful of users currently have EMSs installed at their dairy barns [47]. Nevertheless, according to BADER and BERNHARDT, this adoption rate is expected to considerably increase [47], mainly because of EMSs' advantages of saving costs [48], increasing on-farm power utilization rates [49] and hence, enabling the electric energy self-sufficiency of barns [50].

Self-sufficiency in terms of electricity is achievable by dairy farms since farms with an installed power generation system have the chance to generate more electricity than they actually consume [14].[10] Trend Research – a company focused on the research of market trends, reveals that 10.2 % of the electric net nominal capacity from renewable sources in 2018 is provided by farms[11], while farmers hold 73.9 % of the installed capacity in biogas, 15.9 % of the electric power capacity from PV systems and 2 % of the installed electric wind turbine capacity in Germany [52]. In this context, a report from Arla – one of the largest dairy companies in Germany [9] – indicates that, in global comparison, German dairy farms have more than twice as often a PV system installed (58 % in Germany vs. 25 % worldwide) [53]. Furthermore, projections by FEUERBACHER et al. show that a relatively new renewable energy generation approach – installing PV on agri-land, called agrivoltaics (AV) – has the potential to cover 8.8 % of the total electricity consumption in Germany, i.e., 51.3 TWh, with only 10 % of most cost-efficient farms adopting AV [54]. 9.3-11 % of this capacity, i.e., 4.8-5.6 TWh, is expected to come from the dairy sector [54]. Findings from [55,56] support this analysis by

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[10] The use of storage solutions, e.g., battery storages, increases the chances of having a self-sufficient electricity supply at dairy barns – especially in case of farms solely generating electricity with PV or wind systems [45].

[11] In 2018, the electric net nominal capacity from renewable power plants in Germany was at 118.3 Gigawatt (GW), generating a total of 210.8 Terrawatt hours (TWh) [51].

indicating that an increasing share of German farmers intends to invest into renewable energy generation. Since solar technology, however, comes with a volatile distribution of power generation volumes, dairy farms tend to apply storage solutions in order to increase their self-sufficiency level, e.g., ice water storage for cooling the produced milk [43,45]. One reason for this strive for self-sufficiency is that farmers place high value on energy supply security, especially to be prepared for the worst-case scenario – a grid blackout. A survey conducted by the Bavarian state ministry of food, agriculture and forestry (StMELF[12]) and the Bavarian state control association (LKV[13]) revealed, for example, that 48 % of dairy farms located in Bavaria have self-owned emergency power units. [57]

1.2 Derivation of the Research Questions

As indicated by this dissertation's title, the target of this dissertation is to push the boundaries of research on electric energy management at German dairy farms, i.e., to pose and address new relevant research questions (RQs). The derivation of this goal is outlined in the following.

When screening current literature, two major reviews [35,37] can be found providing an overview of globally published research articles on energy management at dairy farms: SHINE et al. conducted a wholistic screening of literature streams on direct and indirect energy use at dairy farms, on energy consumption models and on other dairy farm energy data analyses [35]. MOHSENIMANESH et al. limit their review solely on electric energy management [37]. In sum, as illustrated in Figure 1.4, nine focus topics regarding the research on electric energy management at dairy farms were obtained from [35,37]. Besides studies collecting actual data samples on dairy farms' electricity consumption (focus topics A1) [41,46,58–66] – with most sample farms being located in Europe and North America [35,37], there are also models available to calculate a dairy farm's electricity consumption based on input data and assumptions (focus topic A2) [36,41,67–74]. Some of these models also include the calculation of related GHG emissions (focus topic A4) [67,68]. Furthermore, there is an academic interest in the financial impact of a dairy farm's electricity consumption, i.e., there are studies dealing with the calculation of electricity costs both based on actual and modelled data (focus topic A3) [40,62,64,67,68,75–77]. [35,37] Comparable studies can also be found with regards to electricity generation, i.e., studies modelling electricity generation at dairy farms (focus topic B2) [78], researching the impact of power generation systems on the financials of a dairy

[12] Staatsministerium für Ernährung, Landwirtschaft und Forsten (English: State ministry of food, agriculture and forestry)

[13] Landeskontrollverband (English: State control association)

farm (focus topic B3) [78], and analyzing GHG emission mitigation at dairy farms through electricity generation (focus topic B4) [79]. [35] For Irish dairy farming, Murphy et al. introduced one of the most wholistic tools in terms of electric energy data analyses, which falls back on multiple models covering focus topics A2–A4, and B2–B4 [80]. Furthermore, Shine et al. [35] and Mohsenimanesh et al. [37] list multiple studies pointing out strategies to improve a dairy farm’s electric energy efficiency (focus topic A5) [61,62,77,81–83].

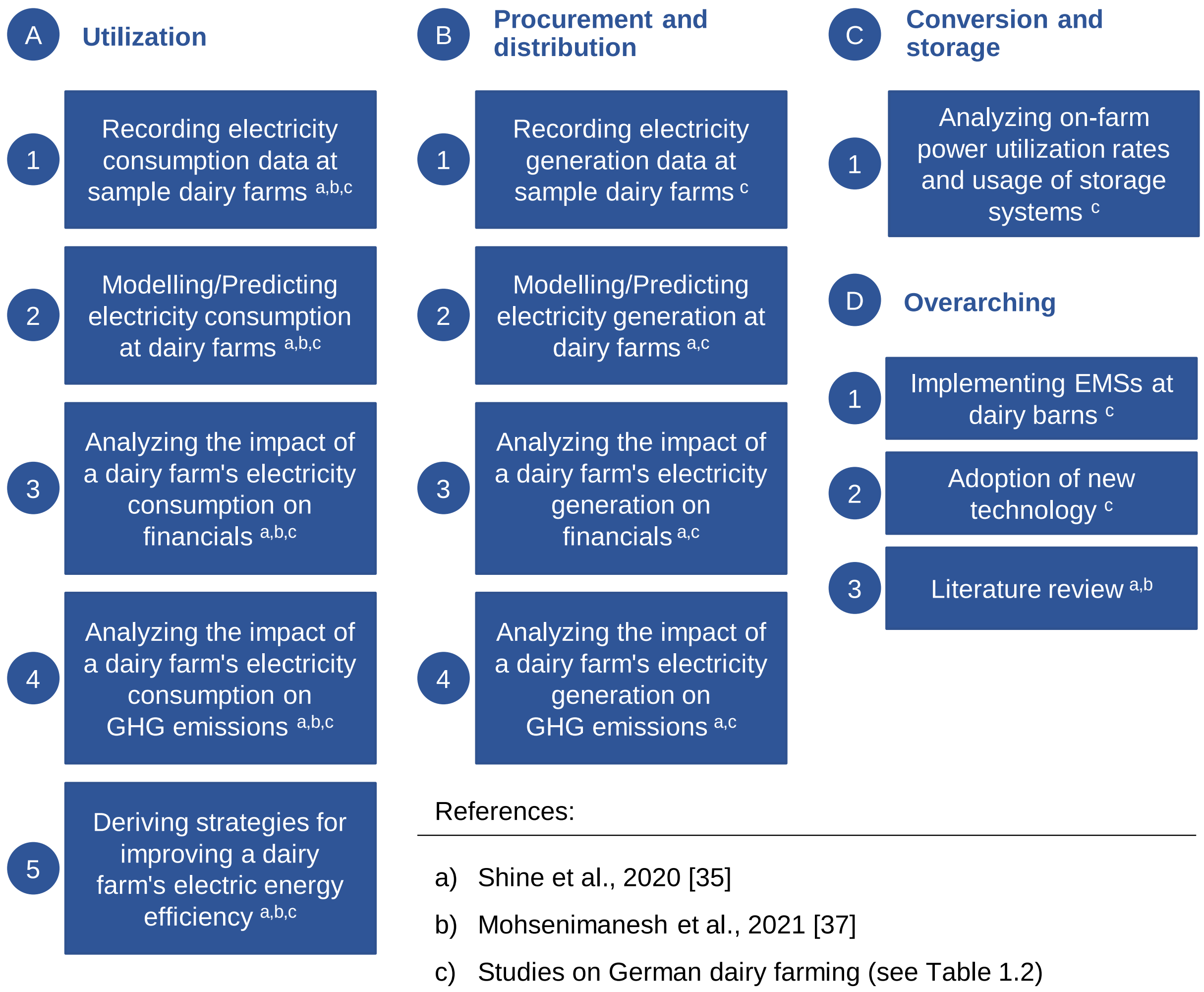

Figure 1.4 Focus topics of research on electric energy management at dairy farms

A review of research on electric energy management at German dairy farms (see Table 1.2) shows that studies on German dairy farming cover all of the previously described focus topics (A1–A5, and B2–B4). In fact, there are four additional research topics addressed, i.e., there are studies on EMSs [14,47] (focus topic D1), publications on the adoption of new technology (focus topic D2) [47,54], articles on on-farm power utilization (focus topic C1) [43,45,84], and publications dealing with actual data records of electricity generation at dairy farms (focus topic B1) [43,45].

Table 1.2 Research articles on electric energy management at German dairy farms (published in the 2010s onwards)

Research focus	Publisher; Year of publication	Research title	Key results
A1; A3	Neser et al.; 2012 [40]	Stromverbrauch und Energieeffizienz im landwirtschaftlichen Betrieb	• Collected data from 2007 on the annual electricity consumption from 5.823 German dairy farms and put the resulting aggregated data in relation to the farms' herd size • Analyzed the impact of technical features on electricity costs with focus on selected barn components (vacuum pump, milk cooling system)
A2	Kraatz; 2012 [36]	Energy intensity in livestock operations – Modeling of dairy farming systems in Germany	• Wholistically modelled the energy intensity of a fictious German dairy farm while limiting the consideration of electricity consumption to a farm's milking process
A1; B1; C1	Neiber and Neser; 2015 [43]	Energy Consumption and Improvement of the Energy Efficiency in the Agricultural Animal Husbandry	• Measured the actual electricity consumption at nine Bavarian dairy sample farms, including a percentage distribution along technical barn components • Visualized the daily distribution of electricity consumption and generation at one Bavarian dairy sample farm • Calculated the on-farm power utilization rate for two fictious dairy farms
A1; A3	Oberschätzl et al.; 2015 [85]	Energieverbrauch automatischer Fütterungssysteme in Praxisbetrieben	• Recorded data on electricity consumption of feeding systems at three Bavarian dairy farms and calculated related costs
A4	Kiefer et al.; 2015 [86]	Integration of ecosystem services into the carbon footprint of milk of South German dairy farms	• Analyzed the carbon footprint of 113 dairy farms from Southern Germany, including a calculation of GHG emissions from electricity consumption
A1	Höld et al.; 2016 [49]	Integrated Dairy Farming – Basic requirements for a useful energy distribution in a dairy barn	• Visualized the load profile of a feeding system from a one-day measurement at a German dairy farm, including details on the load profile of one specific feeding period
A1; B2; C1	Bernhardt et al; 2017 [84]	Energy management of automatic dairy farms with integration in regional grids	• Visualized the variances of electricity consumption at a Bavarian dairy barn across months with details on 14 barn components • Modelled the electricity generation of a German dairy farm (with PV and biogas; with and without power storage) for one fictious day
A3; A4; A5	Wettemann and Latacz-Lohmann.; 2017 [87]	An efficiency-based concept to assess potential cost and greenhouse gas savings on German dairy farms	• Researched strategies on reduction of costs and GHG emissions for a sample of 216 dairy farms from Northern Germany considering multiple input factors (e.g., electricity and fuel)

A1	Oberschätzl et al.; 2018 [88]	Studies on electrical energy consumption of an automatic feeding system in dairy cattle farming	• Analyzed the electricity consumption of automatic feeding systems at two Bavarian dairy farms, including details on various feeding parameters (e.g., total mixing time or number of feed components)
A4; B4	Hijazi et al.; 2020 [89]	Greenhouse gas emissions and energy balance in energy self-sufficient dairy cowsheds-CowEnergy	• Calculated the GHG emissions of one Bavarian dairy farm (equipped with an EMS), while also considering (mitigated) emissions related to electricity generation and consumption
A4	Hijazi et al.; 2020 [90]	Life cycle assessment of different dairy farms considering building materials for barns, milking parlors and milking tanks	• Wholistically modelled the GHG emissions of three Bavarian dairy farms, including emissions from electricity consumption. The sample farms showed differences in terms of herd size, technical equipment, feeding routines, and construction of the barn
D1	Bernhardt et al.; 2021 [14]	Development of the Technical Structure of the “Cow Energy” Concept	• Introduced the technical concept of an EMS for a German dairy barn, including a description of interfaces, data sets and planned functionalities of the central control unit
A1	Höhendinger et al; 2021 [50]	Cowenergy – possibilities of energy management in energy self-sufficient dairy cowsheds	• Documented a 26-days observation of electricity consumption at one Bavarian research stable with focus on selected barn components (hot water boiler, scrapping and milking robots, air compressor)
A1; A5	Höhendinger et al; 2021 [91]	Impacts of Divergent Moving Drives on Energy Efficiency and Performance of Various AMS in Operative Conditions	• During an observation period of 6 months, the electricity consumption of 2 AMS was recorded at a Bavarian dairy farm with details published on selected barn components (milking robot, vacuum pump, air compressor, and boiling water cleaning system) • Discussed strategies for improving the electric efficiency of AMSs (e.g., pointed out the advantages of an electrical moving drive)
B2; B3; D2	Feuerbacher et al.; 2022 [54]	Estimating the economics and adoption potential of agrivoltaics in Germany using a farm-level bottom-up approach	• Estimated the adoption potential for AV at German farms, including forecasts for the dairy sector • Analyzed the effect of AV adoption on farm economics, e.g., the financial impact of AV on a farm’s contribution margin
D1; D2	Bader and Bernhardt; 2023 [47]	Predicting the acceptance of the introduction of energy management system and testing its functionality in automated barn systems - "CowEnergySystem"	• Predicted the future adoption of EMSs at Bavarian dairy farms with the help of ADOPT (Adoption and Diffusion Outcome Prediction Tool)
A1; B1; C1	Höhendinger et al; 2023 [45]	Requirements and Economic Implications of Integrating a PV-Plant-Based Energy System in the Dairy Production Process	• Provided a one-year time series analysis of electricity consumption, generation, and self-sufficiency of a Bavarian dairy farm’s milking process

When analyzing financials related to dairy farms' electric energy management, SHINE et al. underline the need to make country-specific monetary analyses, e.g., due to country-individual electricity tariffs [35]. Looking at publications in the respective focus topics (A3 and B3) focusing on German dairy farming, it is however striking that majority of existing studies limit their research to the analysis of energy-related costs, i.e. the costs for purchasing electricity [40,85,87]. From the studies listed in Table 1.2, only FEUERBACHER et al. address revenues from electric energy management, i.e., consider electricity sales from AV to calculate the contribution margin of AV built on agri-land of German dairy farms [54]. Yet, research from other industries shows that energy-related revenues are not limited to electricity sales: In fact, energy-related revenues can also result from other management decisions, such as data sharing and mutual energy supply along the supply chain [92,93] – which both can be assigned to the term supply chain energy management (SCEM) [92,94,95]. With this in mind, the first RQ of this dissertation is determined as:

How will energy-related revenues at German dairy farms change during the next 10 years? (RQ 1)

- How to model energy-related revenues at German dairy farms? (RQ 1.1)
- Which assumptions have to be made to predict the change of energy-related revenues of German dairy farms during the next 10 years? (RQ 1.2)
- What is the impact of SCEM on the future development of energy-related revenues of German dairy farms? (RQ 1.3)

Next, as stated by [32] and as underlined by Table 1.1, there is missing quantity and accuracy of data on electricity consumption at dairy farms (focus topic A1). This is because (1) data on power use at barns is typically not yet recorded automatically (see section 1.1.5), and (2) farm management decisions (e.g., automation of the milking process) impact the actual amount of electricity consumed at a dairy barn (see section 1.1.5). Hence, only dairy farms with similar characteristics (e.g., same herd size) and comparable technical barn components are expected to have a similar electricity consumption [96]. Nevertheless, farm-individual data on electricity use is required to improve the accuracy of GHG footprint calculations (see section 1.1.4). This is aspired by stakeholders in the German dairy sector in order to initiate emission mitigation strategies, meet emission targets by the German government (see section 1.1.4), and hence positively impact the sector's reputation in the public [32]. Thus, there is a need to scale data collection on electricity use at German dairy farms.

In other farm management areas, such as animal health monitoring or dairy herd management, the availability and usability of farm data grew with the increasing popularity of Digital Farming solutions such as FMISs [21]. A similar effect could be expected when applying digital services on electric energy management. In fact, already in 2011, ROBBEMOND and KRUIZE suggested energy management as a FMIS module, including the functions of "[...] adjusting fuel use of tractors during field operations or recording the energy use of cold stores" [97]. Current studies, however, show that most of today's FMISs are still not covering digital services on energy management [98–100]. For example, KASSAHUN et al., who reviewed FMIS applications specifically for dairy farms, point out eight FMIS focus fields [98]. Most of these FMIS applications deal with animal and milk data (e.g., cow activity and cell count of milk) [98].

Even though the as-is offering of FMISs is already screened by multiple researchers [98–100], there is still insufficient transparency on the actual demand for FMIS functions [99]. For example, researchers looked into multiple use cases for analyzing electric energy data (see Figure 1.4). Yet, it is unclear whether dairy farmers would actually apply such digital services. Against this background, the second RQ of this dissertation is defined as follows:

What is the market opportunity for FMIS providers to offer digital energy management services (DEMSs) to German dairy farmers? (RQ 2)

- Which DEMSs are most relevant for German dairy farmers? (RQ 2.1)
- Do farm characteristics have a significant impact on how farmers evaluate the relevance of DEMSs? (RQ 2.2)
- Which DEMSs are already available to German dairy farmers? (RQ 2.3)

Despite the fact that selected Digital Farming solutions already have high popularity with German dairy farmers (see section 1.1.3), several platforms offering digital services to the agri-sector have recently announced their failure [101–103]. Nevertheless, especially digital agri-ecosystems offer a series of advantages to the German dairy sector including the provision of new business models [104,105], and the chance for providers to secure a high market share [26]. Against this background, the third RQ of this dissertation is:

How to successfully implement DEMSs as part of digital agri-ecosystems? (RQ 3)

- Which types of digital agri-ecosystems are to be differentiated? (RQ 3.1)
- What have been major reasons for the past failure of digital agri-ecosystems? (RQ 3.2)
- Which methodology should be applied to decide on which DEMSs to implement as part of a digital agri-ecosystem? (RQ 3.3)

1.3 Structure of the Dissertation

The structure of this dissertation follows the guidelines of the Technical University of Munich (TUM) School of Life Sciences [106]. This dissertation comprises one shared first authorship and two first authorship publications. In addition to the formally required structure, this dissertation also includes a chapter outlining the contributions of the doctoral candidate Theresa Theunissen to the project “Development of an IT and business concept for an energy management platform addressing the dairy value chain (“DairyChainEnergy”)” [107]. This project was initiated based on findings from studies that were published in the context of this dissertation (see chapter 4). In Figure 1.5, the structure of this dissertation is visualized by summarizing the scope and key insights per chapter.

CHAPTER	SCOPE	KEY INSIGHTS
1 **Introduction**	• Outlining the **motivation and background** behind this dissertation's research topic • Deriving this dissertation's **RQs** • Describing the **structure** of this dissertation	• This dissertation investigates new RQs on **electric energy management at German dairy farms**, including an analysis related to revenues and DEMSs
2 **Materials and Methods**	• Giving an **overview of the materials and methods** used to address the dissertation's RQs • Providing **details on selected methods** applied	• **Eight methods** are applied in the context of this dissertation • Data was gathered from **sample farms**, via expert interviews, and from public sources
3 **Publications**	• **Summarizing the three major research articles** published in the context of this dissertation • Describing the **author's contributions**	• One research article was published in the **Journal of the ASABE** • Two research articles were published in the journal **'Agriculture'** of the Multidisciplinary Digital Publishing Institute (**MDPI**), including one shared first authorship
4 **DairyChain-Energy**	• Outlining the **contributions of Theresa Theunissen** to the definition of DairyChainEnergy's IT and business concept	• The **Minimum Viable Product (MVP)** of DairyChainEnergy includes **three DEMSs**
5 **Discussion**	• Putting key findings of this dissertation **into context with** adjacent research • Discussing **limitations** of conducted studies • Outlining **follow-up research** potentials	• This dissertation contributes to **six focus topics** of research on electric energy management at German dairy farms • Next to addressing RQs from chapter 1, this dissertation makes **additional contributions to the research field** (e.g., provides data records on German dairy farms' electricity consumption and generation

Figure 1.5 Structure of this dissertation[14]

[14] Key insights were taken from chapters 1, 2, 3, 4, and 4.1 of this dissertation.

2 Materials and Methods

This chapter provides an overview of methods and materials used to answer the three RQs of this dissertation (see Table 2.1). In accordance with the TUM regulations [106], the following sections 2.1 and 2.2 outline only a sub-set of these methods and materials. The focus is set on those that are not yet sufficiently described in other scientific sources and that were primarily applied by the doctoral candidate Theresa Theunissen.[15]

Table 2.1 Applied materials and methods to address the dissertation's RQs

RQ (see section 1.2)	**Research article**	**Methods**	**Materials**
RQ 1	1: "Scenario Analysis Indicates Revenue Increase for German Dairy Farmers Through Supply Chain Energy Management" [109]	• Scenario process by KOSOW and GAßNER [110] • Nominal range sensitivity method[16], as described in [111]	• Information and data shared by one dairy sample farm located in North Rhine-Westphalia • Publicly available information and data on the (German) dairy sector and the German electric energy market [35,53,112–117]
RQ 2	2: "Mind the Market Opportunity: Digital Energy Management Services for German Dairy Farmers" [118]	• Empirical market research (online survey[17]), as described in [119] • Chi-squared test, as described in [120] • Market screening method by FLAK [121]	• Information and data shared by survey participants (74 German dairy farmers) • Selected data points from the Farm Accountancy Data Network (FADN) [116] and the "Arla Foods Climate Check Report 2022" [53]
RQ 3	3: "How to Successfully Orchestrate Content for Digital Agriecosystems" [108]	• Root cause analysis, as described in [122] • Methodology for Creating Methodologies by SMITH and APPLE [123] • Expert interviewing, as described in [124]	• Publicly available information on the success and failure of digital platforms and agri-ecosystems [104,125–129] • First-hand insights from a digital agri-ecosystem (NEVONEX), which was shut-down in 2023 [101]

[15] Especially with regards to research article 3, which was published as a shared first authorship [108], not all methods were applied solely by Theresa Theunissen herself (see a description of the authors' contributions in section 3.3).

[16] Details on the sensitivity analysis applied in the context of this dissertation can be found in section 2.2.

[17] More information on the set-up online survey is provided in section 2.1.

2.1 Online Survey on Relevance of DEMSs for German Dairy Farms

In literature, online surveys are a widely applied method to gather information from German dairy farms: For example, scholars have used online surveys for analyzing German dairy farms' work processes [130], enriching current knowledge on German dairy farms' veterinary herd health management [13], or for understanding German farms' acceptance of Digital Farming solutions [131]. The key purpose of the online survey conducted in the context of this dissertation was to analyze the relevance of DEMSs (see RQ 2.1) [118]. The term *relevance* was consciously chosen since it is a phrase that does not require further explanation towards the survey participant [132], and does not assume that a DEMS is already applied at a farm. Hence, it is applicable for an assessment from both existing and potential users.

Research article 2 elaborates how the survey of this study was distributed to German dairy farms and describes the characteristics of the 74 sample farms [118]. Building on that, in the following, additional details are provided on the questions posed in the study's online survey and on the data cleaning process leading to the utilization of only 74 responses: In Figure 2.1 and Figure 2.2, the survey questionnaire is illustrated while showing only those parts of the survey, i.e., 20 questions, that were actually used in the context of research article 2. Furthermore, it was decided to show here the questions in their original form – i.e., in German – since in research article 2, responses were shown only in a translated and simplified way [118]. The questionnaire includes closed questions (e.g., question 3, 12, and 23), hybrid questions (e.g., question 5, 9, and 14), as well as open questions (e.g., question 2,10, and 18) [133]. Furthermore, only those questions were determined as being mandatory (i.e., those marked in Figure 2.1 with a '*'), that were required to navigate the survey participant to the next relevant section of survey questions. For example, if survey participants stated that they do not manage a farm, this would lead to an exclusion from the study (see Figure 2.1). As shown in Figure 2.3, the exclusion of non-farmers (based on question 1) and non-dairy farmers (based on question 5 and 9), reduced the count of responses in scope from 421 to 237. As mentioned in [118], a high amount of these 237 dairy farmers (38 %, i.e., 90 participants) did not provide a complete assessment on DEMSs (see Figure 2.3). Furthermore, one target of this dissertation was to analyze whether the relevance of DEMSs is showing a significant dependence on the sample's farm characteristics (see RQ 2.2). Therefore, only complete data sets (i.e., those with a response to each question shown in Figure 2.1 and Figure 2.2) were considered in the context of the study for research article 2 [118]. Here, especially missing data on the farm's energy management led to a reduction of the sample size (see Figure 2.3).

Figure 2.1 Questionnaire of the online survey used for research article 2 – Part 1

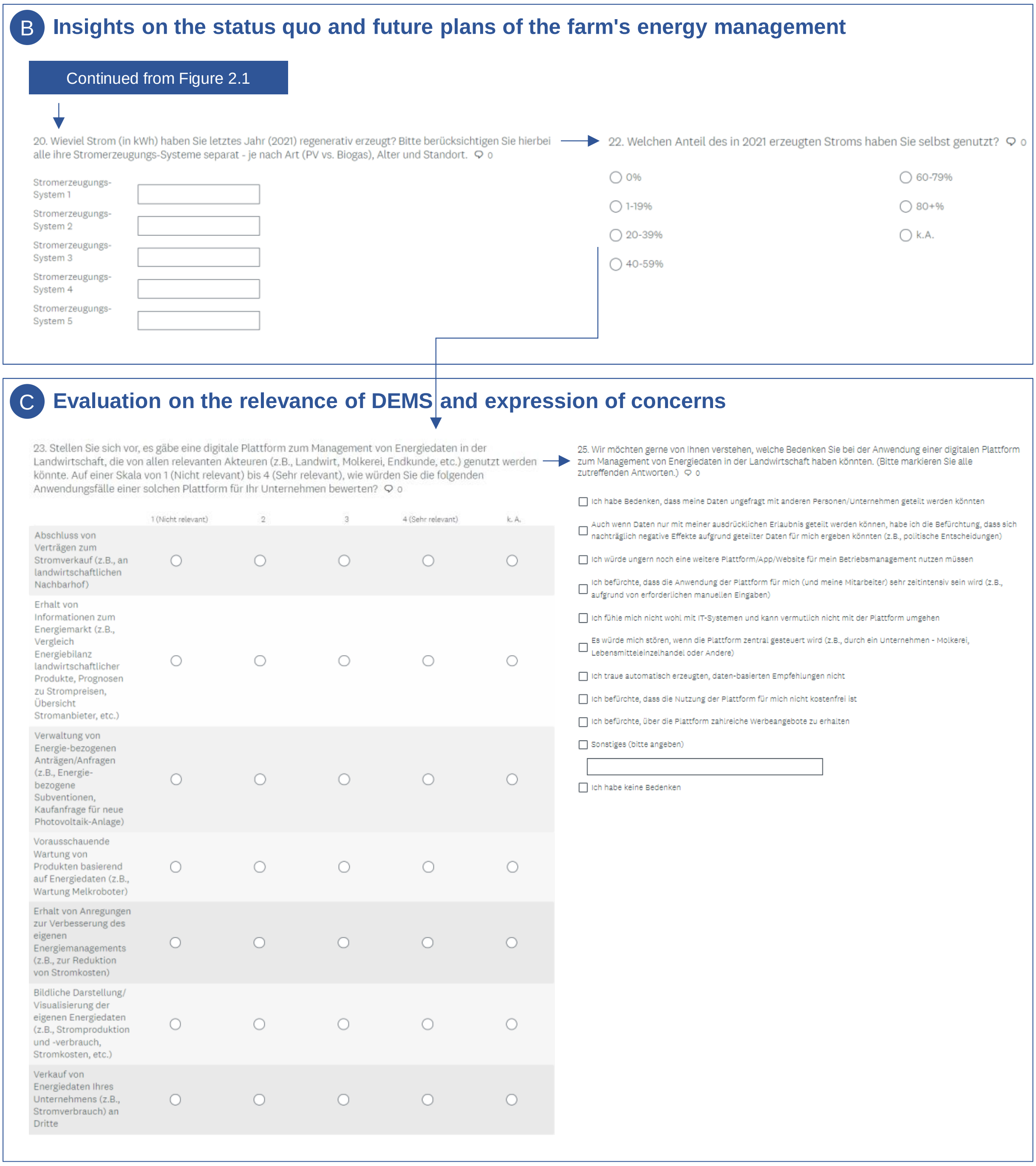

Figure 2.2 Questionnaire of the online survey used for research article 2 – Part 2

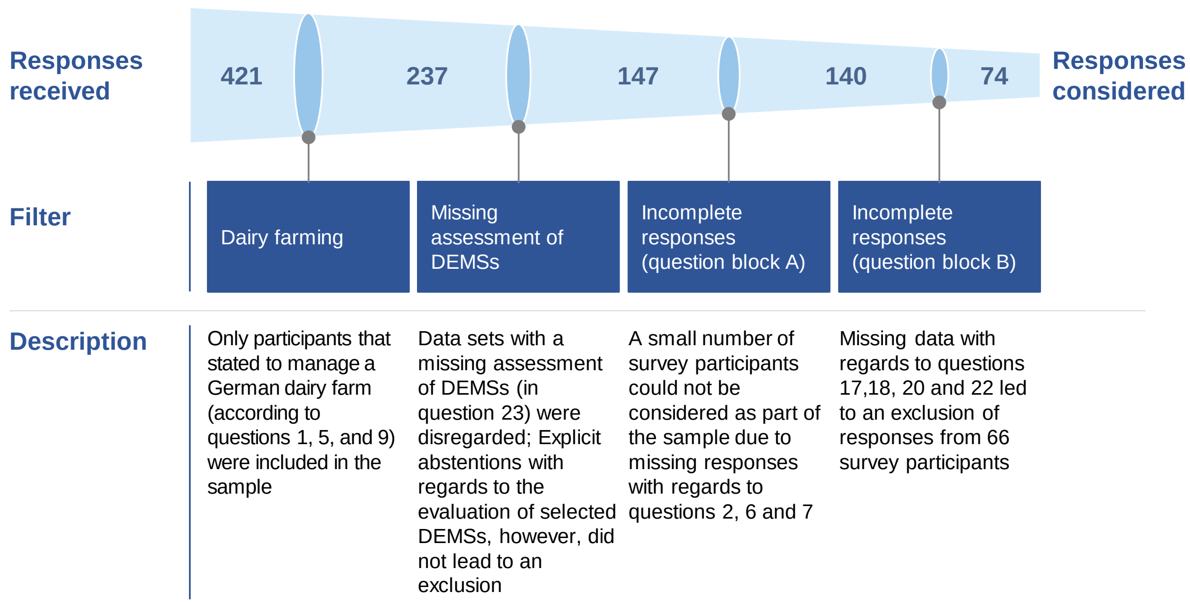

Figure 2.3 Data filter applied to the survey responses

2.2 Sensitivity Analysis on Scenario Trends and Events

Researchers differentiate between various sensitivity analysis methods, each having its own purpose such as simulating probability distributions, or calculating the differences in model outputs in dependence of varying data inputs [111]. A frequently applied method for the latter, is the so-called nominal range sensitivity analysis [111]. This method was chosen in research article 1 to determine the impact of SCEM on energy-related revenues of German dairy farms [109].

As outlined in research article 1, the change in energy-related revenues was not computable for all 2,592 modelled return points since 18 farm archetypes were defined as having no energy-related revenues in 2022. Thus, it was not applicable to use formula 1 from [109] for these 18 farm archetypes. Hence, a nominal range sensitivity analysis was only conducted for 1,338 farm archetypes while considering varying input data related to the modelled trends and events (see part I and II in Figure 2.4). [109] As shown in the code programmed in Jupyter Notebook [134], first the difference of the output is calculated in percentage points while only varying one input factor. In Figure 2.4, the example of one trend (T) “Yearly change of electricity sales market price” (T_4) [109] was illustrated (see part III in Figure 2.4). Hence, for each archetype, the difference in the model output was calculated 72 times to determine the sensitivity towards T_4. Afterwards, the average of these 72 x 1338 calculations was derived as the T_4 sensitivity shown in [109].

I Excerpt from the scenario list

```
scenarios = pd.DataFrame(scenario_values,columns = scenario_columns)
scenarios.head(10)
```

	Yearly rise in number of cows per barn	Yearly change of power consumption per kg of milk produced	Application of SCEM	Application of farm-specific energy management and monitoring	Yearly change of in-farm power utilization rate	Yearly change of electricity sales market price
0	0.0	-0.07	0.0	0.0	-0.12	-0.2
1	0.0	-0.07	0.0	0.0	-0.12	0.0
2	0.0	-0.07	0.0	0.0	0.00	-0.2
3	0.0	-0.07	0.0	0.0	0.00	0.0
4	0.0	-0.07	0.0	0.0	0.12	-0.2
5	0.0	-0.07	0.0	0.0	0.12	0.0
6	0.0	-0.07	0.0	1.0	-0.12	-0.2
7	0.0	-0.07	0.0	1.0	-0.12	0.0
8	0.0	-0.07	0.0	1.0	0.00	-0.2
9	0.0	-0.07	0.0	1.0	0.00	0.0

II Derivation of the return points considered for the sensitivity analysis

```
sensitivity_analysis = pd.DataFrame(revenue_values,columns = revenue_columns)
sensitivity_analysis = sensitivity_analysis.dropna()
sensitivity_values = sensitivity_analysis.values
sensitivity_analysis
```

	Scenario0	Scenario1	Scenario2	Scenario3	Scenario4	Scenario5	Scenario6	Scenario7	Scenario8	Scenario9	...	Scenario134	Scenario135	Scena
0	-87.325823	18.037476	-89.262582	0.000000	-90.407376	-10.661728	-90.407376	-10.661728	-90.407376	-10.661728	...	31.204456	120.467038	25.
1	-78.215419	102.884723	-81.306777	74.094209	-81.306777	74.094209	-81.306777	74.094209	-81.306777	74.094209	...	145.217131	232.190486	134.
2	-71.961747	14.863968	-73.557753	0.000000	-74.501133	-8.785907	-74.501133	-8.785907	-74.501133	-8.785907	...	8.120388	81.678142	3.
3	-55.234703	72.655842	-57.417780	52.324359	-57.417780	52.324359	-57.417780	52.324359	-57.417780	52.324359	...	73.169123	134.588567	65.
4	-87.325823	18.037476	-89.262582	0.000000	-91.420101	-20.093462	-91.420101	-20.093462	-91.420101	-20.093462	...	31.204456	120.467038	25.
...	...	...	...	...	...	...	...	...	...	...	...	...	...	
1347	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	...	464.239504	464.239504	464.
1349	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	...	464.239504	464.239504	464.
1351	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	...	464.239504	464.239504	464.
1353	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	...	464.239504	464.239504	464.
1355	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	...	464.239504	464.239504	464.

1338 rows × 144 columns

III Derivation of the sensitivity towards T_4

```
# Sensitivity analysis for 'Yearly change of electricity sales market price'
sensitivity_change_power_market_price = np.array([])
column = 0
distance = 1
i = 0
for b in scenario_values:
    row = 0
    difference = np.array([])
    a = 0
    while a < len(sensitivity_analysis):
        difference = np.append(difference,sensitivity_values[row][column+distance]-sensitivity_values[row][column])
        row += 1
        a += 1
    column += 1
    i += 1

    if i == 1:
        i = 0
        column += 1
    sensitivity_change_power_market_price = np.append(sensitivity_change_power_market_price, difference)
    if column >= len(scenario_values)-distance:
        break
sensitivity_change_power_market_price_average = np.average(sensitivity_change_power_market_price)
sensitivity_change_power_market_price_max = np.max(sensitivity_change_power_market_price)
sensitivity_change_power_market_price_min = np.min(sensitivity_change_power_market_price)
print('Average: '+str(sensitivity_change_power_market_price_average))
print('Max: '+str(sensitivity_change_power_market_price_max))
print('Min: '+str(sensitivity_change_power_market_price_min))
```

```
Average: 36.353431386418954
Max: 422.82492617272123
Min: 0.0
```

Figure 2.4 Excerpt from the sensitivity analysis implemented in Jupyter Notebook

3 Publications

As mentioned in section 1.3, three research articles have been published in the context of this dissertation. Appendix B – Publication Reprints displays these research articles in full length. In the following, there is provided a short overview of the published articles by briefly summarizing their content, listing bibliographic information, and describing the authors' contributions.

3.1 Research Article 1

Title: "Scenario Analysis Indicates Revenue Increase for German Dairy Farmers Through Supply Chain Energy Management" [109]

Authors: Theresa Theunissen, and Heinz Bernhardt

Published at: Journal of the ASABE[18] 2023, 66(3): 667-675

Available at: https://doi.org/10.13031/ja.15379

Summary: As described in section 1.2, research lacks a common understanding of how electric energy management impacts German dairy farm revenues. Research article 1 addresses this gap by answering RQ 1, i.e., creating a model for calculating and predicting energy-related revenues of German dairy farms. More specifically, as mentioned in chapter 2, it applies the method of KOSOW and GAßNER [110] to conduct a scenario analysis, which allows a consideration of various input factors: Farm-independent parameters (such as the remuneration in the context of the German Erneuerbare-Energien-Gesetz[19] (EEG)), farm-individual variables (such as the dairy herd size), trends describing the future development of key figures (e.g., change of a farm's electric energy efficiency) as well as events (including the adoption of EMSs). Research article 1 provides an overview of these key figures as well as a summary of most relevant formulas used in the calculation model (see RQ 1.1). The output figure of this model is defined as the change of energy-related dairy farm revenues over a ten-year horizon – including revenues from energy data sharing and electricity sales. With regards to electricity sales, one limitation of the conducted scenario analysis is that revenues from electricity sales are only modelled for roof PV systems. This limitation is made because EEG levies differ across electricity generation systems [112] and given that roof PV is the most popular electricity generation system of German dairy farms (see section 1.1.5). With regards

[18] American Society of Agricultural and Biological Engineers

[19] Erneuerbare-Energien-Gesetz (English: Renewable Energy Sources Act)

to the modelled output, the study differentiates between calculations on data from one sample farm, and calculations utilizing assumptions from fictious farm archetypes. For the sample farm, it was found that in 2020 majority of its energy-related revenues came from electricity sales, while only 4.4 % were generated by sharing energy data. One scenario showed that its energy-related revenues will increase by 231 % until 2030, if future electricity sales market prices stay at levels from 2022 and if the sample farm intends to maximize its energy-related revenues with the help of SCEM. To realize these benefits from SCEM, the sample farm needs to switch to direct electricity sales and leverage all options for energy data sharing. Furthermore, research article 1 includes recommended assumptions on the future development of selected key figures (see RQ 1.2). Moreover, a consideration of 144 scenarios for 1,356 fictious farm archetypes leads to general insights on the impact of SCEM on energy-related dairy farm revenues. In this regard, a sensitivity analysis is applied to answer RQ 1.3, i.e., to quantify the impact of SCEM on energy-related farm revenues in comparison to other key figures. [109] A graphical abstract[20] of research article 1 was included as Figure 3.1.

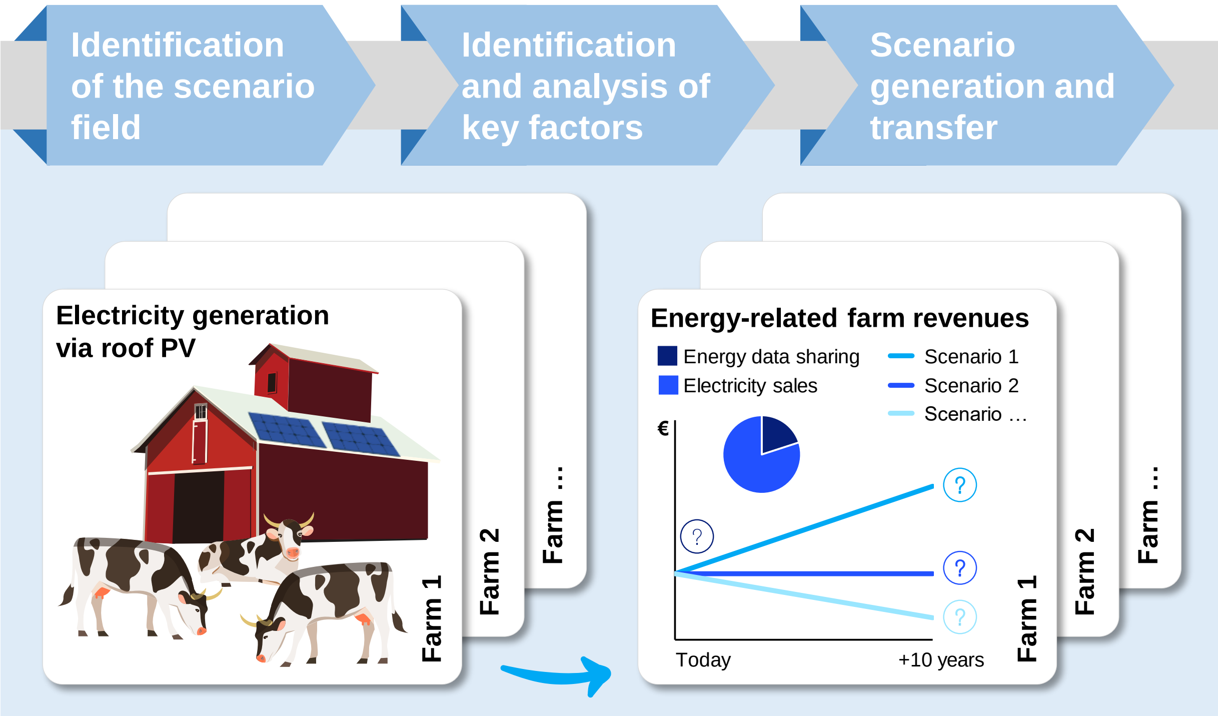

Figure 3.1 Graphical abstract of research article 1

Author contributions: Theresa Theunissen took the lead in writing the manuscript and detailing the research idea of this publication. Theresa Theunissen defined and collected

[20] This graphical abstract (see Figure 3.1) is an own illustration created with insights from [109].

required data, and also implemented the algorithm in Jupyter Notebook (see section 2.2). Furthermore, Theresa Theunissen performed all calculations and visualized the results. Heinz Bernhardt came up with the research idea and provided suggestions during the review process. Overall, the distribution of the research work is quantified as follows: Theresa Theunissen (90 %), and Heinz Bernhardt (10 %).

3.2 Research Article 2

Title: “Mind the Market Opportunity: Digital Energy Management Services for German Dairy Farmers” [118]

Authors: Theresa Theunissen, Julia Keller, and Heinz Bernhardt

Published at: Agriculture 2023, 13(4), 861

Available at: https://doi.org/10.3390/agriculture13040861

Summary: German dairy farmers are increasingly adopting Digital Farming solutions (see section 1.1.3). Furthermore, digital services of existing FMISs focus on the handling of animal data and are not yet dealing with energy management (see section 1.2). Against this background, research article 2 addresses RQ 2, i.e., analyzes the market opportunity for offering DEMSs to German dairy farmers. To do so, it considers both farmers’ interest in DEMSs as well as the current market offering of DEMSs. For this purpose, a German-wide online survey is conducted. This survey asks dairy farmers to evaluate the relevance of seven DEMSs for their dairy farms while also providing additional data on their farms as well as on (planned and made) management decisions (see section 2.1). Insights from this survey indicate that German dairy farmers are interested the most in energy data analyses, which for example can support farmers in improving the energy efficiency of their farms, e.g., in order to reduce farms’ electricity costs (see RQ 2.1). Next, in order to answer RQ 2.2, Chi-squared tests were conducted (see chapter 2) in order to analyze whether the survey responses, i.e., the evaluation of DEMSs, show a significant dependence on the survey sample’s farm characteristics. Results from research article 2 show that this is not the case. Lastly, the as-is market offering of DEMSs is screened following a method of Flak [121] (see chapter 2). It was found that there is only a handful of providers offering DEMSs tailored to the needs of German dairy farms (see RQ 2.3). Thus, the research article concludes that there is a market opportunity for FMIS providers to include DEMSs in their existing offering portfolio. This conclusion is supported by the fact that German dairy farmers will more and more rely on digital solutions (see section 1.1.3), and are expected to increase their investments into renewable energy generation (see section 1.1.5). In sum, also other stakeholders from the dairy supply chain can benefit from DEMSs used at German dairy farms due to an expected increase of transparency on energy data. FMIS operators, however, are also advised to consider potential challenges when starting to provide DEMSs to German dairy farms such as the dependency on the future adoption rate of physical EMSs at barns. [118] Figure 3.2 is a graphical abstract[21] of research article 2.

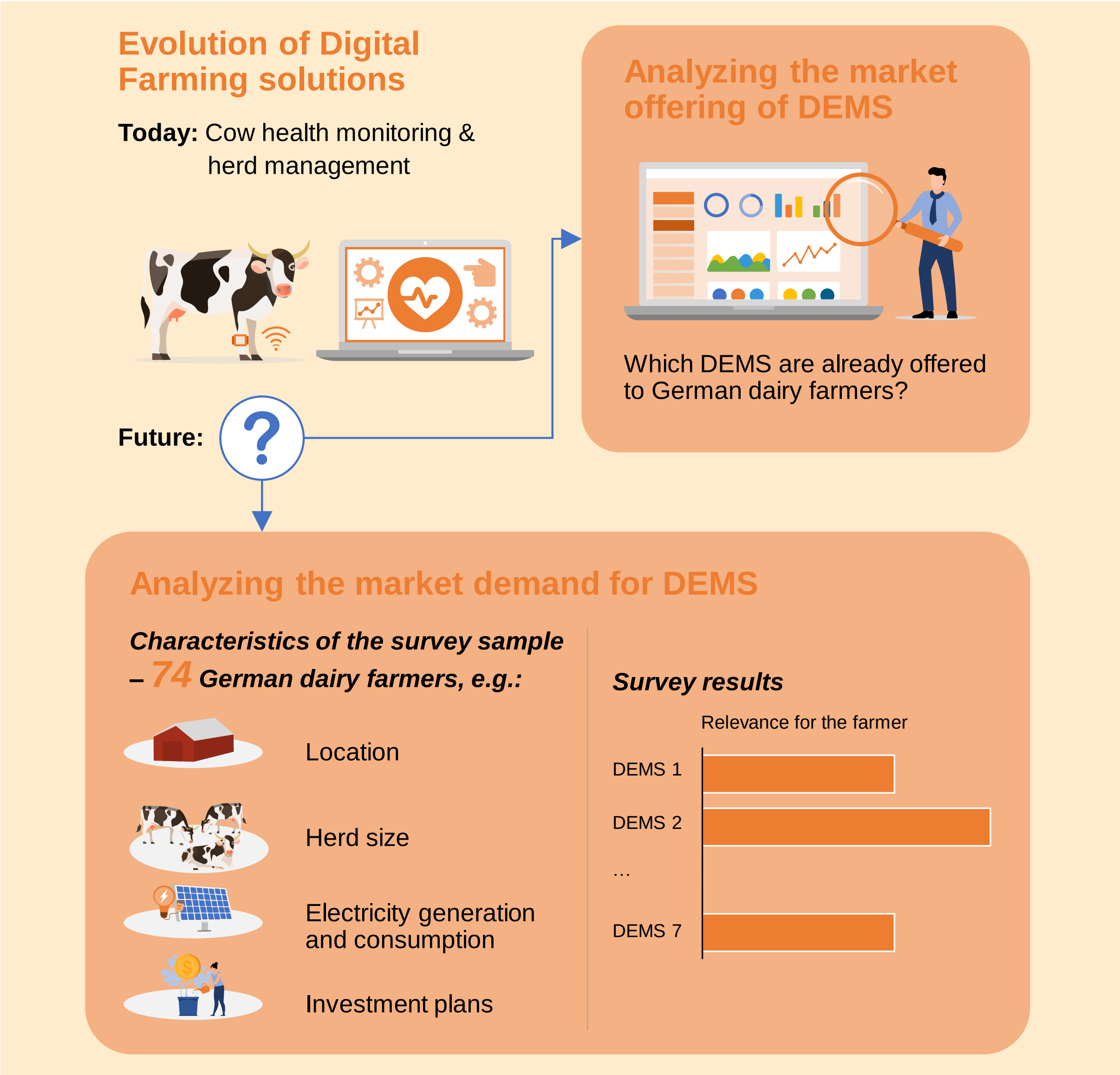

Figure 3.2 Graphical abstract of research article 2

Author contributions: Theresa Theunissen was responsible for the conceptualization of the study, created and distributed the questionnaire, and also wrote the first draft of the manuscript. Theresa Theunissen led the data analysis as well as the visualization of results. Julia Keller contributed to research article 2 with her bachelor thesis, in which she reviewed market

[21] This graphical abstract (see Figure 3.2) is an own visualization based on content from [118].

screening methods, and listed existing energy management solutions offered to the dairy sector [135]. Heinz Bernhardt provided valuable feedback on the study design – especially on the survey set-up, funded the usage of an online survey tool, and made suggestions on the interpretation of results. In total, the authors contributed to research article 2 as follows: Theresa Theunissen (80 %), Julia Keller (10 %), and Heinz Bernhardt (10 %).

3.3 Research Article 3

Title: “How to Successfully Orchestrate Content for Digital Agriecosystems” [108]

Authors: Maximilian Treiber[22], Theresa Theunissen[22], Simon Grebner, Jan Witting, and Heinz Bernhardt

Published at: Agriculture 2023, 13(5), 1003

Available at: https://doi.org/10.3390/agriculture13051003

Summary: A digital agri-ecosystem can comprise more than one digital platform while its digital services are provided by multiple stakeholders (see section 1.1.3). In research article 3, it is outlined that those digital services either include a sensing and smart device layer (IoT agri-ecosystems) or are solely to be found in the cloud and connectivity layer (data agri-ecosystems) (see RQ 3.1). However, despite the benefits expected from a spread of digital agri-ecosystems, in the recent past several digital agri-ecosystems – including NEVONEX[23] – reported their failure (see section 1.2). Therefore, research article 3 analyses failure causes of digital agri-ecosystems. It turns out that one major reason for the shut-down of NEVONEX was an insufficient alignment on the offering portfolio across stakeholders, i.e., especially between the platform operator and the service providers (see RQ 3.2). To address this issue, research article 3 describes a new methodology to support the content orchestration process for the set-up and further development of digital agri-ecosystems. The core of this methodology deals with an evaluation of digital services in terms of six criteria (customer benefit, society impact, economic provider benefit, governance implications, technical feasibility, and resilience). By applying this content orchestration methodology, a ranking of seven pre-defined DEMSs from [118] was derived (see RQ 3.3), as well as a prioritization of DCFSs taken from the NEVONEX team. The testing of the methodology shows that a comparison of results across

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[22] Maximilian Treiber and Theresa Theunissen contributed equally to this research article, i.e., they share first authorship.

[23] NEVONEX intended to provide manufacturer independent digital crop farming services (DCFSs) to operators of agricultural machinery.

digital agri-ecosystems (e.g., a comparison of evaluated DCFSs and DEMSs) is not recommended. In addition, it was pointed out there is not yet an indicator for quantifying the impact of applying the content orchestration methodology on the future success of digital agri-ecosystems. [108] A graphical summary[24] of research article 3 is shown in Figure 3.3.

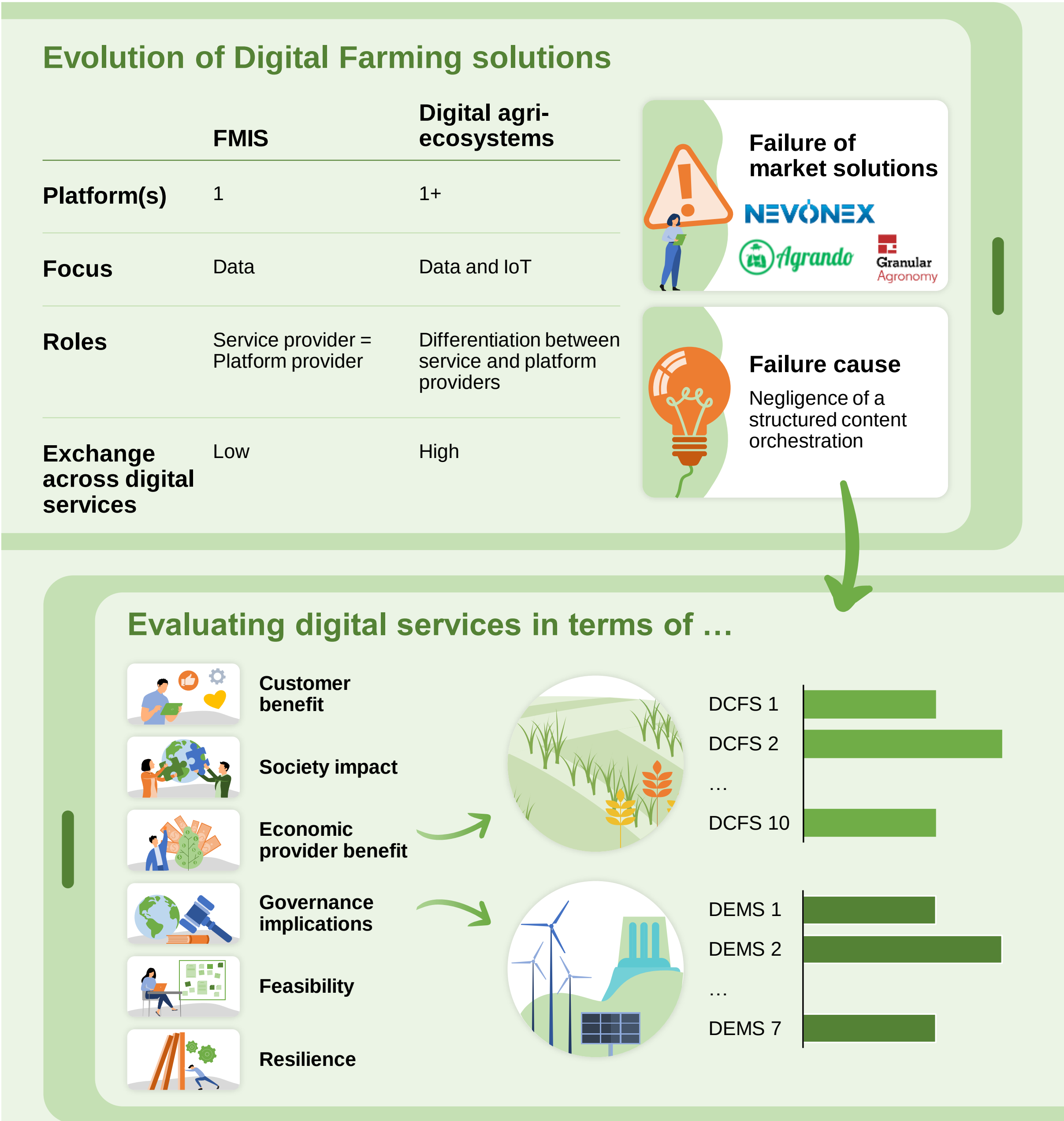

Figure 3.3 Graphical abstract of research article 3

[24] Insights for the creation of this graphical summary (see Figure 3.3) were received from [108].

Author contributions: Maximilian Treiber and Theresa Theunissen contributed equally to the conceptual design of this study, and both had the same contribution share in writing the original draft of the manuscript. Theresa Theunissen was in the lead for writing the following article sections: abstract, introduction, materials and methods, and the result section 3.2 of the research article. The conclusions of the research article 3 were furthermore derived in a joined effort by Theresa Theunissen and Maximilian Treiber. Beyond that, Theresa Theunissen and Maximilian Treiber equally contributed to the visualizations shown in research article 3 and jointly selected the applied methods. During the review process, Theresa Theunissen and Maximilian Treiber took equal parts in editing the original manuscript. Simon Grebner and Jan Witting both contributed to research article 3 in the context of their studies at the Technical University of Munich – Simon Grebner with a master thesis and Jan Witting with a bachelor thesis. While Jan Witting analyzed the customer benefit of DCFSs (to be) offered by NEVONEX [136], Simon Grebner made important contributions to this research article by conducting the expert interviews and drafting the outlined concept on content orchestration [137]. In addition to that, Simon Grebner also provided ideas on the visualization of the research results. Heinz Bernhardt supervised the research work and provided guidance – especially during the review process. Overall, the authors agreed to quantify their contributions as follows: Maximilian Treiber (40 %), Theresa Theunissen (40%), Simon Grebner (10 %), Jan Witting (5 %), and Heinz Bernhardt (5 %).

4 DairyChainEnergy

The findings published in research article 2 show that German dairy farmers regard DEMSs as a relevant digital service category (see section 3.2). The implementation of such digital services is to be realized via a digital platform, e.g., in the form of a FMIS or a digital agri-ecosystem (see section 1.1.3). Based on the findings from this dissertation, a project – called DairyChainEnergy[25] – was started in 2023 targeting to create a concept for the implementation of a digital energy management platform (DEMP) [107]. Hence, the project aims to define an implementation concept for a Minimum Viable Product (MVP), i.e., for a first ready-to-use DEMP prototype for German dairy farming [139].[26] The project activities comprise, for example, a draft of DairyChainEnergy's technical concept, a selection of DEMSs, and a definition of relevant figures for energy data analyses. Key results of these project activities are outlined in the following.

4.1 Technical Concept of the DairyChainEnergy MVP

Time-intensive use is one of the major concerns that German dairy farmers associate with an application of DEMSs [118]. To address this concern, the DairyChainEnergy MVP shall automatically incorporate data from existing Digital Farming solutions, so that digitally available data does not have to be manually entered by the farmer. More specifically, as illustrated in Figure 4.1, data on a farm's dairy herd size and LUs shall be received from HIT – the German tracing and information system for animals [141] –, data on a farm's average milk yield per cow shall be collected via VIT[27] and RDV[28] [141], and data on a farm's electric energy management shall be gathered from EMS providers such as CowEnergy [14]. This set-up is required in order to put farms' electric energy data in relation to other farm characteristics, such as herd size or milk yield. For electricity consumption, this approach is known from literature (see section 1.1.5). Since interfaces to systems like HIT, VIT and RDV have been built already in the context of other use cases (e.g., handling of milk data or herd health management) [141], the novelty of DairyChainEnergy's technical concept resides in the fact that DEMSs shall be

[25] The starting point for this project was set in [138]. The funding for the DairyChainEnergy project was provided by the EU and the federal state of Bavaria [107].

[26] The implementation of the DairyChainEnergy MVP is explicitly not part of the project phase that is outlined in this dissertation. Instead, a new funding approval is required to actually execute the described implementation concept [140].

[27] Vereinigte Informationssysteme Tierhaltung (English: United Information Systems Animal Husbandry)

[28] Rinderdatenverbund (English: Cattle data network)

implemented with the option to integrate data from an EMS (see Figure 4.1). Since, however, EMSs are not yet widely adopted at German dairy farms (see section 1.1.5), a wide range of users will be required to do manual data entries of electric energy data. In the future, this limitation will diminish in importance considering that there is a forecasted rise of EMS adoption at German dairy farms (see section 1.1.5).

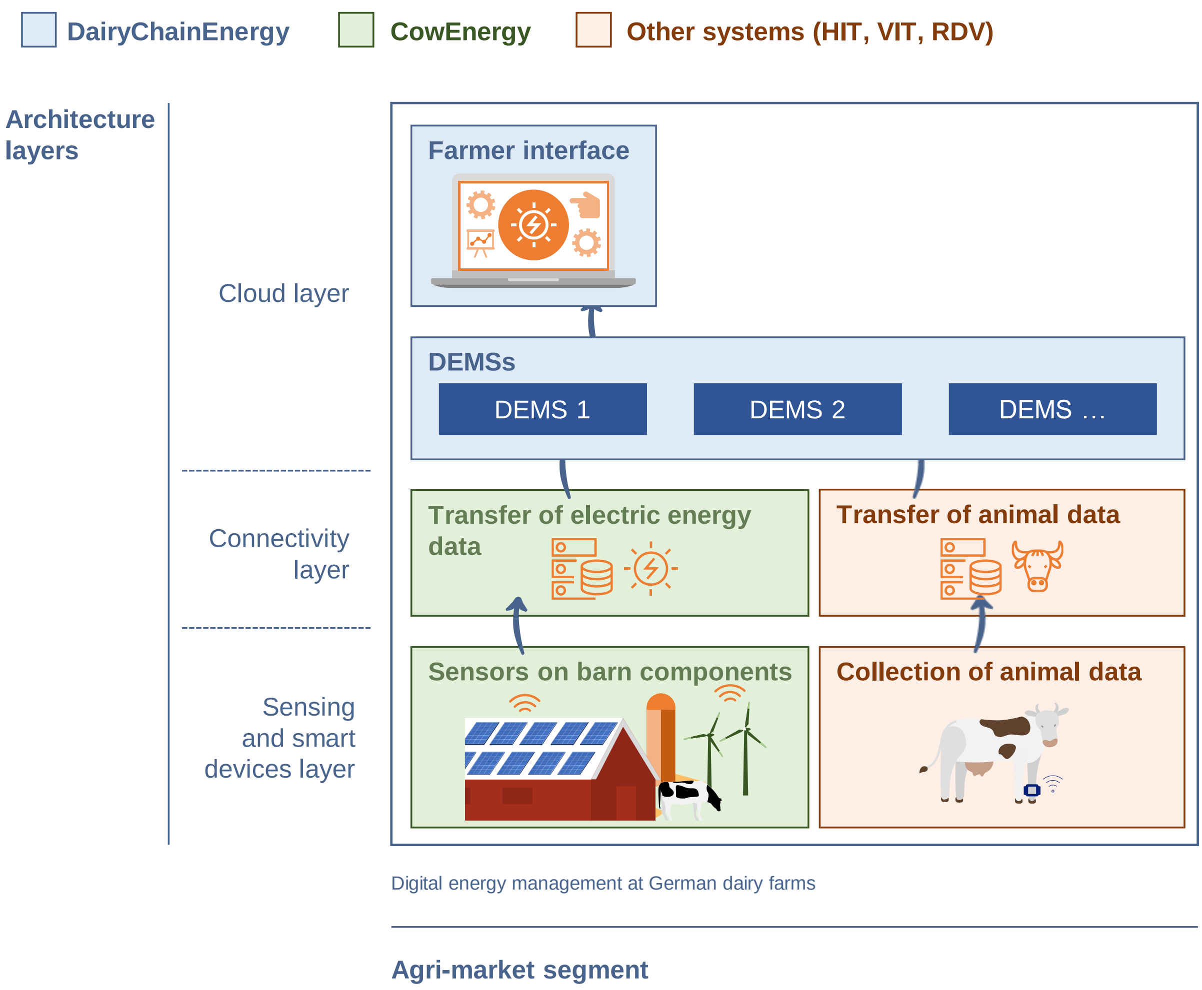

Figure 4.1 Technical concept of the DairyChainEnergy MVP[29]

4.2 Selection and Scope of DEMSs for the DairyChainEnergy MVP

From the sample analyzed in research article 2, 34 % state to intend using a DEMP, while a high share (53 %) is not yet sure on whether to apply such a Digital Farming solution (see Figure 4.2). As discussed in [118], this uncertainty may arise from the novelty of the research topic, i.e., from limited to no experience with applying DEMSs. Comparing insights from

[29] Figure 4.1 is an own visualization in the style of [108].

Figure 4.2 with actual adoption rates of established Digital Farming solutions (see section 1.1.3), it is striking that the sample's intention for applying a DEMP is comparably high. This validates the importance of the DairyChainEnergy research project. Nevertheless, new Digital Farming solutions stay often behind expectations regarding the actual market adoption [21]. Therefore, new studies are required to analyze the future market adoption of DEMSs in more detail.

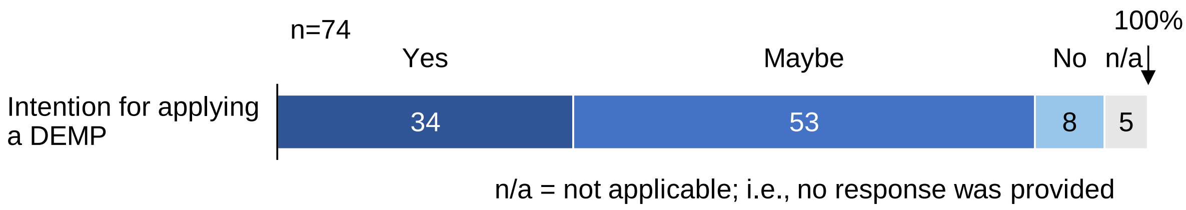

Figure 4.2 Indication on the expected adoption rate of a DEMP – translated[30]

In order to select DEMSs for the DairyChainEnergy MVP, the content orchestration methodology from research article 3 was applied (see section 3.3). In contrast to the study published in research article 3, customer benefit was determined as the most relevant assessment criterion. This led to the decision that the DairyChainEnergy MVP shall comprise DEMSs with highest relevance for German dairy farmers: Energy data visualization, energy data analysis (process optimization), and knowledge service (energy management in the dairy sector) [118]. To detail the implementation concept for these DEMSs, the sample farmers from research article 2 were asked to provide feedback on which aspects of the respective DEMSs are interesting to use for their farms. This approach to conceptualize DEMSs based on actual needs from dairy farmers is new to the research field (see section 1.2).

When reviewing which energy data is visualized in information systems that are discussed in literature, it ca be differentiated between three data categories: Data on energy generation and consumption, financial data related to a farm's energy management, and data on the environmental impact of a farm's energy management [67,80,142]. As shown in Figure 4.3, the majority of the sample (62 %) from research article 2 is interested to have a visualization of data on energy generation and consumption. Less interest is expressed by the sample regarding the use a DEMP for reviewing data on energy-related financial insights (42 %), and energy-related GHG emissions (32 %) (see Figure 4.3). Only 5 % of the sample stated to not intend using a DEMP for reviewing visualized energy data. Based on these findings, for the

[30] The data visualized in Figure 4.2 was gathered from the sample described in research article 2.

DairyChainEnergy MVP, it was decided to prioritize the visualization of data on dairy farms' electricity consumption and generation.

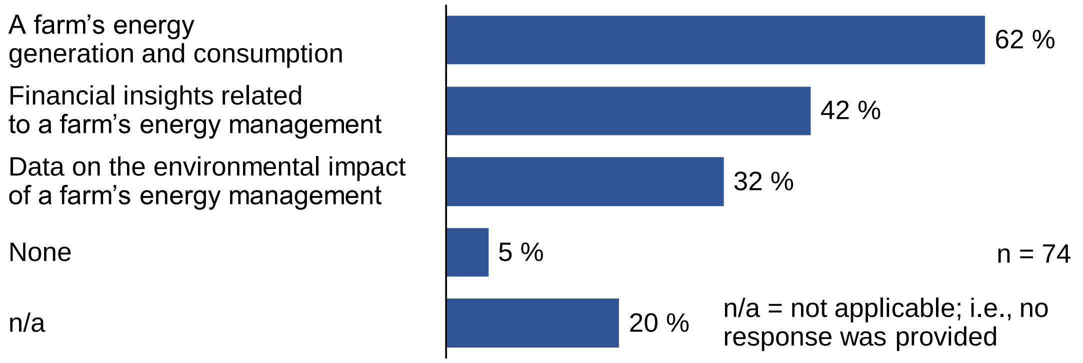

Figure 4.3 Interest of the sample in data categories to be visualized in a DEMP[31]

Next, as shown by MURPHY et al., a dairy farm can derive optimization levers for its electric energy management by analysing how an investment in new technology effects a farm, i.e., the data categories from Figure 4.3 [80]. To understand which investment analyses German dairy farmers are interested to use, a corresponding question was posed to the sample from research article 2. It turned out that the majority of the sample (62 %) is interested in planning investments in energy storage systems (see Figure 4.4). Therefore, this use case was prioritized for the DairyChainEnergy MVP.

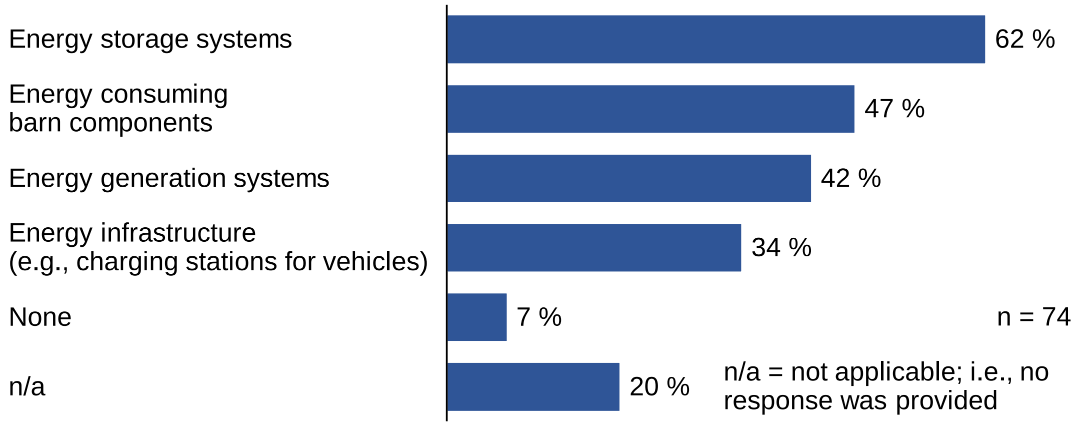

Figure 4.4 Interest of the sample in planning investments in a technology with the help of a DEMS

[31] The responses shown in Figure 4.3 and Figure 4.4 were collected from the sample of research article 2. The sample responses were translated and simplified.

Lastly, for the DairyChainEnergy MVP, the scope for the DEMS *knowledge service (energy management in the dairy sector)* had to be defined. According to insights from the sample of research article 2, as shown in Figure 4.5, German dairy farmers are most interesting in obtaining benchmarks (e.g., on electric energy efficiency) and forecasts (e.g., of electricity market prices). By contrast, experience reports on other farms' energy management practices or news articles on new governmental regulations are of less interest for German dairy farmers (see Figure 4.5).

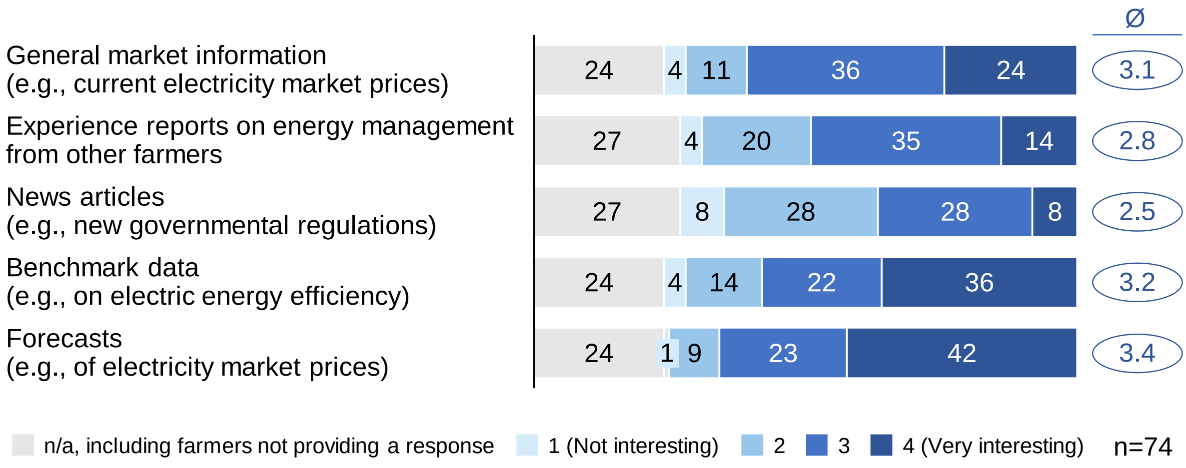

Figure 4.5 Interest of the sample in accessing knowledge items with the help of a DEMS – translated and simplified[32]

4.3 Determination of Key Figures for the DairyChainEnergy MVP

In order to prepare the implementation of DEMSs that were prioritized in section 4.2, it is essential to determine which key figures are to be included in the DairyChainEnergy MVP. The derivation of these key figures is outlined in the following.

As described in section 1.2, most comprehensive research on analyses regarding electric energy data can be found for Irish dairy farming. In fact, there are three open access information systems on electric energy management that can be used by Irish dairy farmers (see Table 4.1): The Decision Support System for Energy use in Dairy Production (DSSED) [80], the Dairy Energy Prediction (DEP) model [67], and the National Artificial Intelligent Dairy Energy Application (NAIDEA) [142]. The speciality of DSSED is that it includes an investment planning function [80], while NAIDEA introduces a new indicator called *Dairy energy rating* to simplify the comparison of electric energy efficiency across dairy farms [142].

[32] The data illustrated in Figure 4.5 was obtained from the sample of research article 2.

Table 4.1 Open access information systems on electric energy management (Irish dairy farming)

Information system	Input parameters (farm)	Input parameters (others)	Output figures
Decision Support System for Energy use in Dairy Production (DSSED) [80]	• Herd size • Specifications on the milking process (e.g., milking start times, number of milking units) • Specifications on barn components (e.g., type of milk cooling system, hot wash frequency) • Milk collection interval • Electricity tariffs (constant vs. night and day)	• Technology as potential future investment (plate cooler; variable speed drive; heat recovery; solar water heating; solar PV; wind turbine) • Investment costs • Level of grand aid • Rate of inflation	• Return on investment for the selected technology • GHG emissions from electricity consumption (current vs. after investment) • Electricity use (current vs. offset) • On-farm electricity utilization rate • Electricity use (day vs. night)
Dairy Energy Prediction (DEP) model [67]RQ 3	• Herd size (dairy cows and LUs) • Total cultivated area • Total milk production per year • Electricity use for field irrigation • Total electricity produced per year	• n/a	• Electricity consumption (total vs. in relation to the herd size vs. in relation to the milk yield vs. in relation to the cultivated land) • GHG emissions from electricity consumption
National Artificial Intelligent Dairy Energy Application (NAIDEA) [142]	• Herd size (dairy cows and LUs) • Total milk production per month • Total electricity use per year • Capacity of electricity generation system (e.g., PV vs. wind) • Capacity of battery storage systems • Specifications on barn components (e.g., low energy lighting, hot water tank capacity) • Specifications on the milking process (e.g., Number of parlour units, average duration of milking per day)	• n/a	• Electricity consumption (total vs. consumer split) • Electricity consumption (total vs. in relation to the herd size vs. in relation to the milk yield) • Electricity consumption over time (monthly) • GHG emissions from electricity consumption • Dairy energy rating

By contrast, for German dairy farming, only one open access information system was found that explicitly deals with electric energy management data (see Table 4.2). This solution developed by KTBL[33] provides an estimation of electricity consumption and electric energy efficiency based on ten input figures that include data on the herd size, milk yield as well as specifications on the milking process and other barn components [96].

Table 4.2 Open access information systems on electric energy management (German dairy farming)

Information system	Input parameters (farm)	Input parameters (others)	Output figures
KTBL[33] – Energiebedarfs-rechner Tierhaltung[34] [96]	• Herd size (LUs) • Annual milk yield per cow • Specifications on the milking process (e.g., conventional milking vs. AMS • Specifications on other barn components (e.g., lightning hours per day)	• n/a	• Electricity consumption (total vs. in relation to the herd size)

Based on insights section 4.2, from Table 4.1 and Table 4.2, the key figures for the DairyChainEnergy MVP were selected as visualized in Figure 4.6 and Figure 4.7. The illustration of data on dairy farms' electricity consumption and generation includes a visualization of (1) absolute numbers, (2) absolute numbers in relation to milk yield and herd size, (3) benchmarks, (4) trends, as well as (5) a split across consumers or systems (see Figure 4.6). However, for the DairyChainEnergy MVP, trends and consumer splits will only be available for dairy farms with an CowEnergy EMS installed. Furthermore, since the investment function of the DairyChainEnergy MVP shall enable calculations regarding electric energy storage systems (see section 4.2), German dairy farmers will receive insights on how such an investment will change their farms' on-farm power utilization rates, revenues, costs and GHG emissions.

[33] Kuratorium für Technik und Bauwesen in der Landwirtschaft (English: Board for Technology and Construction in Agriculture)

[34] English: Energy calculator for livestock farming

Figure 4.6 Visualization of electric energy data – DairyChainEnergy[35]

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[35] Figure 4.6 and Figure 4.7 are own illustrations showing a prototype customer interface created with Figma [143]. The language of this interface is German to make the DairyChainEnergy MVP useable for German dairy farmers. The data shown in Figure 4.6 and Figure 4.7 is fictious.

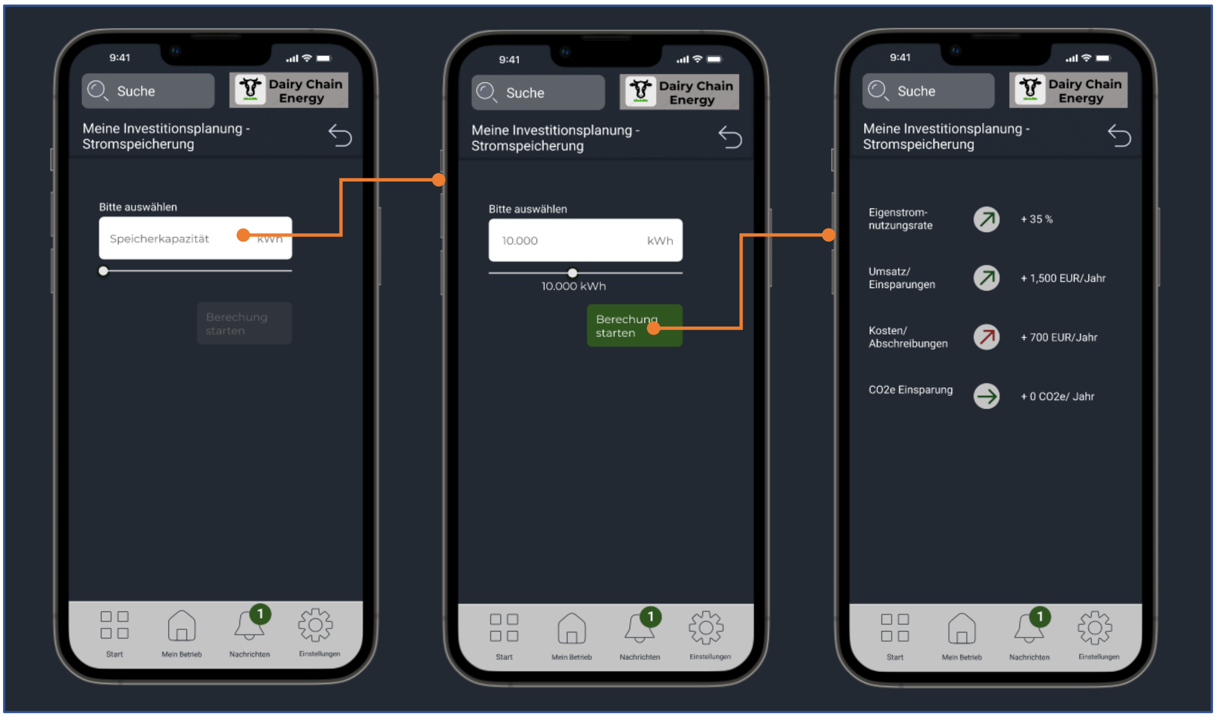

Figure 4.7 Investment planning of electric energy storage systems – DairyChainEnergy

5 Discussion

5.1 Methodological Discussion

As described by THEOFANIDIS and FOUNTOUKI, it is crucial to have a discussion of a study's assumptions and limitations for the advancements of a research field [144]. For this reason, Table 5.1 provides an overview of assumptions and limitations made in the context of this dissertation's studies. A subset of most relevant or discussable assumptions and limitations is reviewed in the following.

Table 5.1 Assumptions and limitations of this dissertation's research articles[36]

Research article	Assumptions	Limitations
1 (see section 3.1)	• A threshold of 2,284.36 kWh*dairy cow^{-1} was assumed for the maximum (max.) electricity generation at dairy farms[37] • Remuneration for energy data sharing requires sharing of insights on both electricity and fuel	• Focus on dairy farms generating electricity via PV (one roof PV system per dairy farm) • Financial impact only considered with regards to electricity sales and sharing of energy data • Changes of electricity generation over time (e.g., due to investment decisions) have not been modelled[37]
2 (see section 3.2)	• Standard values for electricity consumption of private house-holds were used from [145] to clean the survey input data[37] • Calculated the assessment of DEMSs as the mean of the sample's responses[37]	• Small sample size (n=74) compared to other studies on German dairy farming [19,22][37] • No data gathered on the relevance of DEMSs for dairy farms that do not have on-farm electricity generation[37]
3 (see section 3.3)	• Equal weighting of the assessment dimensions when testing the content-orchestration methodology • No differentiation in the assessment of 'society impact' during the methodology testing	• No proof provided on the impact of applying the content-orchestration methodology on the future market success of digital agri-ecosystems • Methodology testing was conducted based on a small set of expert interviews

In research article 1, changes in energy-related revenues were analyzed for a defined set of fictious farm archetypes (see section 3.1). Since the scenario analysis from research article 1 was however limited to one electricity generation technology (roof PV) (see Table 5.1 and section 3.1), and given that a farm's roof space is limited by its stable size, a max. electricity

[36] The assumptions and limitations listed in Table 5.1 were obtained from [108,109,118].

[37] This aspect is discussed in detail during the further course of this section.

generation capacity via roof PV had to be determined per farm archetype [109]. Because no information could be found on a German dairy farm's max. power generation capacity via roof PV, a theoretical threshold of 2,284.36 kWh per dairy cow was derived from publicly available information [109]. However, there is in the meantime new data available on dairy farms' PV electricity generation from more than 70 German dairy farms.[38] This data was received with the help of the online survey described in research article 2 (see section 2.1), that was still open at the time research article 1 was submitted [109,118]. These new insights can be used to review the validity of the estimated threshold (max. roof PV electricity generation of 2,284.36 kWh per dairy cow). As shown in Figure 5.1, the average PV electricity generation per dairy cow is – according to data from the online survey – below that threshold (i.e., at 928 kWh*dairy cow^{-1}).

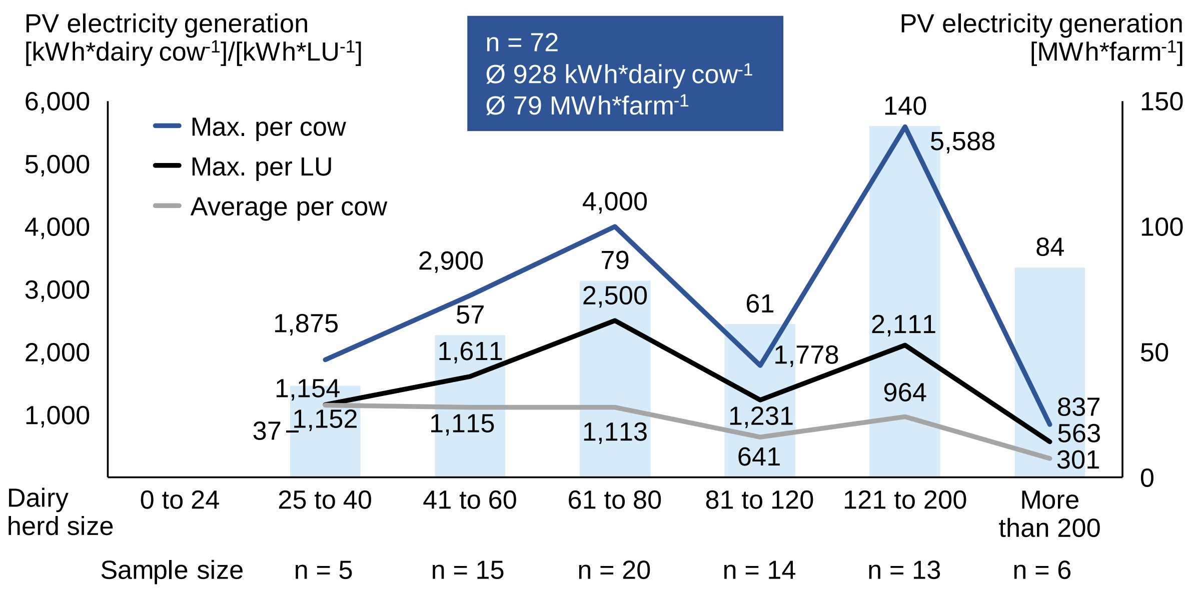

Figure 5.1 Electricity generation via PV in dependence of the dairy herd size[39]

However, 5 of the 72 analyzed dairy farms show a PV electricity generation per dairy cow above that threshold with a max. of 5,588 kWh*dairy cow^{-1}. These 5 dairy farms had on average 93.6 additional LUs, e.g., one stated also to do pig farming. With this in mind, by putting the farms' annual PV electricity generation in relation to their LUs, the max. values

[38] Here, a larger sample size of German dairy farms with PV systems (n=72) is used compared to the PV sample analyzed in research article 2 (n=44) [118]. This is because in research article 2, responses with a missing DEMS assessment were excluded (see section 2.1).

[39] Figure 5.1 was created with data from the online survey described in section 2.1.

observed, i.e., in the unit kWh*LU^{-1}, fit much better to the theoretically derived threshold of 2,284.36 kWh (see Figure 5.1)[40]. Against this background, it is recommended to adjust the model from research article 1 in the context of future studies and define a dairy farm's max. roof PV electricity generation capacity in dependence of a dairy farm's LUs.

Next, as mentioned in Table 5.1, one limitation made in the scenario analysis of research article 1 was that "… we did not model changes in a farm's total electricity generation volume over time (e.g., due to investments, outages, or changes in technical efficiency)…" [109]. Making this limitation was deemed appropriate as factoring in these figures would have increased the complexity of the calculation model [109]. With regards to future investments into energy generation, studies from a German market research company however reveal a new trend [55,56,146,147]: While the share of German farms planning to invest into renewable energy generation was estimated to be at 3 % in 2020 and 2021, 8-10 % expressed investment intentions in 2023 (see Figure 5.2). Also, the total amount of planned investments into renewable energy generation at German farms rose from 0.5-0.7 B € in 2020/2021 to 1.1-1.4 B € in 2023 – thus, it roughly doubled (see Figure 5.2).

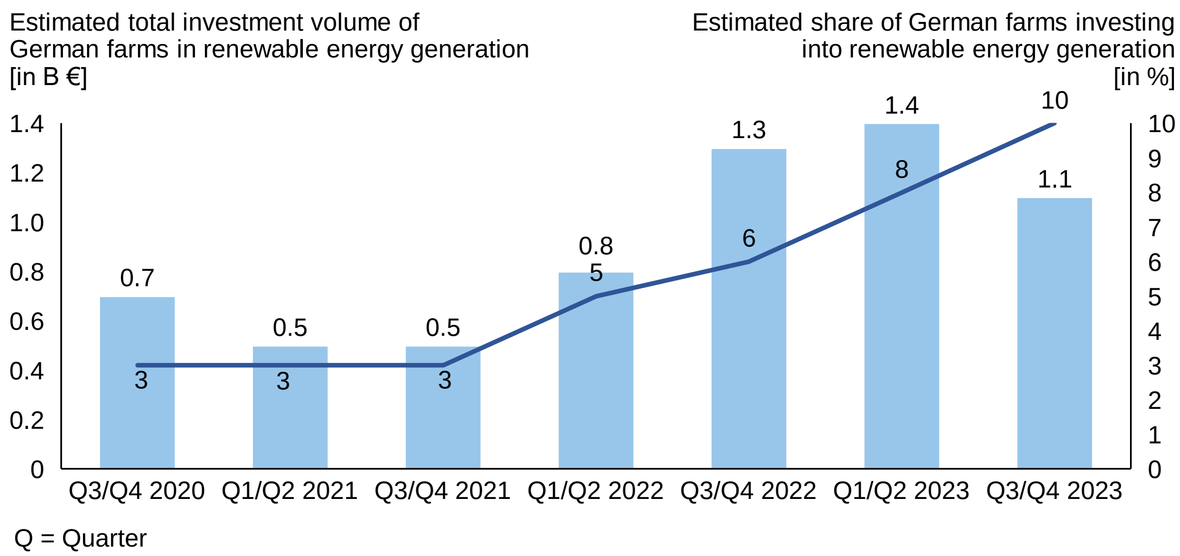

Figure 5.2 Investment plans of German farms regarding renewable energy generation[41]

Hence, even though this trend was not yet foreseeable at the submission date of research article 1 [109], for future studies, it is recommended to consider this trend when modelling a

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[40] Only one dairy farm stated to have a higher electricity generation rate (2,500 kWh*LU-1).

[41] Own illustration with data from [56,55,146,147]. The numbers do not reflect actual investments, but only are only a market forecast based on survey responses from German farmers [56,55,146,147].

scenario analysis of German dairy farms' energy-related revenues. One challenge remaining is to make an assumption on how the data from Figure 5.2 can be transferred specifically to German dairy farming. In this context, research article 2 yields interesting insights concerning this matter given that 66 % of the survey sample stated to have plans for making investments into energy generation until 2025 [118]. A comparison of these findings with data from Figure 5.2 underline the discussion from research article 2, i.e., that the 74 surveyed dairy farmers have an above-average interest in optimizing their farms' energy management [118].

Looking at the analysis from Figure 5.1, the average PV electricity generation per cow is at 79 MWh per farm. In comparison to findings from research article 2 (64 MWh*farm^{-1} [118]), this however means a deviation by 23 %. This deviation may stem from the study's comparably small sample size [148], which is one limitation of research article 2 (see Table 5.1). This limitation arises "… from the set-up of the survey (participants had the option to skip questions) and the novelty of the topic (38% of our survey participants did not provide a complete evaluation on the relevance of DEMS)" [118]. Looking at RQ 2.1, according to calculations described by LEVEUGLE et al., the error margin (e) of the DEMS evaluation – published in research article 2 – is derived as 11.4 %.[42] Hence, it is higher than the recommended max. value for e (5 %) [148]. Yet, to realize a recommended confidence level of 95 % while setting e=5 % [148], a German dairy sample size of n=382 would be required.

Furthermore, as illustrated in Figure 2.3, the study sample comprised only those responses, that showed answers to all questions listed in Figure 2.1 and Figure 2.2. Thus, 73 DEMS assessments from German dairy farmers were disregarded in order to be able to address RQ 2.2 in the context of research article 2 (see Figure 2.3). In fact, 147 German dairy farmers provided an evaluation on the relevance of DEMSs. However, only responses from 74 dairy farmers were considered given that only those provided holistic insights regarding requested data, e.g., farm characteristics, and status quo of the farm's energy management (see Figure 2.3). Thus, considering the study's error margin (e=11.4 %)[42], a comparison of results from research article 2 with the relevance assessment of DEMSs from all 147 dairy farmers enriches the current understanding within that research field. That is due to the lower error margin of this sample (e=8.1 %)[42]. As shown in Figure 5.3, the max. deviation of the samples' mean relevance assessments per DEMS is at 0.2 – for energy data visualization, knowledge service (energy management in the dairy sector), energy marketplace, and energy data marketplace. When comparing the median of DEMS assessments from the two samples, it becomes apparent that only for 'energy data visualization', a different rating was obtained (see

[42] This number was received setting the German dairy farm population (N) equal to 55.8 thousand (see section 1.1.2) and taking a recommended confidence level of 95 % [148].

Figure 5.3). Overall, given the lower error margin of the sample with n=147 dairy farmers, future studies are encouraged to work with the DEMS assessment from that sample. Furthermore, as described in [149], it is recommended to calculate the median when targeting to measure the central tendency of Likert-type data. Nevertheless, in order to answer RQ 2.1, i.e., derive a ranking of DEMSs with regards to their relevance for German dairy farmers, it was consciously decided to calculate the mean of the sample's DEMS assessments. This approach provides a higher level of detail regarding a ranking of DEMSs, i.e., a 5-stage ranking instead of a 3-stage ranking (see Figure 5.3).[43]

	Sample from research article 2		n = 147 (see Figure 2.3)	
DEMS	Relevance (Mean)	Relevance (Median)	Relevance (Mean)	Relevance (Median)
Energy data visualization	3.2	4.0	3.0	3.0
Energy data analysis (process optimization)	3.4	4.0	3.3	4.0
Energy data analysis (predictive maintenance)	2.7	3.0	2.7	3.0
Knowledge service (energy management in the dairy sector)	3.2	3.0	3.0	3.0
Energy marketplace	3.0	3.0	2.8	3.0
Energy data marketplace	2.2	2.0	2.0	2.0
Energy-related documentation and inquiries	3.0	3.0	2.9	3.0
Error margin (e)	11.4 %		8.1 %	

Figure 5.3 DEMS assessments from research article 2 vs. from a sample with n = 147

Next, since electric energy management at German dairy farms also encompasses the private house of a farm [14], in the course of the survey analyzed for research article 2, survey participants were asked to state if the electricity use of their private households was included in the reported total electricity consumption. If yes, they should specify the number of residents living in the farm's private household (see Figure 2.1). With this approach, the resulting figure – electricity consumption excluding the use from private households – turned out to be negative for 3 out of the 180 dairy farms providing data on electricity consumption. This might raise concerns about the validity of this approach. Current literature, however, does not offer a reasonable alternative approach for addressing this issue. Nevertheless, the chosen approach

[43] Figure 5.3 includes data from research article 2 [118]. The derivation of the second sample with n=147 is illustrated in Figure 2.3.

also led to limited comparability of this dissertation's data with studies not excluding the electricity use of private farmhouses.

Lastly, one additional limitation of research article 2 is that no information on the relevance of DEMSs was collected from farms that do not have a power generation system installed (see Table 5.1). Those farms not generating electricity might have different interests in the usage of DEMSs compared to the sample from research article 2. This is underlined by data shown in Figure 5.4: There is an indication that this farm archetype tends to have different energy management characteristics, e.g., a lower electricity consumption per cow or kg of milk produced. Yet, the analyzed sample from Figure 5.4 is very small (n=13) leading to an error margin of e=27.1 %.[42] A validation of this finding is hence recommended to be covered by future research studies.

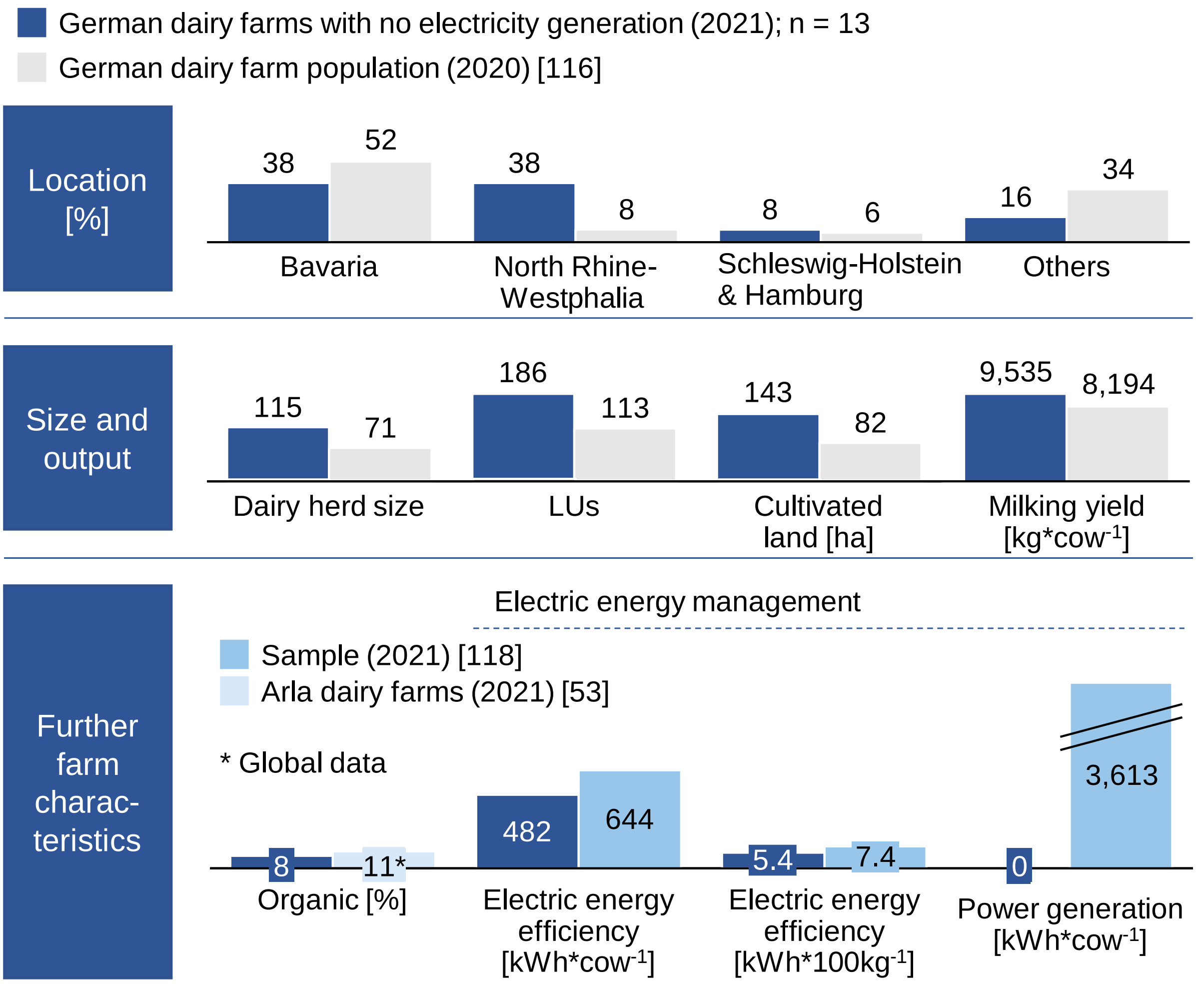

Figure 5.4 Characteristics of German dairy farms that do not generate electricity[44]

[44] Figure 5.4 is an own visualization in the style of [118] with data from [53,116,118].

5.2 Discussion of Key Findings and Avenues for Future Research

As outlined in section 1.2, studies on German dairy farming contribute to almost all internationally addressed focus topics of research around electric energy management at dairy farms. Only one focus topic – a literature review specifically dealing with current research on electric energy management at German dairy farms – has not yet been addressed. In this regard, this dissertation contributes to the research field by providing an overview of literature published since the 2010s on electric energy management at Germany dairy farms (see Table 1.2). On top of that, this dissertation prioritizes the focus topics B3 and D2 based on the RQs formulated in section 1.2 (see Figure 5.5).

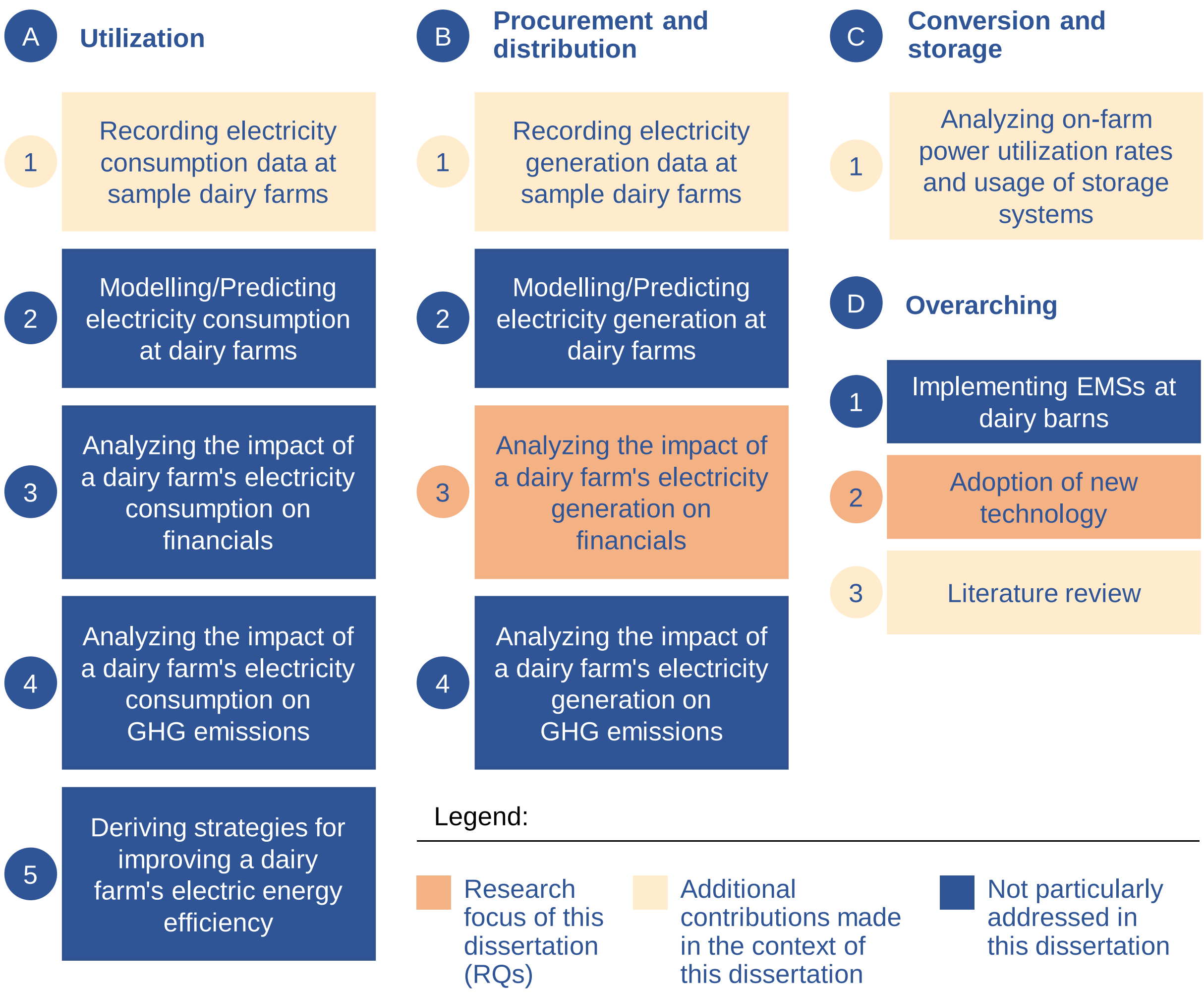

Figure 5.5 Research contributions from this dissertation[45]

[45] Figure 5.5 is an adjusted illustration based on Figure 1.4.

In addition, the three research articles embedded into this dissertation made contributions to the focus topics A1, B1, and C1 by providing data records on electricity consumption, electricity generation and on-farm power utilization at German dairy farms (see Figure 5.5). In the following, key findings from this dissertation regarding these research topics (A1, B1, C1, B3, D2) are discussed and contextualized with current literature. Moreover, avenues for future research are delineated.

5.2.1 Data on Electric Energy Management at German Dairy Farms

The major purpose of the survey from research article 2 was to evaluate the relevance of DEMSs for German dairy farmers (see section 3.2). In addition, the survey also provided data on the electricity consumption at German dairy farms [118]. This is especially valuable given that the most comprehensive German study on the total electricity consumption at dairy farms from NESER et al. published data that was gathered in 2007 – hence data that is from 15 years ago (see Table 1.2). In research article 2, a high amount of responses had to be disregarded due to a missing assessment on the relevance of DEMSs (see Figure 2.3). When however using all applicable survey responses collected in the course of this study to analyze the electric energy efficiency of German dairy farms, a higher sample size of 174 farmers could be used. This improves the confidence level of this dissertation's findings on German dairy farms' electricity consumption to above 80 % (when applying same assumptions as outlined in section 5.1). The results from this new analysis indicate that the average electric energy efficiency of German dairy farms – i.e., their electricity consumption put in relation to the number of cows – has been improved by 5 % since 2007 (see Figure 5.6). Furthermore, when looking at the max. values on electric energy efficiency shown in Figure 5.6, those from 2021 are almost twice as high as those from 2007.[46] This potentially stums from the fact that NESER et al. removed extreme values from their data set [40], while for the analysis of this dissertation only non-plausible data sets were excluded. Moreover, German dairy farmers were also explicitly asked whether their provided number on the farm's electricity consumption includes the use of a private household. If so, the figure was corrected accordingly (see section 5.1). NESER et al. however have not made any statements in that regard [40].

[46] Data shown in Figure 5.6 was obtained from [40,42] and from the survey described in section 2.1.

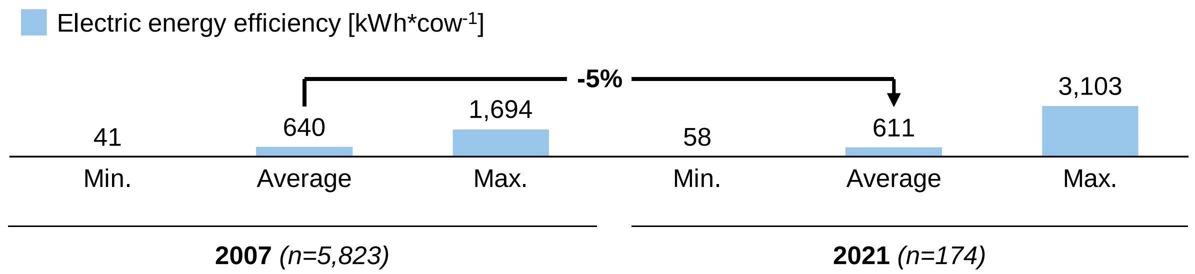

Figure 5.6 Electric energy efficiency at German dairy farms (2007 vs. 2021)

When next analyzing the survey respondents' electric energy efficiency in dependence of the size of the dairy herd, it becomes apparent that there is not a clear relationship between these two figures as it was the case in the publication of NESER et al. [40] (see Figure 5.7). Rather, the electricity consumption per cow of the sample used to create Figure 5.7 is for farms with a herd size above 80 lower compared to farms with a dairy herd size below or equal to that threshold (691 vs. 544 kWh*cow^{-1}).

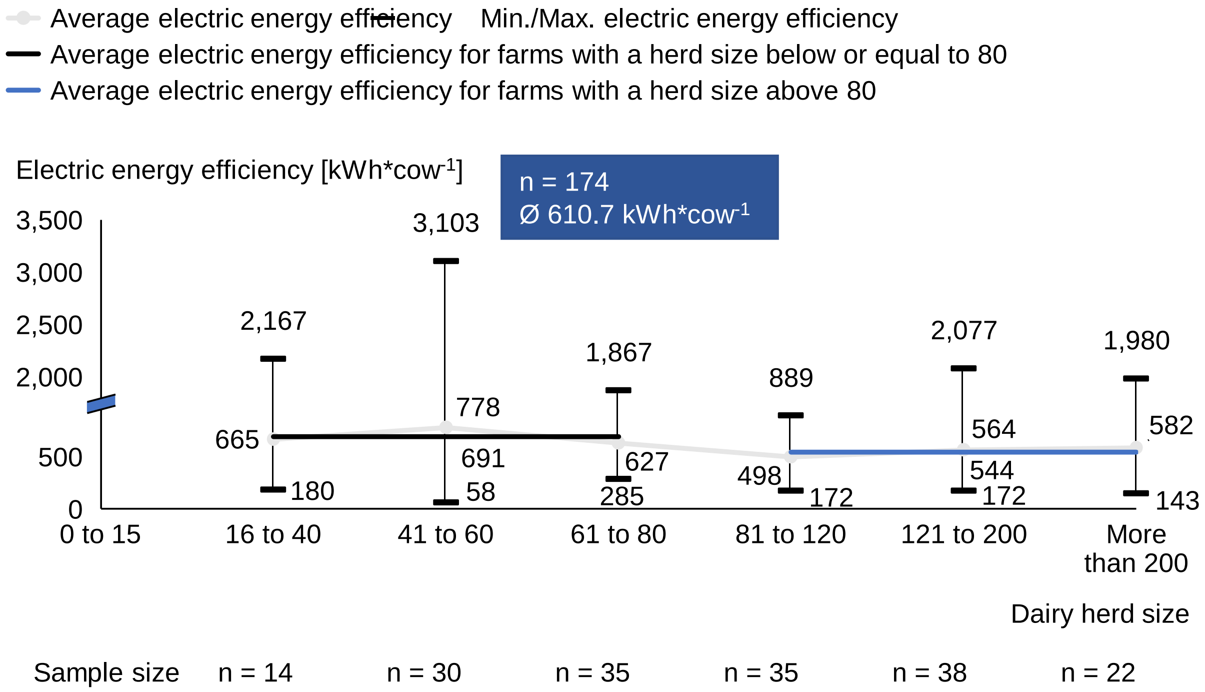

Figure 5.7 Electric energy efficiency [kWh*cow^{-1}] in dependence of the dairy herd size[47]

[47] Figure 5.7 is an own visualization following the style of [40]. It shows survey data that was gathered during the preparation of research article 2 (see section 2.1).

Equally applicable is this to the electricity consumption per kg of milk produced (8.7 vs. 5.5 kWh*100kg^{-1}) – as shown in Figure 5.8. This difference in the electric energy efficiency between smaller and larger dairy farms is even higher given that the sample farms with a larger herd size tend to have a higher milk yield per cow (see Figure 5.8). This relationship between herd size and milk yield is known from literature [57].

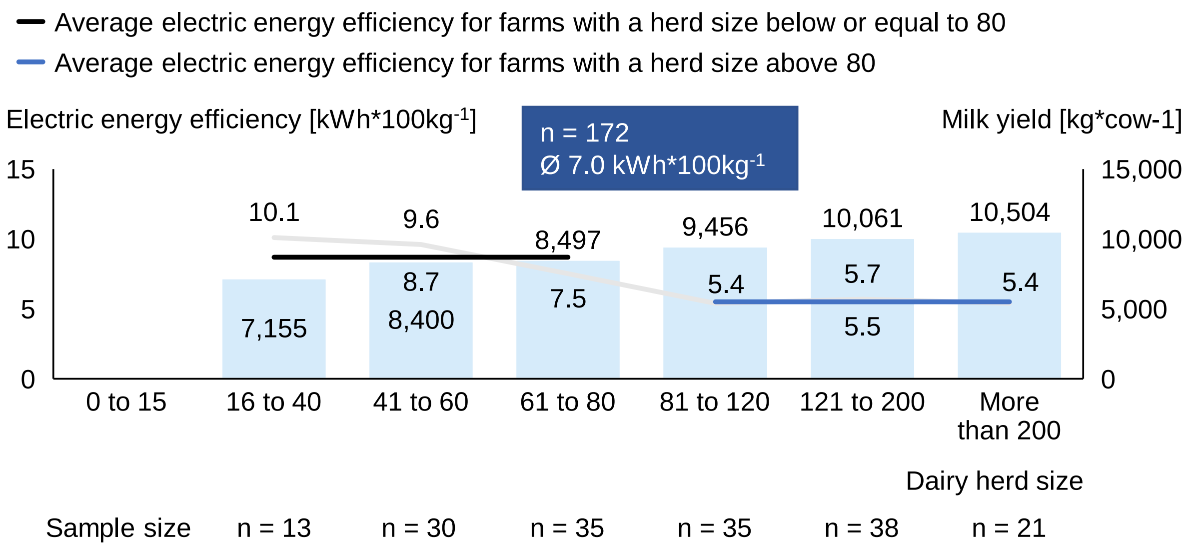

Figure 5.8 Electric energy efficiency [kWh*100kg^{-1}] in dependence of the dairy herd size[48]

Beyond that, the analyses on the average electric energy efficiency of German dairy farms from Figure 5.7 and Figure 5.8 show a 5.2 %-5.4 % deviation from findings published in research article 2.[49,50] The latter fact underlines the importance of the methodological discussion from section 5.1. Nevertheless, this dissertation adds valuable new insights to the research field because, for example, annual data on a German dairy farm's total electric energy efficiency – as electricity consumption put in relation to a farm's milk yield – has not yet been available in literature (see Table 1.1). Furthermore, the results from this dissertation also show

[48] Figure 5.8 was created based on data collected in the context of the survey described in section 2.1.

[49] The data point of 5.2 % can be received as follows: In research article 2, an average electric energy efficiency of 644 kWh*cow^{-1} was detected across the sample (n = 74) [118]. The new analysis from Figure 5.7 with a higher sample size (n = 174) reveals an average electric energy efficiency of 610.7 kWh*cow^{-1}.

[50] The data point of 5.4 % was received by comparing the electric energy efficiency – calculated in relation to the milk yield – from Figure 5.8 (0.07 kWh*100kg^{-1}; n = 172) with the findings from research article 2 (0.074 kWh*100kg^{-1}; n = 74) [118].

that there is still an improvement potential of 26.3 % with regards to the electric energy efficiency of German dairy farms.[51] This is concluded by comparing the findings from this dissertation's survey data to farms using an AMS and energy-optimized technology (see Table 1.1).

As a synthesis of this section, it can be stated that this dissertation contributed to an enrichment of current knowledge on electricity consumption and power generation – especially with regards to PV – at German dairy farms. However, as described in section 5.1, a sample size of 382 dairy farms is recommended to achieve a confidence level of 95 % with regards to survey data from German dairy farms. Hence, future research could conduct a nation-wide study with a higher sample size to validate the findings from this dissertation on today's electricity generation and consumption at German dairy farms. In this context, scholars could analyze the key figures – power generation and consumption – with regards to multiple farm characteristics (such as applied technology, e.g., milking system, or management practices, e.g., confinement vs. grazing farming) as it is done by adjacent literature [35]. In order to be able to draw high-confidence conclusions from this, future research necessitates ensuring a minimum (min.) sample size per relevant farm archetype. Specifically, the following differentiation of German dairy farm archetypes is recommended to be considered: (1) conventional vs. organic farming [35], (2) AMS vs. conventional milking [35,43], (3) no on farm-electricity generation vs. on-farm electricity generation (see section 5.1), and (4) power generation via PV vs. biogas vs. wind [118], and (5) dairy farms with representative differences in the dairy herd size [40]. Furthermore, next to new German-wide studies on electricity generation and consumption at dairy farms, annual data gathered from EMSs, which are already installed at German dairy farms, would be of very high value for the research field. Such data allows for an analysis of the development of electricity consumption, storage, and generation over time with regards to a wide series of barn components. So far, publications capture only EMS data from short time periods or a limited set of barn components (see Table 1.2). In addition, with the assistance of EMSs, data on on-farm power utilization rates could be analyzed in more detail to review the electric self-sufficiency level of German dairy farms. In the survey for research article 2, such on-farm power utilization rates were only gathered in ranges (see Figure 2.2) in order to simplify the data input for the survey participants.

[51] The number 26.3 % is obtained from the average electric energy efficiency shown in Figure 5.7 (610.7 kWh*cow^{-1}) and a data point mentioned by BERNHARDT et al. (450 kWh*cow^{-1}) (see Table 1.1).

5.2.2 Revenues from Electricity Generation at German Dairy Farms

When extrapolating the data from Figure 5.7 and Figure 5.8 to the entire German dairy farm population for 2021, the total electricity consumed by German dairy farms can be estimated to 2.3 TWh. This number is derived when taking into account the total milk volume of 32.51 M tons produced in Germany (see Figure 1.2), and an electric energy efficiency of 7.0 $kWh*100kg^{-1}$ (see Figure 5.8). As shown in Figure 5.9, the same data point is obtained when calculating with an electric energy efficiency of 610.7 $kWh*cow^{-1}$ (see Figure 5.7), and a total number of German dairy cows of 3.83 M (see Figure 1.2). Comparing these insights to findings from 2007, it becomes apparent that the total electricity need at German dairy farms was reduced by 12 % between 2007 and 2021.[52] This comes on the one hand from a reduction in the total number of dairy cows (see section 1.1.2) – this figure fell by 5.9 % from 2007 to 2021 [16].[53] On the other hand, it is the result of an improved electric energy efficiency (see Figure 5.6). Furthermore, as illustrated in Figure 5.9, data from this dissertation indicate that German dairy farms reach the point of having a balance between their total electricity consumption and the total on-farm generated power via PV. Publicly available information enable a top-down estimation of the total PV electricity generation at German dairy farms: 210.8 TWh have been generated in 2018 by renewable power systems in Germany (see section 1.1.5), while 38.7 % of that volume comes from PV (45.8 of 118.3 GW net nominal capacity) [52]. Since 15.9 % of that PV capacity is provided by farmers (see section 1.1.5), and given that 21.7 % of German dairy farms were specialized on dairy in 2018 (62.8 of 266.7 thousand farms [15,150]), the actual PV electricity generation volume at German dairy farms can be estimated to 2.8 TWh[54] in 2018. This estimation is however subject to a high level of uncertainty since no indication was found in literature on how the total PV electricity volume generated at farms is distributed across different farm types such as dairy, pig or poultry farming. To address this matter, findings from this dissertation can be used to apply an alternative approach for calculating the total electricity volume generated at German dairy farms: For 2021, taking the average PV electricity generation volume of 928 $kWh*cow^{-1}$ (see Figure 5.1), the average German dairy herd size of 70 cows per farm (see section 1.1.2), and the total number of dairy farms in Germany – 55.8 thousand (see section 1.1.2), and assuming that 58 % of those farms actually generate electricity via PV (see section 1.1.5), the PV electricity generation volume from German dairy farms can be estimated to 2.1 TWh[54] (see

[52] The data point 12 % stems from the total electricity consumed by German dairy farms in 2007, which can be estimated to 2.6 TWh assuming a total number of 4.1 M German dairy cattle [16], and an electric energy efficiency of 640 $kWh*cow^{-1}$ [42].

[53] The data point 5.9 % is calculated in 2007, when there were 4.07 M dairy cows in Germany [16].

Figure 5.9). Applying the same bottom-up approach but with the assumption of 79 MWh generated per dairy farm (see Figure 5.1), the total electricity generated via PV at German dairy farms results to 2.6 TWh[54]. However, when putting these findings in context with the max. PV capacity of 20 TWh[55], so far only 10.5-14 % of that capacity has been actually realized at German dairy farms (see Figure 5.9). This might be one reason for new legal regulations on the installation of roof PV [45]. Overall, German dairy farms have the chance to expand their relevance as PV power providers in Germany. Against this background, future research should analyze how future investments in energy generation technology will impact German dairy farms' total electricity generation and energy-related revenues (see section 5.1).

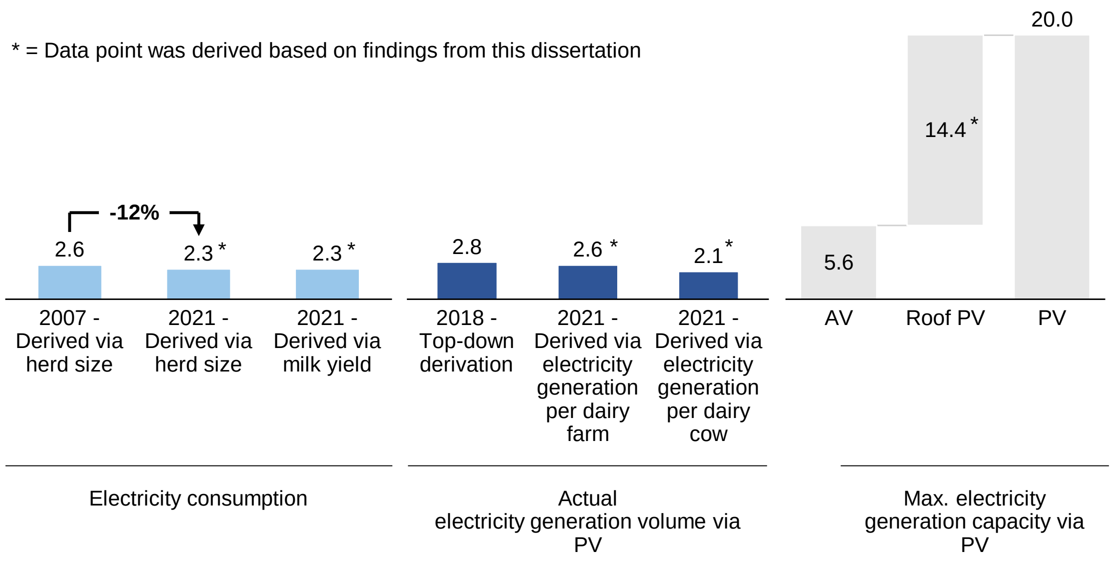

Figure 5.9 Estimations on the total electricity consumption and PV power generation at German dairy farms in TWh

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[54] 70.3 % of that PV electricity can be expected to come from roof PV, and 12.7 % from AV [151].

[55] This number was received by considering a max. AV capacity of 5.6 TWh at German dairy farms (see section 1.1.5), and an estimated total roof PV power generation capacity of 14.4 TWh. The max. roof PV capacity was obtained from publicly available information as well as from insights provided in the context of this dissertation: The max. roof PV electricity generation capacity can be derived based on an average of 113 LUs per dairy farm [116] on 55.8 thousand dairy farms in Germany (see section 1.1.2), and a roof PV power generation capacity of 2,284.36 kWh per LU (see section 5.1). Considering that the German government will allow a construction of 177.5 GW AV until 2040 [10], the max. AV capacity of German dairy farms could be much higher than the 5.6 TWh. This forecast of FEUERBACHER et al. is based on an AV capacity of 44.3 GW [54], hence covers only 25 % of the legally permitted AV capacity. It is however not yet clear how this max. AV capacity of 117.5 GW will be distributed among farm types. This topic should be addressed by future research studies.

In the scenario analysis from research article 1, it was modelled that in ten years, German market prices for PV electricity will either stay at the price level from 2022 or fall back to values known from 2020 [109]. The actual development of the German solar market price in 2023 does not contradict this assumption: In fact, even though there was an increase of the German solar market value by 807 % from 2020 to 2022, prices fell by 64 % in 2023 (see Figure 5.10). Nevertheless, since 2021, in case of newly installed PV electricity generation systems, it is worth considering to do direct electricity sales instead of using EEG levies: For PV systems with a capacity of more than 10 kilowatt peak (kWp) installed in January 2023, EEG levies are less or equal to 7.1 Cent*kWh^{-1} while the solar market value for 2023 can be estimated to 8.13 Cent*kWh^{-1} (see Figure 5.11). Findings from this dissertation indicate that the majority of German dairy farmers do not have PV plants with more than 100 kWp (see Figure 5.1), and hence can make use of EEG levies.[56] Therefore, as discussed in research article 1, German dairy farmers should review which electricity distribution type is advantageous for their farms [109]. This consideration is very farm-specific [109], e.g., given that EEG levies for PV plants installed before 2012 exceed the all-time highest annual German solar market value of 22.31 Cent*kWh^{-1} [113,117].

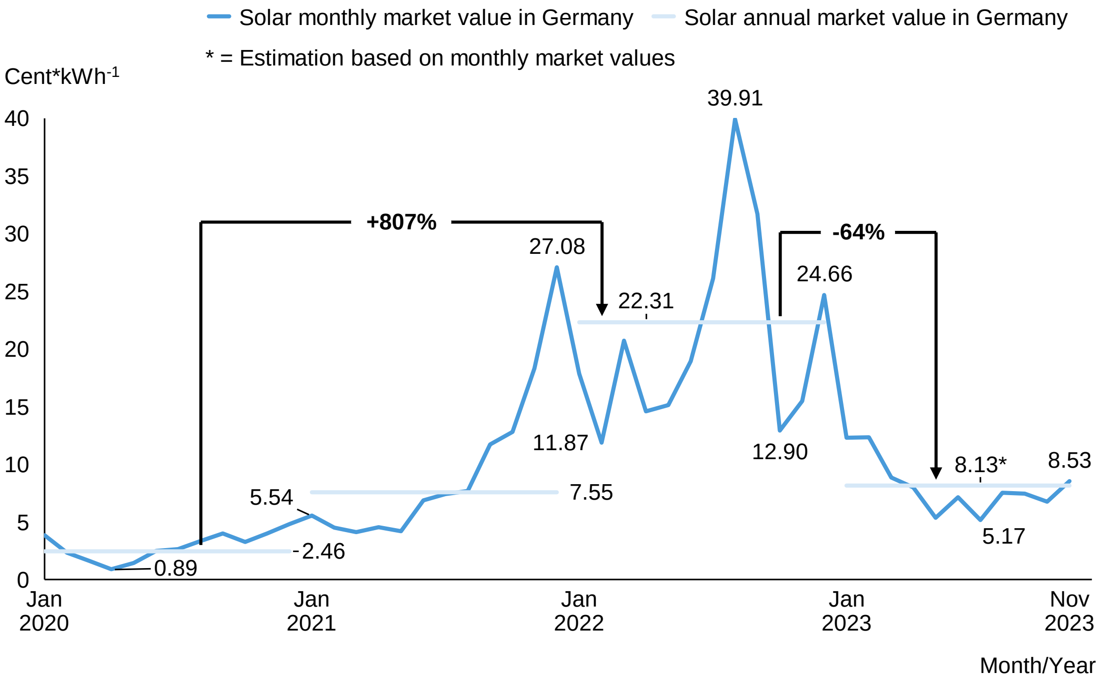

Figure 5.10 Development of German solar market values[57] (since 2020)

[56] Since 2016, owners of newly installed PV plants with a capacity of more than 100 kWp do not receive EEG levies and thus have to do direct electricity sales.

[57] The style of Figure 5.10 was copied from [109]. Data shown in Figure 5.10 was taken from [113].

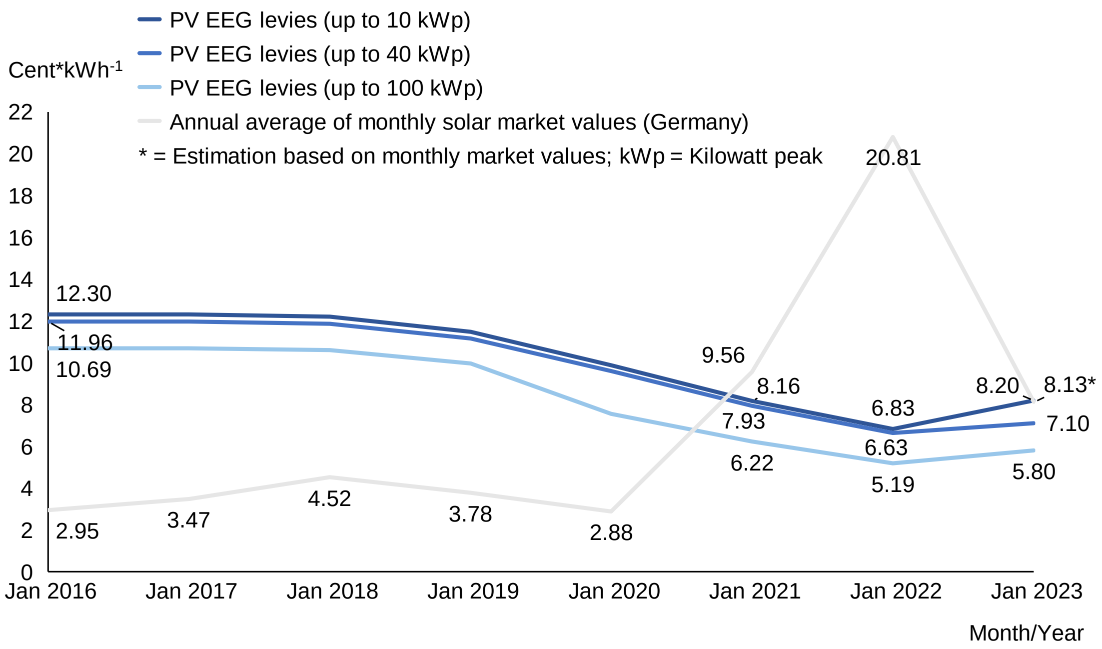

Figure 5.11 EEG levies in comparison to German solar market values[58]

5.2.3 Adoption and Implementation of DEMSs

As outlined in [138], the target picture of the DairyChainEnergy project envisions a DEMP that offers DEMSs not only to German dairy farmers, but also to other stakeholders of the dairy supply chain. In order to conceptualize this target picture, it is first required to extend RQ 2, i.e., to evaluate the market opportunity for offering DEMSs to relevant stakeholders of the dairy supply chain, e.g., dairy factories, food retailers, end consumers, or other providers of agri-services and products [152]. A starting point for future research on this matter is provided by [152]. The key limitation of this study is, however, that its results are based on survey data from a very small sample size. For example, in [152], less than ten dairy factories provided an evaluation on the relevance of DEMSs. Given the challenge of obtaining appropriate sample sizes, an alternative approach to estimate the future adoption of DEMSs per stakeholder group is the application of ADOPT as used by BADER and BERNHARDT to predict the future adoption of EMSs at German dairy farms (see Table 1.2).

Furthermore, as outlined in section 1.1.4, there is a strive for reducing GHG emissions of the German dairy sector. DEMSs can contribute to this goal by (1) creating transparency on GHG emissions from energy consumption (see section 1.2), and (2) providing insights on how to improve the energy efficiency of the production of dairy products [118]. In this context, findings from this dissertation confirm the relevance of DEMSs for German dairy farms (see

[58] Data for Figure 5.11 was obtained from [113,117].

section 3.2). As discussed in sections 5.2.1 and 5.2.2, the volume of electricity generated at German dairy farms is expected to increase leading to higher revenues from energy management. The electricity generation at farms is however not impacting the GHG balance of dairy farms [31]. For the GHG calculation of dairy products, it only counts which type of energy was used [87].

Lastly, the adoption and implementation of DEMSs in agriculture is not restricted to Germany or the dairy sector. As with other research on Digital Farming, it is recommended to differentiate between developed and developing countries given differences in infrastructure (e.g., internet access) and as-is usage of machinery [27]. In addition, scholars are advised to research the usage of DEMSs for other types of livestock farms, e.g., pig or poultry farms, given that comparable advantages are to be expected.

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7 Appendix A – Publication Record

Main publications embedded into this dissertation:

Theunissen, T.; Bernhardt, H. (2023). Scenario Analysis Indicates Revenue Increase for German Dairy Farmers Through Supply Chain Energy Management. *Journal of the ASABE*, 66(3), 667-675.

Theunissen, T.; Keller, J.; Bernhardt, H. (2023). Mind the Market Opportunity: Digital Energy Management Services for German Dairy Farmers. *Agriculture*, 13(4), 861.

Treiber, M.[59]; Theunissen, T.[59]; Grebner, S.; Witting, J.; Bernhardt, H. (2023). How to Successfully Orchestrate Content for Digital Agriecosystems. *Agriculture*, 13(5), 1003.

Additional publications created in the context of this dissertation:

Theunissen, T.C.; Bernhardt, H. Revenue increase for German dairy farmers through cross-value chain energy management. In *Proceedings of the 2022 ASABE Annual International Meeting Houston*, TX, USA, 17–20th July 2022; American Society of Agricultural and Biological Engineers: St. Joseph, MI, USA, 2022.

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Other publications:

Bernhardt, H.; Stumpenhausen, J.; Bader, C.; Theunissen, T.; Grebner, S.; Höhendinger, M. Dairy farms as a hub for sustainable, climate-neutral and regional energy supply. In *Proceedings of the XX CIGR World Congress: Sustainable Agricultural Production—Water, Land, Energy and Food*, Kyoto, Japan, 5–10th December 2022.

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[59] Maximilian Treiber and Theresa Theunissen contributed equally to this research article.

8 Appendix B – Publication Reprints

In this section, reprints of the three research articles from section 3 are included, while considering the following:

- For the publication “Scenario Analysis Indicates Revenue Increase for German Dairy Farmers Through Supply Chain Energy Management” (see section 3.1), a permission was received from the Journal of the ASABE to re-print the research article in this dissertation.
- The publication “Mind the Market Opportunity: Digital Energy Management Services for German Dairy Farmers” (see section 3.2) is open access. No restrictions to reprint apply (see open access license by the Multidisciplinary Digital Publishing Institute – MDPI).
- The publication “How to Successfully Orchestrate Content for Digital Agriecosystems” (see section 3.3) is open access (MDPI). No restrictions to reprint apply.

Scenario Analysis Indicates Revenue Increase for German Dairy Farmers Through Supply Chain Energy Management

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Highlights

- The research field of supply chain energy management (SCEM) is introduced and applied to the German dairy sector.
- Changes in farm revenues are quantified, considering electricity sales and remuneration for energy data sharing.
- Results show that SCEM could become the most relevant driver for increasing energy-related revenues at dairy farms.

Abstract. *The dairy sector of the German food industry is vital not only for providing nutrition to people but also for promoting environmental responsibility. However, sustainability efforts in the sector must be balanced with profitability goals, and farmers face the challenge of operating profitably while also seeking new, sustainable sources of income. Energy management is one such lever that can help establish sustainable revenue streams for farms. Currently, energy management at dairy farms is mostly limited to the barn's boundaries, and there has been no comprehensive study yet around profit-oriented collaboration on energy management along German dairy supply chains. This lack of collaboration not only hinders revenue growth for dairy farms but also complicates the achievement of sustainability targets, which can negatively impact the sector's public perception. To address this issue, we have applied supply chain energy management (SCEM) as a research field that examines energy-related interdependencies along the dairy supply chain. Our scenario analysis assessing the future revenue change for German dairy farmers through the application of SCEM indicates that it has the potential to become the most relevant driver for increasing energy-related revenues at farms. For example, our studies on a sample farm with 56,950 kWh photovoltaic systems show that it can increase its energy-related revenues by 170% simply by adapting its energy (data) distribution mode in the context of SCEM. Based on these findings, we recommend conducting further studies within the research field of SCEM, which is the aim of the new initiative DairyChainEnergy.*

Keywords. *DairyChainEnergy, Electricity sales, Energy data sharing, Food industry, Income, Profitability, SCEM, Sustainability.*

The food industry causes 26% of worldwide Greenhouse Gas (GHG) emissions, placing the sector in the focus of sustainability targets set by global organizations and governments (Poore and Nemecek, 2018; Gil et al., 2019). In order to fulfill this environmental responsibility while meeting global food demand, the aspired long-term goal is to achieve net-zero supply chains, i.e., to realize emission-neutral end-to-end food production (IPCC, 2018). However, handling this trade-off while running a profitable business in Germany poses a challenge—especially for dairy farmers. First, running a farm comes with high operating costs (e.g., for labor, feed, maintenance, fertilizers, contractors, and electricity) (Tauer, 2006; Hansen et al., 2019), a fact that has recently been exacerbated by the rise in euro inflation rates (Binder and Kamdar, 2022). Beyond that, dairy farmers have to deal with revenue shifts, e.g., due to volatile milk prices, resulting in planning uncertainty for the farmer (Tauer, 2006). However, despite this uncertainty, a dairy farm has to continuously invest (e.g., in new technology) in order to meet regulatory requirements and improve its environmental footprint (Dörr and Nachtmann, 2022; Malliaroudaki et al., 2022). Against this backdrop, demand in the dairy sector is high for approaches that have a positive impact on both a dairy farm's profitability and its GHG balance. One such promising approach is energy management, which comprises "the procurement, conversion, storage, distribution, and utilization of energy" (VDI, 2018). This is because, for example, if a farm produces renewable energy, it will boost its revenues (e.g., via sales of electricity to the grid) and also mitigate its carbon footprint (Boadzo et al., 2011; Malliaroudaki et al., 2022).

However, looking at how energy management is currently conducted in the dairy sector, it is apparent that most effort focuses on the dairy farm itself. There is knowledge on how to reduce a farm's energy consumption and related

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costs (Boadzo et al., 2011; Shine et al., 2020; Mohsenimanesh et al., 2021), how to make a farm energy self-sufficient (Hijazi et al., 2020), how farmers should best invest in energy technology (Shine et al., 2019), and how to optimize on-farm GHG footprints (Fournel et al., 2019). In contrast, so far, only a small share of research has looked at energy management along the dairy supply chain (from farm to end consumer), e.g., end-to-end energy mitigation strategies (Malliaroudaki et al., 2022) or concepts on farm-grid interaction (Bernhardt et al., 2017).

Strikingly, this approach to managing energy along the supply chain, called supply chain energy management (SCEM), is already receiving much higher attention in other industries given its benefits of realizing GHG mitigation, cost reduction, and revenue increase (Smith and Schmitt, 2013; Yang et al., 2017; Yuyin and Jinxi, 2018). In this context, the field of SCEM comprises activities such as energy data sharing, knowledge distribution, the application of a joined energy auditing approach, or mutual energy supply (Smith and Schmitt, 2013; Somjai et al., 2019). To translate these findings to the dairy sector and analyze how SCEM impacts farms' profitability, the target of this study is to quantify revenue changes for German dairy farmers through the application of SCEM. To do so, we detailed and expanded the approach of Theunissen and Bernhardt (2022).

Materials and Methods

In order to achieve this study's target, a research method needs to be selected that is able to quantify the impact of various influencing factors and uncertainties. This is because, for example, yield-effecting management decisions (e.g., herd size) and market conditions (e.g., market prices) are significantly impacting farms' revenues (Gerhardt et al., 2022). To consider these dependencies, we decided to apply a scenario analysis, i.e., to quantify farm revenues under consideration of varying input assumptions. As a methodology, we followed the approach from Kosow and Gaßner (2008), as illustrated in figure 1, comprising the following steps: identification of the scenario field, identification and analysis of key factors, and scenario generation and transfer. In the following sub-sections, it is outlined how this three-step approach has been applied in the context of this study.

Identification of the Scenario Field

The scenario field, i.e., the topic of our scenario analysis, is set equivalent to the target of this study. Hence, it is

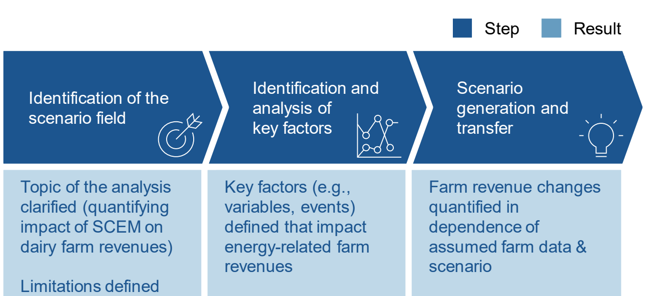


Figure 1. Followed approach (scenario analysis) from Kosow and Gaßner (2008) to quantify energy-related farm revenues.

specified as quantifying revenue changes for a German dairy farm through the application of SCEM, whereas energy-related revenues comprise income from both electricity sales and energy data sharing. While selling electricity is already an established revenue source for dairy farmers (Boadzo et al., 2011), remuneration for energy data sharing is a rather new concept in the dairy supply chain (Arla, 2022). However, this data transparency is a prerequisite for the success of SCEM (Smith and Schmitt, 2013), and demand for this transparency is high. Retail stores intend to sell net-zero labeled food products to end consumers (Malliaroudaki et al., 2022); the public sector needs transparency for well-informed political decisions (Worthy et al., 2022); contractors need data-driven insights to improve their products and maintenance services (Gerhardt et al., 2022); and regional grid operators can stabilize their power balance by leveraging data on electricity generation and use (Bernhardt et al., 2017).

To quantify energy-related farm revenues and prove applicability of the approach, a scenario analysis was conducted for a German sample farm located in North Rhine-Westphalia. The purpose of this sample farm analysis was to provide valuable insights for the farm owner and to serve as a template for other farmers on how to conduct such a scenario analysis themselves. Moreover, to show how SCEM impacts the revenues of German dairy farms overall, a generic sector scenario analysis was performed. However, given that there are more than 50 thousand dairy farms in Germany, all showing differences both in terms of animal and energy management (e.g., milk yield and electricity consumption) (FADN, 2023; Shine et al., 2020), a reasonable set of farm archetypes needs to be selected in order to represent the majority of German dairy farms while having a cognitively processable scenario output (Kosow and Gaßner, 2008). The definition of these farm archetypes is done as part of key factor identification.

According to Kosow and Gaßner (2008), in addition to defining the scenario field, the first step of a scenario analysis also includes a determination of out-of-scope limitations. In the context of this study, the following limitations are to be accepted: First, given that the pricing logic and regulatory framework in Germany differ across energy generation systems (Langniß et al., 2009), we limited our scenario field to one system that is very popular among German dairy farmers (Arla, 2022): electricity generation via roof photovoltaic systems. Furthermore, due to high uncertainty with regard to future political decisions (Isermeyer et al., 2019), we did not quantify the impact of SCEM on new or additional subsidy programs (e.g., monetization of carbon farming). Lastly, to reduce the complexity of the scenario analyses, we did not model changes in a farm's total electricity generation volume over time (e.g., due to investments, outages, or changes in technical efficiency) and assumed to have only one roof photovoltaic system per farm archetype (instead of multiple systems with varying capacities and setup dates).

Identification and Analysis of Key Factors

As the second step of Kosow et al.'s scenario analysis approach, key factors need to be identified and analyzed, i.e., "variables, parameters, trends, developments, and events that receive central attention during the further course of the scenario process" (Kosow and Gaßner, 2008). Considering the identified scenario field, "change in energy-related farm revenues" is defined as the output variable looking at a 10-year period, comprising farm revenues from electricity sales and energy data sharing (fig. 2).

In the dairy sector, incentives for data sharing are typically provided in the form of a milk price surcharge (V_3) (Arla, 2022), whereas a farm's total milk volume results from the average milk yield per cow (V_1) and the herd size (V_2)—with an observable trend in Germany that the average number of cows per barn is rising (T_1) (Statista, 2022). Some dairy factories already pay up to four euro cents kg^{-1} milk for shared GHG emission data (Arla, 2022), of which about one quarter is traceable to the farm's energy management (Thoma et al., 2013; Malliaroudaki et al., 2022), i.e., 1 cent kg^{-1} of payment in the context of SCEM. The prerequisite for realizing such remunerations for a farm is the farmer's willingness to share the data (E_2) (Arla, 2022).

To also achieve revenues from electricity sales, a farm has to generate electricity that is not fully consumed by the farm itself. When modeling power consumption using state of the art methods, it is typically set in relation to the amount of milk produced (V_5) and can be significantly impacted by a farm's future management decisions (T_2), such as investments in automated systems and replacements of energy inefficient barn components (Shine et al., 2020). Furthermore, revenues from electricity sales are also highly dependent on the grid price (Boadzo et al., 2011). However, in Germany, providers of power generation systems can get support from the so-called renewable energy act (EEG levy - P_2) that was introduced in 2000, i.e., at a time of low electricity market prices (P_3) (Langniß et al., 2009). Yet, due to recent market changes, the attractiveness of EEG levies has declined given that direct electricity sales prices are rising (T_4) (Murphy et al., 2022). Nevertheless, the date at which a photovoltaic system was setup (V_4) and the total amount of electricity produced (V_6) have a significant influence on what is the most profitable type of electricity distribution (V_8)—EEG versus direct sales. This is because the EEG remuneration is fixed per setup date and electricity volume and is paid only over a period of 20 years (P_1) (Langniß et al., 2009). Hence, while there is a volume-dependent remuneration for EEG photovoltaic systems, the solar market value for direct electricity sales is applied as a volume-independent measure in our model (Netztransparenz, 2022). Moreover, low electricity sales prices and an insecure energy supply can incite a farmer to work on the in-farm power utilization rate (V_7), i.e., the share of generated electricity directly consumed at the barn (Bernhardt et al., 2017). In Germany, there are already prototypes that are able to influence this key figure by controlling a farm's electricity utilization curve (Bernhardt et al., 2017; Höhendinger et al., 2021). By applying such a farm-specific energy management and monitoring system (E_1), a farm's in-house power utilization rate can be set to 100%, if applicable; some farms generate more electricity than they are able to consume (Bernhardt et al., 2017). Lastly, if a dairy farmer decides to start collaborating in the context of SCEM (E_2), the farm will expand its flexibility in distributing electricity. For example, next to EEG and direct sales to the grid, it could sell electricity directly at the barn (e.g., to business partners or service providers in the form of e-mobility contracts) (Riedner et al., 2019). Overall, as shown in figure 2, three parameters, eight variables, four trends/developments, and two events are to be considered in the scope of the identified scenario field.

To conduct the scenario analyses with those key figures, the data shown in figure 3 was selected: For quantifying the revenues of the sample farm, data from 2020 was gathered. The farm is equipped with three roof photovoltaic systems (40/14/10 kWp systems, set up in 2013/2014/2015), whose generated electricity (V_6 = 56,950 kWh) is consumed by the farm itself at a rate of 40% (V_7) or sold to the regional grid at EEG levies (V_8). Compared to peers (FADN, 2023; Shine

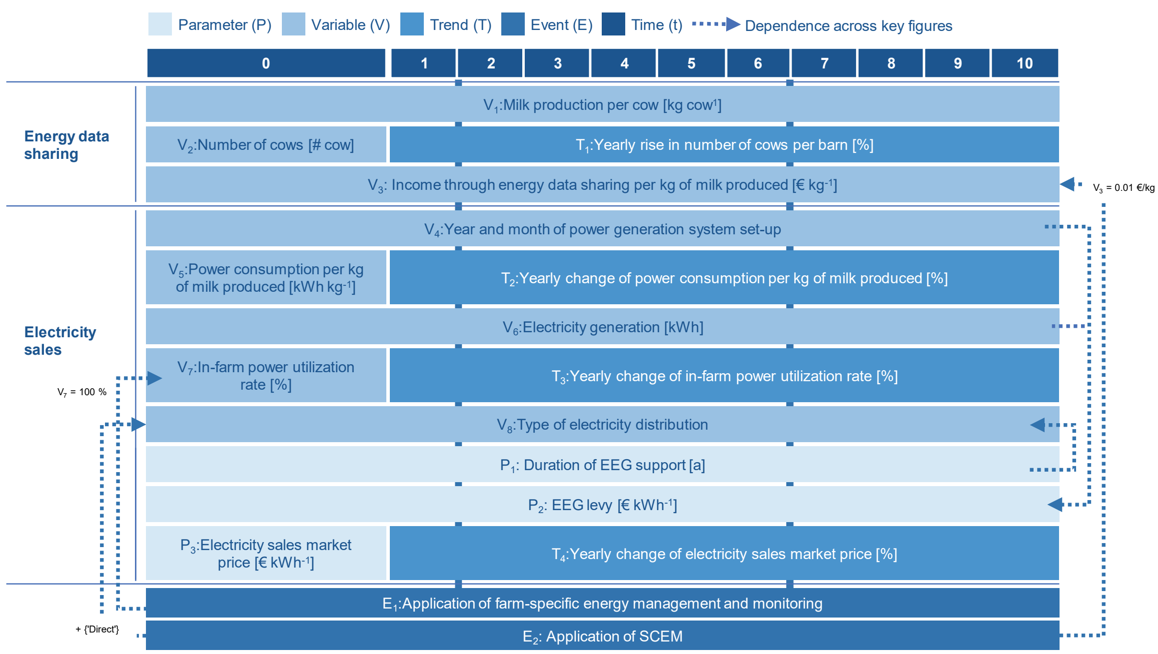
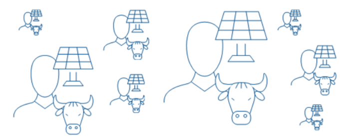


Figure 2. Illustration of key figures in scope of the identified scenario field based on Theunissen and Bernhardt (2022).

Sources:
[0] Arla, 2022
[1] Langniß, et al., 2009
[2] Netztransparenz, 2022
[3] Shine, et al., 2020
[4] Linnemann, et al., 2021
[5] Dairy farmer
[6] Statista, 2022
[7] Sonnenplaner, 2022
[8] FADN, 2020



		SAMPLE FARM ANALYSIS (2020 → 2030)	GENERIC SECTOR ANALYSIS (2022 → 2032)
Parameters	P_1 [a]	{20}[1]	
	P_2 [€ kWh^{-1}]	*EEG levies (Date- and capacity-specific)* [7]	
	P_3 [€ kWh^{-1}]	*Solar annual market value 2020:* {0.02458}[2]	*Solar annual market value 2022:* {0.22306}[2]
Variables	V_1 [kg cow^{-1}]	{11,167}[5]	{7,257; 9,526}[8]
	V_2 [cow]	{78.7}[5]	{42; 74; 387}[8]
	V_3 [€ kg^{-1}]	{0.0003}*[5]	{0; 0.0025}[0]
	V_4	{'Jun 2013'; 'Jul 2014'; 'Jul 2015'}[5]	{'Jan 2000'; 'Jan 2005'; 'Jan 2010'; 'Jan 2015'; 'Jan 2020'}[1]
	V_5 [kWh kg^{-1}]	{0.078}[5]	{0.03868; 0.04891; 0.073}[3]
	V_6 [kWh]	{56,950}[5]	{20,000; 50,000; 150,000; 250,000}[1]
	V_7 [%]	{40}[5]	{20; 60}[4]
	V_8	{'EEG'}[5]	{'EEG'}[1]
Trends	T_1 [%]	{0}[5]	{0; 3.5}[6]
	T_2 [%]	{0}[5]	{-7; 0; 7}[3]
	T_3 [%]	{0}[5]	{-12; 0; 12}[4]
	T_4 [%]	{0; 25}[2]	{-20; 0}[2]
Events	E_1	{'Yes'; 'No'}	
	E_2	{'Yes'; 'No'}	

* Based on information from 2019.

Figure 3. Data base for farm-specific and generic sector scenario analyses.

et al., 2020), the farm has an above-average milk yield per cow (V_1 = 11,167 kg cow^{-1}), but also a relatively high electricity consumption (V_5 = 0.078 kWh kg^{-1}). Considering findings from Shine et al. (2020) and Höhendinger et al. (2021), the latter can be explained by the barn's conventional milking system and other stable equipment such as climate conditioning and heating systems for the cows' drinking water. Furthermore, milk from the sample farm is sold to a dairy factory that remunerated the farm's sharing of energy data with 0.0003 € kg^{-1}. Looking at the future development of the sample farm, its owner stated that they did not intend to change the herd size (T_1) or make investments affecting the farm's future electricity consumption (T_2) or its in-farm power utilization rate (T_3).

For the generic sector analysis, as defined in the scenario field, the data set was collected with the target of reflecting the range of dairy farm characteristics in Germany. According to the Farm Accountancy Data Network (FADN)—a public database by the German Federal Ministry of Food and Agriculture (BMEL), the average yearly milk yield per cow (V_1) ranges from 7,257 to 9,526 kg cow^{-1} across German states (FADN, 2023). Data on the herd size (V_2) were also taken from FADN (2023). While Bavarian dairy farms are rather small with 42 livestock units, farms in Brandenburg have the largest average herd size with 387 cows per barn. On average, a German dairy farmer owns 74 cows (FADN, 2023), a figure that has increased by 3.5% annually since 2000 (Statista, 2022). Against this backdrop, we assumed scenarios where farms either grow at this rate or stay as is (T_1). Moreover, electricity generation systems were considered in the generic sector analysis since the start of the EEG subsidy support in the year 2000 with distributed setup dates (V_4) and capacity (V_6) in order to be able to model the differences in EEG subsidies over time (Langniß et al., 2009). Furthermore, data on dairy farms' electricity consumption (V_5) were taken from Shine et al. (2020), and, following insights from Linnemann (2021), the self-consumption from photovoltaic systems (V_7) was expected to range from 20% to 60%. Next, as is typical in Germany, electricity that is not consumed in-house is sold to the grid (V_8) in the scope of EEG (Linnemann, 2021). On top of that, we considered two specifications for V_3: farms that are already sharing their energy data (Arla, 2022) and farmers who are not. Furthermore, with regards to T_2 and T_3, data points were defined based on observable margins in V_5 and V_7. For both the sample farm and generic sector analysis, the future development of electricity sales market prices (T_4) was modeled as staying either at a 2022 level or dropping back to magnitudes as seen in 2020 (Netztransparenz, 2022). Hence, no further inflationary effects on electricity market prices were included in our model due to recent efforts by the German government to limit energy consumer prices (Bundesregierung, 2023). Lastly, values for the three parameters were received from publicly available knowledge: the duration of EEG support is paid for 20 years (Langniß et al., 2009), month- and capacity-specific EEG levies were taken from Netztransparenz (2022), and the German solar annual market values are accessible in Sonnenplaner (2022).

Scenario Generation and Transfer

In order to generate scenarios and therefore quantify the output measure, mathematical correlations between key input figures need to be defined (Kosow and Gaßner, 2008). Following this approach and respecting predefined limitations of the analyses, equation 1 shows the calculation logic for determining revenues changes (eq. 2) while considering the farm's energy-related revenues, the barn's electricity sales price (eq. 3) as well as the in-farm use of self-generated electricity (eq. 4).

$$RC = \frac{R_t - R_0}{R_0} * 100 \quad (1)$$

$$R_t = V_1 * V_2 * V_3 * \left(1 + T_1\right)^t + ESP_t * \left(V_6 - EUF_t\right) \quad (2)$$

$$ESP_t = \begin{cases} P_2, if\ V_8 = 'EEG' \\ P_3 * \left(1 + T_4\right)^t, otherwise \end{cases} \quad (3)$$

$$EUF_t = min\left\{V_1 * V_2 * V_5 * \left(1 + T_1\right)^t * \left(1 + T_2\right)^t ;\ V_6 * min\left\{1; V_7 * \left(1 + T_3\right)^t\right\}\right\} \quad (4)$$

where parameters (P), variables (V), trends (T), and time (t) are taken from figure 2 and

RC = Energy-related revenue changes of a farm [%]
R = Energy-related revenues of a farm [€]
ESP = Electricity sales price of a farm [€/kWh]
EUF = In-farm utilization of self-generated electricity [kWh].

Results And Discussion

Sample Farm Analysis

Applying equations 2 to 4 with data from figure 3, the sample farm's energy-related gross revenues in 2020 were quantified as €5.829, of which 95.6% came from EEG electricity sales to the regional grid at an average levy of 13.97 Cent kWh^{-1}, with the residual 4.4% being related to energy data sharing with the farm's cooperating dairy factory (fig. 4). However, looking at the farm's total gross revenues in 2020, energy-related income accounted for only 1% (fig. 4). The majority of income was related to milk sales (62%), followed by subsidies (15%) and animal sales (11%); comparable orders of magnitude are known from the literature (Pelegrini et al., 2019). Nevertheless, when considering recent developments in the German electricity market (fig. 4), the farm's future income from electricity sales can be increased by considering a change in electricity distribution.

This is also shown by the results of the sample farm's scenario analysis (fig. 5), which indicate a rise in energy-related net revenues when increasing flexibility in electricity distribution and enabling energy data sharing in the context of SCEM (E_2). However, in relation to the farm's total revenues, the majority of scenarios indicate that energy-related revenues will not exceed the farm's core income streams, such as milk sales or subsidies. This is due to assumptions made during the key factor analysis (scenarios 1 to 8) for the future development of electricity market prices (T_4, fig. 3). In contrast, if electricity market prices kept rising (see additional approximation in fig. 5), as from January 2020 to December 2022 at a yearly average of 86% (Netztransparenz, 2022), energy management would become the farm's most relevant source of income.

Generic Sector Analysis

Using variables $V_{1\text{-}8}$ (fig. 2) and data for the generic sector analysis from figure 3, 1,356 farm archetypes were created to form a representative sample within the German dairy sector (fig. 6). To do so, all possible data combinations across variables $V_{1\text{-}8}$ were permitted, with the following exceptions: Not applicable combinations for farm archetypes with no electricity generation were excluded, i.e., if V_6 is "NA," $V_{4/7/8}$ had to be "NA" as well. Beyond that, given that a farm's electricity generation via roof photovoltaic systems is limited by the stable size, combination options of V_2 and V_6 were restricted considering a maximum electricity generation of 2.284,36 kWh cow^{-1}. This threshold value was received using

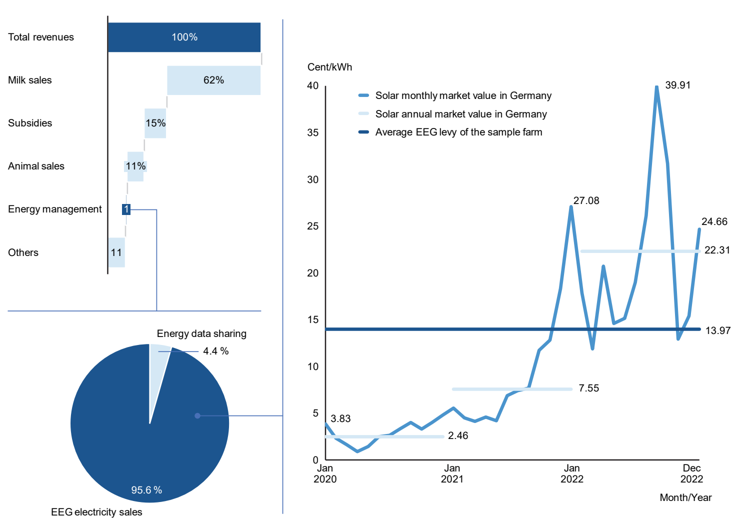


Figure 4. 2020 gross revenues of the sample farm and the development of electricity sales prices (EEG levy of sample farm vs. market values from Netztransparenz [2022]).

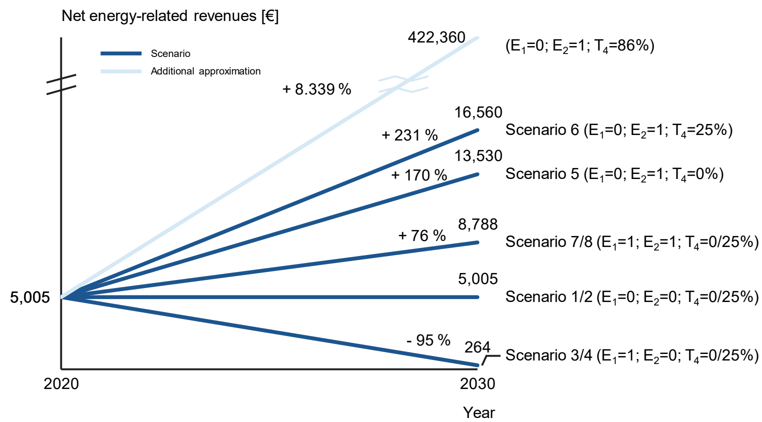


Figure 5. Results of the sample farm scenario analysis—change in energy-related net revenues.

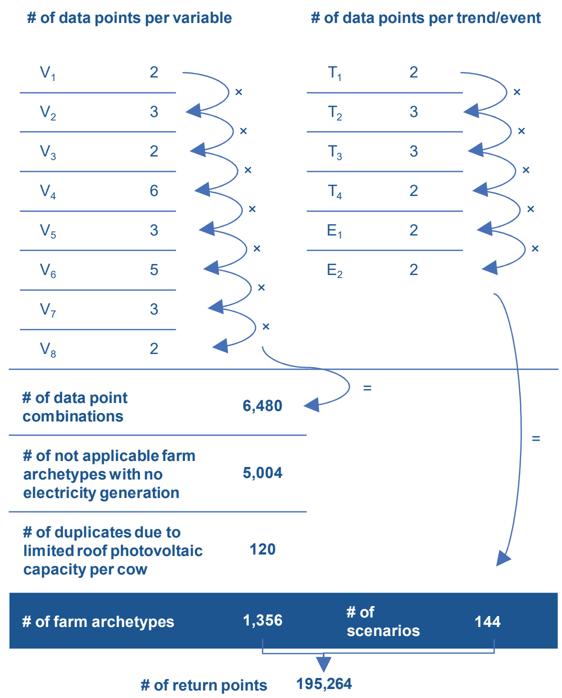


Figure 6. Derivation of farm archetypes and scenarios for the generic sector analysis.

the space requirement for cows in a German organic barn (6 qm cow^{-1}), utilizing a yield factor of 0.77 to reflect non-optimal orientations of stable roofs, assuming an average roof pitch of 40°, a 50% share of slatted floor in total stable size, and an optimal yield of 183.33 kWh qm^{-1} (Agriconcept, 2022; Solaranlagen-Portal, 2022; Ess-Kempfle, 2022). In addition to the determination of farm archetypes, 144 scenarios were defined based on data from figure 3 for trends T_{1-4} and the binary occurrence of events E_{1-2} (fig. 6).

Bringing these farm archetypes and scenarios together, the generic sector analysis comprises 195,264 return points in total (fig. 6). Looking at the output illustrated in figure 7, in 41% of the cases, energy-related revenues are expected to increase, with the highest forecast of 6,956% for farm archetype 847 (V_1 = 9,526 kg cow^{-1}; V_2 = 387 cows; V_3 = 0 € kg^{-1}; V_4 = ‘Jan 2020’; V_5 = 0.03868 kWh kg^{-1}; V_6 = 20.000 kWh; V_7 = 60%; V_8 = ‘EEG’) and scenario 85 (T_1 = 3.5%; T_2 = -7%; T_3 = -12%; T_4 = 0%; E_1 = ‘No’; E_2 = ‘Yes’). Furthermore, a minority of return points (3%) show no revenue changes, and 2,592 return points are incalculable when applying equation 1 since energy-related revenues of related farm archetypes equal 0. The remaining 106,029 return points show a forecasted revenue decline, which can be attributed to increasing in-farm utilization, higher power consumption, ending EEG support, and/or declining electricity sales market prices. With -100%, the highest revenue decline is shown for farm archetype 0 (V_1 = 7,257 kg cow^{-1}; V_2 = 42 cows; V_3 = 0 € kg^{-1}; V_4 = ‘Jan 2000’; V_5 = 0.03868 kWh kg^{-1}; V_6 = 20.000 kWh; V_7 = 60%; V_8 = ‘EEG’) and scenario 130 (T_1 = 3.5%; T_2 = 7%; T_3 = 12%; T_4 = -20%; E_1 = ‘Yes’; E_2 = ‘No’).

Finally, in order to analyze differences in the influence of key figures on the scenario output, the sensitivity of energy-related revenue changes was measured by looking at all trends T_{1-4} and events E_{1-2}. Hence, it was detected that the output figure changed absolutely when considering a change of one key figure while keeping all other key figures as is. To do so, and to generate one sensitivity result for each trend and event, the average absolute difference in energy-related farm revenue changes was measured across all return points. With the help of such a sensitivity analysis, it was revealed that implementing SCEM (E_2) has on average the highest positive impact on energy-related farm revenues (fig. 8). This is because E_2 is the only key figure that is impacting both income streams (energy data sharing and electricity sales) across all farm archetypes. Beyond that, a rise in the number of cows per barn (T_3) also has a positive impact on future energy-related farm revenues, mostly traceable to a higher total income from energy data sharing. Next to a bigger herd size, the recent trend of rising electricity market prices (T_4) is also beneficial for farm incomes, but only for those farms with a direct electricity distribution in the context of SCEM. In contrast, an increase in the in-farm power utilization rate (T_3), or an application of farm-specific energy management and monitoring (E_1) has a negative effect on energy-related farm revenues. However, this does not mean that increasing in-farm power utilization or applying an energy management and monitoring system should not be considered by a farmer given the benefits of cost reduction and self-sufficiency (Bernhardt et al., 2017; Höhendinger et al., 2021). Finally, even though a change in power consumption per kg of milk produced (T_2) might be interesting for

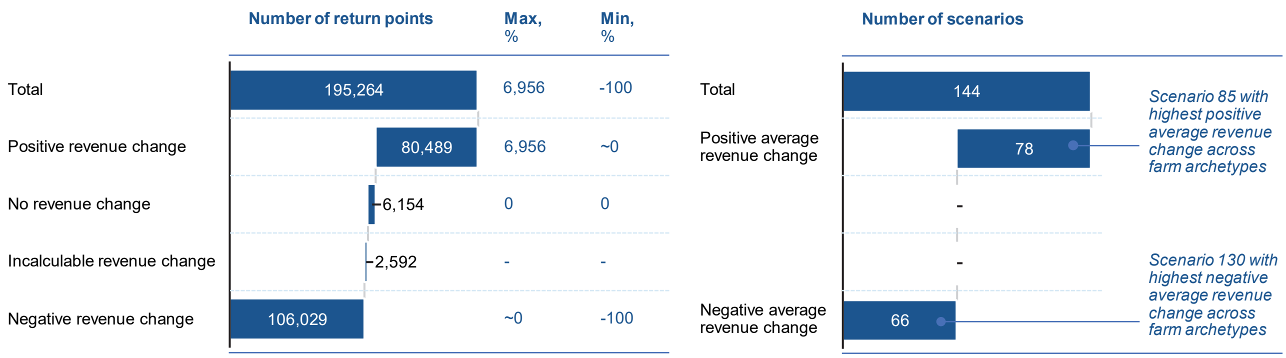


Figure 7. Results of generic sector scenario analysis—change in energy-related farm revenues.

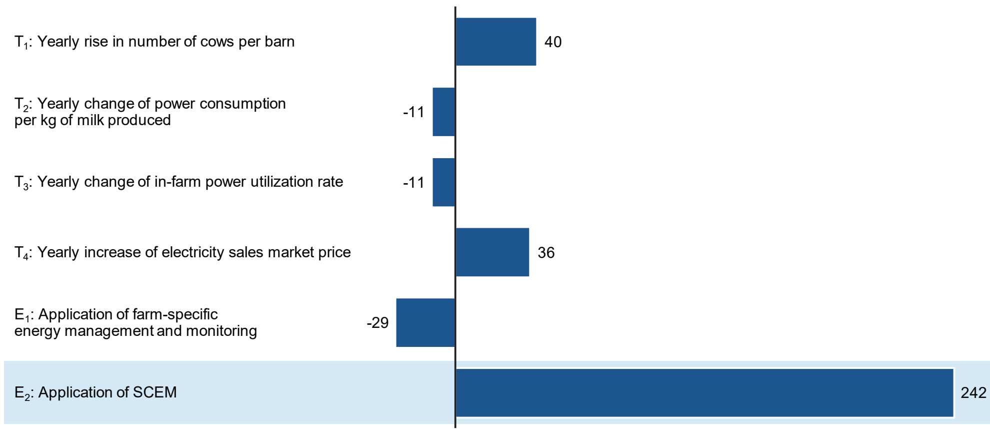


Figure 8. Sensitivity of energy-related revenue changes for trends and events in percentage points.

farmers given its effect of reducing costs (Shine et al., 2020), our sensitivity analysis shows its negative effect on a farm's income.

In the end, it is the farmer's decision on which strategic goal has the highest priority for the farm: revenue increase vs. cost reduction vs. other targets (e.g., self-sufficiency). If priority is set on revenue increase, the benefits of SCEM can be best utilized at a German dairy farm by having a high energy generation capacity, sufficient digital maturity to implement direct energy distribution and data sharing, and an overall willingness to cooperate with other stakeholders along the dairy value chain.

For future studies looking at how SCEM impacts the revenues of dairy farms outside of Germany, the overall structure of our scenario analysis can be taken as a starting point. However, a revision of the data input assumptions is required for non-German farms given country-specific differences in political frameworks, market conditions, and infrastructure. For example, the concept of EEG levies is unique worldwide, and electricity market prices significantly vary across countries (Langniß et al., 2009; Statista, 2023). Furthermore, the predominance of photovoltaic systems for energy generation on dairy farms is much more profound in Germany than in other European countries (Arla, 2022). Nevertheless, SCEM is expected to be beneficial for the revenues of dairy farms outside of Germany, especially in countries with existing infrastructure for electricity distribution and a striving for more sustainability in agriculture. Hence, dairy farmers in developed countries should be aware of SCEM as a lever for boosting energy-related farm revenues and should assess their options for electricity sales and energy data sharing. By contrast, energy management in developing countries has to focus first on creating a functional energy infrastructure as a basis for enhancing the technical maturity of dairy farms before addressing the benefits of SCEM (Sovacool, 2012).

Conclusions

In this study, considerable progress has been made in researching energy management as an instrument for dairy farmers to improve a farm's profitability. The novelty of our study is found in exploring the collaboration aspect of energy management along the supply chain and its effect on dairy farm revenues in Germany. Results of our scenario analyses show that the impact of SCEM on dairy farms' future revenues is expected to be significant if a farm is willing to adjust its electricity distribution mode and is open to sharing data with other stakeholders along the supply chain. For example, our studies on a sample farm with 56,950 kWh photovoltaic systems show that it will be able to increase its energy-related revenues by 170% just by adapting its energy (data) distribution mode in the context of SCEM. Results of a sensitivity analysis also show that SCEM has a much higher positive effect on energy-related revenues compared to other key figures, such as the recent rise in electricity market prices. However, to maximize energy-related revenues, farmers have to prioritize SCEM over other strategic goals such as energy self-sufficiency.

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Mind the Market Opportunity: Digital Energy Management Services for German Dairy Farmers

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Abstract: The adoption of farm management information systems (FMIS) is on the rise at German dairy farms given their benefits in supporting and automating decision-making processes. However, the offering scope of FMIS for dairy farmers is limited, with digital services mostly focusing on animal-related data and overall economic insights. By contrast, digital energy management services (DEMS) are not yet established as an integral part of FMIS despite their expected positive contribution to a dairy farm's ecological sustainability and profitability. Against this background, the aim of this study was to find out if there is a hitherto undetected market opportunity for FMIS providers offering DEMS to German dairy farmers. To achieve this aim, the as-is market offering was screened looking at seven pre-defined DEMS, and customer preferences were investigated based on online survey responses from 74 German dairy farmers. Results of the survey indicate a high relevance of DEMS, which especially applies for optimization-oriented energy data analyses. The market coverage of such digital services, on the other hand, is not yet adequate. Hence, for providers of FMIS, we see a promising market opportunity to expand their offering by starting to deploy selected DEMS to German dairy farmers.

Keywords: digital farming; farmer survey; FMIS; profitability; sustainability

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1. Introduction

"The German dairy industry is the most important branch of the German agricultural and food industry and occupies a leading position within the EU." [1]. That is why dairy farmers are in special focus among the public, e.g., with regard to ecological sustainability and animal welfare aspects. To manage this responsibility, German dairy farmers increasingly rely on technology and value the benefits of automation and digitalization [1]. In this context, the highest adoption at German dairy farms is shown for so-called Farm Management Information Systems (FMIS), which provide digital services to farmers and other relevant stakeholders via multi-functional online platforms [2–5]. Today, in practice, FMIS for dairy farms typically include digital herd management and health monitoring services focusing on animal-related data (e.g., weight, milk yield, and first calving age) [1,6]. Demand for this kind of digital service is high given their direct impact on a herd's animal welfare and health [1], leading to measurable improvements in dairy farms' most relevant income streams (milk and animal sales) [7]. Furthermore, the data basis enabling such digital services is retrievable from a variety of embedded systems (e.g., cow transponders) and cyber-physical systems (e.g., automatic milking systems), whose adoption is on the rise at German dairy barns [3,5,8]. Furthermore, although data transfer among those systems often still requires manual effort from the farmer [8], the functionality of digital herd management and health monitoring services is already very advanced, including the application of artificial intelligence (AI) data analytics [9].

By contrast, digital services on ecological sustainability for dairy farmers, comprising Greenhouse Gas (GHG) emission calculators and digital energy management services (DEMS), are not yet even in the scope of most FMIS [6,8]. However, the necessity of having such services is high given their expected contribution to achieving global sustainability goals [10]. In this context, especially for DEMS, technical prerequisites and economic incentives preexist. While input data for GHG emission calculators typically have to be collected manually by the farmer [11], the data basis for DEMS can be gathered automatically via a central control unit from on-farm energy production systems (e.g., photovoltaic systems), energy storage solutions (e.g., electric batteries), and energy consuming technology (e.g., lightning and automatic feeding systems) [12]. Furthermore, DEMS can have a positive impact on the economic situation of a farm, e.g., by increasing revenues through electricity sales and energy data sharing [13] or by reducing costs through energy savings [14]. For example, since the spot market price for electricity in Germany rose from 4.87 cent kWh^{-1} in February 2021 to almost 13 cent kWh^{-1} in February 2023 [15], farms were able to significantly increase their revenues when selling energy directly to others [13]. Moreover, findings from [16] show that the electricity consumption at dairy farms ranges from 0.039 to 0.073 kWh per kg of milk produced, which reveals a savings potential of almost 47% for high-consuming farms, that at least can be partially realized through the application of DEMS (e.g., with the help of data analyses on energy consumption patterns [17]). Next to such economic benefits, an application of DEMS is also supposed to support a farmer in his day-to-day business, e.g., by predicting outages of farm equipment [14] or by visually processing on-farm energy data [18] and comparing it to peer and industry benchmarks [17].

Against this background, offering DEMS to German dairy farmers might be a promising market opportunity for providers of FMIS. However, in the literature, no comprehensive study on this hypothesis could be found. Instead, the state of the art on energy management at dairy farms is primarily looking at physical systems (such as energy consuming farm equipment and energy generation technology) and, e.g., their impact on a farm's total energy consumption, energy generation capacity, and environmental footprint [19]. Research on digital farming solutions for energy management in the dairy sector, however, is rare [13,20]. With this in mind, the present study aims to evaluate the market opportunity for offering DEMS to German dairy farmers by scanning customer needs and analyzing the competitor landscape [21], in order to test the following three hypotheses: (1) The relevance of DEMS for German dairy farms is high; (2) it varies significantly across farms; and (3) the market offering (maturity, function scope, and quantity) of DEMS for German dairy farmers is low. To test these hypotheses, we conducted a German-wide online survey for dairy farmers to receive insights on the target market and reviewed the DEMS offering for German dairy farmers from both academia and industry.

2. Materials and Methods

2.1. Selection of DEMS and Set-Up of Our Online Survey for German Dairy Farmers

To address the research target of this study, we considered seven DEMS from [20] in the scope of our analysis (Table 1), which were selected due to their already high adoption in other industries [18], high attention from academia [14,17], or due to a proven economic relevance for the dairy sector [13]. The market interest in these DEMS was analyzed with the help of online survey responses collected in the period from September 2022 to January 2023. In this survey, farmers were asked to share: (1) personal data (e.g., age) and general insights on the farm itself (e.g., location, herd size); (2) information on the as-is status of the farm's energy management (e.g., installed electricity generation systems) and its adoption of digital services; (3) insights on the farm's strategic goals with regard to its energy management (e.g., investment plans); (4) an evaluation of the seven predefined DEMS with respect to their relevance for the farm; and (5) concerns regarding the application of DEMS. Farmers were approached either directly (using publicly available contact data from the German Chambers of Agriculture), via social media (Instagram, Facebook, WhatsApp), or through partner companies of our Chair (three agri-service firms and one dairy factory)—all located in Bavaria or North Rhine-Westphalia (NRW). During the course of this data gathering, we strived to collect responses from farms with different characteristics (e.g., dairy herd size, milking yield) and did not specifically contact farms with an outstanding interest in energy management. In total, 237 responses from German dairy farmers were collected, of which 74 data sets—hereafter referred to as our sample—contained comprehensive and causally reasonable responses regarding the five survey blocks listed above. Hence, a relatively high share of questionnaires (69%) was not usable to test this study's hypotheses, which comes from the set-up of the survey (participants had the option to skip questions) and the novelty of the topic (38% of our survey participants did not provide a complete evaluation on the relevance of DEMS).

Table 1. Description of the seven DEMS from [20] in scope of this study.

Digital Energy Management Service (DEMS)	Description
Energy data visualization	Visualization of on-farm energy data (e.g., total energy consumption and generation, energy-related costs and revenues) to increase transparency and understanding of the status quo [18]
Energy data analysis (process optimization)	Analysis of energy data to optimize farms' on-site energy management, including power generation planning and efficiency improvement [14]
Energy data analysis (predictive maintenance)	Analysis of on-farm energy data to improve performance of farm equipment and power generators [22], including fault and outage detection [14]
Knowledge service (energy management in the dairy sector)	Provision of insights on the German energy market (e.g., forecasts on the electricity market prices), including relevant findings from the dairy sector (e.g., peer and industry benchmarks) [17]
Energy marketplace	Marketplace for trading energy with focus on selling electricity from the farm to third parties, including real-time interaction and dynamic pricing [14]
Energy data marketplace	Marketplace for selling energy data from the farm to stakeholders of the dairy sector and beyond (e.g., retailers, manufacturers of farm equipment, public sector) [13]
Energy-related documentation and inquiries	Management of energy-related files (e.g., documentation of energy data in subsidy request forms, generation of purchase requests)

2.2. Characteristics of the Survey Sample

In the sample, respondents are between 23 and 63 years old, with a majority having the farm located in Bavaria (61%) or NRW (32%). In 2021, the sample farms' herd size averaged 115 dairy cows with an annual milking yield of 8877 kg per cow. On average, 143 ha of land are cultivated per farm. A comparison of these farm characteristics with insights from the European Farm Accountancy Data Network (FADN) reveals that the mean farm size of the sample is almost 62% bigger compared with the German dairy farm population, while showing a comparable milk yield (Figure 1) [23]. Beyond that, the sample includes a disproportionately high number of farms from NRW [23], which might come from our selected way of distributing the survey. Looking at additional measures to characterize the sample, 18% stated to not only distribute their milk via a dairy factory but also to have a direct marketing channel. On top of that, 22% of the sample identified as organic farms, and 88% of the respondents are convinced that their farms will remain in existence for at least the next 15 years. Furthermore, most survey participants (91%) claimed to not only do dairy farming but to also be active in other agri-business segments, such as crop farming (70%), forestry (57%) and cattle breeding/fattening (46%). Moreover, all sample farms have renewable energy generation systems on site. All respondents in the sample stated to have photovoltaic (PV) systems installed, while 41% of them indicated to also operate other renewable energy generation systems such as biogas or wind. In this context, it is relevant to know that findings from the Arla Climate Check Report with 1309 responses from German dairy farmers indicate that the share of German farms generating energy is significantly smaller compared with the sample (Figure 1) [24].

The total amount of electricity produced per farm ranged from 2 to 7150 MWh in 2021, whereas those farms with multiple energy generation systems showed an above-average electricity yield (Figure 2). The highest output is generated by farms with wind turbines (3051 MWh per farm). Sample farms with solely PV systems produced on average 64 MWh of electricity in 2021. Furthermore, the sample's mean electricity consumption (0.074 kWh per kg of milk produced; 644 kWh per cow) fits with the current state-of-the-art [16,25]. To calculate these values, we asked the survey participants to claim if private electricity use was considered part of the farm's total power consumption and excluded such private electricity use, by taking into account the number of household members (1–2; >3) per farm and data from [26]. In the end, as expected [12], there is an overall electricity surplus among the sample farms, with an average electricity generation of 462 MWh and a mean electricity consumption of 76 MWh per farm (Figure 2).

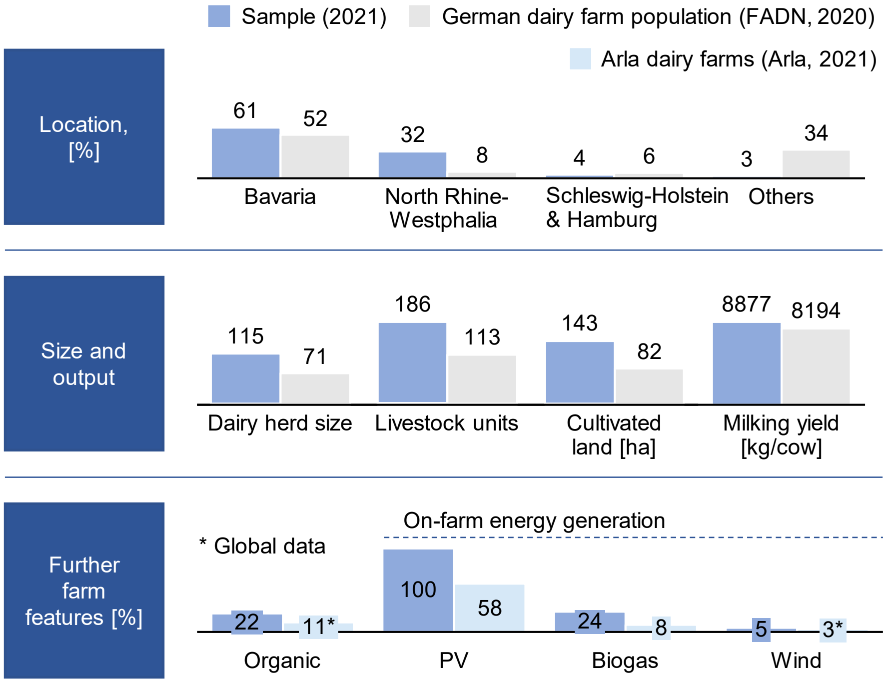


Figure 1. Farm characteristics of the survey sample compared to data from [23,24].

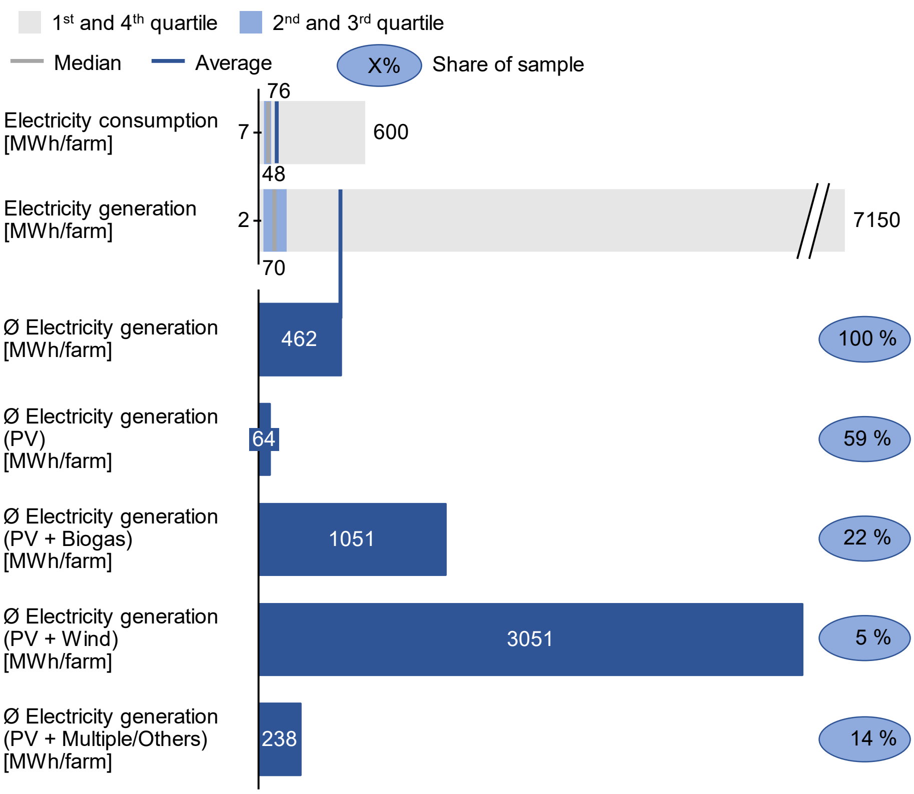
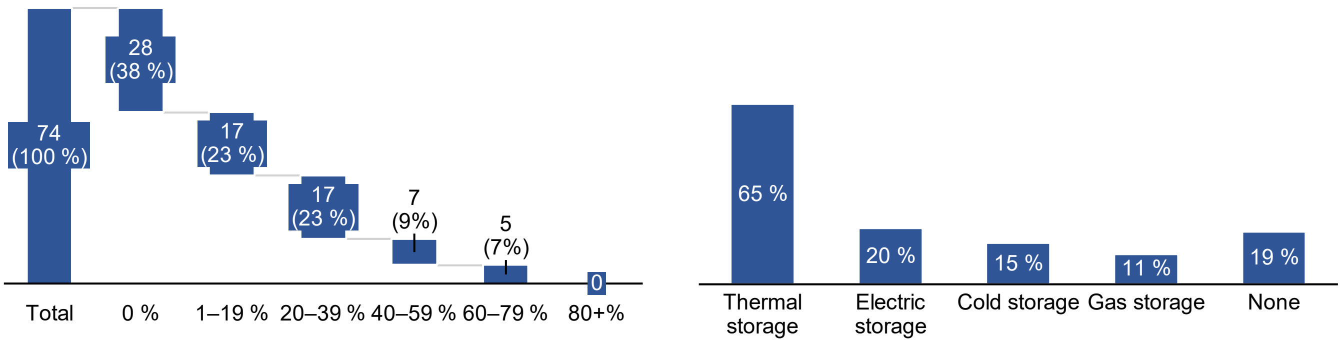


Figure 2. Electricity consumption and generation of the sample farms in 2021.

However, not all sample farms but around three quarters (72%) generated more electricity than they consumed in 2021. Moreover, the generated electricity was not fully utilized by the farm itself but was partly distributed to the grid (Figure 3a). This on-farm power utilization rate significantly varied among the sample farms: While 38% distributed all of their electricity, 7% specified their on-farm power utilization rate as being above 60%. An on-farm electricity use of at least 80% was not reached by any of the sample farms. However, farms with an electric storage system installed (20%) showed, on average, a higher on-farm utilization of the self-generated electricity: 47% of those sample farms achieved an on-farm power utilization above 40%. Even though comparable effects were not observable for other storage systems, most of the respondents within the sample relied on thermal storage solutions (65%), followed by cold (15%) and gas (11%), respectively (Figure 3b). In this context, 26% of the sample farms stated that they had multiple energy storage systems, while 19% did not have any at all.



(**a**) (**b**)

Figure 3. (**a**) Share of on-farm electricity utilization in 2021 across the sample; (**b**) Installed energy storage systems at the sample farms.

2.3. Approach for Screening the as-is Market Offering

In order to evaluate the market opportunity for DEMS offered to German dairy farmers and hence test the third hypothesis of this study, next to analyzing customer needs, we also had to look at the as-is market offering. To do so, we loosely followed the method of [27], i.e., (1) searched for DEMS provided to German dairy farmers; (2) collected and documented insights on the as-is market offering; and (3) analyzed the compiled dataset. In this context, search results were generated by screening both white and gray literature, including online articles, websites, and agri-magazines, as well as products presented at agri-exhibitions. In the style of ref. [27], a data collection template was used in order to document results from our market screening in a structured manner. In this context, we determined which DEMS are associated with the found market solutions and analyzed the as-is market offering with a focus on the maturity, function scope, and quantitative availability of DEMS tailor-made for German dairy farmers.

3. Results

3.1. Market Relevance of DEMS for German Dairy Farms

In order to measure the interest from German dairy farmers in DEMS and hence test the first hypothesis of this study, survey participants were asked to rate the relevance of DEMS for their farms on a scale from 1 to 4, with the option to abstain (Figure 4). In this study, it was shown that the overall interest in DEMS is high, as reflected by an average evaluation of 2.9. In this context, the assessment varies across the seven pre-defined DEMS, with a highest score of 3.4 shown for energy data analysis (process optimization). Similarly good assessments (3.2 and 3.0) were generated for energy data visualization, knowledge service (energy management in the dairy sector), energy marketplace, and energy-related documentation and inquiries. With a score of 2.7, the relevance of energy data analysis (predictive maintenance) was assessed as relatively low. Nevertheless, the lowest score (2.2) was gathered for energy data marketplaces—a result that could come from the general caution of German farmers to share data with others, especially when data rights are unclear [5]. Against this background, the first hypothesis of this study can be confirmed, although there are case-specific differences in the relevance of DEMS. On top of that, 5–11% of the sample did not provide an assessment on the relevance of DEMS (i.e., responded with 'n/a'), which can be seen as an indicator for the novelty of the research field (i.e., German dairy farmers have been barely confronted with similar research questions).

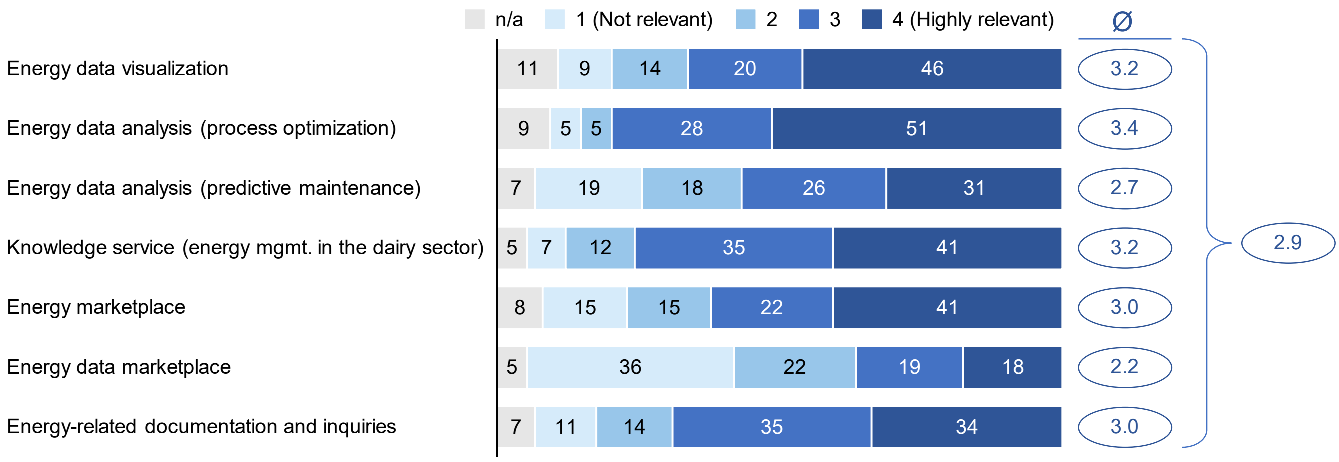


Figure 4. Sample farmers' responses on relevance of DEMS on a scale from 1 (Not relevant) to 4 (Highly relevant)–translated and simplified.

Given that farm characteristics such as farm size or the farmer's age can have an impact on the adoption rate of digital services at farms [28] and hence also on the relevance of DEMS, the sample's assessment from Figure 4 was analyzed in more detail (Table 2). Hence, in order to test the second hypothesis of this study, it was investigated whether the sample's assessment of DEMS significantly varied in dependence on selected farm characteristics. To do so, for figures with continuous values (such as total electricity generation), we differentiated between sample farms with values below the respective median (M) and those with values equal to or higher M. Furthermore, for cases with an observed deviation of more than 0.20 points from the average assessment of a DEMS, we conducted a chi-squared test to look for significant differences ($p < 0.05$) [29]. Results of this analysis show that in the case of three DEMS—energy data analysis (process optimization), knowledge service (energy management in the dairy sector), and energy-related documentation and inquiries–only low deviations were observed, i.e., deviations below 0.20 points from the average assessment of the respective DEMS. In the case of the other four DEMS—energy data visualization, energy data analysis (predictive maintenance), energy marketplace, and energy data marketplace—six Chi-squared tests were conducted with none of them indicating significant dependence between the sample farm characteristics and the relevance assessment of DEMS ($p < 0.05$). The highest correlation was shown between the dairy herd size and the relevance of energy data visualization ($p = 0.0582$). Hence, the second hypothesis of this study has to be rejected since there is no indication for the necessity of segmenting customers when providing DEMS to German dairy farmers. Instead, it is more important to consider the differences in digital service valuation across DEMS, i.e., to prioritize DEMS with a higher value for dairy farmers.

Table 2. Stated relevance of DEMS dependent on farm characteristics (translated and simplified), including information on the sample share and the *p*-Value in selected data fields.

Digital Energy Management Service (DEMS)	Age of Farmer		Dairy Herd Size		Location		Milk Yield Per Cow		Total Electricity Generation		Electricity Consumption per kg of Milk		On-Farm Electricity Utilization		Organic Farm	
	<M	**≥M**	**<M**	**≥M**	**Bavaria**	**NRW**	**<M**	**≥M**	**<M**	**≥M**	**<M**	**≥M**	**<20%**	**≥20%**	**Yes**	**No**
Energy data visualization	3.2 (46%)	3.1 (43%)	2.9 (45%)	3.4 (45%)	3.2 (54%)	3.2 (28%)	3.2 (46%)	3.1 (43%)	3.1 (47%)	3.2 (42%)	3.1 (47%)	3.2 (42%)	3.1 (55%)	3.2 (34%)	3.5 (18%)	3.1 (72%)
			p = 0.0582 *												*p* = 0.3599	
Energy data analysis (process optimization)	3.4 (47%)	3.4 (43%)	3.4 (43%)	3.4 (47%)	3.4 (53%)	3.4 (31%)	3.3 (45%)	3.5 (46%)	3.4 (49%)	3.4 (42%)	3.4 (47%)	3.4 (43%)	3.3 (57%)	3.6 (34%)	3.6 (19%)	3.3 (72%)
Energy data analysis (predictive maintenance)	2.7 (46%)	2.8 (47%)	2.6 (45%)	2.9 (49%)	2.7 (58%)	3.0 (28%)	2.6 (50%)	2.8 (43%)	2.8 (46%)	2.7 (47%)	2.6 (46%)	2.8 (47%)	2.7 (57%)	2.8 (36%)	2.8 (22%)	2.7 (72%)
					p = 0.6231											
Knowledge service (energy mgmt. in the dairy sector)	3.0 (46%)	3.3 (49%)	3.0 (46%)	3.3 (49%)	3.1 (57%)	3.2 (31%)	3.0 (47%)	3.3 (47%)	3.0 (47%)	3.3 (47%)	3.1 (47%)	3.2 (47%)	3.1 (59%)	3.2 (35%)	3.1 (19%)	3.2 (76%)
Energy marketplace	2.9 (46%)	3.0 (46%)	2.8 (45%)	3.1 (47%)	3.0 (45%)	3.0 (31%)	2.8 (45%)	3.1 (47%)	2.9 (46%)	3.0 (46%)	2.6 (45%)	3.3 (47%)	2.9 (57%)	3.0 (35%)	3.0 (19%)	2.9 (73%)
											p = 0.1426 *					
Energy data marketplace	2.3 (49%)	2.1 (46%)	2.0 (47%)	2.4 (47%)	2.1 (58%)	2.4 (30%)	2.0 (49%)	2.4 (46%)	2.0 (47%)	2.3 (47%)	2.4 (47%)	2.0 (47%)	2.2 (58%)	2.2 (36%)	2.0 (20%)	2.2 (74%)
					p = 0.0811						*p* = 0.5127 *					
Energy-related documentation and inquiries	2.9 (46%)	3.1 (47%)	2.9 (45%)	3.0 (49%)	2.9 (55%)	3.0 (31%)	2.9 (47%)	3.1 (46%)	3.1 (46%)	2.9 (47%)	3.0 (47%)	2.9 (46%)	3.0 (59%)	2.9 (34%)	3.0 (19%)	3.0 (74%)
Total	**2.9 (47%)**	**3.0 (46%)**	**2.8 (45%)**	**3.1 (47%)**	**2.9 (56%)**	**3.0 (30%)**	**2.8 (47%)**	**3.0 (46%)**	**2.9 (47%)**	**3.0 (46%)**	**2.9 (47%)**	**3.0 (46%)**	**2.9 (58%)**	**3.0 (35%)**	**3.0 (19%)**	**2.9 (73%)**

Data fields with deviation from average assessment above 0.20 were highlighted in grey. In case of data fields marked with *, a chi-square test was conducted based on the four quartiles of the respective farm characteristic.

3.2. As-is Market Offering of DEMS for German Dairy Farmers

In the context of our work, we identified only four market solutions that provide at least one of the seven pre-defined DEMS tailored to German dairy farms. Hence, in order to test the third hypothesis of our study, the DEMS of these market solutions were rated on a scale from 1 to 4 while focusing on the following three dimensions: maturity, function scope, and relative quantity of DEMS (Table 3). In this context, the maturity of a DEMS was assessed by determining its technology readiness level (TRL) [30], while the relative quantity was measured across the seven pre-defined DEMS.

Table 3. Selected scale to evaluate maturity, function scope and relative quantity of DEMS.

Assessment Dimension	Scale 1	Scale 2	Scale 3	Scale 4
Maturity	TRL 9	TRL 5–8	TRL 2–4	TRL 1
Function scope	Comprehensive functionality	Majority of functions contained	Limited number of functions included	No functions implemented yet
Relative quantity	>30%	11–30%	1–10%	0%

As a result, the as-is market offering of DEMS tailored to German dairy farmers turned out to be very limited, so that the third hypothesis of this study can be confirmed. Solutions are available that provide energy data visualization, optimization-oriented energy data analyses, and sector-relevant insights on energy management (Figure 5). Other DEMS are not yet available at an adequate TRL or are not tailored to the special needs of German dairy farms. Overall, the as-is market offering for German dairy farms lacks richness in functionality, such as the visualization of energy-related financial insights or the detection of farm system outages based on energy data. The existing function scope of the as-is market offering is outlined below.

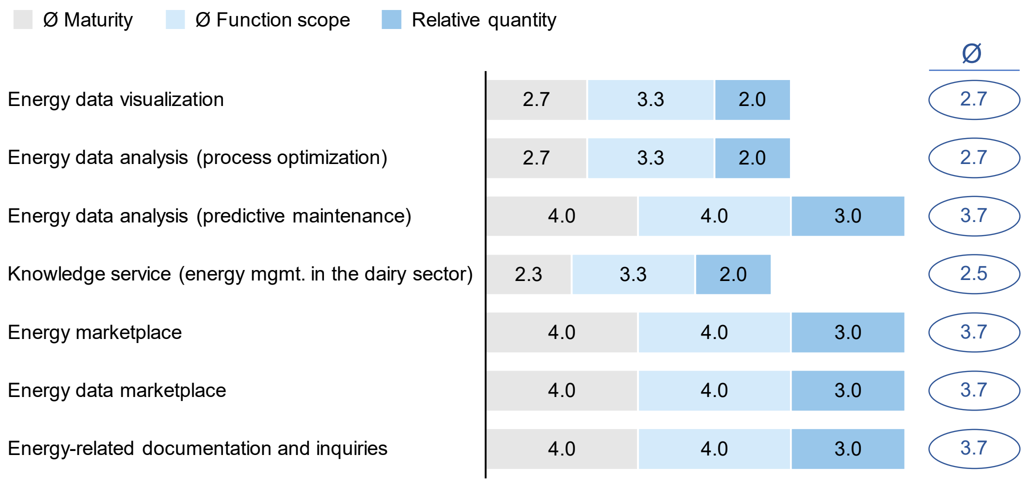


Figure 5. Maturity, function scope and relative quantity of DEMS in the as-is market offering tailored to German dairy farms.

The energy management system "CowEnergy", which was introduced by ref. [12], is already implemented at a German dairy farm and includes, in addition next to physical systems, a selection of DEMS. The "CowEnergy" solution visualizes farm system-specific energy generation and consumption over time as well as the amount of stored energy. Besides that, "CowEnergy" processes generic data, e.g., to serve the farmer with insights on the German power grid [31], and also does automated energy data analyses optimizing a farm's on-farm power utilization [12]. Comparable research targets are pursued by the "SmartFarm" project [32], while both solutions focus on providing physical energy management systems. As opposed to that, in 2022, a concept called "DairyChainEnergy" was introduced by ref. [13] aiming to provide DEMS to stakeholders of the German dairy sector. The targeted function scope of "DairyChainEnergy" comprises all seven DEMS in the scope of this study; the solution, however, is still at TRL 1. By contrast, a market solution that has already been tested by more than seven thousand German dairy farmers is the QM-Milch sustainability tool. Within this tool, a farmer provides manual input data on ecological, economic, social, and animal welfare issues. Hence, the focus of the QM-Milch sustainability tool is not only on farms' energy management; however, the farmer is able to receive insights from peer benchmarks [33].

Next to these four solutions, there are also other DEMS available in the German market that are not tailored to dairy farms but rather suitable for a wider range of companies and private households. For example, "Cells Energy" is a marketplace that enables direct marketing for selling generated electricity to others [34], and providers of energy generation technology typically offer digital maintenance services to their customers [35,36]. However, due to their broad customer bases, those solutions are not able to holistically address the needs of dairy farmers. For example, predictive maintenance services based on energy data should not be limited to an energy generation system of one specific provider but should cover all relevant systems at the barn.

3.3. Market Opportunity for Offering DEMS to German Dairy Farmers

To evaluate the market opportunity for offering DEMS to German dairy farmers, we took an aggregated look at our study results on the relevance and market coverage of DEMS (Figure 6). By doing this, we see that for DEMS with the highest relevance for our survey sample, such as energy data visualization or energy data analysis (process optimization), there are already first-market solutions available. By contrast, other DEMS with comparably high relevance (e.g., energy-related documentation and inquiries) are not yet available in a tailored offering for German dairy farmers. Against this background, there definitely is a market opportunity for FMIS providers to integrate DEMS into their as-is service offering, especially for those planning to deploy multiple DEMS to German dairy farmers. When doing this, both DEMS with the highest relevance for the customer, e.g., energy data analysis (process optimization), as well as those with the greatest novelty for the market, e.g., energy-related documentation and inquiries, should be included in the digital service offering portfolio of a FMIS provider.

X Highest score (Highest relevance; Lowest market coverage) X Lowest score (Lowest relevance; Highest market coverage)

DEMS	Relevance (Customer needs)*	Market coverage (Competitor landscape)**
Energy data visualization	3.2	2.7
Energy data analysis (process optimization)	3.4	2.7
Energy data analysis (predictive maintenance)	2.7	3.7
Knowledge service (energy mgmt. in the dairy sector)	3.2	2.5
Energy marketplace	3.0	3.7
Energy data marketplace	2.2	3.7
Energy-related documentation and inquiries	3.0	3.7

*According to responses from our survey sample; ** Looking at market solutions tailored to German dairy farms

Figure 6. Market opportunity for DEMS considering customer needs and market coverage.

4. Discussion

4.1. Investment Intentions and Concerns of German Dairy Farmers

Also in the future, farmers are planning to further invest in energy management, with investments in energy generation systems expected to become the biggest investment block at farms [37]. This predominant interest in expanding energy generation capacities was confirmed by our survey results (Figure 7a) and can be attributed to farms' striving to become energy self-sufficient, increase profitability, and mitigate GHG emissions [12,13,38]. Beyond that, 65% of our sample voiced a plan to invest in energy storage solutions until 2025, while 27% plan to spend on expanding the farm's energy infrastructure (e.g., implementing charging stations for electric vehicles). Hence, even though the focus of future energy management investments across the sample will remain on energy generation and storage solutions, 27% of the sample also stated to invest in energy management systems, including DEMS. This finding shows that even if a DEMS is evaluated as being highly relevant for a farm, this will not automatically imply actual investments. Reasons for that could be the insufficient as-is market offering but also farmers' overall concerns about applying DEMS. In this context, major concerns raised by our sample, as illustrated in Figure 7b, are related to unclear data rights (70%), advertising (58%), and high time investment efforts (51%). Furthermore, 51% of the sample did not like the idea of DEMS being managed by a central entity, even though that is how digital services are typically provided [2]. By contrast, lack of IT skills was not a major obstacle for the sample respondents. Hence, all in all, the sample's concerns about DEMS do not differ significantly from farmers' overall restraints when using digital services [5].

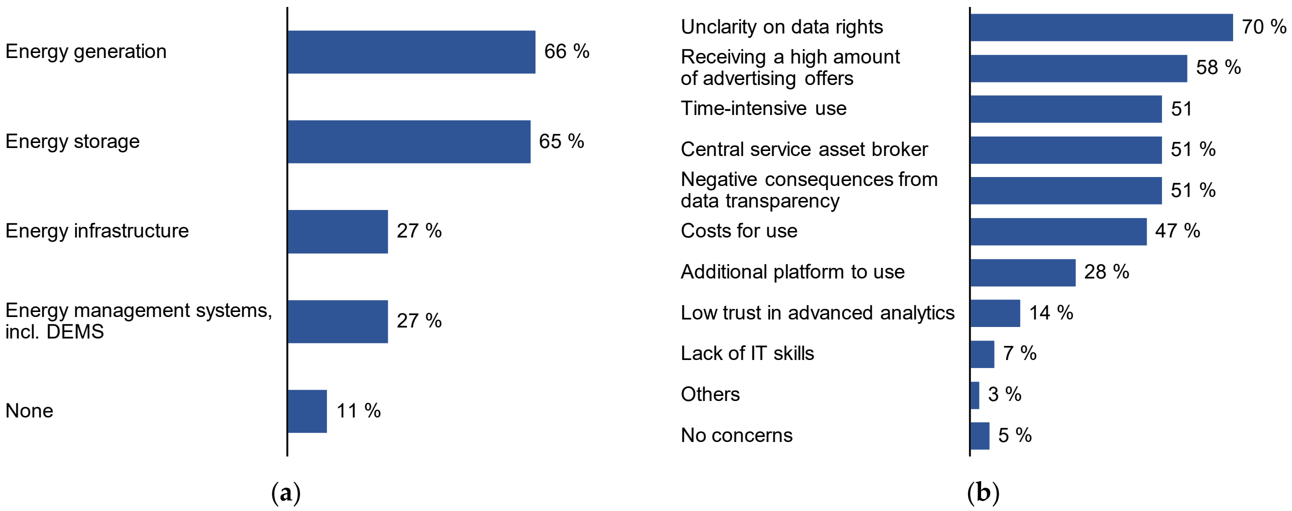


Figure 7. (**a**) The sample's energy management investment plans until 2025–translated and simplified; (**b**) Concerns of the sample about applying DEMS–translated and simplified.

4.2. Applicability of Our Study Results to the German Dairy Farm Population and Other Stakeholders from the Dairy Sector

The major limitation of this study is the relatively small size of the survey sample (74 responses), which was used to analyze the relevance of DEMS for German dairy farms. Due to this and given that certain sample farm characteristics (e.g., on-farm energy generation) deviate from those observable in the German dairy farm population, it can be questioned how applicable our study results are to the majority of more than 50 thousand German dairy farms [23]. However, findings from ref. [37,39] indicate that the characteristics of German dairy farms will, in the future, be more aligned with those of the sample (e.g., larger dairy herd size, more on-farm energy generation) so that our survey results can be used to better assess the future customer needs of German dairy farms. On top of that, the outlined value-add of DEMS (e.g., reduction in energy-related costs) is valid for all German dairy farms.

In addition to that, the results of this study are not only useful for FMIS providers but are also insightful for other stakeholders in the German dairy sector. For example, with an increased adoption rate of DEMS and hence increased transparency on energy data, stakeholders from the downstream supply chain (e.g., dairy factories and retail stores) will have a better chance to provide net zero energy milk [38], and providers of on-farm equipment can improve their offering (e.g., by drawing conclusions from energy data on the on-site utilization of a product) [22].

4.3. Challenges when Providing DEMS to German Dairy Farmers

When thinking about integrating DEMS as part of FMIS, providers should be aware of particular challenges in the context of deploying DEMS to German dairy farmers. In contrast to many other digital agri-services, DEMS can have critical effects on the functionality of a farm's infrastructure, i.e., bugs or structural system errors can have severe consequences, with power outages being the worst case scenario [40]. Hence, the demand for resilience is even higher with DEMS compared with other digital services. Furthermore, most farms do not yet have central control units installed to collect energy data at the dairy barn as input for DEMS, given the novelty of this technology [12]. Hence, for farms, the implementation of such a physical energy management system, as a pre-requisite for leveraging most benefits from DEMS, will pose an on-top investment that is not directly affecting a dairy farm's core income streams. Against this background, we expect a combined offering package, including a physical energy management system and a selection of DEMS, to be most valuable for the farmer. On top of that, when deciding which DEMS to deploy, FMIS providers should also think about how to leverage synergy effects during the implementation process. Lastly, to holistically evaluate the market opportunity of each DEMS from a company-perspective, a FMIS provider should critically review its capabilities, resources, and market channels for deploying a DEMS and evaluate the expected return on investment [21]. For example, to manage the challenges outlined above, a FMIS provider should review the expertise of its own staff with regards to knowledge on the German energy market, implementation of digital farming solutions (e.g., development of AI services), and legal framework conditions (e.g., data rights in Germany).

5. Conclusions

The novelty of this study lies in the detailed analysis of market demand and the offering of DEMS for German dairy farms. Hence, our analyses provided valuable insights on which digital services are most relevant for dairy farmers and which of those are not yet adequately covered by the as-is market offering. For example, digital services such as energy data analyses for process optimization were evaluated by our sample as being the most relevant DEMS but are not yet adequately provided by the market. To close this market gap, we recommend further work on how to implement such DEMS. Besides that, the farmer survey conducted in the context of this study provided valuable insights on the status quo of energy management at German dairy farms. Looking at our sample, photovoltaic is the most prominent energy generation technology, most farms generate more electricity than they consume, and thermal storage systems are the most common solution for accumulating energy.

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Article

How to Successfully Orchestrate Content for Digital Agriecosystems

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Abstract: Since the 2000s, digital ecosystems have been affecting markets—Facebook and Uber being prominent examples. Looking at the agrisector, however, there is not yet a winner-takes-all solution in place. Instead, numerous digital agriplatforms have emerged, many of which have already failed. In the context of this study, it was revealed that reasons for such failures can be manifold, with one key challenge being the orchestration of platform content. Because, however, publicly available knowledge on this regard is limited, we decided to introduce a methodology for the evaluation of digital agriecosystem services, enabling providers to optimize their existing offering and to prioritize new services prior to implementation. By deploying our methodology to digital agriecosystems with two different application focuses (DairyChainEnergy—data agriecosystem on energy management for dairy farmers, and NEVONEX—IoT agriecosystem comprising digital services for agrimachinery), its applicability was proven. Providers of digital agriecosystems will benefit from applying this new methodology because they receive a structured decision-making process, which takes the most relevant success criteria (e.g., customer benefit, technical feasibility, and resilience) into account. Hence, a resulting prioritization of digital agriservices will guide providers in making the right implementation choices in order to successfully generate network effects on their digital agriecosystems.

Keywords: agriecosystem; DairyChainEnergy; methodology; NEVONEX; platform; root-cause analysis

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1. Introduction

Digital ecosystems—as defined in ref. [1], e.g., Google, Facebook, Amazon, Airbnb, or Uber—have already proven their potential for changing or even disrupting existing markets. Between 2015 and 2020, publicly traded platforms increased in number from fifty to over one hundred fifty platforms, with five out of the ten most successful digital companies on the Fortune's Digital 100 being listed as digital ecosystem providers [2]. Their core added value lies in collaboration, networking, and openness, as well as in the provision of interlinked services. Multiple markets are already substantially dominated by such digital ecosystems—a phenomenon that is known as the "winner-takes-all effect"—advantaging solutions with a certain market-share threshold. Hence, digital ecosystem markets tend to sooner or later turn into either mono- or oligopolies [1]. In the agricultural (agri-) market, there are still no such dominating solutions—neither across nor within market segments (e.g., animal health monitoring, trading of agrigoods, farm management, etc. [3]). Instead, there is a rising number of digital farming solutions, such as embedded systems (e.g., sensors) for data gathering, mobile solutions (e.g., tablets) for on-site system accessibility, or digital platforms (e.g., farm management information systems (FMIS)) enabling the collaboration of multiple stakeholders [4]. Digital agriecosystems, on the other hand, orchestrate one or multiple digital platforms comprising a variety of interlinked digital agriservices that are provided, supported, and consumed by several stakeholders [1,5].

In the literature of this research field, there is still no common agreement on nomenclature; however, there is a noticeable differentiation between two types of digital agriecosystems: there are digital ecosystems with integrated Internet of Things (IoT) devices (IoT agriecosystems) [6] and those focusing on the processing and distribution of data (data agriecosystems) [5] (Figure 1). In this context, IoT solutions typically focus on one agrimarket segment, such as crop farming (e.g., NEVONEX—equipping agrimachinery with digital crop-farming services (DCFSs)) [7], energy management (e.g., CowEnergy—optimizing dairy barn on-farm power utilization) [8], or logistics (e.g., SISTABENE for tracking and tracing of agrigoods) [6]. This is because the architecture of an IoT agriecosystem's physical and connectivity layers must be tailor-manufactured by considering the market segment's specific requirements and framework conditions. For example, the NEVONEX IoT ecosystem operates based on electronic control units (ECUs) for agricultural machinery [9], whereas the use of CowEnergy requires implementing interfaces into the barn's most relevant technical equipment [8]. This is because digital services of IoT agriecosystems are used to automate and optimize the execution of on-site processes (e.g., optimized control of a tractor's tire-pressure control system [10] or real-time prioritization of electricity consumers in the barn [8]). In contrast, data agriecosystems such as Agri-Gaia, 365 FarmNet, or Xarvio serve stakeholders along agrisupply chains with digital services that are mostly restricted to the cloud layer (e.g., artificial intelligence (AI) data analytics solutions) but not necessarily limited to only one market segment [5,11,12]. Due to the dependency on actors or systems supplying data to this type of digital ecosystem, the maturity of data ecosystems is, however, comparably low [13]. Hence, the chances for scaling a data agriecosystem are much higher if there are already IoT agriecosystems in place to build upon. This is, for example, observable in livestock farming, wherein the market opportunity for providing digital energy-management services (DEMSs), e.g., in the context of the DairyChainEnergy project, is founded in existing IoT solutions such as CowEnergy [14].

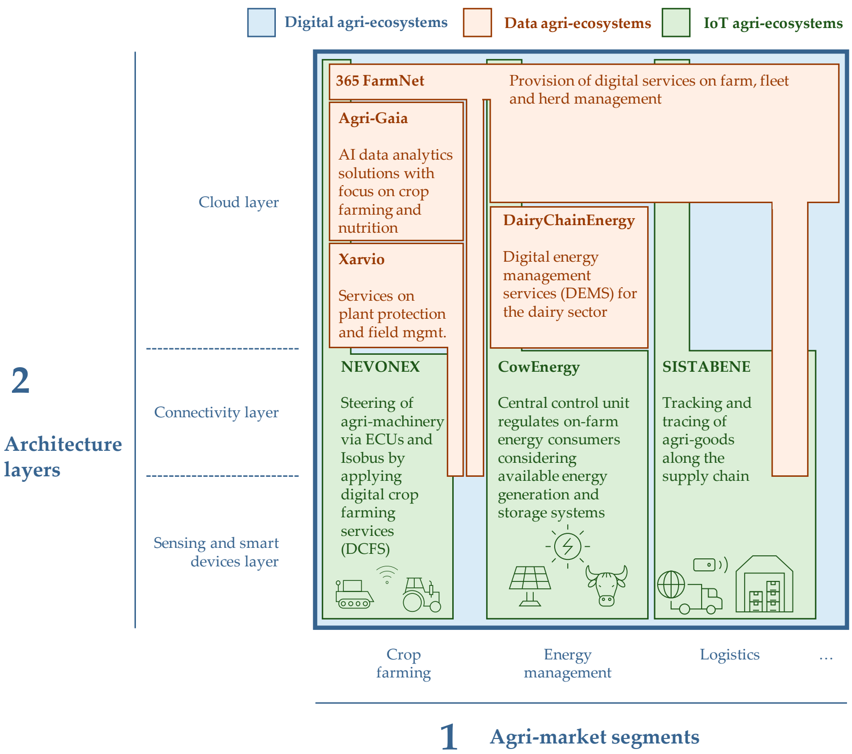

Figure 1. Digital agriecosystems—Types, scope, and examples [3,4,6,7,9,13,14].

Overall, digital agriecosystems—both IoT and data agriecosystems—can bring major benefits to the market (e.g., efficiency increase, cost reduction, and fraud prevention) and can enable the implementation of innovative business ideas (e.g., new channels for sales or collaboration) [15,16]. Beyond that, as observable in other industries, digital ecosystems can also improve the quality of digital services offered to the market [13]. However, despite this promising added value, a series of digital agriecosystems and platforms, including NEVONEX, Agrando, and Granular, recently announced their failures (e.g., due to low adoption or strategic reorientation) [17–19]. Because, on the other hand, success stories are rarely found and companies (such as Microsoft or Amazon Web Services) are still eager to conquer the market with new digital agriecosystems [20], our study aims to elaborate on ways to contribute to the future success of digital agriecosystems. Therefore, content orchestration is identified as one of the missing key success factors in current research, and a novel methodology for orchestrating content is developed based on the identification of relevant success criteria for the implementation of digital agriecosystem services. Further, this created methodology is consecutively evaluated on two real-life examples of digital agriecosystems to prove its applicability in practice.

2. Materials and Methods

To achieve this paper's research target, two methods have been applied as illustrated in Figure 2. First, with the help of a root-cause analysis (RCA) in the style of ref. [21], causalities behind failures of digital agriecosystems were investigated. In this regard, for step I.1 (data collection), learnings from the build-up and shutdown of NEVONEX, as well as publicly available information on failure causes of digital agriecosystems from [16,22–25], were leveraged as input for this RCA. Next, a causal factor chart was created to organize and visualize events, conditions, and occurrences that led to failures of digital agriecosystems (step I.2). After deriving related root causes for such failures (step I.3), which are outlined in Section 3.1, we were able to derive the recommendation (step II.4) for developing a new methodology that addresses avoidable, strategy-related failure causes, more specifically, a methodology on content orchestration for digital agriecosystems (Section 3.2). In the context of this study, this methodology was shaped, executed, and enhanced with the help of findings from the RCA and additional insights from the literature [26–30], following a ten-step approach from ref. [22]. For example, to prove its applicability, we tested our newly developed methodology (step II.7) with the help of the two digital agriecosystem projects: NEVONEX and DairyChainEnergy (Section 3.3).

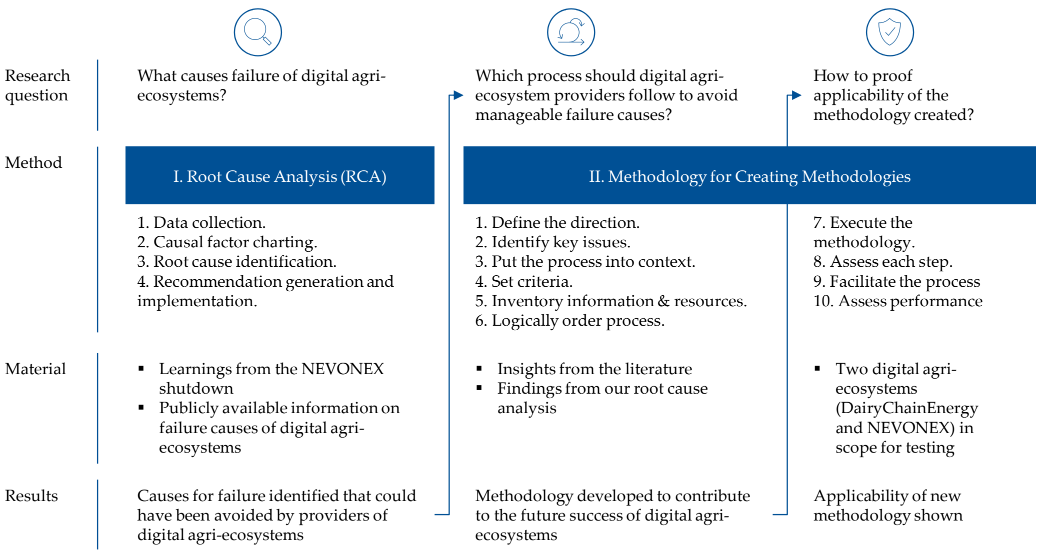

Figure 2. Leveraged materials and methods to achieve this work's research target [21,22].

3. Results

3.1. Causality behind Failure of Digital Agriecosystems

The following paragraph identifies well-known and addressable success factors for digital ecosystems from the literature, followed by a root-cause analysis of the NEVONEX ecosystem ramp down. Comparing the identified root causes from the RCA to well-known, addressable success factors yields blind spots in the existing quiver of available methods and identifies the reasons why digital agriecosystems fail, despite following current state-of-the-art knowledge during implementation.

In the state-of-the-art literature, success and failure factors of digital platforms are comprehensively reviewed across industries. For example, ref. [22] pointed out that it is important to coordinate platform sides and digital interfaces with the scope of the firm operating the platform. Furthermore, ref. [23] identified thirty success factors for digital platforms and clustered them into three domains: corporate value integration, platform value, and platform architecture. In contrast, Cusumano et al. focused on failure causes and showed that many digital platforms fail during their first years following market launch due to mispricing, lack of trust, poor competitor analysis, and/or late market entry [24]. When looking beyond that, to the agridomain, it becomes apparent that there are additional challenges to overcome for making a digital ecosystem successful. For example, the authors in ref. [16] elaborated on a series of agrispecific challenges for implementing IoT technology that were clustered into business issues (cost, business models, and lack of adequate knowledge), technical issues (interference, security and privacy, choice of technology, reliability, scalability, localization, and optimization of resources), and sectoral issues (regulatory challenges and interoperability). In a related vein, the researchers in [25] identified sector-specific influencing factors for startups in the agridomain to overcome critical mass. For example, they state that it is beneficial to leverage the curiosity of early adopters in the agrimarket to further develop and improve digital solutions, but it is also very challenging for providers to overcome local growth [25].

In addition to these findings from the literature, during the preparation of this study, the NEVONEX project was shut down [17] so that first-hand information on the failure causes of digital agriecosystems could be derived by carrying out an ex post RCA. In this analysis, we focused on failure causes that could have been addressed and hence avoided by the providers of DCFSs. For the NEVONEX ecosystem, four remaining experts from the project were invited to develop the RCA together with the author throughout collaborative online meetings. The data were collected and clustered in mind maps. This RCA yielded a list of twenty-six root causes, which were clustered into three categories: "operations related" (9), "technology risk" (7), and "content orchestration related" (10). Root causes resulting from day-to-day business (e.g., human-resource capacity for daily stakeholder interaction) were labeled as "operations related," whereas technology-related challenges (e.g., high complexity of required technical infrastructure) were labeled as "technology risks". In contrast, failure causes related to content orchestration came from disagreements of stakeholders on the choice of digital services and low transparency on how this content choice would affect the digital agriecosystem and its stakeholders (e.g., digital service providers) [31]. However, whereas in the context of the NEVONEX project there were already methods applied to overcome operational and technical challenges, a decision-making process to adequately manage the digital ecosystem's content orchestration was missing.

3.2. Introducing a Three-Phase Content-Orchestration Methodology for Digital Agriecosystems

To address one of the main causes behind the failure of digital agriecosystems identified in the context of our RCA, we applied steps II.1 through II.6 from Figure 2 to develop a methodology for organizing the orchestration of content on both evolving and mature digital agriecosystems. Hence, the purpose of this new methodology lies in enabling providers to explore pros and cons of digital ecosystem services prior to actually implementing them by considering their effects on stakeholders and the digital agriecosystem as a whole. To do so, we logically ordered the required steps for fulfilling this purpose, from content ideation to prioritization, resulting in a three-phase methodology (Figure 3). First, an exploration of promising application fields (A1–A3) is carried out based on work from [26–28], yielding a longlist of digital services eligible for the scope of the respective digital agriecosystem.

For this exploration, an early-on involvement of different stakeholder groups (including potential consumers of the agriecosystems, e.g., farmers, and business partners, such as installation providers in the context of focus-group workshops or comparable formats) is recommended, whereas the choice of participants is decisive to ensure a good understanding of the status quo (with regards to both the agrimarket and the capabilities of the respective agriecosystem) as well as a sufficient degree of creativity and innovation [27]. In doing this, inappropriate use cases (e.g., digital services that are not backed up by an adequate market demand) are already filtered out in the first phase of our methodology. Next, to prepare the evaluation of digital services from the ideation longlist, providers can select from a predefined set of assessment criteria (customer benefit, society impact, economic provider benefit, governance implications, technical feasibility, and resilience). As pointed out in [29,30,32], the first three of those criteria are majorly relevant for assessing the value of a digital service, whereas the latter three criteria predominantly evaluate the implementability of a digital service. For example, when assessing the resilience of a digital service, threats for cybercrime must be taken into consideration [32]. In this context, this step (B1) ensures that ecosystem-specific characteristics can be taken into consideration (e.g., an economical assessment of digital services can be neglected when it comes to nonprofit digital farming solutions such as those from AgGateway that, for example, aim to establish an industry standard for processing data from precision agriculture [33,34]). Hence, if a criterion is regarded as not being relevant for the respective digital agriecosystem, it can be weighted with zero, i.e., eliminated from the assessment. In addition, there is a chance to determine a critical score per evaluation criterion that must be met by a digital service in order to remain in consideration (B2). In doing this, digital services that are not able to meet the minimum requirements of the respective digital agriecosystem will be filtered out. Next, to actually conduct the assessment per digital service and evaluation criterion, a mix of methods (e.g., exploratory expert interview, quantitative survey, tangible ecosystem design, and literature review) is applied to consider all criteria for evaluation. As the output from step B3, each digital service is assigned with an evaluation score from 0 to 5 on a Likert scale [35], which is used later on to aggregate the findings from the analysis and to create a ranking among the digital services in scope (C1). Hence, a weighted average of all six criteria assessments is to be calculated in order to form one assessment score per digital service in order to easily compare digital services with each other. Relevant stakeholders (especially service asset providers and brokers) should be aligned on the digital service ranking (C2) in order to ensure a future strategy fit (e.g., to make sure that the platform infrastructure can meet the technical requirements of newly planned digital services).

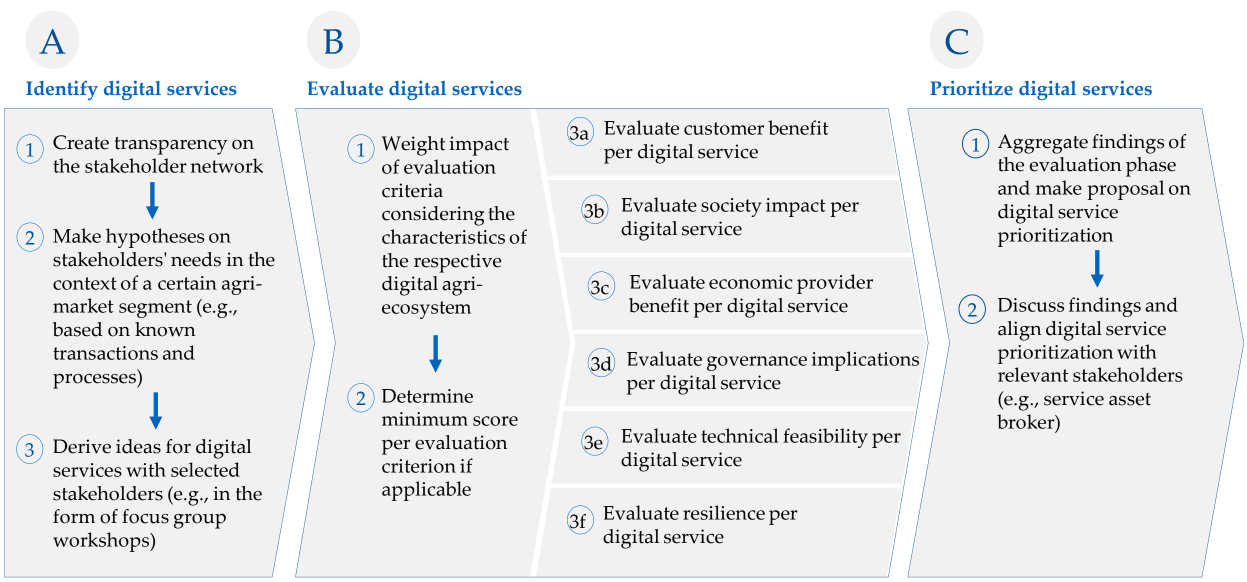

Figure 3. Newly introduced three-phase content-orchestration methodology for digital agriecosystems.

3.3. Testing our Methodology: NEVONEX and DairyChainEnergy

To validate its applicability, we tested our methodology with the two digital farming solutions, NEVONEX and DairyChainEnergy, following steps II.7 through II.10 from Figure 2. The scope for this testing was determined as follows: In the case of DairyChainEnergy, which is, so far, still in its conception stage, digital services were taken from [14], wherein the customer relevance of seven DEMSs was already analyzed in detail. For NEVONEX, in contrast, the use case exploration was carried out in a threefold approach: ideas for the DCFSs were received from (1) a review of functionalities on farm equipment (including those enabled by sensors and actuators), (2) a process-focused analysis of data streams of agrimachinery, and (3) feature ideation workshops conducted in the context of the NEVONEX project in the period from 2019 to 2022. As the result of this process, fifty-two use cases were received, of which ten DCFSs were determined to be within the scope of this study (Table 1).

Table 1. Description and implementation status of ten DCFSs from NEVONEX within the scope of this study.

Digital Crop-Farming Service (DCFSs)	Description	Implementation Status (before NEVONEX Ramp Down)
Spot-spraying offline	Drone scans crop—spot-spraying application map is created in the cloud and transferred to conventional sprayer wirelessly via NEVONEX data infrastructure. NEVONEX task controller (TC) executes the application map and sprayer applies active ingredients. Site-specific, based on the identified weeds from drone survey.	Proof of Concept (POC) [36]
Fleet management	Logging of machine data (e.g., position, fuel consumption, etc.) with upload to cloud and display in front end.	Commercially available [37]
Tire pressure control	Improved automatic control of tire pressure from a unified user interface (UI).	Commercially available [38]
Setup assistant	Seeds, fertilizers, and active ingredients (that are equipped with a QR code) are scanned so that implements are adjusted according to the properties of the goods (e.g., scanning pesticide and sending information about buffer zones to sprayer [39]).	Not implemented
ISOBUS terminal	TC for the handling of application maps. VT (virtual terminal) for operating ISOBUS implements available on tablet in NEVONEX cockpit app.	TC commercially available in "geoNex App" and "Xarvio Digital Service" [40]
Maintenance and service assistant	CAN BUS and system diagnosis. Service history is made available to local machine dealers (manufacturer independent). Remote CAN-BUS diagnosis and pop-up notifications (e.g., for greasing intervals).	Partly commercially available as function of NEVONEX Cockpit App [41]
Automated process data acquisition	Automated logging, cleaning, and management of process data from agrimachinery, including external sensor information and machine implement identification.	POC
Automatic guidance	Visually assisted manual guidance system, comparable to AgOpenGPS [42] or Reichardt Smart Guide [43].	Not implemented
N-sensor liquid manure	NIR sensor scans crop and adjusts application rate of liquid manure in a map-overlay approach for a variable rate application on the fly.	Not implemented
NEVONEX onboard	In-cabin customizable dashboard (including widgets); in-field synchronization between cooperating machines (compare Fendt Smart Connect [44]).	In development

For both NEVONEX and DairyChainEnergy, all predefined assessment criteria from our content-orchestration methodology were regarded as equally relevant for estimating the future success of DCFSs and DEMSs. Looking at the first assessment criterion (customer benefit), DCFSs were evaluated in May 2022 by decision makers from the German sector of farm machinery dealerships, who were in direct contact with end customers and responsible for their companies' strategic portfolios. Because those interviewed experts have a cumulative market experience of 120.5 years and work at companies that already serve the NEVONEX platform as installation providers, both market expertise and familiarity with the product are given to formulate a valid assessment of customer benefits of DCFSs. In contrast to conducting direct customer surveys, as conducted for DEMSs in ref. [14], such expert surveys can give the advantage of providing insights on aggregated market trends and actual purchase behavior. To ensure compatibility with our methodology, regarding the results from both the end-customer surveys and expert interviews, the scale of given assessments was adjusted accordingly. Next, the societal impacts of DEMSs and DCFSs were reviewed with the help of literature insights, while the economic provider benefit was estimated as being equally moderate across all digital services. Lastly, input for the remaining assessment criteria (governance implications, technical feasibility, and resilience) were received in the context of interviews with industry experts, whereas DCFSs were mainly assessed by specialists from NEVONEX, and insights on DEMSs were received from more independent livestock-farming experts. After the evaluation of each criterion by the experts using five-point Likert scales, the results were aggregated for each DCFS and DEMS by forming the arithmetic mean for each service over all assessed criteria. As a result, a ranked list of digital services was derived for both NEVONEX and DairyChainEnergy (Figure 4).

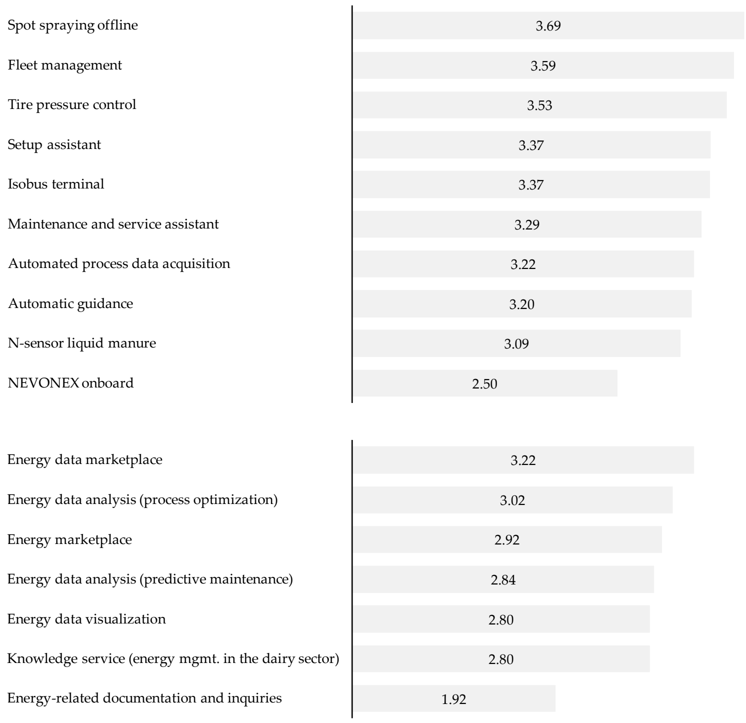

Figure 4. Results of the methodology test—Assessment of DCFSs and DEMSs within the scope of this study.

4. Discussion

Our study results proved the applicability of our methodology for different agrisectors (crop farming and dairy) and types of agriecosystems (IoT agriecosystems and data agriecosystems) and created transparency for the prioritization of digital services for both cases (NEVONEX and DairyChainEnergy). The results indicate that "spot spraying offline" and "energy data marketplace" are the most promising digital services in the context of our methodology. Even though the execution of the methodology was time-intensive due to the necessity of setting up tailored questionnaires and selecting suitable experts, if planned correctly, the output from the interviews can not only be used in the context of our methodology but can also serve as valuable insights when implementing a digital service (e.g., when designing a technical infrastructure and making architectural choices [45]). In this context, the quantity and objectivity of experts assessing a digital service is critical [46]. In our study, for example, experts assessing the DCFS of NEVONEX were familiar with and involved in the development of the NEVONEX agriecosystem since its introduction in 2019 [47], and therefore could have been biased [46]. This could be one reason explaining why the DCFS of NEVONEX received, on average, a better rating compared to the DEMS in the scope of the DairyChainEnergy project. Our methodology, however, was not designed for, and hence is not applicable to, evaluating the probability of success among different digital farming solutions; it is only valid for assessing the digital services of one digital agriecosystem. This is reasonable because digital platforms differ in terms of value creation, the interdependency of platform participants, and growth patterns [31]. Hence, despite the higher rating of DCFSs compared to the DEMSs in the scope of our study, there is not a lower future success probability implied for DairyChainEnergy. One reason for this is that the target markets of both solutions differ in regard to forecasted market growth, technological conditions, and market reach of competitors. In general, the crop-farming industry is digitally more mature and interlinked than the livestock-farming sector. For example, there is an oligopoly in livestock farming, with six major players dominating the market and owning the interfaces on the physical layer. In comparison, for crop farming, the ISOBUS standard (ISO11783) has put pressure on dominant market players regarding the interoperability of their equipment. [48] Hence, a solution such as NEVONEX already benefits from an advanced interoperability, whereas the data basis for DEMSs in most German dairy stables is not yet collected automatically [8]. Against this background, the variety of established digital services in crop farming is much higher compared to the as-is portfolio of DEMSs, i.e., many farmers already have some experience with DCFSs, also in conjunction with other precision-farming technology [49]. In contrast, digital services in energy management for dairy farms might have appeared to be more abstract for our sample farmers and experts [14].

Looking at how the application of our methodology supported the future development of the two digital agriecosystems, it became apparent that the methodology is most helpful at an early concept stage. This is because digital agriservices show high variety (e.g., in terms of technical requirements and affected stakeholders), and hence have different demands on the set-up of the respective digital agriecosystem (e.g., on its IT architecture [45]). Thus, when there is clarity on the timeline of digital services to be implemented, which are already at an early concept stage, a misfit of platform capabilities and digital service requirements can be avoided, leading to higher cost efficiency and shorter implementation times, as well as to higher customer satisfaction. However, given that in digital ecosystems there can be different parties involved for the provision of platforms and digital services [1], our methodology can also be of high value for coordinating the ecosystem growth on a regular basis across business partners. To do so, interdependencies among digital services are to be analyzed and fundamental agreements on the implementation (including timeline and budget) must be made. In this context, stakeholders have to check whether the digital agriecosystem is able to fulfill the technical requirements of the prioritized digital services, whether synergy effects can be used when implementing cross-dependent digital services, and what set of digital services can be implemented under the given budget and capacity restrictions.

However, measuring the impact of our methodology on the future success of digital agriecosystems is challenging. First, this is because of a time shift between applying the methodology and collecting possible metrics (such as the number of service asset consumers or generated profit per digital service). Beyond that, given that a well-conducted content orchestration is only one factor for establishing a successful agriecosystem (Section 3.1), there is no possibility for quantifying the isolated impact of our methodology retrospectively. Nevertheless, learnings from the NEVONEX ramp down revealed how critical it is to manage content orchestration proactively, which is why our methodology should be leveraged as a best practice for managing the service portfolios of digital agriecosystems. In the case of NEVONEX, unfortunately, our methodology was applied too late; hence, even promising DCFSs from NEVONEX (Table 1) will no longer be available in the market.

5. Conclusions

The findings of this study will support providers of digital farming solutions in improving the content orchestration of their platforms and hence contribute to enhancing the digital service offerings in the sector. Insights from a real-life established and by now shut-down agriecosystem (NEVONEX) were leveraged to document first-hand knowledge on failure dimensions of digital agriecosystems. Although many of those failure dimensions can be avoided with the help of existing methods from the literature, no structured approach to orchestrate upcoming digital service portfolios was found, which raised the need to address this topic. The derived methodology for prioritizing digital services when setting up or expanding digital farming solutions applies a mix of techniques to evaluate digital services along six success criteria (customer benefit, society impact, economic provider benefit, governance implications, technical feasibility, and resilience). Based on the resulting ranking of potential digital ecosystem services, platform providers find guidance in prioritizing and facilitating the development and implementation of said services on their platforms. As a result, providers of digital agriecosystems now have a tested methodology at their disposal to optimize their digital service offerings and hence set their platforms up to successfully generate network effects.

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