Howard *et al. Energy Informatics* 2022, **5**(Suppl 4):57
https://doi.org/10.1186/s42162-022-00245-0

Energy Informatics

REVIEW

Open Access

Application of energy informatics in Danish research projects

Daniel Anthony Howard*, Zheng Ma and Bo Nørregaard Jørgensen

From Energy Informatics.Academy Conference 2022 (EI.A 2022)
Vejle, Denmark. 24-25 August 2022

*Correspondence:
danho@mmmi.sdu.dk

SDU Center for Energy Informatics, The Maersk Mc-Kinney Moller Institute, University of Southern Denmark, 5230 Odense, Denmark

Abstract

To enable sound scientific research in future energy informatics projects, it is necessary to obtain an overview of the current state of the research field to identify unaddressed gaps and challenges. Therefore, this paper aims to investigate the research trends and achievements within energy informatics in a Danish context within the last three decades. This paper reviews 207 energy informatics projects collected until the second quarter of 2022. Quantitative analysis results show that most projects have focused on applying energy informatics through energy-aware control of end-user consumption. The qualitative review finds an emphasis on data usage and end-users which aligns with the quantitative review. Furthermore, it tends to focus on specific end-users, e.g., buildings and heat pumps. Four overall recommendations are established: (I) Increased emphasis on research for sector coupling to aid in unlocking energy system flexibility, (II) project data value chain output, focusing on structuring and managing the data to make it applicable for future re-use, (III) utilizing industrial loads and incorporating an end-user perspective, (IV) inclusion of research institutions for the improved overall output of the projects through interdisciplinary solutions.

Keywords: Danish, Energy informatics, Project review, Domain trends, Funding applications

Introduction

Innovation and research development are essential to the green transition (Tanev et al. 2010). To ensure independence from fossil fuels, almost all nations worldwide promote the continuous effort in research, development, and implementation of renewable energy sources driven energy technologies and solutions, such as some leading nations, e.g., Denmark and China (Qingnan Li 2016; Ma et al. 2015), and emerging nations, e.g., India and the Philippines (Ma et al. 2019; Billanes et al. 2018). To maintain the position as a global front runner in the green transition, governments must continuously set goals and laws to promote the development of advanced energy technologies and encourage and prepare the environment for promoting a significant adoption of green solutions (Ma et al. 2017a).

Furthermore, the leading nations in the green transition, like Denmark, face different challenges than others. For instance, with the high installed capacity of renewables, the Danish energy system is challenged by the intermittent nature of renewable energy sources leading to potential challenges in the security of supply. In order to mitigate the risk and challenges, there is a need for flexible consumers that can aid in balancing the electricity grid with digital systems at the core to support and automate decision-making (Ma et al. 2017b; Zheng Ma 2016). Information systems have been identified as a core component enabling cross-sectoral control and balancing necessary in a renewable energy system (Fridgen et al. 2020). Using digital technologies, mainly information and communication technology associated with energy, to provide added value through improved energy utilization and management is referred to as energy informatics.

With the radical information expansion currently happening, it can be challenging to realize an exhaustive state-of-the-art review due to the large body of combined publications and work. Therefore, narrowing down the information sources can aid in managing the quantity of information. Information services provided by government offices are an example of an organization that publishes information about the latest research (Walliman 2011). Examining nationally-funded research projects has previously been used to examine energy efficiency in a Chinese context (Du et al. 2018). Investigating the nationally funded projects in a pioneer country in the green transition, such as Denmark, provides valuable insights into the state-of-the-art in the context of the particular country that can be reflected in a global setting due to its pioneer status. Publicly funded Danish energy research projects provide an overview of the topics and challenges faced by the Danish energy system. Within the research projects, a sub-field relating to informatics will provide insight into energy informatics development and research trends.

However, no literature has provided a complete overview of national-funded energy informatics research. Furthermore, the current state of the research and future research directions in the field of energy informatics remains unclear, although energy informatics has been gaining more and more attention in the political agenda. Therefore, to fill this gap, this paper aims to provide an overview of the nationally-funded research project in the energy informatics domain. This paper uses Denmark as a case study since Denmark is a global front-runner in the green transition. Therefore, the findings of this paper may provide valuable insights for current and future research in energy informatics in combination with lessons learned for researchers and companies outside Denmark. Furthermore, this paper applies a scoping review with a quantitative and qualitative assessment to provide key insights into the research field's current and historical trends and challenges.

The structure of the paper is as follows: initially, the public database for previously funded energy research is reviewed, and available data is presented to key funding agencies. Subsequently, the projects are filtered to focus on energy informatics projects before being reviewed quantitatively and qualitatively. Based on the quantitative and qualitative review, key tendencies, gaps, and challenges are identified, providing a foundation for recommendations for future research in the energy informatics field in Denmark.

Background: energy sector and digitalization policy in Denmark

Examining the global emission of CO_2, it is evident that electricity and heat production is the predominant sector contributing to the emissions (International Energy Agency 2021). To combat climate change, there is an urgent need to transition electricity and heat production sources into renewable alternatives. A common denominator for renewable energy sources is the intermittent nature of the generation depending on external parameters, e.g., sun and wind. Denmark is the leading country incorporating renewable energy sources into the energy mix (Ministry of Foreign Affairs of Denmark: Pioneers in clean energy 2022). As evaluated by the World Energy Councils Trilemma Index, it has achieved high ranks in energy security, energy equity, and environmental sustainability. Examine the Eco-innovation index created by the European Commission to compare member states' performance in terms of environmental innovation. As of 2021, Denmark ranks fourth overall and first in the energy productivity indicator, which has remained since 2012. Denmark hence has a strong position related to research within energy which has aided it in its position as a global front-runner.

In a report on digitalization and energy by the International Energy Agency, it is expected that a 5% annual saving can be realized through digitalization in the power sector and upwards of 10–20% in other individual sectors. The Danish Digitalization Strategy from May 2022 was published by the Danish Ministry of Finance (Ministry of Finance 2022). The strategy presents nine central visions for digital development in Denmark, and vision six is using digital technologies to accelerate the green transition. Vision six is expected to aid in reducing greenhouse gas emissions by 15% and 10–30% of the greenhouse gas emissions directly from cities. In the Digital Economy and Society Index (DESI) from 2021, Denmark currently ranks first in the application of digital infrastructure. It hence has a strong foundation for the continuous development of a digital energy system.

Overview of public DANISH energy research funding

Danish public energy research funding is divided into several programs based on the funding organization. Currently, three main funding programs are: the Energy Technology Development and Demonstration Program (EUDP), ELFORSK, and Innovationsfonden. Several historical funding programs are stopped but still recorded in the database for publicly funded Danish energy projects, e.g., ForskEL, ForskVE, and the EU Rammeprogram.

Publicly funded Danish energy projects can be found on the website: https://energiforskning.dk/, which the Danish Energy Agency manages. The website contains information about current and past projects providing a central database for extracting information for Danish publicly funded energy projects. The information provided for the projects is described in Table 1.

Energy Technology Development and Demonstration Program (EUDP)

It is governed by the Danish Ministry of Climate, Energy, and Utilities. The program supports promising projects to aid Denmark in achieving its goal of 70% greenhouse gas emissions by 2030 and climate neutrality by 2050. The program was established in 2007

Table 1 Description of research project information

General information	
Project title	**The given title of the project**
Main responsible	The company or institute in charge of the project, possibly with the specific department specified
Project aim	A high-level short description of what the project aims to achieve
Project description	A detailed description of the project aims and goals and what challenges the project seeks to address. Sometimes a project-specific website is specified with more information
Key figures	
Project period	The project start and end year
Funding year	The year in which the project received funding
Self-financed amount	The amount in million DKK that is self-financed by the project partners
Funding amount	The amount of funding in million DKK that the project has received
Funding percentage	The percentage of funding received in comparison to the total budget
Project budget	The total budget for the project, including both the self-financed and publicly-funded contributions
Participants	
Partner	A list of the partners in the project combined with the funding received for the individual partner and the self-financed contribution per partner
Category	
Program	Which funding program provided the funding for the project, further explanation of the funding programs are given below
Project type	An optional category for the type of project, e.g., demonstration if the funded project focuses on the demonstration of a concept
Journal number	An ID number of the project
Contact	
Contact information	Detailed contact information to the contact person for the project often including name, phone number, email, and address
Miscellaneous	
Final report	If the project has finished and the final project report can be made publicly available, it can be collected from the site

Not all projects have a complete set of information corresponding to the information described in the table

and has since supported more than 1000 projects with combined funding of 5.7 billion DKK. EUDP considers itself technology-neutral and evaluates projects based on criteria, including innovation, climate, and commercialization potential. The EUDP is financed through the Finance Act and the Research Reserve. From the 2018 energy agreement, it was decided that a minimum of 500 million DKK per year should be allocated for the EUDP funding program (Danish Energy and Agency: About the EUDP 2022).

ELFORSK

It is governed by the Danish Ministry of Climate, Energy, and Utilities. It is managed by the distribution companies' interest organization Danish Energy (Green Power Denmark). The program was established in 2002 and contributed a yearly funding amount of 25 million DKK; the funding program specifies a requirement for partners to self-finance 50% of the project budget. The funding program states that it supports electrification and green transition of the Danish energy system using digitalization and sector coupling. ELFORSK specifies that it emphasizes the use of the project results and therefore focuses on the team composition and the involvement of relevant companies (ELFORSK: Om ELFORSK. 2022).

Innovation Fund Denmark

It is governed by the Danish Ministry of Higher Education and Science. It is further divided into several programs with a specific focus, e.g., InnoBooster. The program was established in 2014 and funds a wide variety of projects, including climate solutions, food, health care, transport, and start-ups. The program emphasizes its willingness to fund high-risk endeavors without a need for financial results. The program instead evaluates results on social welfare improvements, increased societal wealth, jobs, reduction of CO_2 emissions, cleaner environment etc. In 2021 the Innovation Fund invested 1.88 billion DKK, and 692 million DKK was pre-allocated for strategic research in carbon capture, green fuels, sustainable agriculture, and circular economy (Innovation Fund Denmark: About Innovation Fund Denmark 2022).

Green Labs DK

It is a part of EUDP and was re-established in 2018 to provide funding for large-scale demonstration projects that aims to provide leading test facilities. The funding program was re-established to promote the establishment of physical test facilities. The funding program appeals to supporting large-scale tests of renewable energy technologies with real-life actors, e.g., consumers, DSOs, and suppliers. Support for establishing large-scale test facilities is given for companies to test and validate how new technology performs under actual system behavior. Furthermore, the funding program emphasizes the possibility of enabling the test of data-driven technologies in a large-scale setup (Danish Energy and Agency: Green Labs DK 2022).

Methodology

To obtain an overview of the previously funded research projects in energy informatics, the overall workflow followed the four steps below:

1. Extract publicly funded research projects
2. Sort and filter projects relating to energy informatics
3. Conduct a quantitative and qualitative assessment of the projects
4. Evaluate trends, challenges, achievements, and gaps

After extracting the information presented in Table 1 for individual projects in the database, the collected projects were sorted based on selected keywords to find projects focusing on research within energy informatics. After filtering the research projects, a quantitative and qualitative assessment was performed to evaluate the trends, challenges, achievements, and gaps that can be observed. Lastly, recommendations for future research are provided based on the current gaps and challenges observed.

Project selection criteria

As the energy research project website categorizes projects based on their goals and objectives, the categories from which relevant projects should be extracted were selected. As several categories focus on developing specific technologies, e.g., wind, solar power, biofuels, hydro, etc., these categories were excluded. Thereby the remaining relevant categories for project extraction were:

- Energy efficiency
- Smart grid and systems
- Others

After collecting projects within the three categories, the projects should be filtered to only include projects relevant to energy informatics. To filter the projects, the projects were sorted based on keyword matches in the title or the project description.

The keywords used can be seen below:

- Cloud
- Data
- Digital
- Intelligent
- IoT

To ensure correct filtering, all words were compared on a lower-case basis to ensure that capitalization does not affect the final result. Note that all funding for Annex and IEA participation was excluded as these were not considered relevant for examining the conducted research within the field but rather a means of knowledge sharing among stakeholders. After extracting and filtering relevant projects, several quantitative parameters were examined to obtain an overview of the general funding project characteristics. The selected projects were examined in terms of project duration, funding agency, funding amount, and project partners.

A qualitative review of the project aims and challenges was done to support the quantitative examination of projects.

Results

The projects were collected in the second quarter of 2022. The collection and filtering process is outlined in Fig. 1. As can be seen in Fig. 1, an initial amount of projects of 1756 were collected, which were predominantly based on the energy efficiency category.

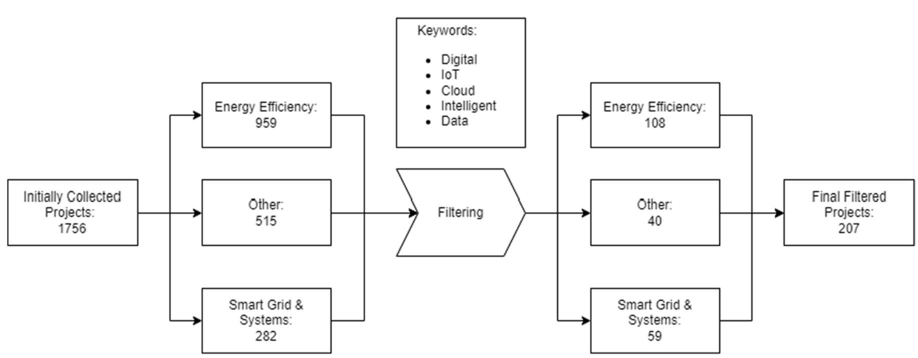

Fig. 1 Collection and filtering of energy projects

Through the subsequent filtering for energy informatics-related projects, the number of projects was further reduced to 207 total. The complete list of projects selected can be seen in the appendix.

As can be seen from Fig. 1, only approximately 11% of the energy efficiency-related projects met the filtering requirements, whereas approximately 21% of the smart grid and systems met the filtering requirement. The higher return from the smart grid and systems category shows a tendency for projects in said category to rely on energy informatics principles. Similarly, the energy efficiency category does not, to the same extent, rely on energy informatics principles but can be a result of improvements made to existing technology to improve the overall performance and hence energy efficiency.

The response to each of the selected keywords can be seen in Fig. 2. Note that the projects may respond to more than one keyword entailing the sum of keyword responses to exceed the number of returned projects. As seen from the keyword returns in Fig. 2, most projects mention data and intelligence as part of either their title or project description. Digital, IoT, and cloud are not as common. From Fig. 2, it can be seen that data and intelligence are often components used for energy informatics projects pointing toward using data for intelligent decision-making.

Quantitative review of energy informatics research projects

Descriptive statistics are used to understand the tendencies and characteristics of energy informatics projects. Initially, the number of funded energy informatics projects by year is examined as this provides an understanding of the general popularity and importance of the field. The number of energy informatics-related projects initiated per year can be seen in Fig. 3.

As seen in Fig. 3, there has been an increasing amount of energy informatics projects being funded. The earliest project was in 1996, with increasing yearly projects.

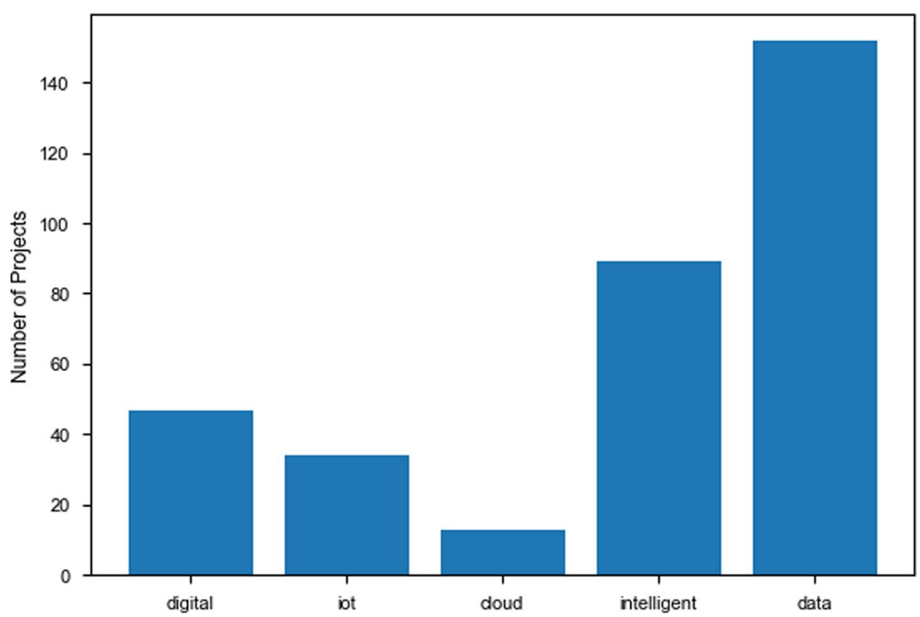

Fig. 2 Energy projects keyword hits

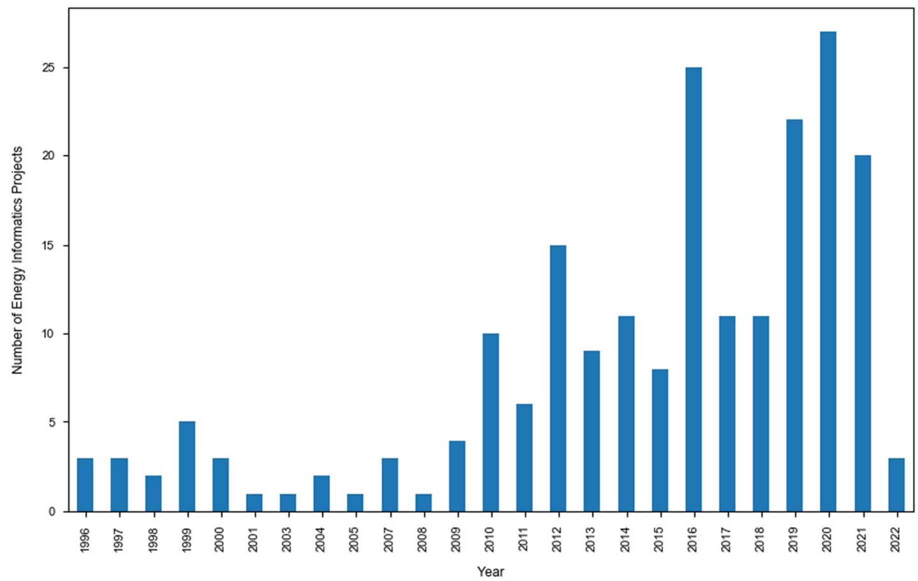

Fig. 3 Number of energy informatics projects started per year

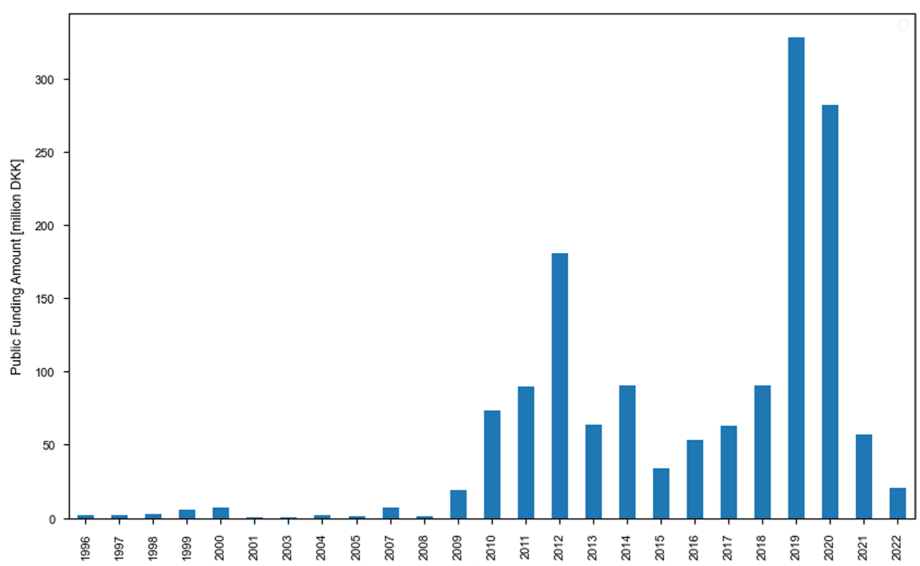

Fig. 4 Public funding given to energy informatics projects per year

Due to the data collection being conducted in the second quarter of 2022, 2022 does not contain all potential projects for that year and should not be compared to other complete years. To understand the funding provided for projects, the yearly public funding was summed, as seen in Fig. 4.

Examing the public funding given to energy informatics projects as seen in Fig. 4, since 2009, there has been a substantial increase in funding given to energy informatics projects. Note that the public funding only reflects projects that were actualized. Hence the funding amount does not correspond to general research interest but

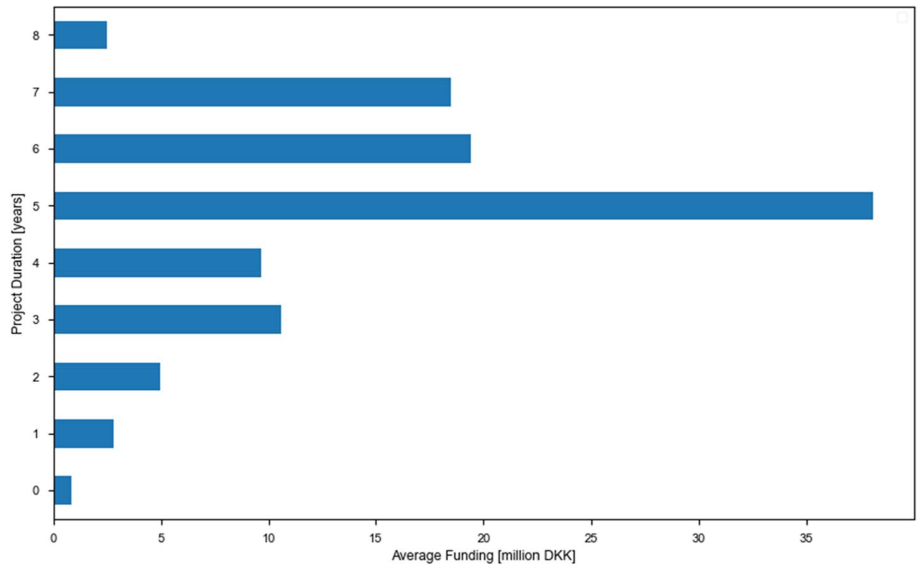

Fig. 5 Average project budget based on project duration

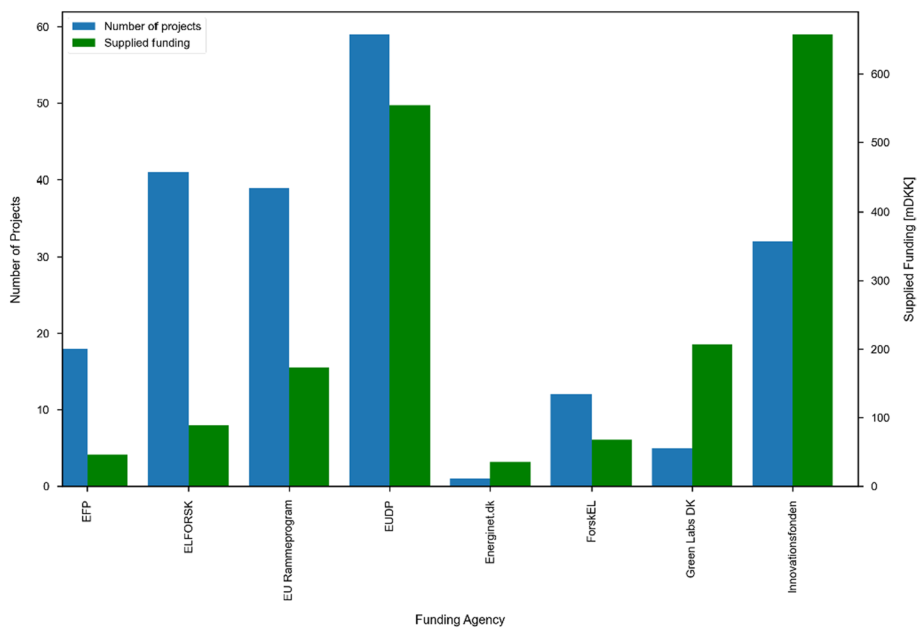

Fig. 6 Number of projects funded by each funding program and the supplied amount of funding

rather the ability of project applicants to receive funding from the funding agency. Examing the average funding based on the project duration can be seen in Fig. 5.

As seen from Fig. 6, there is an average increase in funding as the project duration increases, with a substantial increase once the project duration is five years. A project with a duration higher than five years diminishes the average funding, meaning that from an economic perspective, applying for funded projects in excess of five years may not be beneficial. Considering that five years may be challenging in terms of finding and holding project partners, three-year funding could be beneficial. To examine the source of funding, the related funding program should be reviewed, examining if any funding program has a higher likelyhood of providing funding than others. The number of projects funded by each funding agency can be seen in Fig. 6.

As observed in Fig. 6, the largest number of projects have been funded by the EUDP program. EFP, EU Rammeprogram, Energinet.dk, and ForskEL are historical funding programs that are no longer used. The EUDP shows to be the funding program with the highest number of funded energy informatics projects, whereas its subsidiary Green Labs DK has funded the least. The lower number of funded projects can result from the Green Labs DK program not being reinitiated before 2018 hence not having the same opportunity to fund projects. Furthermore, the Green Labs DK emphasizes funding for large-scale test facilities making the projects less common. Therefore, the average funding for a Green Labs DK project is also higher than a EUDP project. Figure 6, furthermore, shows that the Innovation Fund Denmark funds a significant amount of projects with higher average funding compared to EUDP. Examing the funded energy informatics projects and the typical project duration can aid in establishing the project's common time horizon. The typical duration of the energy informatics projects can be seen in Fig. 7.

As seen in Fig. 8, most projects are funded as three-year projects, with more than five years being uncommon. A few projects are funded within one year, i.e., started and ended in the same year. The number of projects being funded with a three duration is in line with the typical budget based on the duration seen in Fig. 5. As energy informatics is an inherently interdisciplinary field, the number of project partners involved is an essential parameter as knowledge-sharing among project partners is an important aspect of improving the value of the proposed solution. The number of project partners can be seen in Fig. 8.

As seen in Fig. 9, most projects have only a single project partner, i.e., a project conducted by a single company or institution. There is a decrease in the number of projects

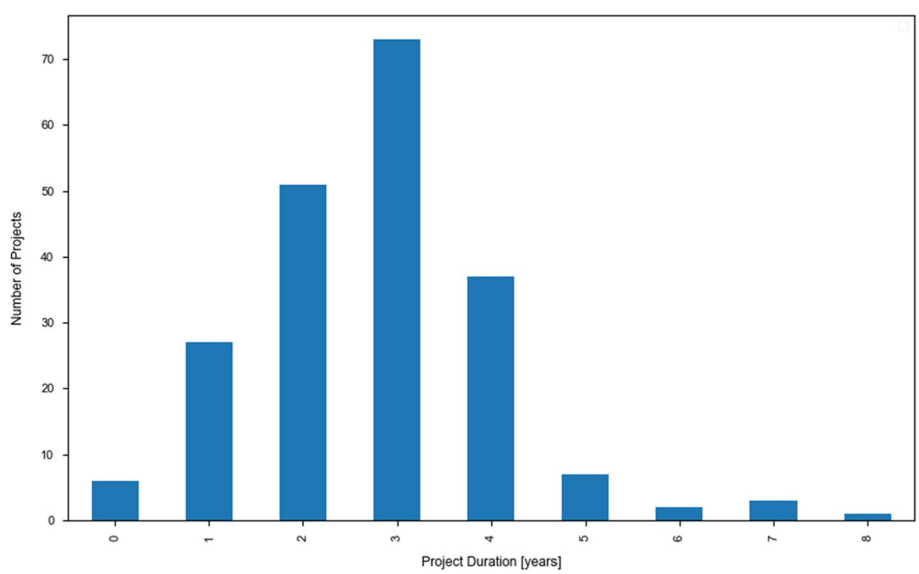

Fig. 7 Project duration for energy informatics projects

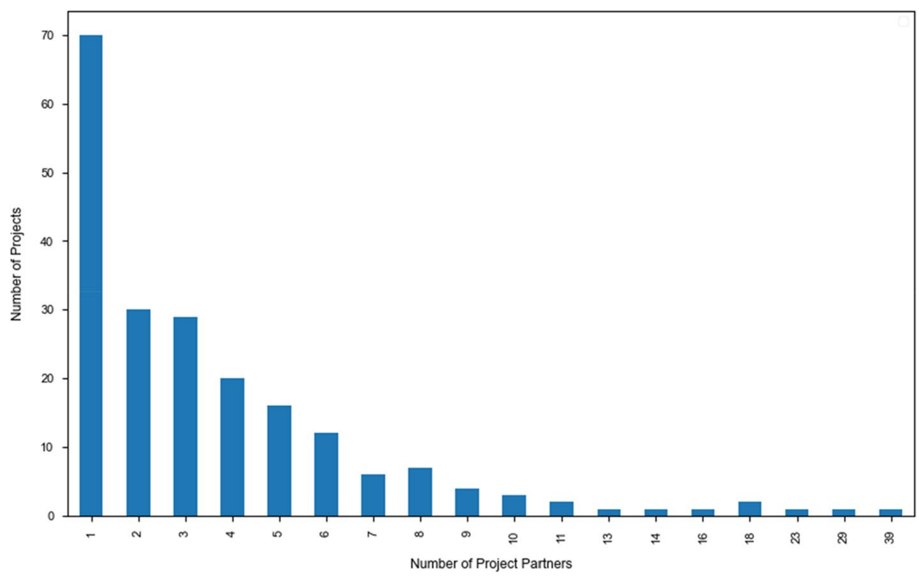

Fig. 8 Number of project partners for energy informatics projects

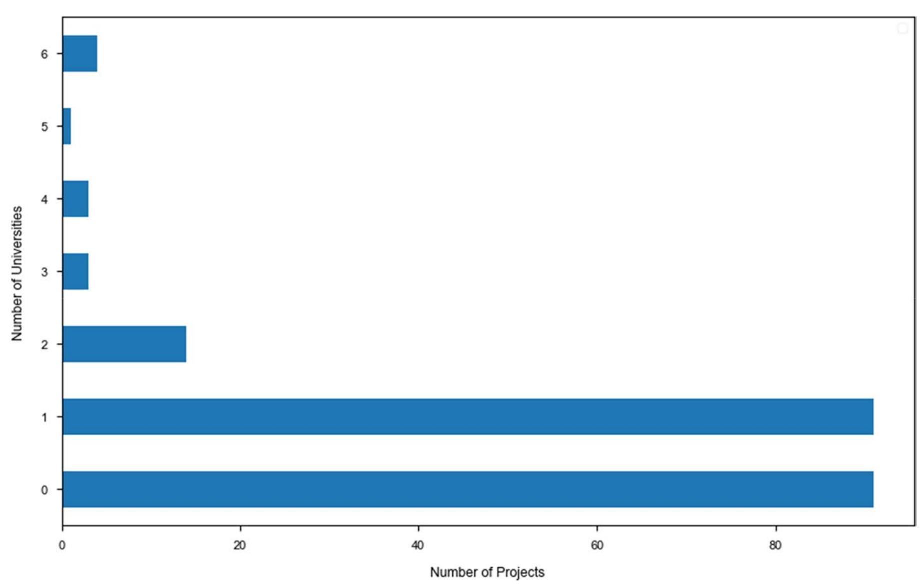

Fig. 9 Number of research institutions associated with a project

as the number of project partners increases, with the project having the most partners being 39 project partners. Having more than three project partners in a project is not as common. A low number of project partners can lead to problems in knowledge silos and lacking interdisciplinary aspects.

Research institutions serve as an essential project partner as they can aid in providing expert knowledge in the field, increasing the overall value of the projects. Examing if a project has at least one university partner, it could be established that 116 projects included a university project partner, and 91 projects did not include collaboration with a university. Hence, over half of the collected energy informatics projects include at least one university partner; however, there is also a substantial amount of projects not including university project partners. University project partners bring expertise and systematized research approaches to a project and can hence help lift the project's overall value. The inclusion of research institutions also aids in diminishing knowledge silos and repetitive projects and experiments as the universities publish results and methodologies.

As the projects with a university partner may include more than one, it was examined how many projects had multiple research institutions collaborating. The number of projects with the number of university project partners can be seen in Fig. 9. Note that the universities were grouped by set name, meaning unique entries were included, but if the university was included twice due to different institutes collaborating at the same university, this was included as two separate entries, i.e., two partners. The universities included a mix of Danish and foreign universities.

As seen in Fig. 9, most projects with a university partner only have a single university project partner. The highest number of university project partners is six, combining Danish and foreign universities. There is a benefit to including multiple research institutions as they often bring expert knowledge in different fields. Furthermore, working with multiple university project partners gives potential for research sparring and collaboration across institutions, which promotes the project's overall value and general research.

Energy informatics word clouds

A title-based world cloud was created to understand the trends and topics examined in Danish energy informatics projects, as seen in Fig. 10. Using the titles, the words should capture the main focus and aspects of the individual project. Some words were left out, primarily comparisons of popular words and word articles.

As seen from the word cloud in Fig. 10, a series of words have been used repeatedly throughout the energy informatics projects. In line with the response to keywords used in Fig. 2, there is a similar tendency where both intelligent and data are frequent keywords. Examining the use-case words, it can be seen that heat pumps, buildings,

Fig. 10 Combined project titles word cloud from all years

lighting, and ventilation are all frequently addressed topics. Energy optimization, consumption, and efficiency are addressed in the output words. The technology used for addressing the topics are control, data, and IoT, showing that a significant amount of use-cases for energy informatics thus far in the Danish context has been focused on the energy on the consumer side through improved control enabled by IoT sensors. As the word cloud presented in Fig. 10 represents all projects collected to examine changes in trends, the word cloud for a single year should be examined. Examining the word clouds for different years (2011 and 2021) provides an opportunity to examine the development of trends in the field within the last decade. The word cloud for 2011 can be seen in Fig. 11.

As seen in Fig. 11, the focus of energy informatics projects in 2011 was on buildings and control. The outputs showed to be energy efficiency, optimization, and electricity production. Examining the word cloud for projects started in 2021 can be seen in Fig. 12. From Fig. 12, it is evident that the focus of energy informatics has shifted, focusing on energy efficiency and optimization, with ventilation units, buildings, and heat pumps being high frequent application areas. The use of control is still commonly used but includes new technologies, e.g., digital twins and recommendation tools. Furthermore, the word flexibility appears in multiple forms, pointing towards that the energy informatics projects are becoming more concerned with enabling flexibility which aids the energy optimization and efficiency.

Qualitative review of energy informatics research projects

To obtain a comprehensive understanding of the aims and objectives of the collected projects, a qualitative review was performed using grounded theory to obtain a detailed understanding of the projects. The projects' key contributions and promised solutions were examined during the qualitative review. The review of the projects involved examining the projects from an energy and an informatics perspective. In the energy

Fig. 11 Word cloud for projects started in 2011

Fig. 12 Word cloud for projects started in 2021

perspective, the application area refers to the focus area of the energy value chain presented by Ugarte et al. (2015), where the end-consumer will be divided based on the category, i.e., domestic, commercial, industrial, and transportation or other specific use categories. Within the informatics area, the focus is described according to the data value chain described in Curry (2015). A complete table of the projects and value chain placement can be found in the appendix.

Data value chain placement

The data value chain can be divided into categories adapted from Curry (2015): data acquisition, data analysis, data curation, data storage, and data usage. Several projects fit into multiple categories, and the categories in which the projects focus their key contributions were selected, i.e., data storage may have been performed internally in the projects. However, unless stated in the output of the project description, it is not included.

Data acquisition Data acquisition focuses on gathering, filtering, and cleaning data before it can be used for subsequent data analysis and storage. Only a few projects emphasize the data acquisition of the data value chain. PowerLabDK started in 2012 with a combined project budget of 105 million DKK, making it the examined project with the third-highest project budget focusing on data acquisition through the development of smart grid components and systems within the electricity grid (Energiforskning.dk: PowerLabDK 2012). The project includes several facilities collectively connected through supervisory control and data acquisition system. The PowerLabDK provides a platform for simulating the electricity grid and providing a prognosis of system interruptions and ancillary services input. Another project examining large-scale, cost-efficient IoT solutions to improve energy efficiency of medium-large and large buildings focuses on developing a cloud solution for monitoring and diagnosing the building energy consumption and indoor climate (Energiforskning.dk 2020). A similar project titled Smart Green Indoor Climate Manager focuses on intelligent control of HVAC systems in combination with windows in single-family houses to achieve the desired indoor climate with improved energy efficiency (Energiforskning.dk: Smart Green Indoor Climate Manager 2021).

Data analysis The data analysis category focuses on using the raw data to explore and model possible relationships in datasets. Even though only a few projects fall into the data analysis stage, it is assumed that the predominant number of projects included it as a part of the final data usage phase. An early project from 1999 analyzed the energy consumption in terms of electricity and natural gas in domestic consumers (Energiforskning.dk 1999). In a recent project from 2021, data analysis was combined with 3D spectroscopi to identify Oil-in-Water when extracting oil from offshore oil reserves. The project serves as an initial examination of the possibilities before potentially using the data analysis results in a prototype setup in a real case.

Data curation Data curation in the data value chain represents the data management to ensure that the quality requirements are satisfied and that the data is trustworthy, discoverable, accessible, reusable, and fits its purpose (Curry 2015). In a 2021 project focusing on the preemptive maintenance of district heating grids, a tool for fault-detection is developed for improved operation and maintenance enabling a proactive strategy for maintenance. As a part of the tool development, automatic data validation and reconstruction are performed to curate the data for further use. In another project from 2021, titled Human-in-the-Loop digitalization and energy control of buildings, a software solution is developed to merge indoor climate control with user feedback for improved performance (Energiforskning.dk: Human-in-the-Loop 2021). As a part of the developed software solution, AI is used to ensure the quality of the building sensor data.

Data storage Data storage focuses on managing data in a scalable manner that enables and satisfies access requirements for relevant applications. The review of projects shows that attention to data storage in energy informatics projects has increased recently, with almost no projects actively addressing storage solutions before 2019. EnergyLab Nordhavn—New Urban Energy Infrastructure from 2015 seeks to provide new methods of balancing the energy system using Copenhagen Nordhavn as a sizeable living lab (Energiforskning.dk 2015). A large heat pump will be operated within the project to provide demand response for the electricity grid. Furthermore, the project is committed to establishing a data warehouse with integrated real-time data for the project activities to support the developed solutions' symbiosis and efficiency. A project building on similar concepts as EnergyLab Nordhavn is the CITIES—Centre for IT-Intelligent Energy Systems in Cities, which seeks to investigate the combined potential for flexibility (Energiforskning.dk: CITIES 2014). The CITIES project focused on developing and implementing models that could connect flexibility across power, heat, biomass, and gas sectors. As the title of the CITIES project suggests, the integration is primarily founded in the urban environment.

Flexible Energy Denmark FED seeks to unlock energy flexibility across the entire energy system through digitalization concepts (Energiforskning.dk: Flexible Energy

Denmark 2019). FED will establish a nationwide platform for integrating participating facilities to create new synergies across the energy sector. The integration of the facilities will be done through a central data lake that can support the creation of AI-driven solutions within the energy system. The FED was one of the reviewed projects covering multiple aspects of the data value chain and emphasizing data curation and usage.

Data usage The predominant amount of reviewed projects fall into the category relating to the application or usage phase of the data. It should be noted that the data usage phase includes the access to and analysis required to integrate the data in the specific activity.

The 2022 project REALISE focuses on developing a software solution that can aid in economically evaluating hybrid energy parks, e.g., wind and Power-to-X solutions. The software is aimed at providing investment decision support and achieving full potential for potential funding (Energiforskning.dk: REALISE 2022). Another 2022 project that utilizes data for energy efficiency is the project Driver Coach (Energiforskning.dk: EUDP 2022). The project aims at improving the fuel efficiency in the transportation sector through the Driver Coach system, which will provide the driver with suggestions and nudging for improved driving behavior. ACTION from 2020 seeks to develop state-of-the-art power converters that can be demonstrated in several electrical drive applications (Energiforskning.dk: ACTION 2020). ACTION seeks to unlock the flexibility potential available in electrical drives by implementing the power converter. The power converter will also support intelligent measurements that will allow the grid operator to access the components' real-time measurements. The Greenhouse Industry 4.0 project from 2019 is an industry-specific application of energy informatics for improving Danish greenhouse facilities' energy efficiency and flexibility (Energiforskning.dk: Væksthus industri 2019). The project couples digital twins in multiple aspects of the greenhouse to achieve a holistic view of production decisions and energy flexibility implications on the products.

Energy value chain placement

The energy value chain adapted from Ugarte et al. (2015) is categorized into fuels, generation, transmission, distribution, and end-user. The energy value chain represents the phases of the secondary energy of either gas, heat, or electricity.

Fuels Fuels cover the exploitation of primary energy types that can be used for subsequent energy generation. Generally, few energy informatics projects focus on the fuel aspect of the energy value chain. The few projects can be attributed to the projects focusing predominantly on improving the use of fossil fuels. The DAITORC project from 2019 focuses on developing a tool for characterizing underground reservoirs for geo-energy and storage (Energiforskning.dk: DAITORC 2019). Similarly, the project PSPA from 2014 focuses on developing and improving technology for locating oil reserves (Energiforskning.dk: PSPA 2022). The software developed in the PSPA projects aims to support geologists in obtaining an overview of the available geophysical data. Other projects in the fuel phase focused on developing technology for second-generation biofuels (Energiforskning.dk: FUEL4ME 2013; Energiforskning.dk: COMETHA 2014).

Generation Generation refers to the generation of secondary energy from the primary energy types found, e.g., in the fuels. The generation phase of the energy value chain is frequently addressed using energy informatics. The IPOWER project takes a market-based perspective. IPOWER focuses on the trading and market-clearing of available flexibility and increased focus on the interaction between the flexibility providers and consumers (Energiforskning.dk: IPOWER 2011). IPOWER hence aims at providing an increasingly intelligent mode of electricity production. RESPOND is a project that focuses on developing cooperative demand response solutions (Energiforskning.dk: RESPOND 2017). RESPOND will provide a means of optimizing the energy dispatch considering supply and demand. The project is set to work at the building and district level, which will be tested across different residential buildings in varying climate zones.

Transmission The transmission stage covers energy transport from the generation facility to the distribution system. Based on the collected projects, the transmission phase of the energy value chain was infrequently addressed. iTesla seeks to develop an interoperable toolbox for operating the pan-European electricity transmission network, emphasizing coordination and harmonization (Energiforskning.dk: iTesla. 2022). EDGE—Efficient Distribution of Green Energy developed an open-source simulation with fully-integrated control algorithms for coordinating the producers and consumers within the electricity grid (Energiforskning.dk: EDGE 2012). The Danish TSO Energinet uses the software package developed in the project to analyze the electricity grid's balance in response to fluctuating electricity prices.

Distribution The distribution stage covers energy transport from the transmission system to the end-user. The distribution phase is frequently addressed in energy informatics projects. The INTERPRETER project from 2019 seeks to develop ten software applications that provide a tool for grid operators with features lacking in the current grid management solutions (Energiforskning.dk: INTERPRETER 2019). INTERPRETER seeks to overcome some of the limitations of reverse power flows and grid stability issues. The limitations will be addressed through a modular grid management solution. The solution will be validated in three pilot studies in Belgium, Denmark, and Spain. The INTERPRETER project will have a particular focus on the distribution grid.

HEAT 4.0—Digitally supported Smart District Heating presents a sector-specific project for improving the operation of the future district heating system (Energiforskning.dk: HEAT 2018). HEAT 4.0 aims at developing a platform named HEATman, which will use digitalization within the district heating sector to achieve environmental improvements and increase the penetration of renewable energy sources. The knowledge from the previously described CITIES project was integrated into HEAT 4.0. The novelty of HEATman will be the ability of the district heating company to oversee its entire system. The overview will be supported by integrating relevant stakeholders within the district heating sector into the system, e.g., pipe producers and sensor providers.

End-user The end-user covers the final users of energy which can often be subdivided into domestic, commercial, and industrial applications. An end-user segment frequently addressed in energy informatics projects is energy in buildings. Green Lab for Energy Efficient Buildings (GLEEB) is one of the projects with the longest duration, spanning seven years (Energiforskning.dk: GLEEB 2011). GLEEB examines the use of energy components in buildings, i.e., ventilation systems, energy management, measurement, home appliances, etc. Combined, GLEEB provides a means of documentation and testing building energy consumption. The project enables savings across the buildings to reduce the overall energy consumption. Another project focusing on building energy demands is RE-VALUE: Value Creation by Energy Renovation, Refurbishment and Transformation of the Built Environment—Modelling and Validating of Utility and Architectural Value (Energiforskning.dk: RE-VALUE 2016). The RE-VALUE project proposes a model for assessing the influence of energy renovations on the occupants. The project included nine participants, including commercial facilities and housing associations. The novelty of RE-VALUE was considering occupant perception in addition to climate and economic factors. UserTEC—User Practices, Technologies, and Residential Energy Consumption is another project within the energy field in buildings (Energiforskning.dk: UserTEC 2013). Similar to RE-VALUE, UserTEC focuses on the occupants within the building. UserTEC recognizes that a significant potential for energy savings is not being realized due to incorrect usage. UserTEC aims to examine the types of occupants and categorize them to target new energy-saving technologies.

The FEEdBACk project started in 2017, also focuses on the consumers within the energy system (Energiforskning.dk: FEEdBACk 2017). The project aimed to develop solutions for incentivizing consumers in three groups: office, domestic, and schools. The consumers were located in different climate zones spread across Europe. The solution was proposed to provide gamification of the energy flexibility participation experience. Another project focusing on developing a product for industrial use is Electronic Systems Manufactured for Climate ELMAC (Energiforskning.dk: ELMAC 2018). The project focuses on developing a proactive- design-and-monitoring strategy to help industries adjust their product to climate-specific parameters. Essentially the project develops a risk prediction model that, through big data analytics, can perform predictive maintenance decisions. The product is aimed at industries with outdoor products.

Qualitative review summary

Using the projects identified in the energy value chain and data value chain respectively, the projects could be summarized in a Pivot table to examine the number of projects in each combination. The Pivot table can be seen in Table 2, note that the combined

Table 2 Pivot table of the project focus in the data and energy value chain

	Data acquisition	Data analysis	Data curation	Data storage	Data usage	Total
Fuels	3	5	3	0	3	14
Generation	5	5	1	5	16	32
Transmission	0	0	0	0	2	2
Distribution	1	0	7	2	20	30
End-user	13	15	13	20	118	179
Total	22	25	24	27	159	257

number of projects exceeds the collected number of projects due to some of the projects focusing on multiple aspects of either value chain.

As seen in Table 2, the qualitative review reveals a focus on the end-user segment and data usage in case-specific applications. The end-user category emphasized buildings, HVAC, cooling, lights, and heat pumps. Otherwise, the energy value chain stages generation and distribution phases are addressed in energy informatics projects. In the data value chain, a predominant number of projects focus on utilizing data for business activities. Ideally, data usage should cover the entire or parts of the data value chain which can explain the lower number of projects in the other data value chain phases.

Discussion

Based on the selected projects' quantitative and qualitative examination, some general tendencies and challenges could be observed, which should be addressed in future research. The tendencies revealed in the initial quantitative examination of projects could be confirmed and elaborated in the qualitative review. The predominant research projects focus on concrete case studies with energy informatics tailored to the specific application. Danish energy research has shifted the focus towards more data-driven solutions, and there is an emphasis on digitalizing the energy sector. It seems evident that most projects conducted within the energy research ecosystem are developed from an energy system and grid perspective (Ma et al. 2020), which is expected as the researchers often have a background within the energy field.

Future research may be beneficial to conduct the energy research from a consumer perspective in which the flexibility implications are considered (Billanes et al. 2017); most projects assume that the flexibility will be there without considering the discomfort induced to the provider. Generally, the inclusion of industrial energy flexibility has not been studied in detail by any of the reviewed projects besides specific case studies (Howard et al. 2021a; Howard et al. 2021c). Therefore, to enable large-scale use of industrial energy flexibility, it will be beneficial to develop a framework for evaluating the potential energy flexibility that can be supplied by industrial consumers based on their risk willingness (Værbak et al. 2019).

From a political point of view, it is essential to ensure that SMEs are digitalized and equipped with the necessary knowledge that can be achieved through close collaboration with universities (Ministry of Finance 2022). From a technical point of view, it is essential to transition the industry into industry 4.0 to provide an information basis for evaluating potential energy flexibility. Thereby, the industry can benefit from state-of-the-art technologies, e.g., Digital Twins, for performance optimization and what-if scenario testing (Howard et al. 2021b).

Specific technologies have been emphasized for energy informatics research, i.e., buildings, lights, ventilation, heat pumps, and cooling (Howard et al. 2020b). Energy informatics have generally seen use in terms of providing energy-aware control of the technology. Energy informatics have effectively aided in improving the performance of all of the technologies. Energy informatics have also seen application in the transportation sector, where the predominant focus has been on electric vehicles' intelligent charging and behavior (Ma et al. 2021; Fatras et al. 2021). Energy informatics have also been used in several district heating projects where the primary purpose is monitoring, fault detection, and diagnostics (Howard et al. 2020a). The electrical transmission and distribution grid have similar use of energy informatics.

Most of the reviewed projects emphasize the use and application of data in a specific case for, e.g., control. Applying data in a specific case enables the verification of the concept for the specific case; however, obtaining and using data for a specific case does not promote replicability and FAIR principles. In recent research, there has been increased attention to building and maintaining data lakes or warehouses with platforms providing a central access point. It is essential to strategize the handling of data before, during and after a project.

In several of the examined projects, similar datasets are being collected for different areas and actors in the energy system, which is redone every time a new project is started. Data lakes and warehouses should be emphasized to further the general research and utilize findings from previous projects. Data lakes or warehouses would allow users to test solutions on similar data sets to examine similarities and differences.

From a political point of view, the recent Danish Digital Energy Hub that was started in 2022 promotes data lakes. The Digital Energy Hub provides an innovative ecosystem in big data, AI, and IoT for energy in Denmark. Using a Data Lake-centered innovation ecosystem in the Digital Energy Hub is set to ensure coordination and synergy between stakeholders and provide the basis for enhanced innovation strength and competitiveness of Danish companies, primarily in the digital and energy sectors (Energy and Hub 2022). From a technical point of view, it will be necessary to ensure detailed metadata descriptions to properly utilize the data. Furthermore, considerations of anonymisation and pseudonymization should be handled as well as cyber security issues and redundancy.

Furthermore, increased attention should be put on the data curation and acquisition phases in which the data is collected, and the data quality is ensured to build a strong foundation for further data analysis and data usage. In, e.g., the industry, a significant proportion of energy informatics relevant data is not currently measured, stored, or difficult to access through third-party software; therefore, there is still a need for acquiring the data. The lack of attention to building strong data foundations for projects can possibly be attributed to the recent ample attention given to AI solutions focusing more on application.

From a political point of view, it is essential to consider the time and effort required for company personnel to extract and collect the data and emphasize digitalization's value. As a part of the Danish Digitalization Strategy, the program SMV:Digital was started to aid SMEs in digitalization. To promote strong data foundations, it could be beneficial for funding agencies to make funding applicants emphasize their contribution to the data value chain. From a technical point of view, there is a need to provide IoT solutions and establish the appropriate integrations. Lastly, industries should be aided in the identification of critical data points. Industries often collect data from a primarily operational perspective. However, the datasets required for building energy informatics projects may differ and not be actively collected or disregarded.

Based on the examined Danish energy research, it is evident that substantial time and effort have been assigned to the development of the energy system in order to make it ready for the inclusion of increasing amounts of renewable energy generation units and flexibility. However, it has become increasingly apparent in recent years that the focus has shifted towards the synergies and potential for consumers to act within the energy system. There is a clear tendency within the projects to pool available data in assigned access points that will enable the use of Big data analytics and AI to optimize the participating facilities' performance and provide a knowledge base for the inclusion of new participants. In the future, it is believed that it will be beneficial to coordinate data storage in a way that does not provide a fragmented approach where individual projects will all develop similar solutions leading to data siloes.

Sector coupling has been described as imperative for providing increased flexibility for renewable energy systems, enabling cross-sectoral control and balancing by energy informatics (Fridgen et al. 2020). There are only a few energy informatics-related projects targeting sector coupling in Danish energy research. As described by the Danish TSO, Energinet sector coupling is essential for achieving a flexible energy system that can support the continuous inclusion of renewables. Hence research using energy informatics for sector coupling should be emphasized in the future. From a political point of view, several Danish lighthouse projects have been established as a part of the REACT-EU project, where one has been set to focus on developing and demonstrating sector coupling solutions. From a technical point of view, there is a need to focus on application-based solutions that showcase and promote the possibilities of sector coupling. Within sector coupling, Power-to-X is a fundamental technology, and there is a technical need for investigating and identifying electricity market participation options for the identified Power-to-X processes.

Conclusion

This paper examines 207 energy informatics projects conducted with Danish public funding. The project information was extracted from the Danish research database for publicly funded research projects: www.energiforskning.dk in the second quarter of 2022. The selected projects were examined quantitatively and qualitatively.

Quantitatively, the number of research projects that have received public funding has increased continuously over the last decade with shifting research trends based on title word frequency analysis. The research trends have shifted from being dominated by the application areas of buildings and electricity generation broadening into additional application areas and increased emphasis on energy efficiency and optimization.

Qualitatively, the projects were reviewed according to their placement on the energy value chain and data value chain. Through the quantitative and qualitative review, key research trends and tendencies could be uncovered, providing a basis for future research recommendations. Based on the reviewed energy informatics projects, a series of bullet-points to summarize recommendations for future research could be established:

- Increased emphasis on research for sector coupling to aid in unlocking energy system flexibility and provide insights into the interactions and limitations between different technologies. E.g., Power-to-X opportunities have received attention as a possibility for dealing with excess wind power.
- Attention to the entire data value chain in projects. Outlining data strategies for projects before, during, and after to ensure that the data is appropriately managed.

Increased focus on the output of projects can be located in multiple phases of the data value chain related to the project, i.e., structuring and managing the data to make it applicable for future re-use. Applying the FAIR principles during the project is advised.

- The research should aim at utilizing the industrial loads and incorporating an end-user perspective. The research examined focuses heavily on buildings and domestic consumers. Furthermore, energy flexibility is often considered from a grid perspective and not a consumer perspective which is essential for unlocking flexibility. Lastly, the increased attention to sector coupling should possibly be extended to include industrial loads and renewable generation synergies.
- Including research institutions in projects can aid in combining expertise across fields, which can lead to improved overall output of the projects through interdisciplinary solutions, considered an inherent trait of energy informatics. Furthermore, a large proportion of projects only include a single research institution as a project partner, which should be increased and possibly include foreign research institutions to promote cross-collaboration between research institutions and further the overall field.

Appendix

Project title	Data category	Energy category
Fleksible borgerenergifællesskaber til øget vedvarende energi, FLEX-CEC	Data usage	Domestic Commercial Industrial
Intelligent laderegulator til køretøjer	Data usage	Transportation
REALISE: Datadrevet løsninger for design og investeringsstrategi af vedvarende energi parker	Data usage	Generation
ACTION	Data usage	Distribution
VPP4ISLANDS	Data usage	Distribution
Scaling the Solstroem carbon offsetting system: IOT connectivity, and security on the demand-side	Data storage	Generation
Smart fejlforudsigelse og lokalisering for distributionsnet	Data usage	Distribution
Udvikling af intelligent solar gadebelysning	Data usage	Commercial
INTERPRETER	Data usage	Generation Distribution
FLEXGRID	Data usage	Generation Distribution
PreHeat	Data usage	Domestic
PERFORM—Forbedring af geotermiske anlægs drift gennem fælles vidensopbygning og teknologiudvikling	Data storage	Generation
Smart citizen-centered local electricity to heat systems (SMARTCE2H)	Data usage	Domestic
Flerlags aggregatløsninger til at lette optimalt efterspørgselsrespons og gitter fleksibilitet	Data usage	End User
HEAT 4.0—Digitally supported Smart District Heating	Data usage	Distribution

Project title	Data category	Energy category
Flexible Energy Denmark FED	Data storage Data curation Data usage	End User
Cloud BMS	Data usage	Storage
Optimal spændingsregulering i mellemspændingsnettet	Data curation Data usage	Distribution
Analyser af elforbruget på time-niveau	Data usage	End User
GOFLEX	Data usage	Distribution
HotMaps	Data curation Data usage	Distribution
FlexReStore: Flexible Retail Stores	Data usage	Commercial
Security Assessment of Renewable Power Systems	Data usage	Industry
REMOTEGRID	Data curation Data usage	Distribution
CASH Pump—Intelligent styring og aggregering af varmepumper i små og mellemstore virksomheder	Data usage	Industry
HotMaps	Data curation Data usage	Distribution
HotMaps	Data curation Data usage	Distribution
SABINA	Data usage	Distribution
SmILES	Data storage	Storage
THERMOS	Data usage	Distribution
EConGrid	Data storage Data usage	End User
Dynamic topology data in distribution grids	Data storage	Distribution
TinyPower	Data usage	End User
SmarterEMC2	Data usage	End User
SUS—Green Lab for smart byudvikling og service	Data storage	End User
CITIES—Center for IT Intelligente Energi Systemer i Byer	Data usage	End User
PROAIN—Proaktiv integration af bæredygtig energi der muliggør aktive distributionsnet	Data curation Data usage	Distribution
GreenCom Top-UP	Data usage	Distribution
Nikola—Intelligent Electric Vehicle Integration	Data usage	Transportation
Smart Grid Open	Data acquistion	End User
iDClab—Intelligent DC Microgrid Living Lab	Data usage	Distribution
TotalFlex	Data usage	Generation End User
Consumer acceptance of intelligent charging	Data usage	Transportation
Styring, beskyttelse og fleksibelt elforbrug i LV-net	Data usage	Distribution
Integrering af husholdninger i det smarte elnet (IHSMAG)	Data acquistion	Domestic
Nabovarme baseret på jordvarme med intelligent styring	Data usage	Domestic
PRO-NET	Data usage	Distribution
EDGE—Effektiv distribution af vedvarende energi	Data storage	Distribution
PowerLabDK	Data acquistion Data usage	Generation
Intelligent opladning af elbiler	Data usage	Transportation
IPOWER—strategisk platform for innovation og forskning i intelligent elproduktion	Data storage Data usage	Generation

Project title	Data category	Energy category
Intelligent fjernstyring af individuelle varmepumper	Data usage	Domestic
Elforsyning som frekvensstyret reserve—implementering og praktisk demonstration	Data analysis Data usage	End User
PowerLabDK	Data acquisition Data storage	Generation
Udvikling af et sikkert, rentabelt og miljøvenligt moderne el-system	Data usage	Generation
Potentialeundersøgelse af intelligente energisystemer	Data storage	Industry
IT baseret driftoptimering af fjernvarmedistribution	Data usage	Distribution
SHAR-LLM	Data storage	End User
SmartEnCity	Data Curation	End User
Smart Green Indoor Climate Manager	Data aquistion Data usage	Buildings
Beslutningsstøttesoftware baseret på digitale tvillinger for energioptimering og drift af bygninger	Data storage Data usage	Buildings
Human-in-the-Loop, Digitalisering og energistyring af bygninger—HuiL-DEMand	Data curation Data usage	Buildings
Fjernvarme sensor energi	Data acquistion	Distribution
Ny IoT teknologi baseret på induktion i plejecentre	Data aquistion	Ventilation
Undersøgelse af besparingspotentialet ved bedre installation og indjusteringer af varmepumper, samt bedre finansiering af varmepumper	Data usage	Heat pumps
Smart Ready Building Control	Data usage	Buildings
Udvikling af en intelligent, energieffektiv og adaptiv styring til et varmepumpedrevet ventilationsanlæg	Data usage	Heat pumps
Internationale standarder for belysning, globale energibesparelser	Data storage	Light
Optimering af ventilationsanlægs energiforbrug med kunstig intelligens	Data usage	Commercial
Databaseret energioptimering i industrien	Data usage	Industry
Digitalt Orakel til Ultra-Lavtemperaturfrysere	Data analysis Data usage	Cooling
Energieffektiv aftenbelysning og dagslysstyring i forhold til geografisk orientering	Data usage	Light
EUDP 2021-II Driver Coach: Energieffektivisering af transport gennem nye on-board systemer til chauffører	Data usage	Transportation
Data-dreven smarte bygninger: data sandkasse og konkurrence	Data analysis Data usage	End User
Solcelledrevne IoT løsninger—Grøn IoT	Data usage	Light
Data i anvendelse: Energieffektiviseringer på baggrund af adfærdsrettet kommunikation ("Diana")	Data acquisition Data usage	Buildings
Effektiv datadrevet idriftsættelse og funktionsanalyse fokuseret på energi og indeklima	Data analysis Data usage	Buildings

Project title	Data category	Energy category
Test af energifællesskaber i praksis på to større boligbebyggelser til fremme af fleksibilitet og elbesparelser i slutforbruget	Data analysis Data usage	Domestic
Kompakt termokemisk opbevaring til boligvarmesystemer, der bruger grøn elektricitet	Data usage	Domestic
Energieffektiv intelligent HVLS ventilator (High Volume Low Speed)	Data usage	Ventilation
Intelligent energieffektiv procesventilation	Data usage	Ventilation
Energieffektiv Programmering af Kollaborative Robotter	Data usage	End User
Udvikling af hurtigt regulerende varmepumper ved anvendelse dynamiske modeller	Data usage	Heat pumps
LED-lys som IoT-infrastruktur for bygninger og industrielle anvendelser	Data Storage Data usage	Light
EASY-E—Nem energi-effektivitet gjort tilgængelig for industrien via termisk topologiopti-mering	Data usage	Industry
HESTIA	Data analyis Data usage	Generation End User
Cool-Data Flexible Cooling of Data Centers	Data usage	End User
Intelligent Energistyring (Timebaseret elpris og Solcellestyring kombineret)	Data usage	End User
Autonome overvågning af begroning på skibe, vejen til en mere energieffektiv skibsfart	Data usage	Transportation
Omkostningseffektive stor skala IoT-løsninger til energieffektivisering af mellemstore og store bygninger	Data acquisition Data storage Data usage	Buildings
Prædiktiv og Proaktiv Vedligeholdelse af Fjernvarmesystemer	Data curation Data usage	Distribution
Nem Databaseret Energiledelse	Data usage	Industry
Fjernvarme Tilstandskontrol til Asset Management	Data usage	Distribution
Cirkulær LED-energi—intelligent genanvendelse af energioverskud i belysningen	Data usage	Lights
Digital twins for large-scale heat pumps and refrigeration systems	Data usage	End User
Forbedret drift af varmesystemer i bygninger i flere etager for at realisere lave temperaturer i fjernvarmenet	Data usage	Buildings
Datadrevne energieksperter som skabere at øget energieffektivitet bygningssektoren	Data storage Data usage	Buildings
Smart4RES	Data usage	Generation
ComBioTES	Data usage	Storage
Minimering af CO2-aftryk ved intelligent styring af fleksibelt elforbrug	Data usage	End User
Udvikling af CO2 baseret luft til luft varmepumpe til tørringssystem i fødevareindustrien	Data usage	Industry Heat pumps
KVS—Kombinerede ventilationsprincipper og -strategier for IAQ	Data storage	Ventilation
Next practice—smarte kommunale data	Data acquisition	Buildings

Project title	Data category	Energy category
IoT baseret intelligent tilstandskontrol og styring af HVAC	Data usage	Ventilation
Væksthus industri 4.0	Data analysis Data storage Data usage	Industry
Tilstandsbaseret servicekoncept for ventilationsanlæg baseret på IoT drifts- og energidata	Data usage	Ventilation
IoT-baseret dataopsamling til bedre bygningsdrift og –design	Data acquisition Data storage	Buildings
iVENT 2020—Intelligent energieffektiv decentral ventilation af etageejen-domme	Data usage	Ventilation
Udvikling af større luft/vand varme-pumper med naturligt kølemiddel	Data usage	Heat pumps
Intelligent varmestyring til element-produktion	Data usage	Industry
REWARDHeat	Data usage	End User
iCeiling—intelligent køle og varmeloft med energilagring: Hybrid ventilation, køling og opvarmning med decentral varmepumpe, energilagring og intel-ligent styring	Data usage	Ventilation
Electronic Systems Manufactured for Climate ELMAC	Data usage	Industry
Automatisk datagenkendelse og informationsfeedback til SMV	Data usage	Industry
Intelligent styring af energioptim-erede laboratorier	Data usage	End User
RESPOND	Data analysis Data usage	End User
BlueGrid—Fleksibel energiudnyttelse i spildevandsforsyningen ved fuld systemintegration	Data usage	Industry
Integrerede løsninger til dagslys og kunstlys	Data curation	Light
Fremtidens Ventilationsanlæg	Data usage	Ventilation
FEEdBACk	Data usage	Commercial Domestic
Intelligent udsugning til energieffektiv boligventilation	Data usage	Ventilation
Energibesparende JensenLED Smart-Tube i intelligente løsninger	Data acquisition Data analysis	Light
Intelligent Energistyring i Mindre Boligblokke	Data usage	Buildings
SmartHeat	Data usage	Storage
RE-VALUE: Værdiskabende ener-girenovering og transformation af det bebyggede miljø—Modellering og validering af arkitektonisk og brugsværdi	Data curation Data analysis	Buildings
Smøreoliebesparelser i store 2-takts dieselmotorer gennem feedback regulering	Data usage	Transportation
A + E:3D—Digitalt værktøj for arkitek-tonisk energioptimering og -renover-ing i de tidlige designfaser	Data usage	Buildings
Kosteffektiv intelligent lysstyring for enkel implementering af dynamisk lys og optimering af energiforbrug	Data usage	Light

Project title	Data category	Energy category
SAVE-E Energibesparelser: Hvordan reduceres adfærdsmæssige, økonomiske og strukturelle barrierer for samfundsmæssigt attraktive energibesparelser og -effektivisering	Data usage	End User
multEE	Data storage	End User
COMBI	Data acquisition Data analysis	End User
HYPERCOOL	Data usage	Cooling
A + E:3D—digitalt værktøj til arkitektonisk energioptimering og -renovering i de tidlige designfaser—fase 2.1, Renovering	Data usage	Buildings
Kompakt, Intelligent, Kraftfuld Elektrisk Drivlinje til elektriske køretøjer	Data usage	Transportation
Kombineret dagslys og intelligent LED belysning—få dagslys ind i bygningerne—tillægsbevilling	Data usage	Light
Energieffektiv mælkekøling med intelligent styring	Data usage	Cooling
Energibesparelser via spændingsregulering	Data usage	Domestic
UserTEC—Brugerpraksis, teknologi og boligers energiforbrug	Data acquisition + Data curation	Buildings
A + E:3D—digitalt værktøj til arkitektonisk energioptimering tidligt i designfasen af bygninger, fase 2	Data usage	Buildings
Modellering og simulering af intelligente facader	Data usage	Buildings
Intelligent soldreven LED-belysning	Data usage	Light
Intelligent styring af dynamisk LED-belysning	Data usage	Light
Green Lab for energieffektive bygninger (GLEEB)	Data storage Data curation	Buildings
Energieffektiv Intelligent Gadelampe	Data usage	Light
Kombineret dagslys og intelligent LED belysning—få dagslys ind i bygningerne	Data usage	Light
A + E:3D—digitalt værktøj til arkitektonisk energioptimering tidligt i design fasen af bygninger, version 1.0	Data usage	Buildings
EnergyFlexHouse family: Intelligente energiydelser i lavenergiboliger baseret på brugerdreven innovation	Data usage	Domestic
PCM concrete—bedre indeklima og mindre energiforbrug	Data curation	Buildings
Den intelligente faresti	Data usage	Industry
Dansk højkvalitetsdesign med intelligent LED lys	Data curation	Light
Den intelligente gasmåler	Data acquisition	Domestic Industrial
ARKITEKTUR og ENERGI—kravspecifikation til digitalt værktøj for energioptimering tidligt i designprocessen	Data storage	Buildings
Avanceret styring af intelligente facader—Syddansk Universitet/Forskerpark	Data usage	Buildings
Udvikling af integrerede modeller for multifunktionelle facader	Data usage	Buildings
Energibesparelser på renseanlæg ved integreret optimering	Data usage	Industry

Project title	Data category	Energy category
Energioptimal styring og overvågning af køleanlæg	Data usage	Cooling
Energibesparende lyddæmper-koncept	Data curation	Transportation
Generisk værktøj til energioptimering af røggasrensningsanlæg	Data usage	Industry
Reduktion af energiforbruget til skoleventilation	Data curation	Ventilation
Referencedata for bygningsdeles livstidsenergiforbrug og emissioner	Data acquisition Data storage	Buildings
Teknologi-afklaring vedrørende styrbar afbryder	Data usage	End User
Intelligente VVS-komponenter til forbedret energieffektivitet	Data usage	End User
Opgørelse af energirelaterede miljøpåvirkninger ved renovering	Data acquisition Data curation Data usage	Buildings
ODYSSEE-MURE	Data storage	End User
PEAKapp	Data usage	End User
PremiumLight_Pro	Data usage	Light
REEEM	Data acquisition Data analysis	Generation
Laboratorie for hurtigladning	Data curation	Transportation
DREAMS Digitally supported Environmental Assessment for Sustainable Development Goals (SDGs)	Data usage	Generation
SATO	Data storage Data analysis Data usage	Buildings
ROROGREEN Green RORO shipping through digital innovation	Data usage	Transportation
Kontrol af Olie-i-vand vha 3D Spektroskopi	Data analysis	Fuel
Intelligent styring af ventilation og køl på containerskibe	Data usage	Ventilation Cooling
Kontrolmetoder og komponenter for osmotisk saltkraft og barske miljøer	Data usage	Generation
iGLEEB—Intelligente bygningsinstallationer og decentrale integrerede energisystemer	Data usage	Buildings
Udvikling og Demonstration af Avanceret Inversionsteknologi for Optimeret Reservoirkarakterisering—DAITORC	Data usage	Fuel
AURES II	Data curation	Generation
Digital Energy Lab	Data storage Data usage Data analysis	Generation
MOBISTYLE	Data usage	End User
RePower	Data usage	Buildings
RePower	Data usage	Buildings
progRESsHEAT	Data usage	Generation
Digital Factory	Data usage	Industry
Probabilistic Seismic Prospect Assessment—PSPA	Data analysis Data usage	Fuel
ALPBES—Avanceret estimering og forudsigelse af levetid for batterier	Data analysis	Storage
COMPETT—Competitive Electric Town Transport	Data acquisition Data usage	Transportation
SELECT—Suitability of ELEctromobility for Commercial Transport (A)	Data usage	Transportation
FUEL4ME	Data curation	Fuel
Performance Plus	Data usage	Generation

Project title	Data category	Energy category
COMETHA	Data curation	Fuel
TRANSFORM	Data analysis Data usage	End User
Databaser til formidling af projekter støttet af de danske energiprogrammer	Data usage	End User
iTESLA	Data usage	Transmission
BioREC—Bioteknologi i olieindvinding	Data curation	Fuel
Det geotermiske energipotentiale i Danmark—reservoiregenskaber, temperaturfordeling og modeller for udnyttelse	Data analysis Data usage	Generation
Samspillet mellem regulering, bilvalg og bilernes energiforbrug	Data usage	Transportation
Marsvin ved Horns Rev—service og datalog af PODs	Data acquisition	Generation
Forsyningssikkerhed for det største vandkraftpotentiale i Vestgrønland, Imersuaq (FORSYN)	Data acquistion Data analysis	Generation
Reguleringen af det liberaliserede elmarked	Data usage	Transmission
Inspektion af off-shore gasledninger for tildækning og frie spænd	Data acquistion Data analysis	Fuel
Husholdningernes energiforbrug—dataanalyse	Data analysis	Domestic
Tildækningsgris—inspektion af gasledninger	Data acquistion Data analysis	Fuel
Analyseaktiviteter og data vedr. husholdningers energiforbrug	Data analysis	Domestic
Projekt Palæogen Sydvestgrønland	Data usage	Fuel
Bestemmelse af mætningsfunktioner	Data acquisition Data analysis	Fuel
ENERFUND	Data usage	Buildings
HRE	Data usage	Generation

Abbreviation

EUDP Energy Technology Development and Demonstration Program

Acknowledgements

Not applicable.

About this supplement

This article has been published as part of *Energy Informatics Volume 5 Supplement 4, 2022: Proceedings of the Energy Informatics.Academy Conference 2022 (EI.A 2022)*. The full contents of the supplement are available online at https://energyinformatics.springeropen.com/articles/supplements/volume-5-supplement-4.

Author contributions

DAH analyzed and interpreted the data, and conducted the first draft of the manuscript. ZM and BNJ reviewed and edited the manuscript. All authors read and approved the final manuscript.

Funding

This project is part of the project "IEA IETS Annex Task XVIII—Digitization, artificial intelligence and related technologies for energy efficiency and reduction of greenhouse gas emissions in industry" funded by EUDP (Case no.134-21010).

Availability of data and materials

Data on projects available from: https://energiforskning.dk/projekter

Declarations

Ethics approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

Competing interests

The authors declare that they have no competing interests.

Published: 21 December 2022

References

Billanes JD, Ma Z, Jørgensen BN (2017) Consumer central energy flexibility in office buildings. J Energy Power Eng. 2017(11):621–630. https://doi.org/10.17265/1934-8975/2017.10.001
Billanes JD, Ma Z, Jørgensen BN (2018) The Bright Green Hospitals—case studies of hospitals' energy efficiency and flexibility in Philippines. International Conference on Power and Energy Systems. Colombo, Sri Lanka: IEEE
Curry E (2015) The big data value chain: definitions, concepts, and theoretical approaches. In: Cavanillas J, Curry E, Wahlster W (eds) New horizons for a data-driven economy. Springer, Cham. https://doi.org/10.1007/978-3-319-21569-3_3.
Danish Energy Agency: About the EUDP (2022a) https://www.eudp.dk/en/om-eudp. Accessed 21 Jun 2022
Danish Energy Agency: Green Labs DK—søg tilskud (2022b). https://www.eudp.dk/green-labs-dk-soeg-tilskud. Accessed 21 Jun 2022
Digital Energy Hub: Partner- og medlemskab i Digital Energy Hub (2022) https://www.digitalenergyhub.com/da/partnere-og-medlemmer/. Accessed 04 Aug 2022
Du M, Wang B, Zhang N (2018) National research funding and energy efficiency: evidence from the National Science Foundation of China. Energy Policy 120:335–346. https://doi.org/10.1016/j.enpol.2018.05.058
ELFORSK: Om ELFORSK (2022) https://elforsk.dk/om-elforsk. Accessed 21 Jun 2022
Energiforskning.dk: Husholdningernes energiforbrug—dataanalyse (1999) https://energiforskning.dk/projekter/husholdningernes-energiforbrug-dataanalyse. Accessed 27–06 2022
Energiforskning.dk: Green Lab for energieffektive bygninger (GLEEB) (2011) https://energiforskning.dk/projekter/green-lab-energieffektive-bygninger-gleeb. Accessed 21 Jun 2022
Energiforskning.dk: IPOWER—strategisk platform for innovation og forskning i intelligent elproduktion (2011) https://energiforskning.dk/projekter/ipower-strategisk-platform-innovation-forskning-intelligent-elproduktion. Accessed 21 Jun 2022
Energiforskning.dk: EDGE—Effektiv distribution af vedvarende energi (2012) https://energiforskning.dk/projekter/edge-effektiv-distribution-vedvarende-energi. Accessed 21 Jun 2022
Energiforskning.dk: PowerLabDK (2012) https://energiforskning.dk/projekter/powerlabdk-0. Accessed 21 Jun 2022
Energiforskning.dk: FUEL4ME (2013) https://energiforskning.dk/projekter/fuel4me. Accessed 27 Jun 2022
Energiforskning.dk: UserTEC—Brugerpraksis, teknologi og boligers energiforbrug (2013) https://energiforskning.dk/projekter/usertec-brugerpraksis-teknologi-boligers-energiforbrug. Accessed 21 Jun 2022
Energiforskning.dk: CITIES—Center for IT Intelligente Energi Systemer i Byer (2014) https://energiforskning.dk/projekter/cities-center-it-intelligente-energi-systemer-byer. Accessed 21 Jun 2022
Energiforskning.dk: COMETHA (2014) https://energiforskning.dk/projekter/cometha. Accessed 27 Jun 2022
Energiforskning.dk: EnergyLab Nordhavn—nye energiinfrastrukturer i byer (2015) https://energiforskning.dk/projekter/energylab-nordhavn-nye-energiinfrastrukturer-byer. Accessed 21 Jun 2022
Energiforskning.dk: RE-VALUE: Værdiskabende energirenovering og transformation af det bebyggede miljø—modellering og validering af arkitektonisk og brugsværdi (2016) https://energiforskning.dk/projekter/re-value-vaerdiskabende-energirenovering-transformation-bebyggede-miljoe-modellering. Accessed 22 Jun 2022
Energiforskning.dk: FEEdBACk (2017) https://energiforskning.dk/projekter/feedback. Accessed 25 Jun 2022
Energiforskning.dk: RESPOND (2017) https://energiforskning.dk/projekter/respond. Accessed 20 Jun 2022
Energiforskning.dk: Electronic Systems Manufactured for Climate ELMAC (2018) https://energiforskning.dk/projekter/electronic-systems-manufactured-climate-elmac. Accessed 21 Jun 2022
Energiforskning.dk: HEAT 4.0—Digitally supported Smart District Heating (2018) https://energiforskning.dk/projekter/heat-40-digitally-supported-smart-district-heating. Accessed 27 Jun 2022
Energiforskning.dk: Udvikling og Demonstration af Avanceret Inversionsteknologi for Optimeret Reservoirkarakterisering—DAITORC (2019) https://energiforskning.dk/projekter/udvikling-demonstration-avanceret-inversionsteknologi-optimeret-reservoirkarakterisering. Accessed 27 Jun 2022
Energiforskning.dk: Flexible Energy Denmark FED (2019) https://energiforskning.dk/projekter/flexible-energy-denmark-fed. Accessed 21 Jun 2022
Energiforskning.dk: INTERPRETER (2019) https://energiforskning.dk/projekter/interpreter. Accessed 21 Jun 2022
Energiforskning.dk: Væksthus industri 4.0 (2019) https://energiforskning.dk/projekter/vaeksthus-industri-40. Accessed 21 Jun 2022
Energiforskning.dk: ACTION (2020) https://energiforskning.dk/projekter/action. Accessed 21 Jun 2022
Energiforskning.dk: Omkostningseffektive stor skala IoT-løsninger til energieffektivisering af mellemstore og store bygninger (2020) https://energiforskning.dk/projekter/omkostningseffektive-stor-skala-iot-loesninger-til-energieffektivisering-mellemstore. Accessed 21 Jun 2022
Energiforskning.dk: Human-in-the-Loop, digitalisering og energistyring af bygninger—HuiL-DEMand (2021) https://energiforskning.dk/projekter/human-in-the-loop-digitalisering-energistyring-bygninger-huil-demand. Accessed 27 Jun 2022
Energiforskning.dk: Smart Green Indoor Climate Manager (2021) https://energiforskning.dk/projekter/smart-green-indoor-climate-manager. Accessed 27 Jun 2022

Energiforskning.dk: EUDP 2021-II Driver Coach: Energieffektivisering af transport gennem nye on-board systemer til chaufføer (2022) https://energiforskning.dk/projekter/eudp-2021-ii-driver-coach-energieffektivisering-transport-gennem-nye-on-board-systemer. Accessed 27 Jun 2022
Energiforskning.dk: iTesla (2022) https://energiforskning.dk/projekter/itesla. Accessed 27 Jun 2022
Energiforskning.dk: Probabilistic Seismic Prospect Assessment—PSPA (2022) https://energiforskning.dk/projekter/probabilistic-seismic-prospect-assessment-pspa. Accessed 27 Jun 2022
Energiforskning.dk: REALISE: Datadrevet løsninger for design og investeringsstrategi af vedvarende energi parker (2022) https://energiforskning.dk/projekter/realise-datadrevet-loesninger-design-investeringsstrategi-vedvarende-energi-parker. Accessed 27 Jun 2022.
Fatras N, Ma Z, Jørgensen BN (2021) System architecture modelling framework applied to the integration of electric vehicles in the grid. Springer International Publishing, Cham, pp 205–209
Fridgen G, Keller R, Körner M-F, Schöpf M (2020) A holistic view on sector coupling. Energy Policy. https://doi.org/10.1016/j.enpol.2020.111913
Howard DA, Filonenko K, Busk FS, Veje C (2020a) Methodology for evaluation of district heating network efficiency. E3S Web of Conferences. 186. https://doi.org/10.1051/e3sconf/202018601006
Howard D, Ma Z, Engvang J, Hagenau M, Jørgensen K, Olesen J, et al (2020b) Optimization of energy flexibility in cooling process for brewery fermentation with multi-agent simulation. 6th IEEJ International Workshop on Sensing, Actuation, Motion Control, and Optimization. Shibaura Institute of Technology, Tokyo, Japan
Howard DA, Ma Z, Veje C, Clausen A, Aaslyng JM, Jørgensen BN (2021c) Greenhouse industry 4.0—digital twin technology for commercial greenhouses. Energy Inform 4(Suppl 2):37. https://doi.org/10.1186/s42162-021-00161-9
Howard DA, Ma Z, Jørgensen BN (2021a) Evaluation of industrial energy flexibility potential: a scoping review
Howard DA, Ma Z, Jørgensen BN (2021b) Digital twin framework for energy efficient greenhouse industry 4.0. In: Novais P, Vercelli G, Larriba-Pey JL, Herrera F, Chamoso P (Eds) Ambient intelligence—software and applications. Cham: Springer International Publishing; p. 293–7
Innovation Fund Denmark: About Innovation Fund Denmark (2022) https://innovationsfonden.dk/en/about-innovation-fund-denmark. Accessed 03 Jul 2022
International Energy Agency (2021) Global Energy Review: CO2 Emissions in 2021
Ma Z, Christensen K, Jorgensen BN (2021) Business ecosystem architecture development: a case study of electric vehicle home charging. Energy Inform 4:37. https://doi.org/10.1186/s42162-021-00142-y
Ma Z, Asmussen A, Jørgensen BN (2015) Industrial consumers' acceptance to the smart grid solutions: Case studies from Denmark. Smart Grid Technologies—Asia (ISGT ASIA), 2015 IEEE Innovative2015. p. 1–6
Ma Z, Billanes JD, Jørgensen BN (2017a) A business ecosystem driven market analysis: the bright green building market potential. 2017 IEEE Technology & Engineering Management Conference (TEMSCON)2017. p. 79–85
Ma Z, Friis HTA, Mostrup CG, Jørgensen BN (2017b) Energy Flexibility Potential of Industrial Processes in the Regulating Power Market. The 6th International Conference on Smart Cities and Green ICT Systems2017. p. 109–15
Ma Z, Broe M, Fischer A, Sφrensen TB, Frederiksen MV, Jφergensen BN (2019) Ecosystem thinking: creating microgrid solutions for reliable power supply in India's Power System. 2019 1st Global Power, Energy and Communication Conference (GPECOM)2019. p. 392–7
Ma Z, Værbak M, Jørgensen BN (2020) Multi-agent simulation of households' behaviors towards hourly electricity price scheme in Denmark. 2020 IEEE/SICE International Symposium on System Integration (SII)2020. p. 1081–7
Ministry of Finance (2022) Danmarks digitaliseringsstrategi
Ministry of Foreign Affairs of Denmark: pioneers in clean energy (2022) https://denmark.dk/innovation-and-design/clean-energy. Accessed 21 Jun 2022
Qingnan Li ZM, Jørgensen BN (2016) Discussion on China's power sector reforms and where to next? The 13th European Energy Market Conference, EEM 2016. Porto, Portugal
Tanev S, Thomsen MS, Ma Z (2020) Value co-creation: from an emerging paradigm to the next practices of innovation. The 3rd ISPIM Innovation Symposium. Quebec, Canada
Ugarte S, Larkin J, Ree B, Swinkels V, Voogt M, Friedrichsen N, et al (2015) Energy storage: which market designs and regulatory incentives are needed?
Værbak M, Ma Z, Christensen K, Demazeau Y, Jørgensen BN (2019) Agent-based modelling of demand-side flexibility adoption in reservoir pumping. 2019 IEEE Sciences and Humanities International Research Conference (SHIRCON)2019. p. 1–4
Walliman N (2011) Research methods: the basics: 2nd edition (1st ed.). Routledge. https://doi.org/10.4324/9780203836071
Zheng Ma BNJ (2016) Energy flexibility of the commercial greenhouse growers: the potential and benefits of participating in the electricity market. IEEE International Conference on Sustainable Energy Technologies (ICSET 2016). Hanoi, Vietnam: IEEE

Publisher's Note