MAIN RESULTS FROM THE FLEXIBLE ENERGY DENMARK PROJECT 2019-2023

Results obtained in FED

1. Data hub & data lake

1.1 Established Center Denmark as a leading Data Space for Energy (and Water)

Center Denmark is established as a national data hub for smart energy systems (maybe also water) supported by AAU, AU, SDU and DTU - and some of the major energy systems stakeholders.

Center Denmark is now a European EDIH, more precisely 'SEDIH – Smart Energy Digital Innovation Hub'. Furthermore, Center Denmark plays a central role in the new European Test and Experimental Facility for Smart Cities and Communities (CitCom.ai), and Denmark is leading the Nordic Super Node centered around Data Spaces for Power in Europe.

Center Denmark is now involved in national and European research and innovation projects. The projects are all focusing on operating a European Data Space for Energy (and Water) Systems, and the total budget for these is around 130 mill Euros (has to be verified).

The Data Space at Center Denmark is mentioned in several international reports:

- The EU Commission: Data Spaces for Energy, Home and Mobility (Oct 2022)
- Danish Energy Agency: Digitalization Related to Energy Consumption in Buildings (January 2023)
- IEA: A Data Sharing Guideline for Buildings and HVAC System (March 2023)

1.2 Creation of FEDDL as a Danish National Energy Data Lake

The FED Data Lake (FEDDL) has been built to handle huge amounts of energy data from different sources (ranging from private consumers over companies to energy network operators) in the Danish society. FEDDL enables efficient and advanced analysis of the data. It is built to scale, and it uses only open-source technology. FEDDL is thus a foundation for collecting and sharing all types of energy-related data in Denmark to allow AI and machine learning tools to combine, analyze, and predict energy data for the purpose of optimizing the flexible use of renewable energy.

Some of the work behind FEDDL has been described in Hamadou, H. B., Pedersen, T. B., & Thomsen, C. (2020, December). The Danish National Energy Data Lake: requirements, technical architecture, and tool selection. In *2020 IEEE International Conference on Big Data (Big Data)* (pp. 1523-1532). IEEE.

1.3 Work towards On-Demand Cube Exposure of Data in Data Lakes

Cubes are a very popular tool for data analysis. They make it easy to select relevant data and group it at the right level of detail. Traditionally, significant efforts are, however, first spent on cleansing data and specifying hierarchies before a cube can be defined. In a data lake setting, new datasets are easily and often added, but the data is not cleansed, and hierarchies are not defined on beforehand. Work has been done towards making it possible to use cube operations directly on big data sets in a data lake without requiring cleansing or definition of hierarchies on beforehand. A cube will thus be made on-demand and it can then, if needed, be gradually refined. This will be possible via the Python programming language which is very popular among data scientists. It will thus be easy for data scientists to use this and integrate with their existing solutions. Work has been done to define the needed constructs and a prototype is being developed. The work will later be presented in a paper.

1.4 Work towards Privacy-Aware OLAP Querying in Data Lakes

Datasets in the FED Data Lake can contain personal data and different users should be allowed to see different things: External users should never be able to see personal data; Living Lab managers should be able to see data from their own Living Lab, but not personal data from other Living Labs; and finally authorized researchers should be allowed access to the full datasets. Work towards a system that ensures this has been started. A dataset is said to be *k-anonymous* if data related to each individual cannot be distinguished from data from at least *k-1* other individuals. With the proposed system, users have *roles* with permissions to see k-anonymous data for a given k for a given dataset. If a query result does not fulfil the allowed k-anonymity, the query is automatically rewritten. For example, an external user could issue a query about total energy consumption per hour per address. The result of this query will, however, be about individual households (i.e., k=1) and thus contain personal data. The query will therefore be rewritten, e.g., into a query about total energy consumption per hour per street where data about one household cannot be differentiated from data about other households on the same street. Work has been done to formally define how this rewriting should be done. It will later be presented in a paper.

2. Market and grid tools

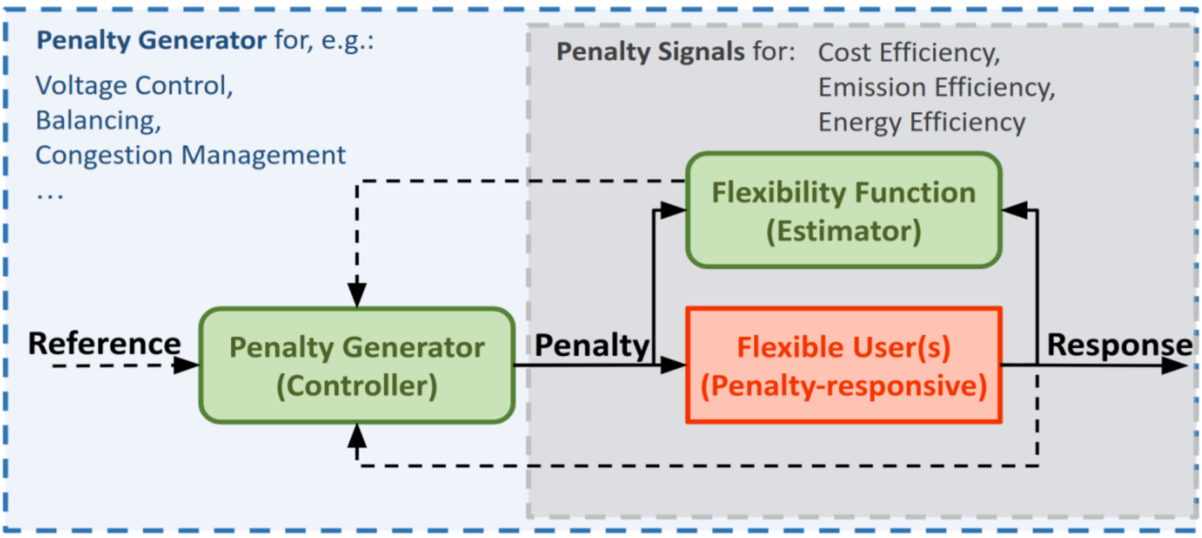
2. 1 Methods for TSO and DSO coordination and grid services

The Smart Energy Operating System (Smart Energy OS) is established as a Data Space designed around a hierarchy of data handling with associated technical and governance rules that aim to ensure coherence across all relevant aggregation levels (wholesale energy markets, transmission networks, distribution networks, and end-use consumers), with a focus on providing solutions on multi-objective criteria like energy efficiency and flexibility. The Smart Energy OS includes a hierarchy of controllers that are able to utilise the flexibility at the building, district and community levels to solve grid related issues for both the TSO and the DSO.

The Smart Energy OS is analogous to an operating-system for a personal computer; guiding fundamental workflows, as well as information, between various hierarchies of the energy system. It utilises 'Minimum Interoperability Mechanisms' (MIMs) as a common and interoperable set of information requirements that ensure that necessary data is accessible between stakeholders.

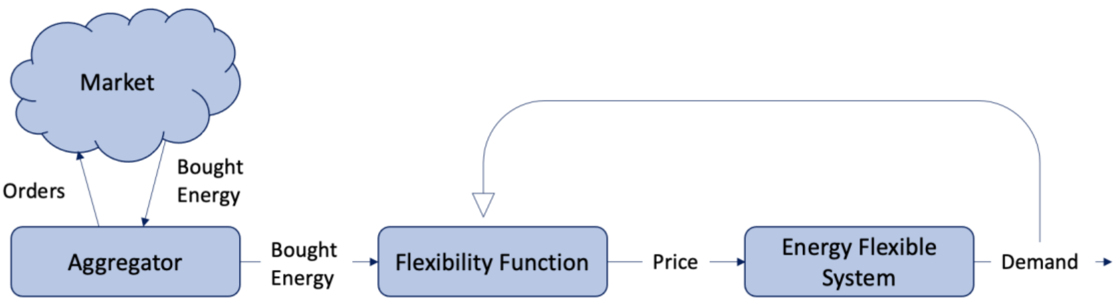
The Smart Energy OS and the Flexibility Function concepts are also mentioned in e.g., the following reports:

- The EU Commission: Data Spaces for Energy, Home and Mobility (Oct 2022)
- Danish Energy Agency: Digitalization Related to Energy Consumption in Buildings (January 2023)
- IEA: A Data Sharing Guideline for Buildings and HVAC System (March 2023)



2. 2 Methods for BRPs and Aggregators; How to link markets with the physics

Solutions for the fundamental question: 'Where does the physics stop and the markets begin?' has been suggested. This is facilitated by the Flexibility Functions (as also described above), and the methods can be used by retailers and aggregators to optimize the used of green power and to minimize the costs for the end-users. See the figure below.



The method has been demonstrated in a number of research papers.

2. 3 Methods for improved wind power (and PV) forecasting.

We consider reconciliation of wind power forecasts in a spatial hierarchy with three aggregation levels. We produce base forecasts for the bottom level consisting of 407 substations (connection points for local groups of wind turbines) in Jutland and Funen.

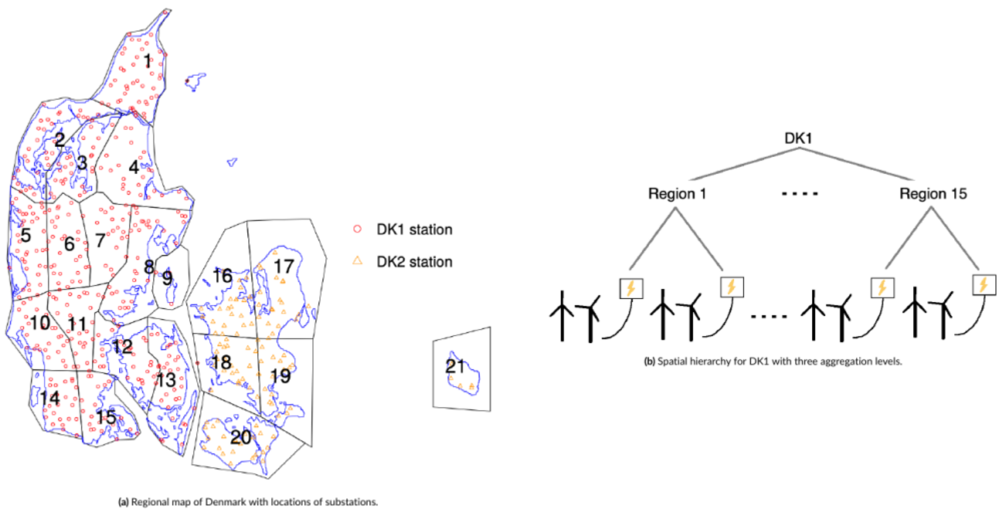


FIGURE 1 (a) Map of Denmark showing the locations of the individual power substations and regions. (b) Illustration of the spatial hierarchy for the western price area DK1 with 15 regions at the middle level and 407 individual substations at the bottom level.

State-of-the-art forecasts from a commercial forecast provider are available for the middle and top levels, which consist of 15 regions and the entire Western Denmark (DK1), respectively. We find that the accuracy of the total forecast can be improved through spatial reconciliation, even with a relatively simple model used at the lowest level of the hierarchy. Computing the base forecasts for the substations using wind speed as the only predictor, the RMSE of the DK1 forecast is reduced by 20.5 pct.

This setup of wind and solar power forecasting ensures a coherency between forecasts seen by eg. BRPs, DSOs and the TSO.

The wind power forecasts are important input for developed state-of-the-art methods for electricity price forecasting. The forecasts are used in the Novasol Demo Site in FED.

2. 4 Integrating Distributed Flexibility in the Power System's Operation

The future of power systems is envisioned to be largely based on renewable generation and distributed flexibility. Yet, integrating existing distributed flexibility into the systems' operational decisions poses a major challenge, given the diversity of consumers' modeling frameworks and controllers. Moreover, in such a system, the operational decisions need to be predictive, multi-stage, as well as TSO-DSO coordinated. In this paper, we consider a generic, grey-box consumer model that can forecast (or schedule) a consumer's consumption profile as a function of pricing signals, and use this model to integrate small consumers massively into a distributed policy for the power system's operational decisions. The consumer model is generic enough to accommodate any type of consumer, while the proposed policy inherently coordinates Transmission and Distribution System

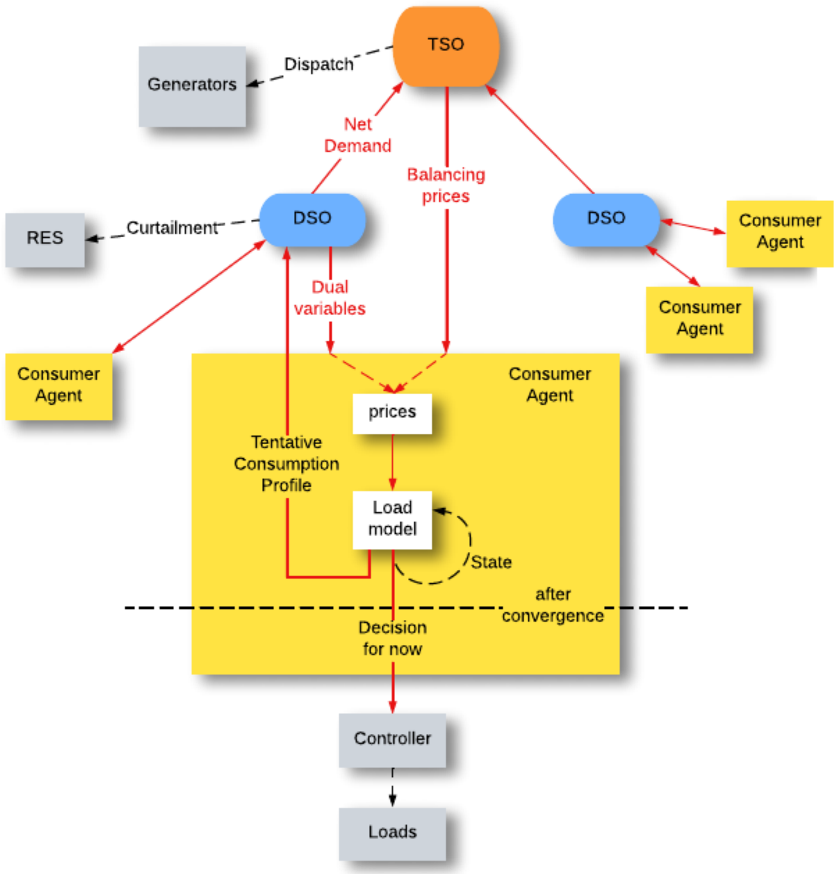


Fig. 2: Schematic diagram of the information exchange and decision process

Operators' decisions in the presence of uncertain distributed flexibility and renewables' generation. The results demonstrate promising convergence properties and short execution times, which is encouraging towards the scheme's practical applicability.

2. 5 Optimal design of DSO networks related to Energy Communities with PV generation and battery storage systems.

This work is carried out in a collaboration with Danish Energy (Dansk Energi).

An extensive study of Renewable Energy Communities (ECs) and their potential impact on the electric distribution grid has been carried out. For that purpose, an optimization model sizing the EC's Photo-Voltaic (PV) and Battery Energy Storage System (BESS) was developed. The model was soft coupled with power flow analysis to investigate the impact of different EC configurations on distribution grids. Different distribution grids (city, urban, village), different EC configuration, different operating strategies and different battery placements were investigated. The results showed that when the grid topology is taken into account when choosing the battery placement, then the EC does not impact the observed minimum and maximum voltage. Moreover, it was found that depending on the EC's operating strategy the *LV grid loading can be reduced by 58 %*. The EC's sizing showed that optimal capacities of PVs and communal batteries were up to three times larger for the case of city grid, following the operating strategy of maximizing the EC's own economic benefit than in other operating strategies and grid layouts.

The following paper is submitted to Applied Energy:

Renewable Energy Communities: Optimal sizing and distribution grid impact of PV and battery storage

3. Long-term energy systems planning considering flexibility potentials

3.1 Clustering and flexibility for Long-Term Energy Planning

In the FED project we aim at generating the information needed for long-term planning while taking into account the estimated long-term flexibility potential. This calls for new methods for a clustering of primarily the commercial and industrial load patterns.

In future power systems, consumers will become a significant source of flexibility. In order to analyse consumers' long-term flexibility potential and improve forecasts of the future hourly load profile, methods for load clustering and patterns tracking their evolution over time are required. In this paper, we propose a clustering methodology that accounts for heterogeneity in consumers' loads in a setting of unsupervised learning. The study considers hourly load measurements from 9412 smart-meters of the Danish commercial and industrial sector. A wavelet transformation is proposed to min-max scaled load data, where the extracted wavelet coefficients are used as input to the K-means clustering algorithm. Through cluster validation, eight clearly distinct load profiles are identified and compared with the industry classification of the cluster constituents. Moreover, the flexibility potential is estimated for each cluster.

The results related to this work will be published in a paper entitled:

Clustering Commercial and Industrial Load Patterns for Long-Term Energy Planning

3. 2 Capturing flexibility for batteries using the FlexOffer model

To solve the problems caused by the intermittent generation of Renewable Energy Sources, the concept of energy flexibility is of utmost importance, and batteries are devices with high potential in this regard. However, current exact mathematical models specifying battery flexibility cannot scale (exponentially growing runtime) with long time horizons and many batteries. The FlexOffer model has been proposed for this purpose, because: 1) it is a general model, capturing all types of flexible assets in a unified format and 2) being approximate, it scales very well in terms of number of devices and time horizons. It has been shown that FlexOffers retain most of the flexibility, while vastly outperforming exact models in optimization and aggregation speed.

This research is described in greater detail in the paper *Capturing Battery Flexibility in a General and Scalable Way Using the FlexOffer Model*, presented in the *SmartGridComm 2021* conference.

3. 3 Modeling uncertainty within the FlexOffer model

As the usage of Renewable Energy Sources in electricity grids increases in popularity, energy flexibility has a crucial role. The most common weaknesses of current flexibility models are: i) being hard-coded for specific devices, ii) not scaling for long time horizons and many devices, iii) losing a lot of flexibility if the model is approximated, and iv) not considering the uncertainty affecting flexibility representations, which causes the model to capture too much excess flexibility when imbalance penalties are high. The FlexOffer model can perform approximations of flexibility with good accuracy across different devices, and scales well to long time horizons and many devices. In order to consider uncertainty, FlexOffer has been extended to a new model, Uncertain FlexOffer, which keeps the good properties while capturing uncertainty. It has been shown that Uncertain FlexOffers vastly outperform exact models in terms of optimization speed and scalability for many devices and longtime horizons, while retaining almost all of the available flexibility.

A short overview of this research can be found in the poster *Uncertain FlexOffers: a scalable, uncertainty-aware model for energy flexibility*, presented at the conference *ACM e-Energy 2022*, and a more detailed description will appear in the paper with the same name, which will be presented at the conference *ACM e-Energy 2023*.

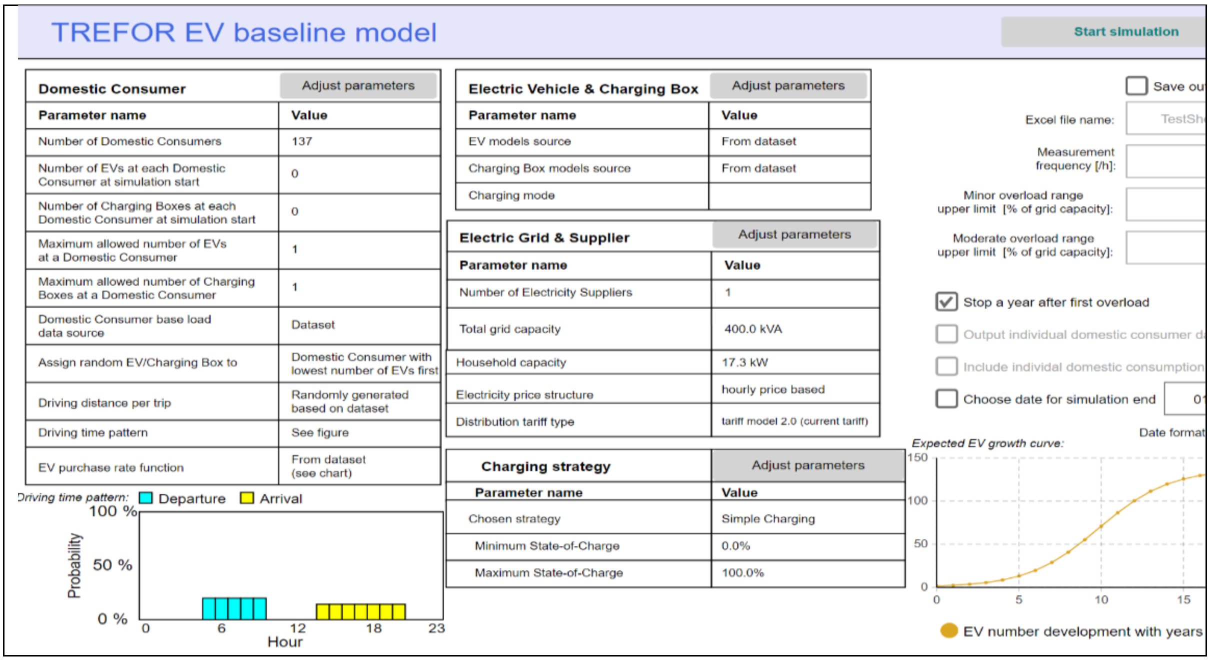
4. Energy Ecosystems

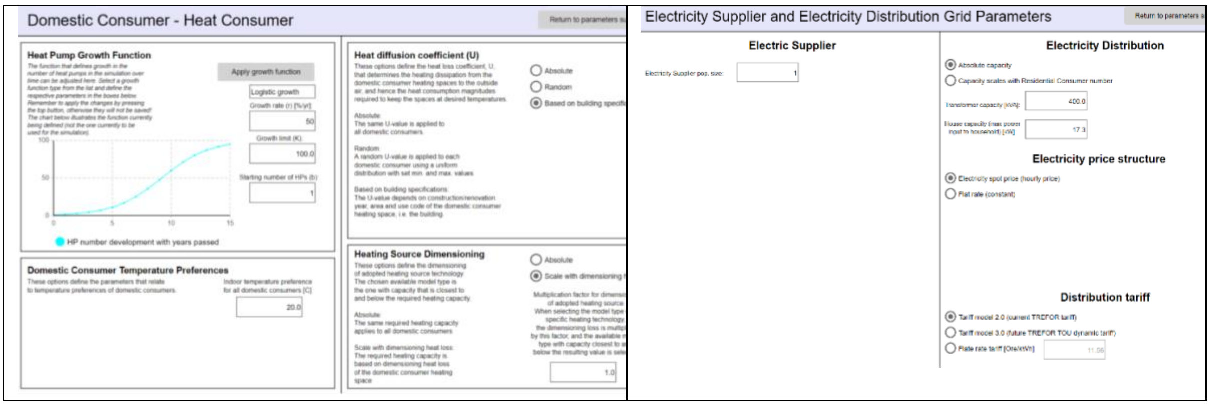
4. 1 Energy Ecosystem Digital Twin Platform

Built on Trefor's Living Lab, the Energy Ecosystem Digital Twin Platform was developed to simulate energy ecosystems, assess the implementation of data-driven smart energy solutions and business models, and analyze the outcomes of these decisions. This platform is employed to evaluate a range of business models for providing the value propositions available from Energy Flexibility Solutions, as well as to study the grid load capacity with respect to substation temperature and analyze the effect of dynamic DSO tariffs.

The Energy Ecosystem Digital Twin Platform includes a variety of distribution grid topologies, components and DERs such as EVs, PVs, batteries and heat pumps. This platform also incorporates consumer behaviour models and DER operations strategies, dynamic distribution tariffs, and electricity prices. It is used to evaluate the performance of various DERs, and the impact of their deployment and operation strategies on the grid, particularly EV charging strategies.

The related publication is:
Ma, Z. Energy Metaverse: a virtual living lab of the energy ecosystem. Energy Inform 6, 3 (2023). https://doi.org/10.1186/s42162-023-00258-3





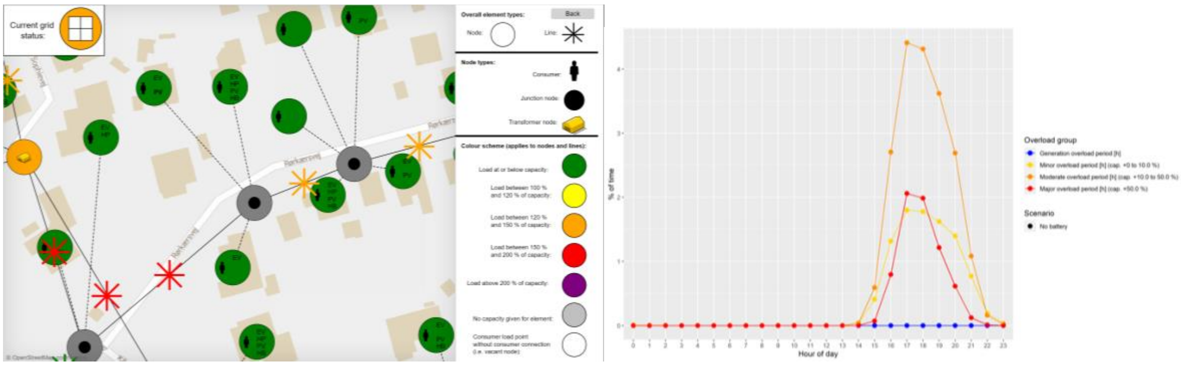
4. 2 DERInGrid: an agent-based simulation tool for power grid state estimation and analysis with distributed energy resources

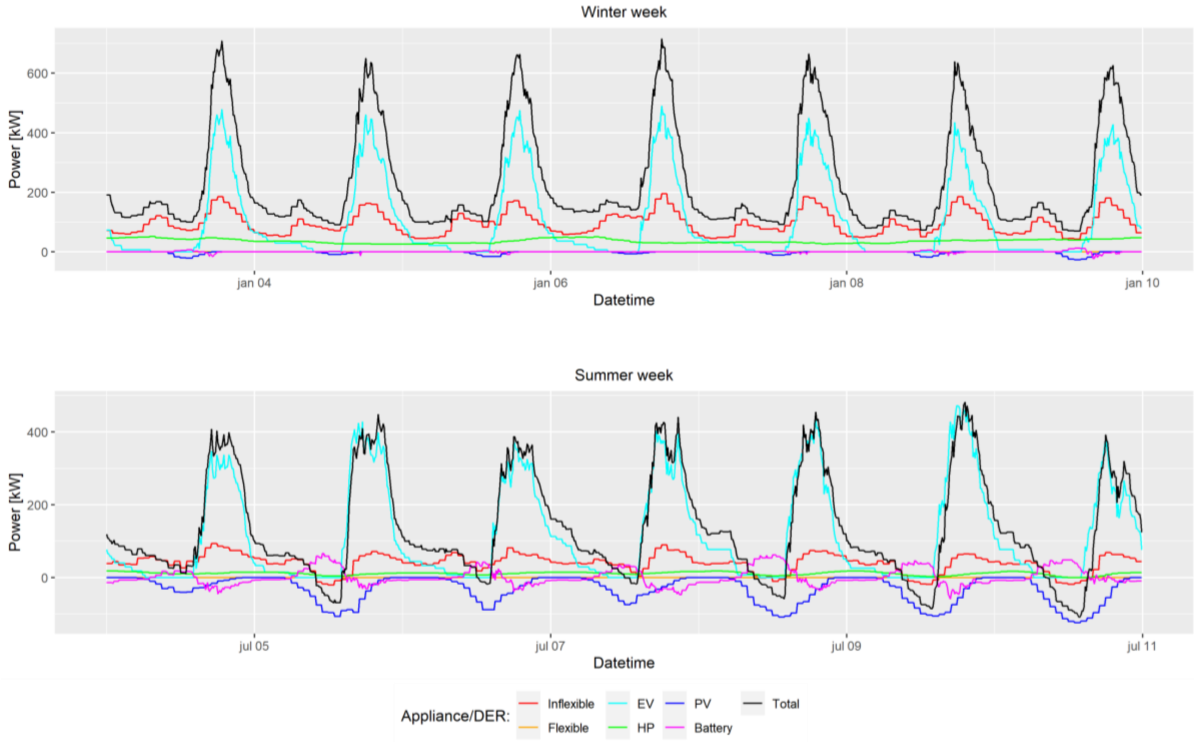
DERInGrid is an agent-based simulation tool that enables electricity system operators to predict the impact of distributed energy resources (DERs) on a power grid. The tool automatically generates a topology representation of the system and its residential consumer connections based on input data, allowing users to conveniently perform simulations on different distribution systems. It also comes with a user-friendly interface for users to adjust parameters for different scenarios.

Tested on two power grids operated by TREFOR, DERInGrid provides operators with valuable insights such as when components in the grid start becoming overloaded and typical timing patterns of these overloads. It also provides power flow time-series measurements for all components and appliances, which can be used to plan cost-effective future grid reinforcement activities and determine whether other solutions, like demand-response or energy management, can be used to alleviate overloads.

The methodology and results relating to the DERInGrid tool have been presented as part of

- Værbak, M. (2022). Agent-Based Framework for Simulating Evolution of Distributed Energy Resources in Energy Systems. [Ph.d.-afhandling, SDU]. Syddansk Universitet. Det Tekniske Fakultet. https://doi.org/10.21996/vny1-bw06
- Værbak, M., Ma, Z., Demazeau, Y. et al. A generic agent-based framework for modeling business ecosystems: a case study of electric vehicle home charging. Energy Inform 4 (Suppl 2), 28 (2021). https://doi.org/10.1186/s42162-021-00158-4





4. 3 Multi-Agent and Multi-Criteria Decision-Making model for investigating energy ecosystem dynamics with Electric Vehicles charging, dynamic distribution tariffs, and electricity pricing

The developed model is a decision support tool consisting of a multi-agent based simulation, a multi-criteria decision-making model and a dashboard. The Multi-agent based simulation represents the energy EV home charging in distribution grids, ecosystem dynamics, and stakeholder behaviors. The multi-criteria decision-making model is for evaluating and selecting State-of-the-Art dynamic distribution tariffs and EV charging algorithms. The Dashboard is for illustrating and analyzing ecosystem situations and relevant ecosystem stakeholders.

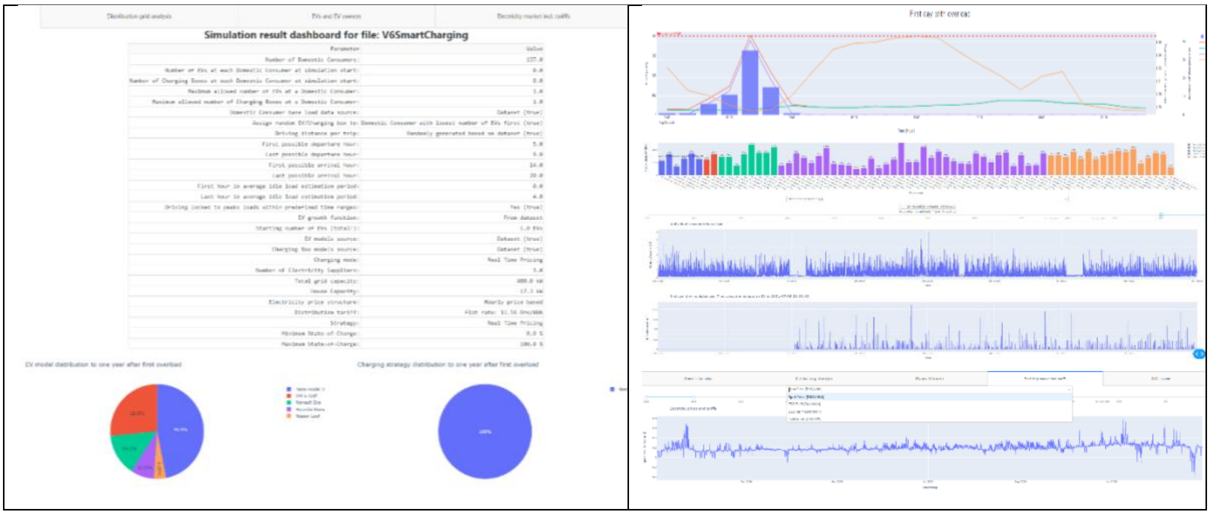
Results obtained in FED

The developed model can help Danish DSOs to identify the load profiles on transformers and tariff revenue; EV users to evaluate EV charging programs and select the optimal charging strategy; Charging Service Providers to investigate different business models for providing charging strategies as a service; Policymakers to investigate the impacts of new regulations on the energy ecosystem.

The developed model is based on living lab data from the areas in Strib and Nr. Bjert with a realistic adoption of electric vehicles and driving patterns for electric vehicle users. The main focus of the model is to investigate the impact of the tariff model 3.0 (compared with model 2.0) with and without various charging strategies on ecosystem stakeholders and the distribution grid's transformer (overload time, size, and frequency). In total 8 charging strategies are investigated.

The findings show that electric vehicles charging based on the day-ahead price signals will in long term (around 2028-2029) create overloads on the transformer. With this strategy (which is available today) the tariff model 3.0 does not have any effect in the long-term creating more frequent overload with a decreased tariff revenue. Furthermore, it is found that a centralized charging control strategy considering the grid conditions, can avoid overloads with limited dissatisfaction among EV users.

The work resulted in the Ph.D. thesis: Christensen, K. (2022). Multi-Agent Based Simulation Framework for Evaluating Digital Energy Solutions and Adoption Strategies. [Ph.d.-afhandling, SDU]. Syddansk Universitet. Det Tekniske Fakultet. https://doi.org/10.21996/kksb-v823



4. 4 Ecosystem Map Generator

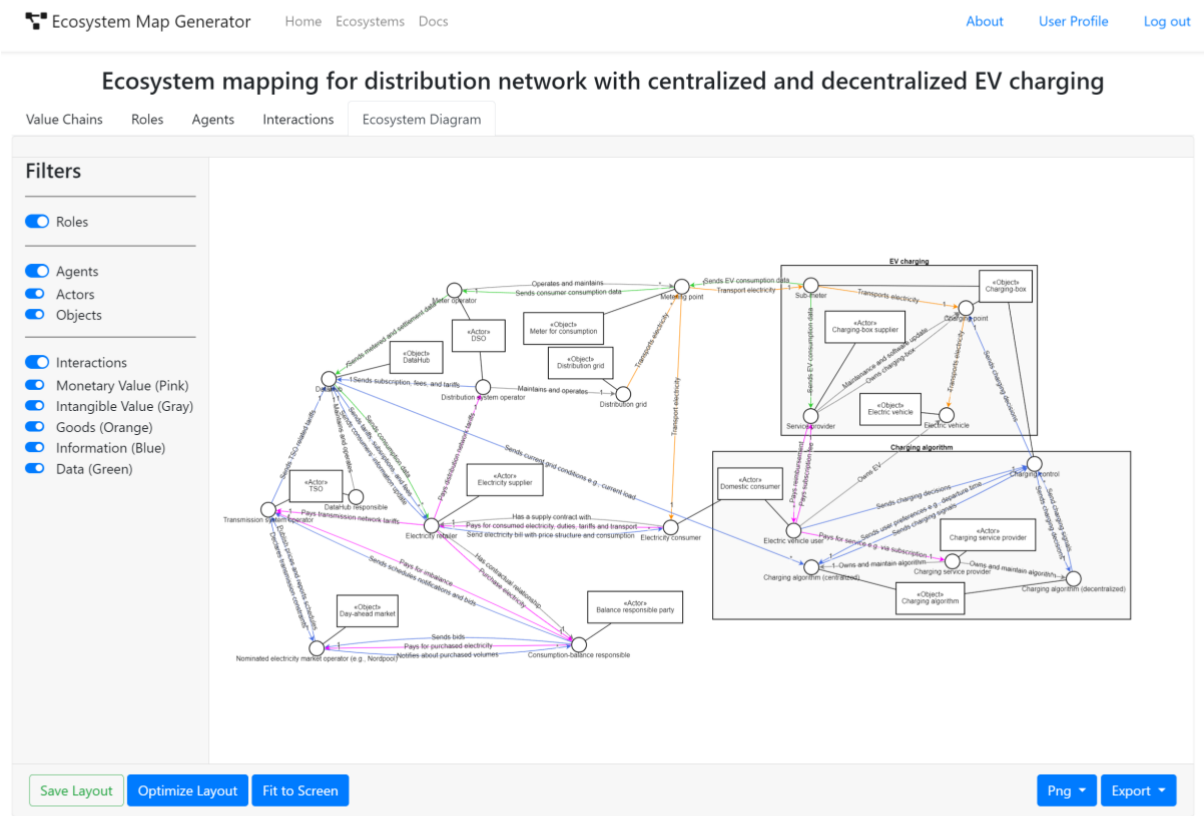
Ecosystem Map Generator a web-based tool (https://ecosystemmapgenerator.sdu.dk/). It supports energy ecosystem analysis and architecture design.

It provides a systematic, easy, and flexible approach for identifying the elements (actors/objects, roles, and interactions) in the targeted ecosystem. It can visualize the value chain and five interactions. It provides code generation for further simulation and modeling.

It has been tested and used for investigating the Danish electricity ecosystem and district heating ecosystem in the FED project.

Theories behind the Ecosystem Map Generator:

- Ma, Z. Business ecosystem modeling- the hybrid of system modeling and ecological modeling: an application of the smart grid. Energy Inform 2, 35 (2019). https://doi.org/10.1186/s42162-019-0100-4
- Ma, Z., Christensen, K. & Jørgensen, B.N. Business ecosystem architecture development: a case study of Electric Vehicle home charging. Energy Inform 4, 9 (2021). https://doi.org/10.1186/s42162-021-00142-y



4. 5 CSTEP Business Opportunity Identifier

The CSTEP-driven business opportunity identifier (https://opportunityidentifier.sdu.dk/) is a web-based tool that provides a systematic approach for ecosystem stakeholders to conduct business opportunity analysis and evaluation.

Results obtained in FED

This tool was developed based on an ecosystem-driven business opportunity identification method, a systematic approach for ecosystem stakeholders to conduct business opportunity analysis and evaluation based on the CSTEP ecosystem analysis and evaluation method. This method includes four correlated steps: Step 1: Identify the five CSTEP dimensions of the business ecosystem; Step 2: Identify potential changes in the business ecosystem; Step 3: Identify future ecosystem trends and timeline; Step 4: Select business opportunities; and Step 5: Potential solution identification.

A case study of the electric vehicle (EV) home charging energy ecosystem in Denmark is applied and demonstrates the application of the proposed method and the implementation of the developed web-based tool.

The related publications are:

- Ma, Z. The importance of systematical analysis and evaluation methods for energy business ecosystems. Energy Inform 5, 2 (2022). https://doi.org/10.1186/s42162-022-00188-6
- Ma, Z., Christensen, K., Rasmussen, T.F. et al. Ecosystem-driven business opportunity identification method and web-based tool with a case study of the electric vehicle home charging energy ecosystem in Denmark. Energy Inform 5 (Suppl 4), 54 (2022). https://doi.org/10.1186/s42162-022-00238-z

STEP 4

Select business opportunities

Note

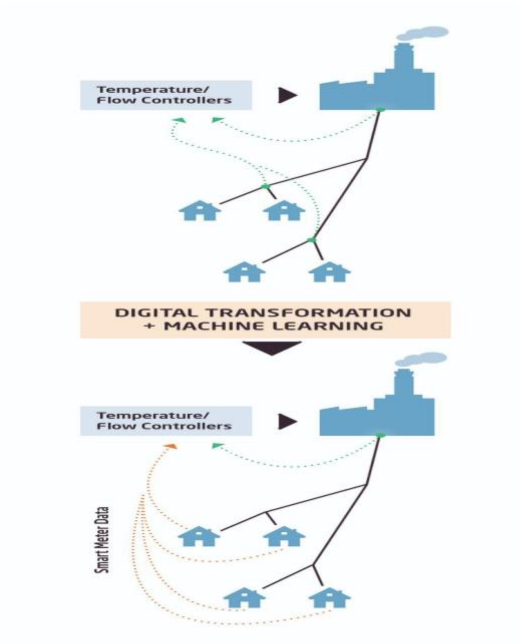
Once all previous steps have been completed a table below is generated.
The table below represents a summary based on all your work from previous steps.
The table is available for download as an Excel file by using the 'Download Results' button.

Transition Stage	Identified Solutions	Related Actor	Related Segment	Related Policies and Targeted Trends	Current Ecosystem Condition	Future Ecosystem Condition
		DSO	Distribution		Regulations for the design of distribution tariffs, such as no price discrimination.	
1.1	Increase in the number of EVs	Domestic consumer	Consumption	Danish climate goals; Governmental agreement of tax relief on green vehicles for securing 775,000 green vehicles by 2030; The Sustainable and Smart Mobility Strategy	The Danish weather (not too hot in the summer and not too cold in the winter) is suitable for EVs	Increase in the number of EVs
1.2	All EV users will adopt an hourly electricity price scheme	Domestic consumer	Consumption	From 2020, all small electricity consumers are eligible to have hourly electricity prices	Today all Danish electricity consumers should, by law, be able to pay by hourly electricity prices Climate goals	All EV users will adopt an hourly electricity price scheme
2.1	Intelligent EV charging strategies that can optimize EV users' bill and reduce CO2 reduction	Domestic consumer	Consumption	Governmental agreement of tax relief on green vehicles for securing 775,000 green vehicles by 2030; 3. Sector roadmap for the energy- and supply sector's contribution to the 70% goal	People may believe in EVs as a good investment or a green solution. And EVs may, in many circumstances, be a good investment (compared to conventional) due to the current and future regulations.	Intelligent EV charging strategies that can optimize EV users' bill and reduce CO2 reduction
2.2	Dynamic distribution tariffs that comply with regulations will be designed and implemented.	DSO	Distribution	Regulations for the design of distribution tariffs, such as no price discrimination.	Distribution tariffs are close to being simple flat rate (one peak period price change during winter)	Dynamic distribution tariffs that comply with regulations will be designed and implemented.
3	DSOs will adopt Intelligent algorithms to enable energy flexibility strategy for sector coupling between EVs and the distribution grid	DSO	Distribution	Sector roadmap for the energy- and supply sector's contribution to the 70% goal; The Sustainable and Smart Mobility Strategy; European Green Digital Coalition	Distribution grids are not dimensioned to the increasing electrification that introduces new Distributed Energy Resources (DERs), such as EVs	DSOs will adopt Intelligent algorithms to enable energy flexibility strategy for sector coupling between EVs and the distribution grid
4	Independent aggregators are allowed to aggregate EVs for participation in the ancillary service market or Vehicle-to-Grid services	Charging-box supplier	Consumption	Sector roadmap for the energy- and supply sector's contribution to the 70% goal; The Sustainable and Smart Mobility Strategy; European Green Digital Coalition	Use Advanced Metering Infrastructure (AMI in EV charging boxes) to collect consumer data (such as charging rate and battery capacity)	Independent aggregators are allowed to aggregate EVs for participation in the ancillary service market or Vehicle-to-Grid services

5. District heating

5. 1 Methods for using meter data for optimized and automated operation of district heating systems

The state-of-the-art temperature optimization requires feedback of the network temperature in the system. Thus, having feedback where the lowest temperatures in the network occurs then if the temperature at this critical point is sufficient then all consumers should be then satisfied. However, as these critical points can change over time, e.g. expansions of the network, pipes getting older etc., then over time the location of the temperature feedback needs to be changed. A new approach were developed where measurements from a group of house smart-meters are used to estimate the network temperatures which can be used as feedback. Hence, making the location of the feedback flexible.



The methods have been developed using data from HOFOR, Brønderslev District Heating and Sønderborg District Heating. The system is now sold to a rather large number of District Heating systems.

The differences between the traditional methods and the new data-driven methods are outlined in Table 1.

	Simulation based TO	Data-driven TO
Approach	• Deductive (simulation/theoretical values)	• Inductive (data-driven, self learning)
Optimal usage	• Simulation of new operational scenarios (where no data exists)	• Control of temperature and flow, reduction of heat loss real time data
Temperature profile	• Temperature calculated using theoretical values for pipes, insulation, soil, etc.	• Temperature estimated using real life data and statistical learning
Distribution net	- Does NOT take into account: • Dirtiness, • Soil properties (temperature, humidity, ..) • Leakage, • Wet or damaged insulation, • Deviations from design values / drawings	+ Take into account: • Dirtiness, • Soil properties (temperature, humidity, ...) • Leakage, • Wet or damaged insulation, • Deviations from design values / drawings
Characteristics	- Constant parameters • Require recalibration, which can be difficult and time-consuming	+ Self calibrating / automated learning • Automatic recalibration for instance due to new costumers, heavy rainfall, damaged insulation, etc.
Production facilities	• New production facilities call for recalibration	• New production facilities call for recalibration

5. 2 Methods for improved heat load forecasting in District Heating systems.

We have developed methods for heat load forecasting which are built on forecasting hierarchies. Also new methods for adaptive forecasting are suggested. This subject is related to the ENFOR and DTU focus related to Fredericia District Heating, but due to data issues with Fredericia DH, data from Varmelast, Brønderslev, and HOFOR has been used. Varmelast provides forecasts and trading for the largest DH system in Denmark.

Main results:

- New method for coherent short and long term forecasting.
- New method for adaptive forecasting tailored to forecasting hierarchies.
- Forecasts are improved with 15 pct compared to a state-of-the-art forecasting method.
- Long-term forecasts are improved with up to 40 pct
- Scenario based forecasting e.g. for optimized use of Pit Thermal Energy Storages

5. 3 Digitalization of residential heating systems

In early 2020, the Department of Computer Science, AAU, started working on the FED project emphasizing smart heating services. The proposed endeavor was to digitalize residential heating systems. Sophisticated heat controllers were designed for individual heat pumps and mixing loops of district heating systems using UPPAAL-Stratego and MATLAB tools [1]. The key achievements of the studies include the following:

Supply-side:

1. Facilitating the integration of renewable energies into heating systems to reduce the share of heating systems in contributing to climate change [2].

2. Unlocking the joint heat-power flexibility to provide demand response in the opposite direction of power imbalance in electricity markets (up-/-down regulations) [3].
3. Increasing heat network efficiency through implementing smart mixing loop control [4].

Demand-side:

1. Minimizing the expected weighted combination of household cost and discomfort [5].
2. Providing personalized heating services that take into account individual preferences and habits to optimize comfort and energy consumption [6].

Methodology and tools:

- We have developed a new methodology and tools suite that advance model-predictive control of flexible energy systems in domestic buildings. Our approach combines recent advancements in stochastic model identification and automatic (near-)optimal controller synthesis. Our method suggests an adaptive model-identification using the tool CTSM-R, and an efficient algorithmic optimized control synthesis based on Q-learning for Euclidean Markov Decision Processes via UPPAAL Stratego.

References

[1] H. Golmohamadi, K. Guldstrand Larsen, P. Gjøl Jensen, and I. Riaz Hasrat, "Optimization of power-to-heat flexibility for residential buildings in response to day-ahead electricity price," Energy Build., vol. 232, p. 110665, 2021, doi: https://doi.org/10.1016/j.enbuild.2020.110665.

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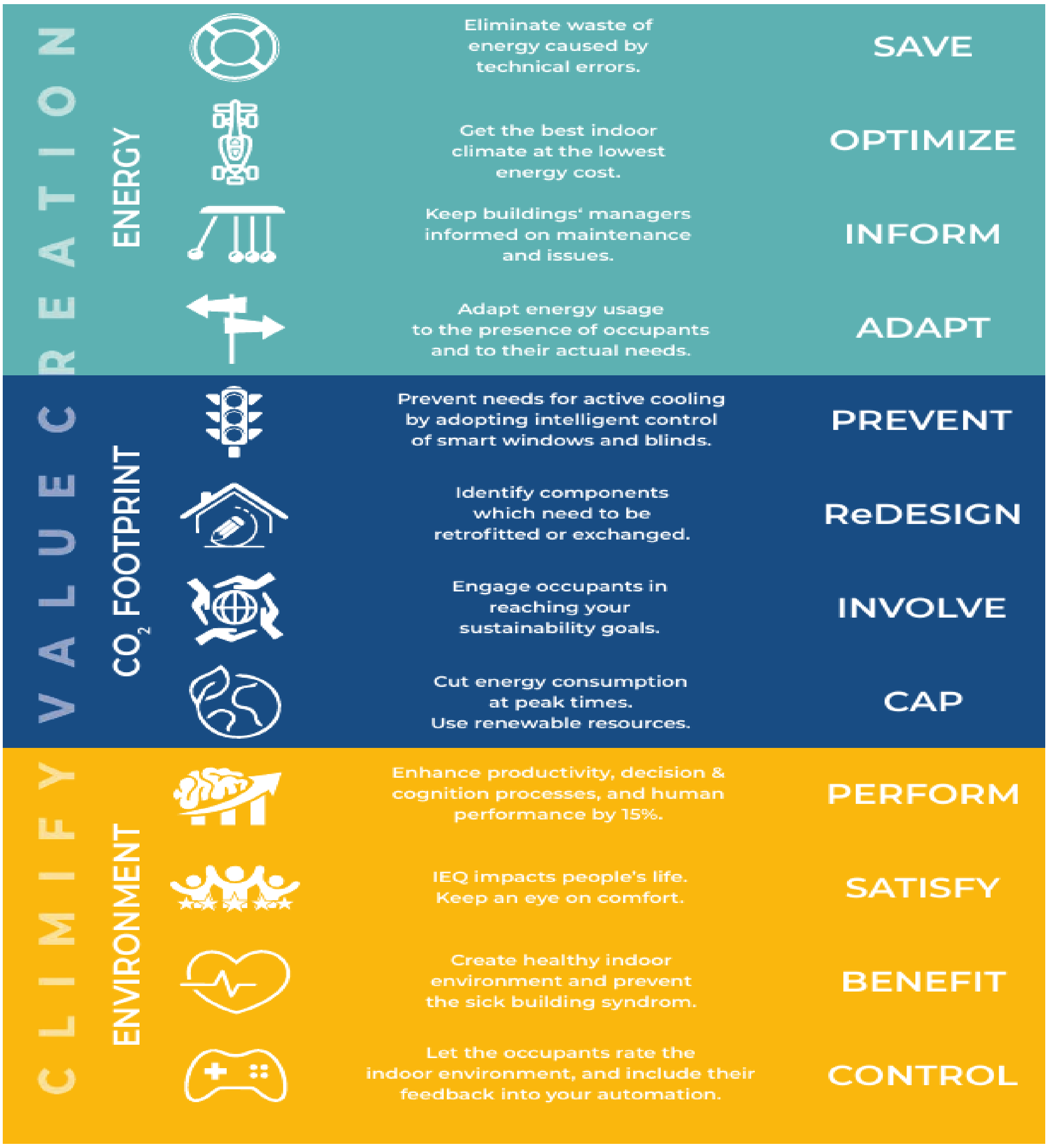
[6] H. Golmohamadi, "Optimal Operation of Residential Heating Systems in Electricity Markets Leveraging Joint Power-Heat Flexibility," in Coordinated Operation and Planning of Modern Heat and Electricity Incorporated Networks, 2022, pp. 289–318.

6. Building monitoring and control

6. 1 Monitoring and Control of the Indoor Climate (Høje Taastrup Living Lab)

New methods for monitoring of the indoor comfort have been established and tested at the Høje Taastrup Living Lab (Borgerskolen). Furthermore, methods for Human-in-the-Loop feedback to the controllers have been developed and tested. The methods are now implemented in a relatively large number of schools and offices in Denmark - and also in Hong Kong and the US.



6. 2 Optimal control with integrated short-term weather forecasting for smart building controllers.

In relation to the Høje-Taastrup Living Lab we have concluded that new controllers with embedded short-term weather forecasting are needed. Consequently we have developed a method for including advanced weather disturbance models in model predictive control (MPC) of energy consumption and climate management in buildings. The performance of certainty-equivalent controllers such as conventional MPC for smart energy systems depends critically on accurate disturbance forecasts. Commonly, meteorological forecasts are used to supply predictions of the ambient air temperature and solar radiation. However, these are not well suited for short-term forecasts. We show that an advanced dynamical and statistical description of the disturbances can provide very accurate short-term disturbance forecasts. Simulation-based studies suggest that significant improvements can be obtained with the developed controllers with integrated short-term forecasts generated by the advanced disturbance model.

In short, electricity savings of 5 - 10% is found while at the same time improving the indoor climate to a level close to that of perfect weather forecasts.

6. 3 Non-linear grey-box models for water based heating systems

Based on data from Borgerskolen in Høje Taastrup we have developed some promising models which are going to be used for control in the HTK Living Lab. More specifically we have developed a non-linear grey-box (GB) model based on stochastic differential equations that describes the heat dynamics of a school building in Denmark, equipped with a water-based heating system. The building is connected to the district heating through a heat exchanger. The heat is delivered to the rooms mainly through radiators and partially through the ventilation system. A monitoring system provides the data on indoor climate in the rooms and on the heating distribution and delivery. Using data, we estimate unknown states and parameters of the heating system model using the maximum likelihood method. Important novelties of this paper include models of the water flow in the circuit and the state of the radiator thermostats. The non-linear model accurately predicts the indoor air temperature, return water temperature and heat load. The ideas behind the model may lay a foundation for GB models of buildings that use all kinds of water-based heating systems such as air-to-water/water-to-water heat pumps. Such GB-models enable model predictive control (MPC) to control e.g. the indoor air climate.

The following paper has been published in Energy and buildings
Non-Linear Grey-Box Modelling for the Heat Dynamics of Buildings

and the following in the Energy & AI:
Identification of non-linear autoregressive models with exogenous inputs for room air temperature modelling

6. 4 Price-based control for CO2 savings and low voltage network ancillary services

In the NOVASOL Living Lab we use price-based control for controlling the heating of swimming pools in Blåvand. Using the Smart-Energy OS (SE-OS) the CO2 - or price-based indirect control provides a setup for storing excess wind and solar power, and at the same time the setup can provide services for the low voltage smart grids. Here the Distributed Energy Sources (DERs), i.e., swimming pools, after receiving the control signals, calculate: i) the optimal consumption profile within the forecast horizon, and ii) the set-point for the thermostat of each individual summer house. The control signal is based on the grid load forecasts, electricity price or CO2 forecasts, weather forecasts, and booking information. Measurements from the summer houses are afterwards collected and used, among other information, to feed price-responsiveness information in the price response model. The heterogeneous and stochastic nature of the responses of the DERs calls for new procedures for: i) predicting how to invoke the needed flexibility, and ii) characterizing and describing the relationship between control signals and the resulting electricity load. Until now we have observed CO2 savings between 10 and 20 pct.

These results have been presented at a large number of international conferences and webinars - see eg. the FED web page.