Final report

1. Project details

Project title	CORE
File no.	64017-0005_12500
Name of the funding scheme	ForskEL/EUDP
Project managing company / institution	DTU Elektro
CVR number (central business register)	30060946
Project partners	DTU Energy, AAU, Vestas, Danfoss
Submission date	23 April 2024

2. Summary

English Summary

The project is to design the 100% renewable based Danish energy system with P2H and P2G, and develop market framework and coordinated operation strategies for the renewable based integrated energy system. The 100% renewables based Danish energy system with thermal and gas storage will be designed in order to maximize the social welfare and improve the cost efficiency. Significant energy storage technologies will be analyzed with specific focus on Danish potentials for using P2G and thermal energy storage technologies in the overall energy system. The impact of integration of electricity, heat, gas and transport sectors on the electric power system will be studied and the flexibility and ramping requirements will be quantified to ensure secure and reliable operation of the integrated system. A new market will be developed to ensure sufficient flexibility and ramping capability in the integrated energy system. Optimal short term dispatch strategies and online control will be developed to ensure the security of the whole system with the least cost. The business models for renewable generation plants coupling with energy storage will be developed. The developed energy system, market and coordination operation strategies will be demonstrated by real time co-simulation in PowerLabDK.

Danish Summary

Projektets mål er at designe det danske energisystem som værende 100% vedvarende vha. P2H og P2G. Derudover vil projektet udvikle en markedsplatform og koordinerede operations strategier for det integrerede energisystem baseret på vedvarende energikilder. Det 100% vedvarende danske energisystem med varme- og gaslagring vil blive designet til at maksimere den sociale velfærd og forbedre omkostningseffektiviteten.

Væsentlige energilagringsteknologier vil blive analyseret med fokus på at benytte P2G og varmelagrings teknologier i det overordnede danske energisystem. Betydningen af at sammenkoble elektricitet, varme, gas og transport sektorerne under el systemet vil blive undersøgt. Derudover vil fleksibilitet og rampe krav blive kvantificeret til at sørge for en sikker og pålidelig operation af det samlede energisystem. Et nyt marked vil blive udviklet til at forsikre om tilstrækkelig fleksibilitet og rampe kapacitet i det integrerede energisystem. For at sørge for sikkerheden i hele systemet ved brug af færrest midler vil optimale korttidsplanlægning strategier og online kontrolmekanismer blive udviklet. Forretningsmodellerne for sammensætningen af energilagre og produktion af vedvarende energi vil blive udviklet. Det færdigudviklede energisystem, markedsplatformen og de koordinerende operations strategier vil blive demonstreret vha. real tids co-simulering i PowerLabDK.

3. Project objectives

The main objectives of the project are to design the 100% renewable based Danish energy system with power to heat (P2H) and power to gas (P2G), develop a new market and optimal dispatch strategies for the integrated energy system to ensure cost effective and secure operation, and study business models for renewable generation plants in the integrated energy system.

The technologies developed and demonstrated include:

(A) develop three main variants energy system scenarios taking into account the balance of gas and thermal storage;

(B) develop P2G and thermal storage technologies to fit optimally in the energy systems;

(C) quantify the flexibility and ramping requirements of integrated energy systems considering the interactions of energy sectors;

(D) develop an updated market for integrated energy systems and a scalable methodology to clear the integrated energy markets in a distributed manner; and

(E) develop optimal dispatch and online control for integrated energy systems based on model predictive control considering the energy sector interactions and dynamics.

4. Project implementation

The project was mostly implemented according to the project plan.

During the project period, several challenges were experienced.

1 PhD student recruited by DTU Elektro was dismissed due to poor performance. In order to deal with this situation, another PhD student was recruited to work on the project. The new PhD student performed very well and delivered results according to the project plan.

Due to the pandemic, it was not possible to have physical project meetings after March 2020. All the project meetings and the final event were held online.

The university partners had much more teaching load because all the reaching was changed to online. Therefore, a 4 month project extension was applied and approved by the EUDP. All the planned project work and milestones were achieved with the 4 month extension.

5. Project results

The original objective of the project was obtained. The obtained technological results are described as follows.

(A) three main variants energy system scenarios taking into account the balance of gas and thermal storage;

(B) P2G and thermal storage technologies to fit optimally in the energy systems; and

(C) flexibility and ramping requirements of integrated energy systems considering the interactions of energy sectors;

(D) an updated market for integrated energy systems and a scalable methodology to clear the integrated energy markets in a distributed manner; and

(E) optimal dispatch and online control for integrated energy systems based on model predictive control considering the energy sector interactions and dynamics.

The details of the obtained technological results are described in the following sections.

5.1 Three main variants energy system scenarios taking into account the balance of gas and thermal storage

This section is the result of the work in Work Package 1 of the EUDP funded project Coordinated Operation of Integrated Energy Systems (CORE).

The purpose of the work of WP1 is to utilise existing energy system scenarios from different Danish actors to analyse how different technologies could affect different types of future energy systems where renewable technologies supply all energy demands. A special focus is on power-to-heat (P2H) and power-to-gas (P2G) technologies, though the scope is not limited to these technologies. The work includes scenarios for both the long-term 2050 energy system where the Danish energy system is based on 100% renewable energy, but also a medium-term perspective for 2035. The medium-term is included as different technologies might have different roles in 100% renewable energy systems than in energy systems with a lower share of renewable energy. In turn, this is useable for policy considerations in regard to which technologies should be implemented early and which should wait until the share of renewable energy in the energy system is higher, and which technologies are only relevant in the transition towards 100% renewable energy.

The scenarios used are from the Danish Society of Engineers' (IDA) report "IDA's Energy Vision 2050" from 2015 [1] and the Danish transmission system operator Energinet's "System Perspective 2035" from 2018 [2]. The energy system scenarios in both of these reports include all energy sectors, though they detail parts of them differently, and both use the years 2035 and 2050 as modelling years, meaning that they have the same years for a medium- and long-term outlook. A reference model for the Danish energy system in 2020 is also made using projections from before 2020, to be used as a representative model for the current Danish energy system. An overview of the scenarios used is shown in Figure 1.

The scenarios are used in a modelling testbed, where the scenarios are set up and adjusted to make them comparable without changing the main aspects of each scenario. More specifically, all scenarios are modelled in the same energy system modelling tool, EnergyPLAN, and all costs are updated so that they are using the same updated technology data. Using the modelling testbed, four different focus areas are analysed:

- Operational analyses of the scenarios under different market price projections. Here the focus is on the operation of technologies based on the original technical setup of the scenarios.
- Electrification of the energy system, where the focus is on the electricity system. More specifically the following has been investigated: Industry electrification, Electricity demand flexibility, and Grid-scale electricity storage.
- Heat sector, where the focus is on the individual and district heating systems. More specifically the following has been investigated: Heat savings, Individual heating solution incl. heat storages, District heating production technologies (combined heat and power units and heat pumps), and District heating storages.
- Renewable fuels in the Danish energy system, where the focus is on the role and production of different renewable fuels. More specifically the following has been investigated: Biogas, Dry biomass, Electrolyser flexibility, and Electrification and electrofuels in transport.

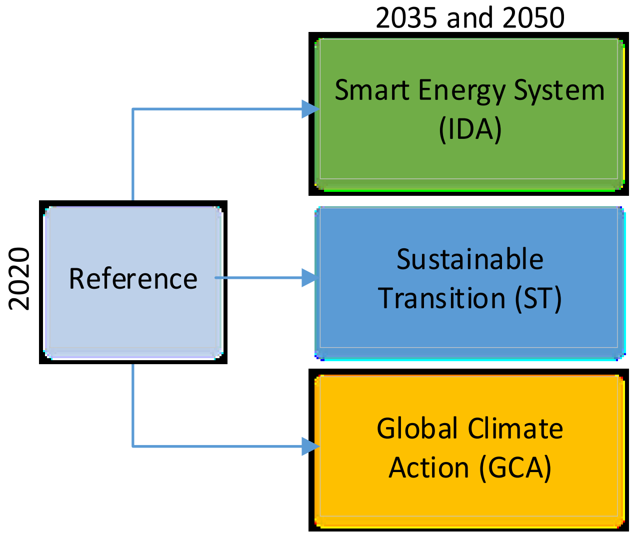


Figure 1 – Scenarios used in the analyses

The following summarises the main findings from each analysed focus area.

Operational analyses:

Going towards increasing levels of renewable energy in the energy system results in decreasing yearly operation of the power and combined heat and power (CHP) plants, even in scenarios with a significant decrease in the CHP and power plant capacity. Even though the yearly operation of these plants is reduced, there are still hours where the full capacity of these units is needed, indicating that the value of these plants shifts from being the energy produced to instead be the capacity offered. As such, markets must adapt to this change in value, as a given capacity of CHP or power plant will require more income per amount of electric energy produced to cover the long-term marginal costs. Another option is to consider this as part of the support system or infrastructure needed in integrated renewable energy systems.

Transmission line capacity is found to be utilised more for the needs of the Danish energy system in 2050 compared to 2035, though the full capacity of the transmission lines is only utilised for needs in the Danish energy system in a small part of the year, especially in scenarios where the transmission line capacity is expanded.

Electrification:

Systems with low internal dispatchable power production capacity are more sensitive to external markets and external electricity prices. This is relevant in the discussions on future energy system electrification, as it is inherently connected to both internal electricity production capacity and transmission capacity, and as also has been the case historically it is expected that energy prices will fluctuate from year to year. Also, long-term predictions of energy prices have shown to be very uncertain, and as such, having internal dispatchable power production capacity reduces the effect of these uncertainties.

For the industry sector, direct industry electrification should be favoured over a fuel shift to hydrogen-based processes due to lower costs and higher system efficiency. Hydrogen should instead be prioritised for specific processes without alternative solutions, or where the value of local utilisation of bi-products is significant enough to make up for the extra costs for the energy system.

Electricity demand flexibility can contribute to increased integration of variable renewable electricity, though the effects of this are limited to the available capacity and electricity demand flexibility only allows the demands to be moved within a relatively short period of max. a week, and flexibility for longer periods is also needed. Uncertainties remain in relation to the actual achievable flexibility amount and the related investment costs needed; as such, there is a continued need for research on quantifying and realising this potential.

Li-ion batteries for grid-scale storage are infeasible based on hourly balancing, and should not be implemented with such a primary role. Li-ion batteries may, however, be useful for other purposes such as back-up capacity or for short-term balancing and frequency regulation, though other already utilised technologies could provide these services. From preliminary technical and economic assumptions, high-temperature rock bed storage seems feasible as a cheaper alternative to li-ion batteries for electricity storage. However, this needs to be verified in future models as improved technical data becomes available.

Heating:

Heat savings are found to be important both for reducing the total annual costs of the energy system but also to reduce the biomass consumption of the energy system. In relation to energy system costs the optimal level of heat savings was found to be approximately 32% compared with the average consumption per m^2 in 2010. This was analysed in the IDA scenario for 2050. Though the biomass consumption should also be considered in this respect, as to keep biomass consumption within sustainable levels. In the IDA scenario for 2050, going from 32% to 42% heat savings increases the total annual cost of the system by less than 0.2% of total annual costs but reduces the biomass consumption by about 3.5% of the total biomass consumption.

In relation to individual heating supply, electric-driven heat pumps should be used as much as possible for individual heating to keep the biomass consumption and the total annual cost of the energy system low. Individual solar thermal as a supplement heating supply can help reduce the use of biomass of the energy system, though its potential is limited due to its production mainly being in the summer period.

Individual heat storage technologies in connection with heat pumps and solar thermal can reduce the biomass consumption of the energy system, but only up to a certain point, depending on the amount of other flexible electricity demands in the scenario, though research has shown that from an energy system cost perspective only low-cost individual storage options should be considered.

District heating is found to be an important infrastructure in all the investigated energy system scenarios, as it allows collection and utilisation of otherwise discarded heat by distributing it to end-users. In the future district heating is expected to be mainly supplied by both large-scale heat pumps, excess heat from electrofuel production, geothermal, and CHP plants. The large-scale heat pumps and CHP plants are found to provide flexibility to the energy system, especially when heat storages are utilised.

For CHP and power plants high electric efficiency of the CCGT is found to provide the energy system with the lowest costs and lowest biomass consumption. Having internal flexible CHP or power plant capacity in the energy system makes it possible to reduce the total annual costs of the energy system, but as shown in other analyses also stabilises the total annual costs in relation to changing international electricity market prices. The use of large-scale CHP units instead of pure power plants is not a necessity for keeping the biomass consumption of the energy system at low levels, as long as the pure power plants are highly efficient and sufficient amounts of other low-cost heat sources for district heating, such as HPs, are available in the system.

Renewable fuels:

Biomass conversion technologies and electrofuels will have a crucial role in future energy systems, but it is also important that the biomass consumption is kept within the sustainable boundaries. Generally, producing any type of liquid or gaseous renewable fuels is more expensive and less efficient than electrification, so priority should always be given to electrification where possible. Electrofuels can supply the demands in the parts of the transport sector where direct electrification cannot.

Electrolysers used as part of producing electrofuels can provide a considerable potential for flexible for the electricity system, provided sufficient hydrogen storage exists. In this the optimal balance for the Danish energy system is found to be somewhere between 2.5 and 4 days of hydrogen storage combined with an electrolyser capacity of about 1.6-1.7 times the minimum needed capacity. The actual sizing depends on the need for electrofuels.

For the transport sector, it is found that liquid electrofuels provides lower energy system and fuel costs than gaseous electrofuels. Electromethanol has the lowest energy system costs, though the costs for electromethane is similar, but only until the cost of vehicles is added in the equation. Generally, methanol provides greater flexibility regarding storage and readiness to be upgraded to other fuels, namely jet fuels, which is a more complicated and energy-intensive process if it would be produced from methane. Fischer-Tropsch fuels may be an alternative if methanol-to-jet fuel pathways will not show sufficient technological maturity in the future.

Compared with producing CO_2-electrofuels, producing bio-electrofuels from biomass gasification results in significantly more biomass consumption in the energy system, but increases the efficiency of the energy system. Though both types of electrofuels are necessary for the future energy system despite the increased costs of CO_2-electrofuels as the fuels are limited by biomass availability and available CO_2-sources.

The results of the analysis indicate that syngas from biomass gasification can be a crucial fuel in combination with biogas both used for power, heat, or industrial purposes, at lower costs than electrofuels. Biogas should always have priority due to the lower cost, but since the agricultural sector outputs limit biogas, it must be complemented by syngas from biomass gasification. In addition, maximising on the use of lower-cost bio-electrofuels reduces the use of biomass for electricity generation, allowing the energy system to be more resilient to external electricity prices.

5.2 P2G and thermal storage technologies to fit optimally in the energy systems

In WP2, present and projected data of significant energy storage technologies were collected - with specific focus on Danish potentials for *using power to gas* and *thermal energy storage* technologies in the overall energy system in WP1. The data provision included economic as well as technical performance data – from literature and in-house data.

Power to gas systems (P2G) includes various types of electrolysis technologies. In the project the focus has been on the most efficient of the electrolysis technologies, the solid oxide electrolysis cell (SOEC) technology.

The main topic was the modelling of the cost of the system based on different boundary conditions, including the location of the electrolysis unit – whether it was co-located with down-stream synthesis with free steam available or as a independent unit to produce hydrogen for a grid. Furthermore, a special mode of operation so-called AC-DC was studied further with a 1D SOEC stack, with a purpose of minimizing internal mechanical stresses during partload and minimize electro-chemical degradation of the cell, extending the lifetime of the SOEC stacks. The modelling framework was also moved into 3D modelling towards the end of the project to simulate the thermal stresses in the SOEC stacks. The P2G energy storage was covered in D2.1.

Thermal Energy Storage (TES) systems are known to play a important role in the integration of renewable energy sources and sector coupling, and as a result, it will provide a cheap and sustainable way to maximize the energy system efficiency and achieve a lower overall cost of energy. Finding a suitable TES for a given temperature range and application can be a difficult choice since most of the technologies are either in the initial phase of commercialization or in the research and development phase. For electrification and district heating applications, Sensible Heat Storage (SHS), specifically a Rock-bed thermal storage system is a suitable candidate since it has a reasonably low construction cost and can store high temperature heat (up to 800°C), which can easily be utilized. An economic tool is developed in MATLAB in order to predict the cost of the storage unit and a Computational Fluid Dynamics (CFD) model is developed in order to study the performance of the rock-bed and the insulation layers. The thermal energy storage was covered in D2.2.

Techno-Economic Analysis

Hydrogen has been identified as a universal energy carrier as it is needed either as feedstock for the chemical industry or for various transportation fuels. Electrolysis can operate at times when excess power is available making it a perfect solution to balance the grid, and store excess electrical energy in the form of chemical energy. Due to these features, hydrogen production via electrolysis of water is now considered a key technology towards sustainable power system. Among all known electrolysis technologies, high temperature steam electrolysis in SOEC is gaining substantial interest due to improved reaction kinetics, high efficiency, inexpensive cell materials, and possibility to operate in reverse mode as a fuel cell. The technology is still in the upscaling phase and the first commercial systems are being deployed. Commercialization will be accelerated if various technical improvements are reached, which would also assist the economic attractiveness of the technology, such as decreased degradation and ability to operate stable and so-called thermo-neutral operation.

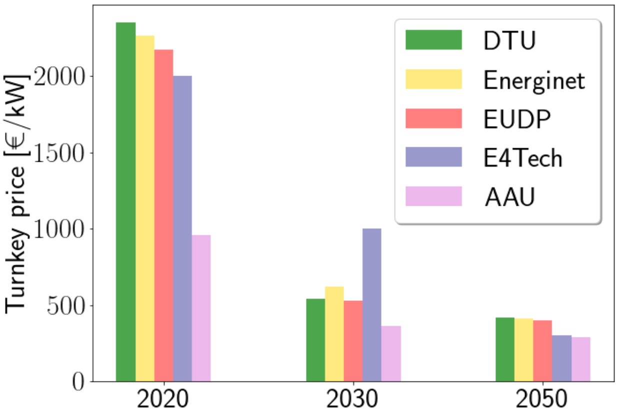


Figure 2 Projected turnkey prices of SOEC for the next decades.

In deliverable 2.1 an analysis of the energy balances during operation, when exchanging heat with downstream processes were elaborated. Here the concepts of thermo-neutral operation was explained, and how a simple 1D model for the operation of an SOEC were obtained and used. This was consequently used to elaborate on the existing efficiency numbers as a function of the temperature supplied to the SOEC unit. It was shown that the efficiency could reach values of 86 % of efficiency LHV with current technology, given that free steam is available. The corresponding efficiency, if no free steam is available was shown to be 71 %.

Based on the efficiency the cost of the system for a nominal production of hydrogen could be derived. This was done consequently and compared with the literature, as presented in Figure 2.

Thermal Energy Storage

The heating and cooling sector makes up to 50% of the total energy demand of the European Union countries today, where a large part of it is comes from fossil fuels which raises serious concerns about the security of supply and climate change [1]. By integrating the Thermal Energy Systems (TES) with the renewable energy resources seems to be an effective way to tackle the unpredictability of the renewable energy sources and increase the share of clean energy in the total energy mix.

In deliverable 2.2 a brief overview of the current TES technologies, see Figure 3, and their applications were provided together with discussions on the figures of merits (efficiency). After this the a techno-economic analysis of a specific thermal energy storage relying on high temperature TES (HTTES) was undertaken. The analysis was based on an existing pilot plant system and the CAPEX was estimated based on an extrapolation from existing data considering known material and construction costs. Furthermore, the OPEX was based on an analysis on simple physical models. Finally, these simple physical models were substantiated using a detailed CFD model.

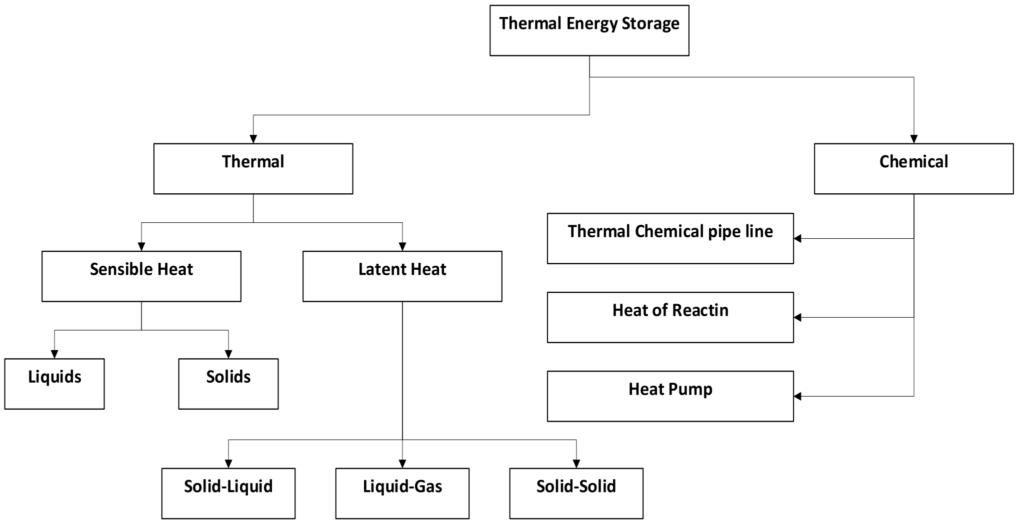


Figure 3: Types of Thermal Energy Storage

The cost of the overall TES unit can be divided into three categories namely; storage cost, charge cost and discharge cost. The storage cost includes the cost of storage material (Rocks), insulation, concrete, and excavation. The charging cost estimate includes the cost of the heater and fan while the cost of discharging includes the cost of the heat recovery steam generator and the fans. By varying the thickness of the concrete (0 mm to 150 mm) and insulation (0 mm to 800 mm) three types of scenarios are considered in order to fit the specific requirements. The radius of the rock bed ranges from 1 meter to 25 meters giving the total thermal storage capacity of 1 MWh to 16 GWh in this analysis. The cost breakdown is given in Figure 4.

Key findings from the Techno-economic analysis performed in the study are given below:

- Rock-bed high-temperature Thermal Energy Storage systems provide a cheap and environmentally-friendly solution to store high-grade and low-grade thermal energy for a longer period of time (weeks or months).
- Almost 90 % of the costs are associated with the conversion components (Charging and discharging components). While the storage unit itself contributes only 9 % of the total cost. This shows very high potential in Heat-to-Heat applications where no conversion components are required.
- The overall efficiency depends on the quality of conversion components, which can be tackled by using heat recovery units with higher efficiencies. Also, the storage efficiency can be increased by using a thicker layer of insulation.
- CFD heat transfer analysis confirmed that a different flow direction for charging and discharging has a significant effect.

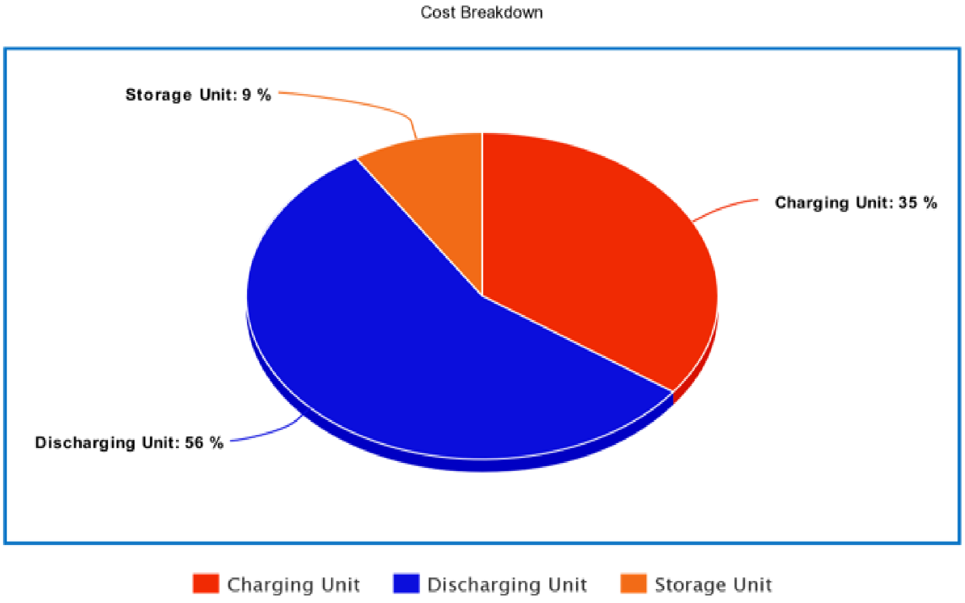


Figure 4: Cost breakdown of an HTTES system.

Modeling of an SOEC operating in AC-DC mode

A 1D model of an SOEC stack was established and utilized further in CORE to simulate so-called AC-DC operation. The 1D model was built in the software Comsol Multiphysics 5.5, and describes following coupled physical phenomena

- Electrical currents
- Electro-chemical reactions
- Mass transport of reactants / products
- Flow in porous media and free flow
- Heat transport in solids
- Heat transport in fluids

The AC-DC mode of operation is a newly invented type of operation, which is still in testing. The purpose of it is to minimize stresses in part load but also to minimize degradation and hereby extend the lifetime of the stacks. Increased lifetime will result in lesser of exchange of SOEC stacks during the SOEC plant’s lifetime leading to lower overall cost.

The principle of the AC-DC operation is that the current is reversed for a short period at a high current frequency. Inverting the current will result in that the cell is operating as a fuel cell, which expels more heat. This heat will balance the endothermic electrolysis when operating in part load. The consequence is a better thermal distribution inside the SOEC stacks with reduced thermal stresses as a consequence.

As an example the temperature distribution inside a SOEC stack distribution along the flow direction in AC-DC mode is compared to a reference operating in conventional SOEC mode is shown in Figure 5. Both are loaded with an average current density of ~0.7 A/cm^2, which is somewhat below the nominally preferred thermo-neutral current density of 1 A/cm^2. This means that the SOEC stack should operate endothermal, which is aso seen from drop in temperature for normal SOEC operation (red curve). The thermal gradients in AC-DC mode of operation is seen to be comparatively smaller due to the shifting of current and consequent internal heating, which will lead to smaller thermal stresses.

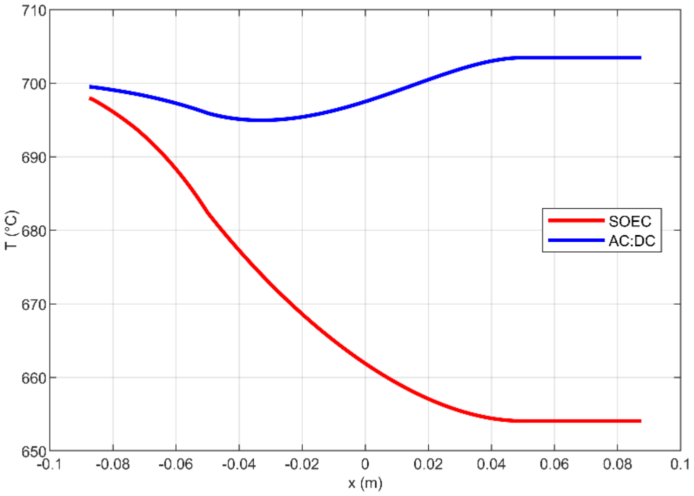


Figure 5 Temperature distribution along the flow direction in an SOEC stack operated in AC-DC mode compared to a reference operating in convetional SOEC mode.

The inverted operation also results in that the driving force for the settling of some impurities is reversed. First experiemental results (not this project) shows that this results in increased lifetime, which is supported by the modelling in CORE.

Modeling of cycling loading and unloading TES system in 2D-axissymmetry

A detailed CFD analysis of the rock bed system was modelled in Comsol Multiphysics 5.5. The model is 2-D axisymmetric, and the simulated charging, resting, and discharging of the heat storage. The model takes into account the following physical phenomena:

- Free and Porous Media Flow.
- Heat Transfer in Solids.
- Heat Transfer in Fluids.

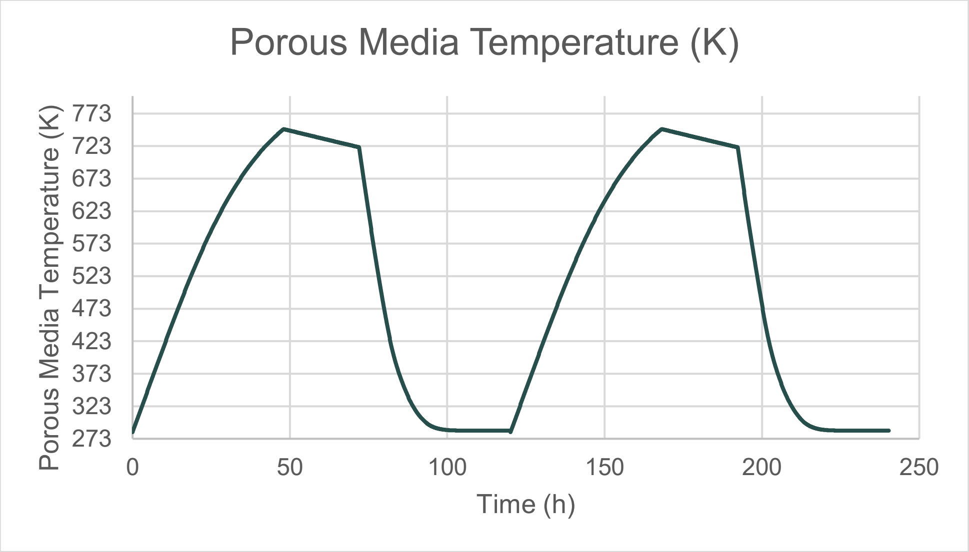


Figure 6: Average rock bed temperature during two charge and discharge cycle.

The model is validated from the experimental results obtained from the pilot plant at DTU Risø as described in deliverable 2.2. A time-dependent study of the rock bed was also performed in order to assess the performance of the system when subjected to consecutive cycling. Figure 6 presents the average rock bed temperature when it is subjected to 48 hours of charging, then resting for 24 hours, and finally discharging for 48 hours. This process is repeated for the second cycle.

5.3 flexibility and ramping requirements of integrated energy systems considering the interactions of energy sectors

WP3 is to quantify the requirements of flexibility and ramping capability in the 100% renewables-based energy systems, which includes two parts: 1) Overview of available flexibility options in the 100% renewables-based energy systems and 2) Ramping requirement assessment of the integrated energy systems.

This task provides an overview of potential demand- and supply-side flexible and ramping resources and their capabilities in integrated energy systems (including electricity, gas, heat, etc.). The 100% renewables-based energy systems require a large amount of support of flexibilities and ramping capabilities from different sources.

At the supply-side, the flexibilities and ramping capabilities can be provided by dispatchable generators, such as hydro power plants, biomass power plants and CHPs. At the demand-side, the flexibilities and ramping capabilities can be provided from different sectors in the integrated energy systems, such as shiftable industrial loads, shiftable household appliances, electric vehicles (EVs), HPs, district heating with heat storages, and power to gas (P2G) stations. Battery energy storage systems (BESS) and EVs (allow V2G mode) can provide flexibilities and ramping capabilities at both supply- and demand-side.

For the purpose of balancing supply and demand in the power systems, flexibility from demand side can provide the same service as the supply side as long as the demand side can be properly regulated and controlled.

Demand side management could provide flexibility on multiple time scales, ranging from seconds to seasons by offering ancillary services (regulation, load-following, contingency). Market designs that emphasize the performance requirements can easily accommodate demand response which is typically capable of providing flexibility.

The required flexibility and ramping requirements are quantified in integrated energy systems with high renewable penetration. Based on the modeling of the 100 % renewables based energy systems of different scenarios studied in WP1, the fluctuations of the net loads (inflexible loads minus non-dispatchable renewable productions) will be quantified (magnitude and variability). The flexibilities and ramping capabilities are required to balance the fluctuations of the net loads and support the system frequency stability. In the future energy systems with 100% renewables congestions at transmission and distribution level may occur often, which require further support of flexibilities.

The system stability and reliability are also critical in the future energy systems. Due to the reduced inertia of the converter-based renewable energies, system disturbances and/or faults can have a severe consequence to the power systems, such as cascade outage. Therefore, the robust and optimal system management and control are important, and the sufficient support of the flexibilities and ramping capabilities is crucial. Modelling and simulations of the future energy systems will be carried out to analyze the system stability and reliability, and the requirements of the flexibilities and ramping capabilities will be quantified in this section.

The full-year time series of various demand and supply were generated with the time resolution of 1 hour, using the simulation tool EnergyPLAN. The corresponding results are given as follows,

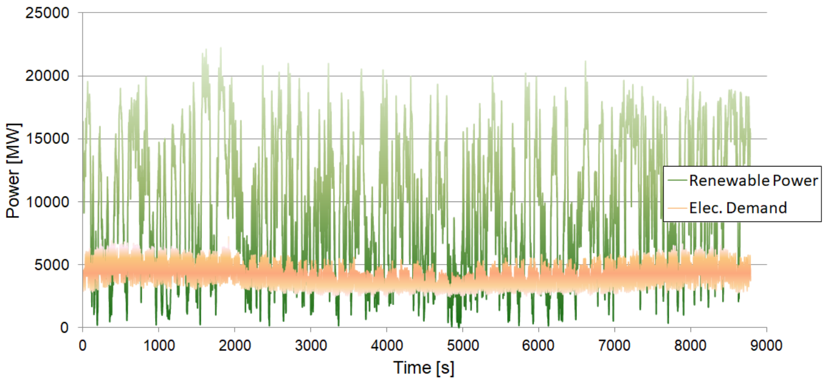


Figure 7 Time series of renewable power generation and inflexible load.

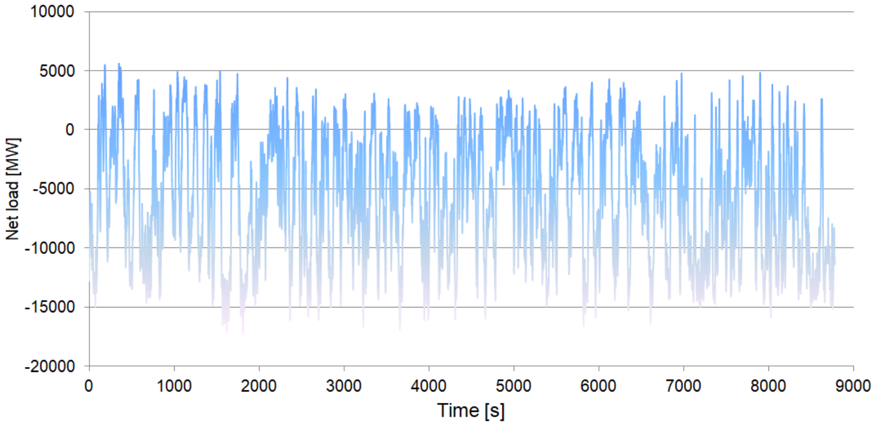


Figure 8 Time series of net load.

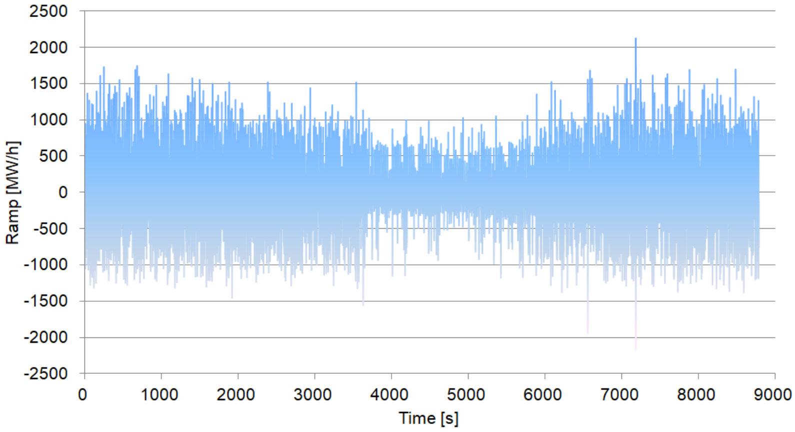


Figure 9 Ramp needs of electricity load.

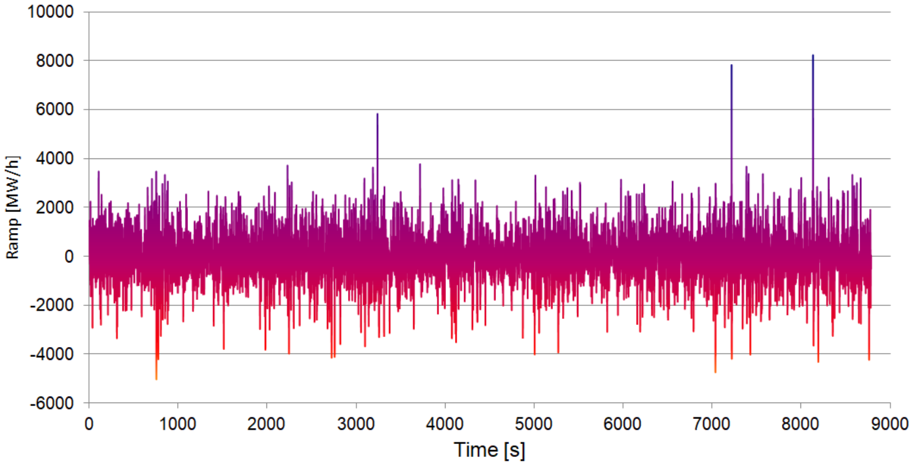


Figure 10 Ramping needs of the net load with renewable energy.

Table 1 Maximum Ramp Requirement.

	Up-Ramp [MW/h]	Down-Ramp [MW/h]
Only Load	2101	2154
Net Load	8220	5044

Figure 7 shows the time series of the renewable power generation and inflexible load. Since in the 2050, the installed capacity of renewable power generation is much larger than the load, the net load is often negative as illustrated in Figure 8, which means that the overproduction of electricity should be balanced by other ways such as energy storage, P2G and P2H.

Figure 9 and Figure 10show the ramp time series with load and net load over a year. From Table 1, it can be observed that the maximum ramping requirement of the system without considering the renewable power generation are 2101 MW/h for up-ramp and 2154 MW/h for down ramp, respectively. However, for the net load, requirements reach 8220 MW/h for the up-ramp and 5044 MW/h for the down-ramp.

5.4 Market Framework Design and Business Model

This section studies the coordination as well as market design problems arising in multi-energy systems. In this regard, different levels of coordination and market design schemes for integrated energy systems are proposed with a focus on power, gas and heat infrastructures. The main focus of this section is to connect optimization frameworks in the context of multi-energy systems with efficient solution methods while accounting for uncertainty, regulatory frameworks, and interactions of agents. For this purpose, optimization models that allow efficient modeling for complex interconnected systems are proposed and equilibrium models are used as market simulation tools. The integrated operation strategies and market frameworks developed in this report shall help to maximize social welfare and performance for better cost efficiency and reliability of the whole energy system.

This section answers the two main research questions: (i) How much value can be derived through coordination of integrated energy systems? (ii) How can the value of multi-energy coordination be harvested while respecting the current market regulatory framework? To answer these questions, this report develops tools applying concepts from the fields of energy system engineering, operations research and game theory. The main contribution of this report is improving the coordination of multi-energy systems through updated operational strategies and market design. For that purpose, this report develops new notions and methods for better coordination of multi-energy systems and concludes with several policy recommendations.

Price-Region Bids in Markets for Integrated Energy Systems

This section introduces the novel price-region bid format to be used in integrated energy markets. This section shows that price-region bids are able to accommodate a broad range of techno-economic characteristics, including complex spatial and temporal couplings, and facilitate market access to non-conventional flexibility providers. It then illustrates that this new bid format is compatible with existing market structures, and satisfies desirable market properties under common assumptions. Three numerical studies are provided in the full version of the report: two Preprint motivating examples based on a district heating utility and a cascaded hydro power plant, and a case study based on an integrated power and heat system. These studies illustrate the inability of existing bid formats to accommodate flexible resources, and show how price-region bids overcome this shortcoming.

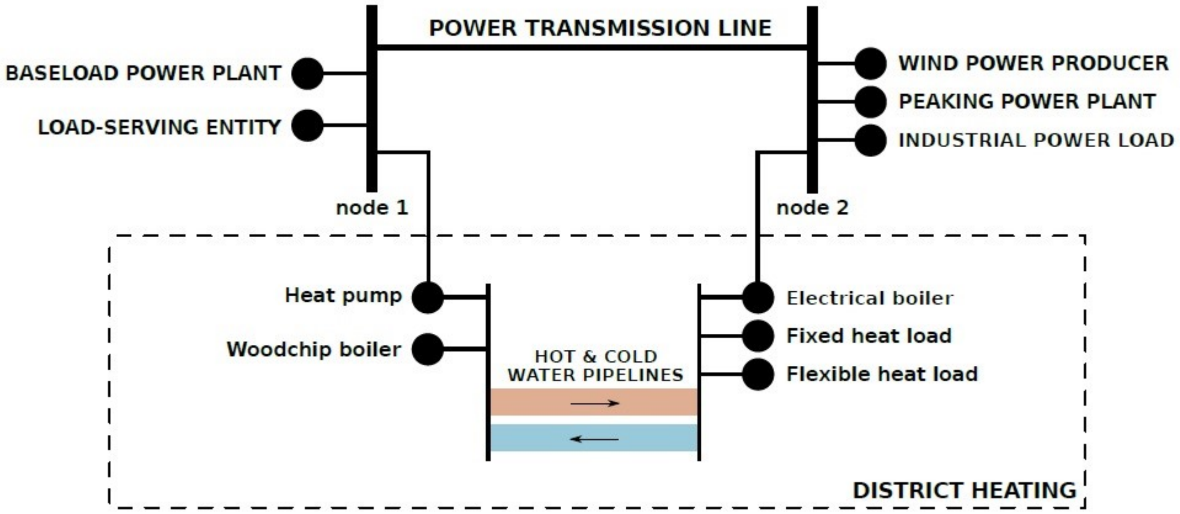


Figure 11 A motivating example based on an integrated power and heat system

This section makes several original contributions. Firstly, the proposed concept of price-region bidding format provides a general framework for market participants to exactly represent any linearly-constrained feasible region of operation and convex piecewise linear cost function. To the best of our knowledge, no existing bid format can cover this range of characteristics. This section shows, in particular, how price-region bids overcome the limitations of price-quantity bids in representing complex flexible infrastructures in integrated energy markets. Secondly, we show that price-region bids can straightforwardly be incorporated into existing pool-based market clearing programs without conflicting with the mechanisms in place.

For a motivating example based on an integrated energy system (power and heat) depicted in Figure 11, this report shows that the proposed bidding format precisely represents flexible resources. Our numerical analysis suggests that allowing price-region bids in an energy market with intermittent sources of renewable energy leads to increased social welfare, due to a better utilization of flexible resources. In our case study, the flexibility from the heat sector is truly valued in the electricity market when the district heating utility participates with price-region bids.

Upgrading the Existing Market Design for Integrated Energy Systems via Financial Instruments

This section proposes a market design based on a soft coordination approach via financial instruments to improve coordination between energy sectors under uncertainty. In view of real-life implementation, an investigation is conducted of utilizing the concept of virtual bidding (VB) in two-settlement markets to enhance coordination. Virtual bidders perform financial arbitrage between two trading floors in energy markets. By taking advantage of price differences, these virtual bidders are defined to improve efficiency in two-settlement wholesale markets. Thus, the role of market participants who perform arbitrage can be expected to bring value to the overall system. These virtual bidders can be players without physical assets or players at the interface of multiple energy sectors. Allowing key players to extend their bidding capabilities to virtual bids does not require major changes for market setup and rules. For the first time, this section proposes the introduction of virtual bidders specifically in natural gas markets. Furthermore, the capability of units at the interface of energy sectors, e.g., gas-fired generators, to improve coordination by performing arbitrage is investigated. Simultaneously, the impact of virtual bidding on coordination of electricity and natural gas markets is analysed.

We quantify the maximum potential of VB for improving both sectoral and temporal coordination in electricity and natural gas markets. For this purpose, we develop three generalized Nash equilibrium problems. These equilibrium models serve as simulation tools for deriving policy implications to explore how much VB can improve the sectoral and temporal coordination in renewable-based electricity and natural gas markets. We also provide analytical insights by comparing our proposed equilibrium models and the ideal benchmark, i.e., the two-stage stochastic co-optimization problem. It is important to highlight that these equilibrium models should be seen as policy tools, since they are not intended to be used for market clearing in practice.

As the core contribution of this section, we first integrate explicit VB to electricity and natural gas markets, which achieves temporal coordination between DA and RT markets in each energy sector. Then, we investigate the possibility of natural gas-fired power plants, who are at the interface of power and natural gas, to behave as implicit virtual bidders. We illustrate that such implicit virtual bidders have potential to achieve both temporal and sectoral coordination in electricity and natural gas markets.

For a case study, the total expected cost of electricity and natural gas systems achieved under different market setups is shown in Figure 12. As expected, the highest system cost corresponds to the sequential setup Seq (first bar in Figure 12), which is a fully uncoordinated model. On the other hand, the fully coordinated ideal model (i.e., last bar in Figure 12) yields the lowest cost. In this case study, the full temporal and sectoral coordination results in a 7.30% cost reduction. The three proposed setups Seq+eVB, Seq+SS and Seq+VB based on virtual bidding provide partial coordination, and therefore, the system cost achieved in those setups is between the upper and lower bounds. Among these three market setups, Seq+VB with both implicit and explicit VB yields the highest cost saving, which is 7.04% (fourth bar in Figure 12).

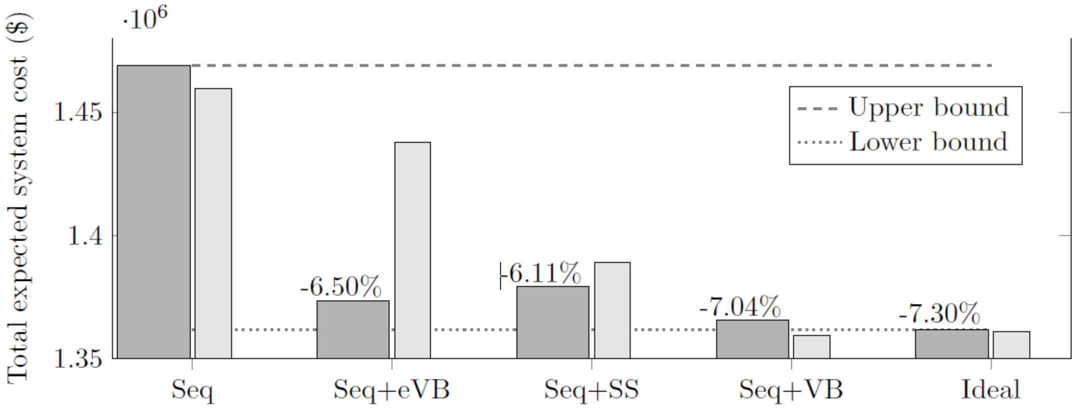


Figure 12 Total expected cost of the electricity and natural gas systems under different market setups. The percentages show the reduction in the total expected system cost compared to that cost in the fully uncoordinated sequential setup (first bar)

An Ideal Market Design for Integrated Energy Systems: A Benchmark

This section proposes an ideal benchmark built upon a full coordination approach. This section focuses on unlocking energy storage from gas and heat grids to cope with variability and responding to uncertainty from the power side. For this purpose, this section accounts for energy ow dynamics and storage effects of multi-energy networks, quantifying the value of the revealed network flexibility. This section is the first work in the literature that comprises all three energy systems accounting for heat and gas grid dynamics. Although full coordination violates existing market regulations, the proposed approach in this section motivates the need to develop mechanisms to unlock and exploit the revealed flexibility within the current regulatory framework. The proposed representation of multi-energy synergies opens up various directions for exploiting the available flexibility in a market environment. Additionally, this work provides a basis to evaluate the efficiency of market-based mechanisms enabling power, gas and heat system agents and the respective energy networks to actively contribute to providing flexibility. The foundation is laid for a comprehensive market design evaluation to improve sector coordination. This translates in a novel market-based approach that aims at coordinating the operation of multi-energy systems and exploiting the revealed flexibility.

To the best of our knowledge, this is the first work that optimizes the combined dispatch problem for the three energy systems together, accounting for their network and ow dynamics, while dealing with arising nonconvexities. We propose a combined power-heat-gas dispatch that models the interactions of the three energy carriers as well as the network flexibility. As an ideal benchmark, this combined energy dispatch assesses the maximum potential of flexibility that the natural gas and district heating networks can provide for renewable-based power systems. This revealed flexibility is quantified in terms of the reduced operational cost of the entire system compared to a dispatch model neglecting the ability of natural gas and district heating networks to store energy. Since the dynamics of heat and natural gas ow introduce nonconvexities, we explore convex quadratic relaxations of the energy ow model in gas and heat systems, including the gas linepack, variable heat temperature and heat mass ow rates as the three degrees of freedom. We recast the original non-convex model as a mixed-integer second-order cone program (MISOCP), and eventually explore the feasibility of solutions achieved.

The flexibility provided by energy storage in the networks allows not only to decouple gas supply from consumption and heat production from demand, but also shifting electricity production and consumption. Network flexibility improves utilization of power production from variable renewable sources. This is evident in reduced wind curtailment over the planning horizon.

We apply the proposed combined power-heat-gas dispatch with convexified formulation on an integrated energy model based on the IEEE 24-bus reliability test system, coupled with a 12-node gas network and a 3-node district heating network over a 24-hour scheduling horizon. We first provide the results obtained for the total operational cost of the integrated energy system. This cost is achieved under varying levels of wind power penetration, which is defined as the ratio of total wind power capacity to maximum electricity demand. Figure 13 shows decreasing operational cost of the integrated energy system for increasing levels of wind power penetration.

We compare these results to a dispatch that does not account for network flexibility. Accounting for ow dynamics and storage in gas and heat pipelines decreases the total system cost by 2% on average compared with the case neglecting network flexibility.

Figure 14 shows the total amount of natural gas and heat supplied and consumed for the entire 24-hour horizon. When modeling linepack, consumption and supply of natural gas and heat do not necessarily need to be matched in each time period. The amount of energy stored in the pipelines (which is highlighted in shaded zones in Figure 14) directly impacts the profiles of natural gas and heat supply.

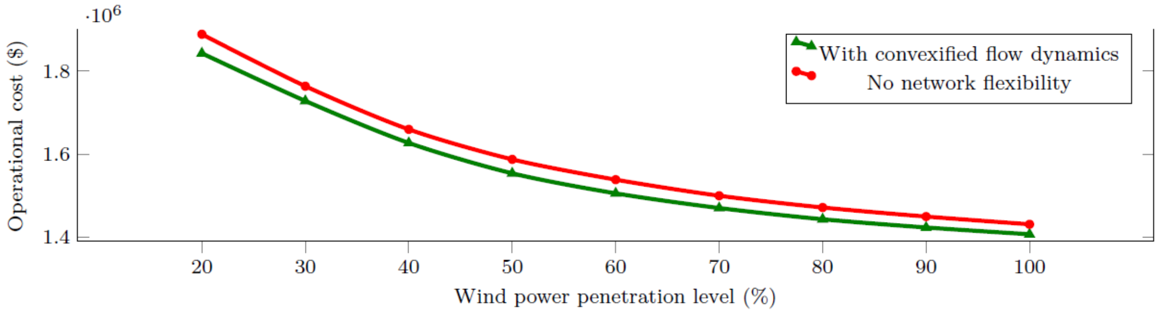


Figure 13 Total operational cost of the entire integrated energy system in cases with and without considering network flexibility as a function of wind power penetration, i.e., the total wind power capacity divided by the maximum power demand.

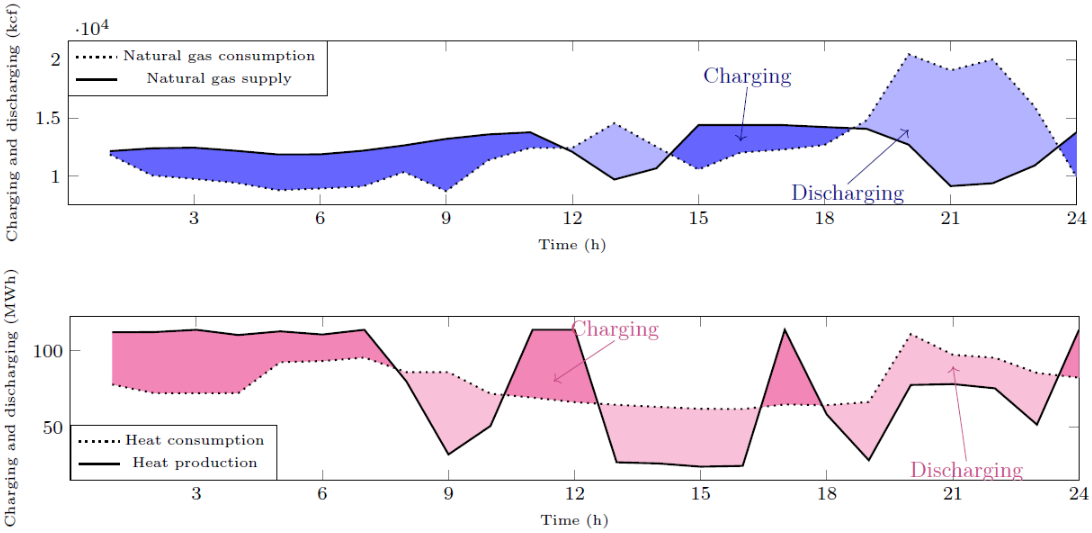


Figure 14 The hourly profiles of natural gas (upper plot) and heat (lower plot) systems, illustrating the hourly total supply, total consumption, and the charging/discharging energy by network

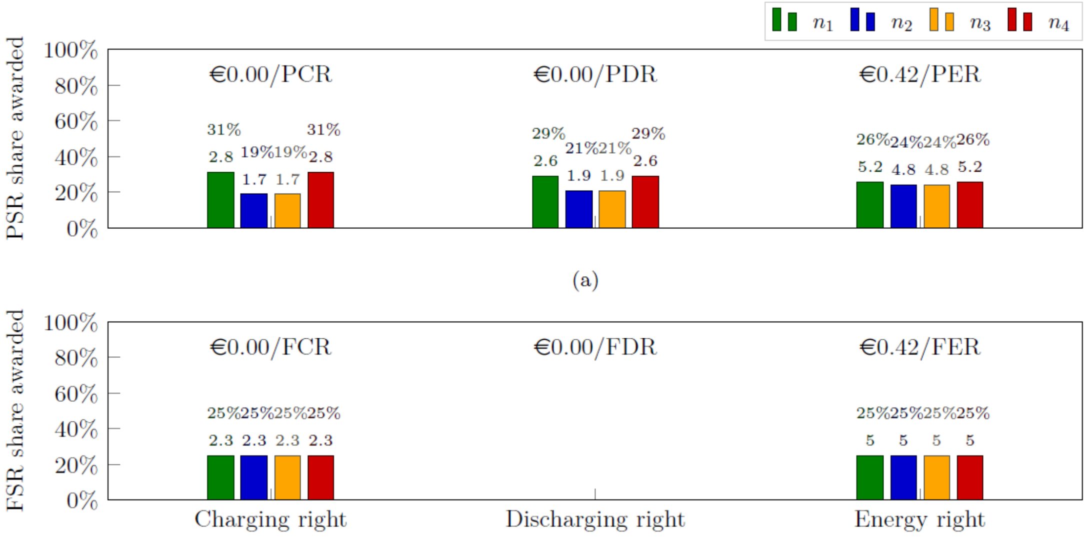
Access Economy for Storage in Renewable-based Energy Communities

This section takes a different perspective, and addresses the market design issue for renewable-based local energy communities in the distribution level. This section explores different market design options based on cooperative and non-cooperative game-theoretic models that enable an economic access to the benefits of energy storage for prosumers without a direct ownership of a storage system. This section compares market outcomes in terms of the community cost as well as the individual cost. It pays special interest to potential uncertainties, and investigate financial instruments that allow storage systems to be utilized by multiple prosumers. In particular, this section explores a case, where a prosumer that owns a storage system provides rights, either physical or financial, rather than participating in the local market as an arbitrageur. Moreover, This section considers a cooperative market design, where energy community members agree on the Shapley value or the nucleolus as a community cost allocation rule. Results show that an access economy for energy storage systems enhances energy communities by reducing the cost volatility for most prosumers, while the expected operational cost of the community as a whole remains unchanged.

A local energy market design that enables an access economy for energy storage systems in energy communities gives rise to two fundamental questions: First, how do potential market designs look like? And second, what are regulatory implications of an access economy for energy storage?

To answer these questions, we consider an energy community that comprises multiple prosumers as well as an energy community manager, who acts as a non-profit oriented system operator. We represent uncertain PV power generation by a finite set of discrete scenarios. We first start with a benchmark case of a non-cooperative market design. In this case, every prosumer, who owns an energy storage system, participates as an intertemporal arbitrageur in local spot markets, where the only product to be traded is energy. We continue with the case, where each prosumer, who owns a storage system, offers physical storage rights (PSRs) in a local forward market, which clears once in advance to spot markets. The energy storage system is then scheduled in spot markets according to the underlying objective of a PSR holder. Similarly, we consider the case of financial storage rights (FSRs). However, under this paradigm the storage system is optimally dispatched from a social perspective by the energy community manager. We move beyond non-cooperative market designs and consider the case of a cooperative market design, where energy community members agree on a community cost allocation rule among all prosumers, while energy storage as well as PV systems are utilized optimally for the whole system. We study implications of different cost allocation rules such as the well-known Shapley value and the nucleolus.

Our main findings are as follows: In a non-cooperative market design, irrespective of the availability or the absence of storage rights, either physical or financial, every prosumer's expected cost remains unchanged. However, most prosumers benefit from an access economy for energy storage through the availability of storage rights by reducing their cost volatility. Cooperative market designs provide a rigorous framework for implementation, though, the Shapley value suffers from stability and might leave incentives for some prosumers to split off the energy community. In contrast, the nucleolus gives rise to a stable community cost allocation. However, its calculation is highly intensive. We find out that non-cooperative market designs scale well in terms of community members, while cooperative market designs do not, and thus, are rather suitable for small energy communities.



(a)

(b)

Figure 15 Market-clearing prices and awarded quantities of physical charging rights (PCR), discharging rights (PDR) and energy rights (PER) as well as those of financial charging rights (FCR), discharging rights (FDR) and energy rights (FER) in percentage of the total available energy storage capacity in the community. Numbers below percentage values indicate the absolute value of total PSR/FSR quantities bought by prosumers n1 to n4.

We apply our proposed game-theoretic models to numerically assess different alternatives of an economic access to storage systems in energy communities. In our non-cooperative market designs the access economy is enabled through either PSRs or FSRs. However, these two paradigms fundamentally follow different approaches. While PSRs enable economic access via operational access for each right holder, FSRs enable economic access through a claim to the intertemporal energy arbitrage earned by the energy community manager, where right values are determined based on the limiting components of an energy storage system. Therefore, PSR and FSR quantities awarded by prosumers differ as shown in Figure 15. According to this figure, charging and discharging right prices for both PSRs and FSRs are zero, while energy rights have a price of e0.42/right.

The market outcomes of the forward market for PSRs are shown in Figure 15a. Prosumers n1 and n4 award a slightly greater share of physical charging, discharging and energy rights compared to prosumers n2 and n3, who award equal shares. Thereby, prosumers n1 and n4 reduce spot market activities and optimally utilize their PV systems for meeting their own demand. Note that prosumers have to award all types of rights, i.e., physical charging, discharging and energy rights, to get operational, and thereby, economic access to energy storage systems.

Figure 15b illustrates the forward market outcomes for FSRs. Here, no prosumer awards financial discharging rights, since the value of those rights in spot markets is zero. However, financial charging and energy rights have positive values, from which all prosumers award equal shares.

5.5 Optimal Dispatch Strategies and Online Control of Integrated Energy System

The installed capacity of the renewable energy sources is increasing at a high rate. In the future renewable energy based power system challenges in the power system stability and security are more likely to happen due to fluctuations and variability of renewable energy sources. Hence, measures on how to accommodate renewable energy sources should be introduced. One of the prominent solutions is the integration of different energy sectors to provide flexibility and increase efficiency of the multi-energy systems. To achieve stable, efficient and low-carbon energy systems, sector coupling and new market regulations are playing an important role.

We propose a coordinated optimization model for a cooperation of integrated energy systems. The subsystems included in the integrated energy system are electrical power system, natural gas system and district heating system. The subsystems are linked with the coupling components providing higher flexibility to the energy systems. The optimal dispatch framework is based on model predictive control and designed for online application.

The main objective of this working package is to develop optimal dispatch and online control algorithm for integrated energy systems. A coordinated optimization model for integrated energy systems is proposed. A linear problem is formulated by considering the balancing equations and subsystems constraints. The model is solved by MOSEK in MATLAB. The system used for simulations is the Danish integrated energy system. The optimal dispatch framework and online control algorithm for integrated energy systems is based on model predictive control.

The development of optimal dispatch and online control for integrated energy systems is performed in three steps as shown in Figure 16.

The first step is development of mathematical models of integrated electric power, natural gas, and district heating systems. Second and third step propose an optimal dispatch framework for integrated energy system. The second step proposes and formulates a day-ahead two-stage stochastic programming approach for integrated multi-energy system including the uncertainty of wind power production. The third step proposes a real-time scheduling approach based on model predictive control. The steps are described in detail in the following subchapters.

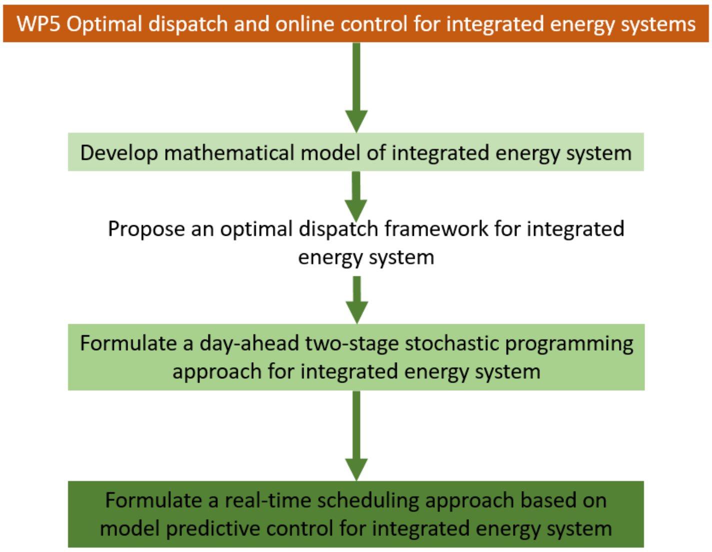


Figure 16 Steps in development of optimal dispatch and online control for integrated energy systems

Mathematical Modelling of Danish integrated energy system

Integrated energy systems are systems consisting of more energy subsystems. The subsystems included in the Danish integrated energy system are electrical power system, natural gas system and district heating system. The subsystems are linked with the coupling components providing higher flexibility to the energy systems. The mathematical models of integrated energy system are developed based on the Danish case study for 2035 and 2050. The Danish integrated energy system is converted to pu system to decrease the computational burden.

The mathematical model of electric power systems includes nodal balancing equation, production and consumption limits, transmission line capacity limits, ramping rate limits and import and export limitations. In the future, it is expected that coal and gas fired power plants will be phased out by 2030. Therefore, the generation includes biomass fired plant and onshore and offshore wind farm. The three biomass fired plants are combined heat and power plants. The consumption side includes electric demand, power to gas (P2G), heat pump, electric boiler and flexible demand in terms of demand response units. The flexible demand is including flexible load providing demand response and vehicle to grid technology. The electric boilers and heat pumps which can also provide a part of demand response are mainly used to provide the heat to the district heating system. Denmark has a number of interconnection with neighboring countries, and therefore, import and export are considered. The neighboring countries Denmark has interconnections with are Norway, Sweden, Poland, Germany, Great Britain and Netherlands.

The model of natural gas system includes the nodal gas balance equation, consumption and production limits, gas storage injection and withdrawal limits and export and import limitations. The pressure drop equation is detailed and dependent on pipeline parameters, pressures and flows. The production includes gas source and P2G, while consumption considers gas demand. The gas interconnection to neighboring countries are Germany and Sweden. There are two gas storages. In order to control the flow in the pipelines, gas compressors are situated in specific pipelines.

The model of district heating system is simplified. The district heating system is divided in district heating areas, due to large and distributed number of heating areas. There are 13 areas. However, the production and consumption balance is maintained for each area. The heat production consists of electric boiler, P2G, heat pump, heat generated from biomass fired plant and flexible heat producers. The flexible heat producers consist of solar based heating, gas boiler, oil boilers, waste heat, etc. Every heat generating unit is limited by its maximum heat power. The considered heat storages are hot water tanks and thermal energy storages, such as pit or tank. Hot water tanks are located near the combined heat and power plant used to store the over production of heat from combined heat and power plant. In cases of underproduction of heat by combined heat and power, the heat is provided by the hot water tank. Thermal energy storages are larger seasonal storages. The detailed model can be found in [1]. Detailed model includes the equations for the continuity of flow, temperature mix, temperature drop and heat balance equation.

The linking units are P2G, electric boiler, heat pump and biomass fired plant. The relationship between heat and electricity generation from biomass fired plant is shown through power to heat ratio. The conversions from electricity to gas and heat through linking unit P2G are demonstrated by efficiencies. The heat pump relationship of electricity and heat is represented by coefficient of performance of the heat pump and the relationship between electric boiler electricity input and heat output is shown by efficiency. The illustration of integrated energy system is shown in Figure 17.

Integration of multiple energy systems provides the flexibility needed for the future Danish energy system. The subsystems linked with the coupling components provide higher flexibility to the energy systems. Sector coupling though power to gas unit shows a great potential of increasing the efficiency of the electric power system and utilization of excess wind power. The further key findings can be found at the end of the document.

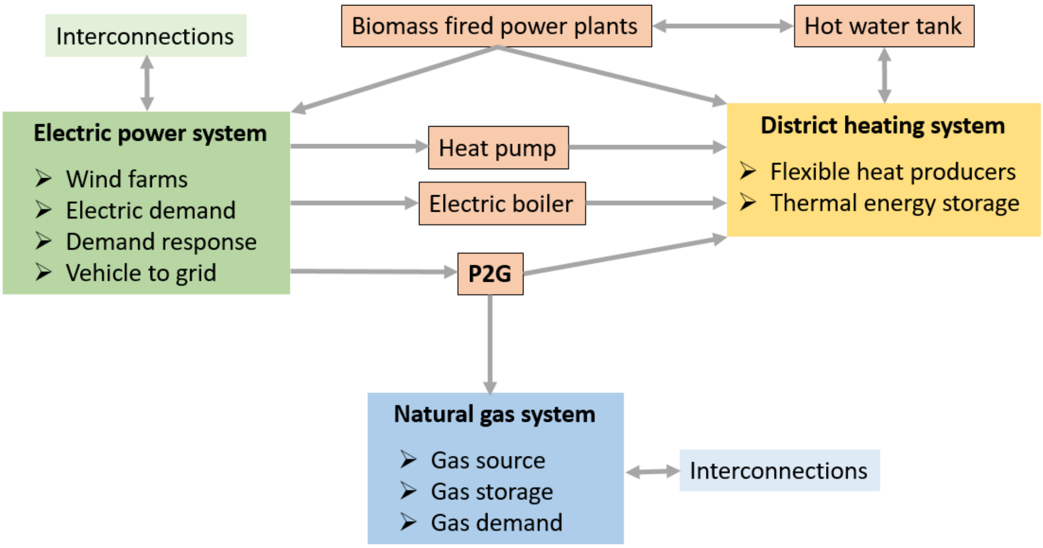


Figure 17 Integrated energy system

Optimal dispatch framework for integrated energy systems for day-ahead scheduling

Second step is formulation of a two-stage stochastic programming approach for integrated multi-energy system including the uncertainty of wind power production. Traditionally, the day-ahead scheduling is represented by a deterministic model where a day-ahead clearing is based on a single deterministic forecast. Deterministic models fail to capture the uncertainties in the integrated energy systems. On the contrary, the clearing can be based on the stochastic forecasts of the uncertain parameters, i.e. stochastic model. Stochastic modeling interacts between the day-ahead operation and real-time operation and includes a realistic range of scenarios. Stochastic optimization requires a large number of scenarios to be included in the optimization problem to obtain a realistic representation of all possible future states with their corresponding probability of occurrence. Figure 18 demonstrates the stochastic programming approach for DA schedule.

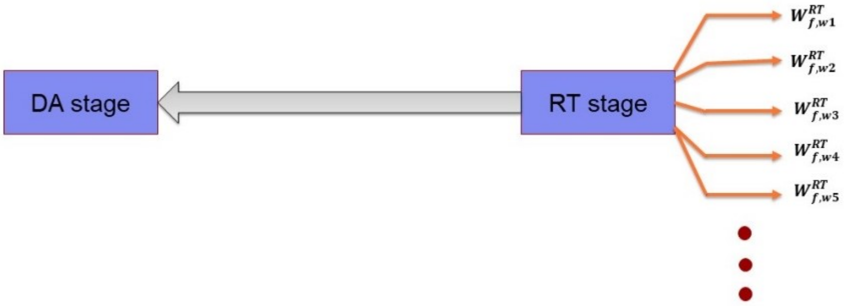


Figure 18 Principle of stochastic day-ahead schedule

The first stage, day-ahead stage, is a stage where operating points of generating units are determined and dispatched. The second stage is a real-time stage and includes a number of realizations and accommodates the uncertainties through reserves. Stochasticity of the uncertainty of wind power production is represented through realistic scenarios and assigned probabilities generated by scenario generation method. Scenario generation algorithm is based on historical observations and provides a more advanced approach to characterize stochasticity of wind power. To reduce computational burden, scenario reduction algorithm is executed. A schematic overview of the proposed SG method and the proposed two-stage scheme is shown in Figure 19.

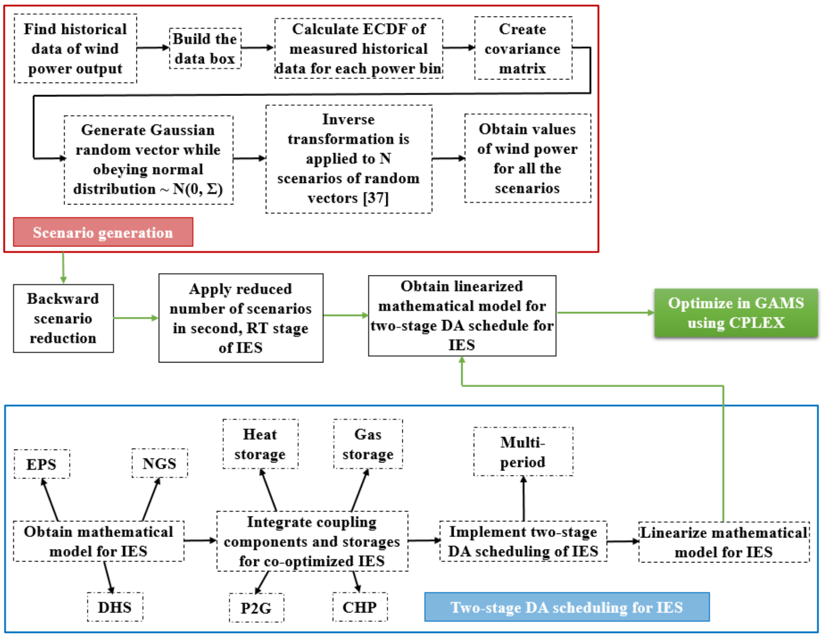


Figure 19 Overview of the proposed method and procedure for obtaining day-ahead scheduling results

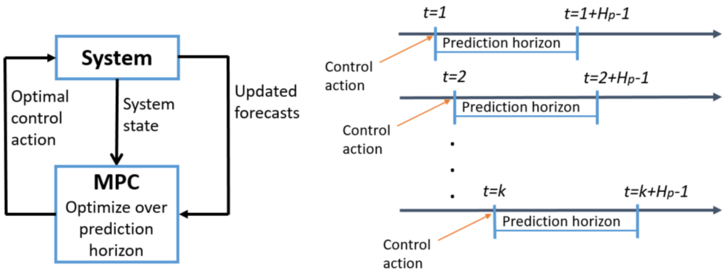
The stochastic programming obtains the optimal and efficient operating points for the next day while taking uncertainties into account. The proposed integration of multi-energy system and stochastic method indicate the improvements in efficiency, flexibility and security of integrated energy systems. As a result, total expected cost is reduced and reserves are optimized. The key findings of a stochastic day-ahead schedule are summarized at the end of the documents leading to a conclusion that the proposed method in is suitable for day-ahead scheduling approach and coordination and joint optimization and operation of several energy subsystems are promising for the future operation of the energy systems.

Optimal dispatch framework and online control algorithm for integrated energy systems based on model predictive control

As the installed capacity of renewable energy sources has been increasing, a mismatch between production and consumption is more frequent in the real-time due to the intermittent nature of renewable energy sources. Moreover, the day-ahead schedule is no longer the optimal and feasible solution for the real-time operation. Therefore, in order to settle the power imbalances in the real-time and to achieve energy efficient system, new solutions should be proposed.

In Denmark, the real-time balancing market is divided into regulating market and balancing market. Regulating market is used by Transmission System Operator (TSO) to purchase the regulating power. Usually, the conventional generators provide the upward and downward regulating power. In the balancing market, the imbalance settlement takes place. A TSO purchases the balancing power in order to compensate for the imbalance caused by the market players. The production imbalance settlements are handled by two-price balancing scheme, while the settlement of consumption imbalance is based on one-price settlement scheme. The mentioned characteristics are currently used for the real-time scheduling and settlement in Denmark. On the contrary to the traditional RT scheduling, an efficient method based on model predictive control can be used. Model predictive control method is forward-looking method which can provide the higher cost and energy efficiency compared to traditional method.

Thus, an optimal dispatch framework for real-time operation is designed based on model predictive control. Model predictive control is an online control applied for short-term dispatch. Based on the measured updated values, the future states of the system are predicted for a specified prediction horizon. Model predictive control makes the optimal scheduling for the current time step based on the measured updated values and future prediction of the uncertainties. Only the first step of the prediction horizon is applied. The principle of MPC is illustrated in Figure 20.



a) b)

Figure 20 a) MPC control strategy b) MPC principle

The real-time scheduling based on the model predictive control ensures the cost and energy efficient energy system while minimizing the deviation from the day-ahead schedule. Model predictive control aims to explore the possibility of energy storages to provide balancing energy, to reduce the operational costs in real-time, to increase flexibility by integration of various energy subsystems, to decrease the deviation from the day-ahead schedule and to increase the provision of reserves by P2G, electric boiler and heat pump.

The overall objective of the model predictive control strategy is efficiently scheduling of integrated energy systems in the real-time while updating the measured values and predicting a few steps in the future based on the obtained real-time measured values. Efficiently implies economic efficiency and flexibility increase while taking measured state and future information of the uncertainties into account. The key findings are summarized at the end of the document and can be verified in [2] and [3].

The model predictive control is performed through deterministic approach and stochastic approach. Stochastic model predictive control explores the flexibility and synergy of integrated energy system and investigates the benefits of stochastic model predictive control based real-time scheduling used in the integrated energy system.

Key Findings

The simulation results are divided into three parts and connected with the corresponding publication. The results of three simulation parts have shown the following.

1) **Integration of multiple energy system**
    - The synergy of different energy subsystems achieve the most optimal economic operation with minimum wind curtailment. Integrated energy systems achieve the lowest operational costs and minimum wind curtailment compared to operation of separated energy systems.
    - Flexibility is increased by integration of electric power system, natural gas system and district heating system
    - Natural gas can provide higher flexibility compared to district heating system. P2G and gas storage are the main flexibility sources in the natural gas system. In contrast, the heat storage is the main flexibility sources in the district heating system. The heat and gas storage strengthen the synergy of different energy subsystems in order to provide more flexibility.
    - The excess electricity from wind turbines can be converted to gas and heat by P2G unit which reduces the wind curtailment. P2G acts as a flexibility source in electric power system. With P2G, the flexibility of the system is increased and total system costs are lower.
    - Findings in [1].
2) **Stochastic scheduling of integrated energy systems**
    - Stochastic scheduling approach ensures the reserves are optimized and aims to reduce the expected system operational costs compared to deterministic approach
    - Stochastic approach in day-ahead considers larger amount of future possible realizations and leads to lower imbalance in the real-time compared to deterministic approach.
    - With coordination and joint dispatch of the energy and reserves in the day-ahead market, system costs are minimized, the flexibility increases due to synergy between multiple energy systems and efficiency and flexibility of the energy system are increased.
3) **Model predictive control**
    - The model predictive control based real-time scheduling provides the cost efficient and energy efficient solution for real-time scheduling. Economic efficiency and flexibility increase is provided by taking measured state and future information of the uncertainties into account.
    - The required computational time is acceptable with operational requirements and online application is possible
    - Model predictive control provides and explores the possibility of energy storages to provide balancing energy, aims to reduce the operational costs in the RT and increase flexibility while decreasing the deviation from the day-ahead planned schedule
    - It increases provision of reserves by P2G, electric boiler and heat pump
    - It is efficiently scheduling operation of integrated energy systems in the real-time while updating the measured values and predicting a few steps in the future based on the new updated measured values.
    - The model predictive control based real-time scheduling provides higher efficiency and flexibility to the system by introducing a higher prediction horizon taking into account larger part of future information. Moreover, systems with higher storage levels and a longer prediction horizon can provide higher economic efficiency and reduce wind curtailment.
    - The length of prediction horizon and time resolution are of great importance for model predictive control based real-time scheduling. The length of the prediction horizon should be selected based on the required computational efficiency and storage capacity in the system. Longer prediction horizon shows higher total cost savings in an integrated energy systems with larger storages.
    - In systems with higher storage levels, a longer prediction horizon can provide higher economic efficiency and reduce wind curtailment in the test system.

Finally, to conclude, the integration of multiple energy systems provides the flexibility needed for the future Danish energy system. Natural gas system and district heating system provide the flexibility for the future renewable based power system.

5.6 Real Time Demonstration and Recommendation

Denmark plans to satisfy 100% of Denmark's energy demand with renewable generation by 2050. Following this target, oil for heating purposes and coal are to be phased out by 2030. According to the energy scenarios for 2020, 2035 and 2050 from the Danish Energy Agency, in order to realize a fossil fuel independent Danish energy system in 2050, there will be a 400 MW wind power expansion annually from 2020 to 2050 in Denmark. It also implicates massive electrification within transport, industry and district heating. It will be a huge challenge to design and operate such an energy system in a cost efficient and secure way. Therefore, this working package aims to model the future Danish electricity systems and study the challenges on the future systems. Meanwhile, the coordinated operation, optimal dispatch and online control of the future Danish energy system are demonstrated in a closed-loop real time test platform in this working package.

The main objective of this working package is to demonstrate the coordinated operation, optimal dispatch and online control of the integrated energy systems. Operational scenarios will be selected according to the Danish future energy system. Real time tests are done to verify the efficiency and security of the developed coordination of electricity, heat and gas systems for optimal operation.

The development of the closed-loop real time test for the future Danish energy systems is performed in three steps, as shown in Figure 21.

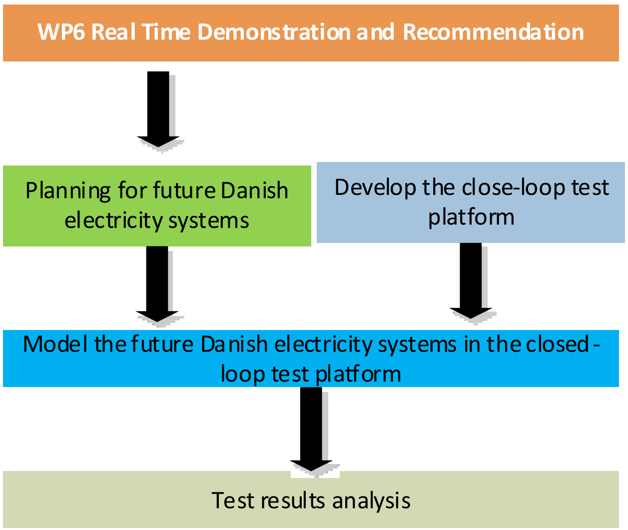


Figure 21. Steps in closed-loop real time test for the future Danish energy systems

The first step is modelling the 2035 and 2050 Danish electricity systems using planning method. The generations, demands, transmission networks and electricity linking lines with neighboring countries are considered in detail in the first step. The second step develops the closed-loop test platform based on the real time digital simulator (RTDS). The third step models the future Danish electricity systems in the RTDS to carry out the closed-loop test. The steps are described in details in the following subchapters.

Planning for future danish electricity systems

This working package will use planning method to model the 2035 and 2050 Danish electricity systems. The framework of the planning method is shown in Figure 21. The inputs of the planning method include the system data of 2020 Danish Electricity Transmission System and the hourly operational data. The system data of 2020 Danish Electricity Transmission System is public and provided by the transmission system operator of Denmark, Energinet. The hourly operational data is delivered by Aalborg University (AAU) under WP1 in this project. WP1 will design the 100% renewable based Danish energy system with power to heat (P2H) and power to gas (P2G) and the transition towards such a renewable based energy system. The results are created for 2025 and 2050 Danish energy systems from a macro point of view. This working package will use the macro results from WP1 to model the specific 2035 and 2050 Danish electricity systems. In this planning framework, the generations, demands, transmission networks and electricity linking lines with neighboring countries are included. According to the macro results from WP1, different scenarios can be generated as inputs for the planning method. As shown in Figure 22, 6 different scenarios are considered.

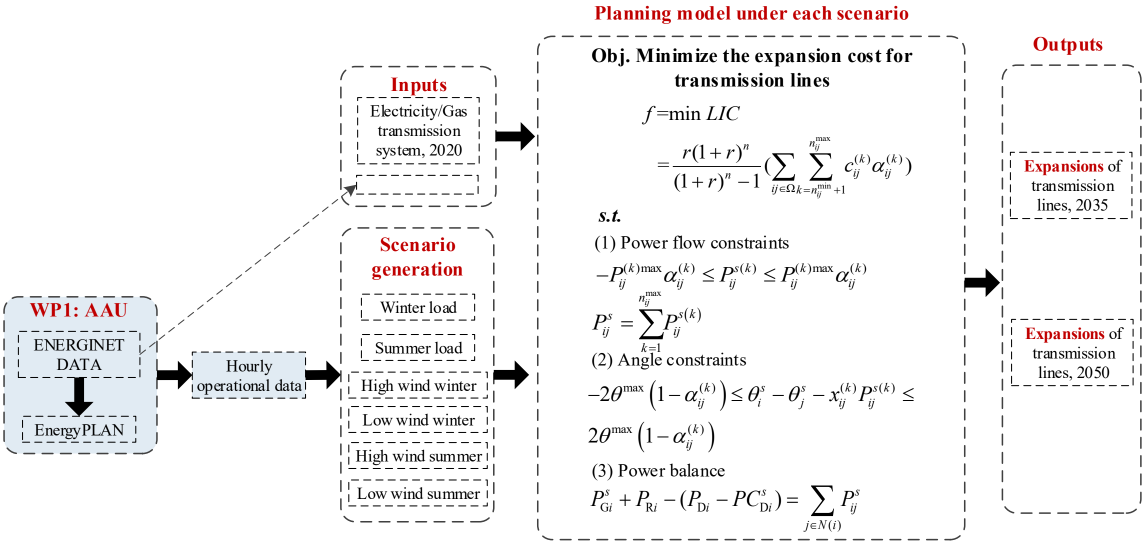


Figure 22. Framework of the planning method

Scenario 1: Winter load (maximum load during winter time);

Scenario 2: Summer load (maximum load during summer time);

Scenario 3: High wind winter (maximum wind generation during winter time);

Scenario 4: Low wind winter (minimum wind generation during winter time);

Scenario 5: High wind summer (maximum wind generation during summer time);

Scenario 6: Low wind summer (minimum wind generation during summer time).

Then the inputs and the scenario data will be used in the planning model. The objective of the planning model is minimizing the expansion cost for transmission lines for the 2035 and 2050 Danish electricity systems. The constraints of the planning model include power flow constraints, angle constraints, power balance at each substation, etc. The outputs of the planning method are the expansion results of the electricity transmission lines of the 2035 and 2050 Danish electricity systems. Based on the expanded electricity systems in 2035 and 2050, the energy goals set in Energy Agreement can be achieved.

Develop the closed-loop test platform

The closed-loop test platform is shown in Figure 23. As can be observed, the closed-loop platform is composed of hardware components and software control functions in measuring and adjusting variables that controls operation process. In the closed-loop test process, the input affects its output meanwhile it is directly or indirectly affected by its output. In the closed-loop system, the feedback information is obtained from the state of the system and is the basis for making decisions. The state of the system is adjusted by decision-making controls and this state will affects future decisions. Due to the large number of electrical devices, complexity of structure and long distances, it is not only expensive but dangerous to directly have test and experiment on the real electricity system. Therefore, most of the current experiment work related to the power grid often adopts the method of offline simulation. In the working package, the closed-loop test system will established with the RTDS and MATLAB optimal MPC based dispatch scheme, as shown in Figure 23.

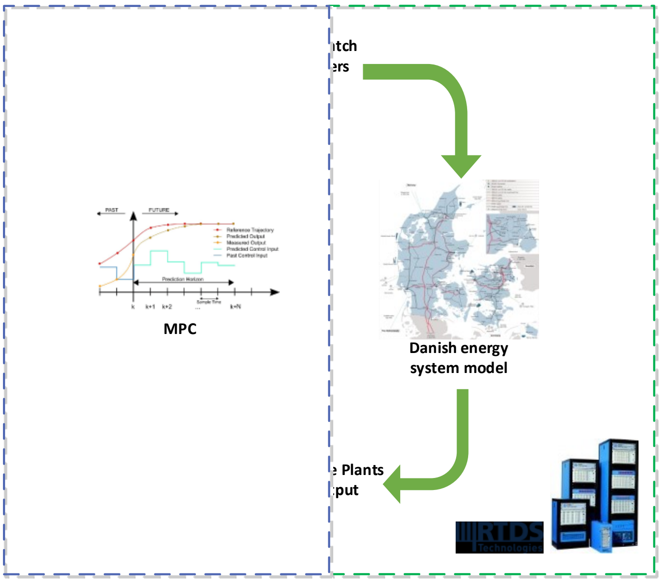


Figure 23. The closed-loop test platform

The interactions between software (MPC in MATLAB) and hardware (RTDS) in the closed-loop test platform are shown in Figure 24. In the first step, the MPC provide the optimal electricity dispatch by calculated the bids of supply and demand data from electricity market. Through TCP/IP protocol, the model of generation sets and loads in RSCAD model will operate as scheduling planned. In the operation of real-time power system, additional energy loss will inevitably occur in transmission lines and other equipment. Then, the flexible generators will act as balancing units to adjust the imbalance in the system. Meanwhile, the output of the flexible generators will be fed back to the controller as a variables, which will affect the entire system operation, to participate in the optimization calculation for the next step.

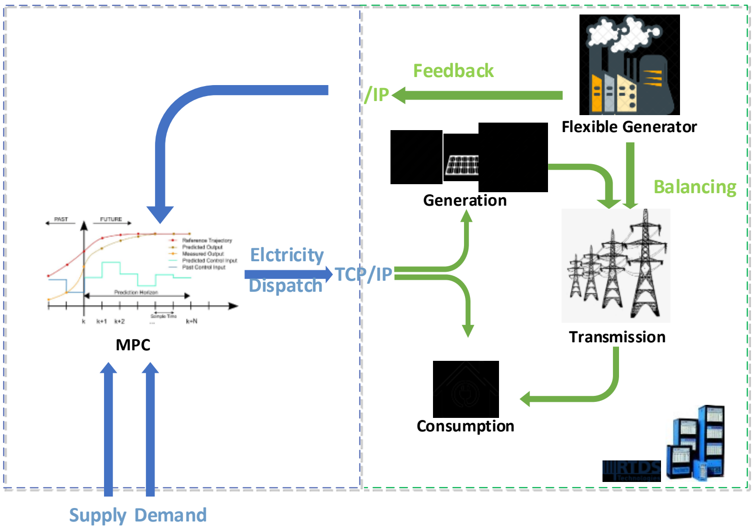


Figure 24. Interactions between software and hardware in the closed-loop test platform

MODEL THE FUTURE DANISH ELECTRICITY SYSTEMS IN THE CLOSED-LOOP TEST PLATFORM

In this working package, the closed loop test for the Danish 2050 transmission system will be presented. Based on the planning results obtained in the first step, there are 18 main-point 400KV buses, as listed in Table 2 and Figure 25.

Table 2. Main-point buses of 400kv of Danish 2050 transmission system

Main buses	Voltage (base: 400kV)	
	mag	angle
Vester Hassing	1.00	6.7
Ferslev	1.00	6.2
Idomlund	1.00	2.4
Tjele	1.01	3.7
Trige	1.02	6.7
Endrup	1.01	4.0
Revsing	1.01	3.6
Landerupgard	1.01	3.8
Kasso	1.00	2.3
Malling	1.01	5.7
Kingstrup	1.01	3.9
Fraugde	1.02	4.2
Herslev	1.01	2.6
Asnaesvaerket	1.02	3.1
Bjaeverakev	1.01	2.0
Ishoj	1.00	0.7
Hovegard	1.00	0.0
Gorlose	1.00	0.2

As can be observed from the planning results of the Danish 2050 transmission system in Table 2 and Figure 25, on the supply side, wind energy and import from neighboring countries are play an important role on meet the demand of electricity consumption, which, in the model with MPC, considered as a fixed output at each time step, while the biomass-based plants on the bus 5, 8 and 16 can be used as flexible power source to adjust the balance of the system. On the consumption side, each bus connected two different type of load, one is the regular load that represents the daily power consumption of basic use, the other is flexible loads like electric boiler, heat pump, etc.

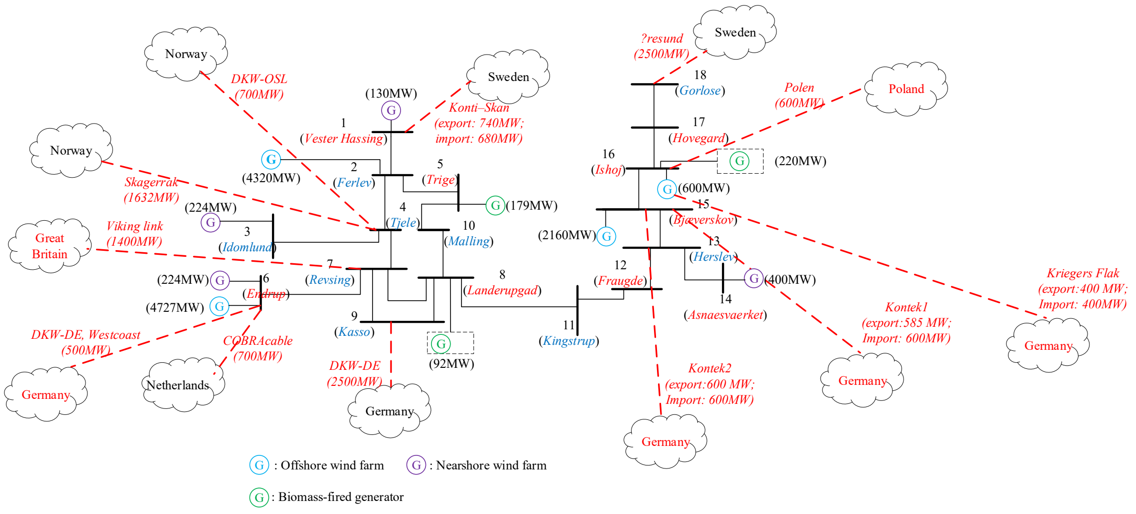
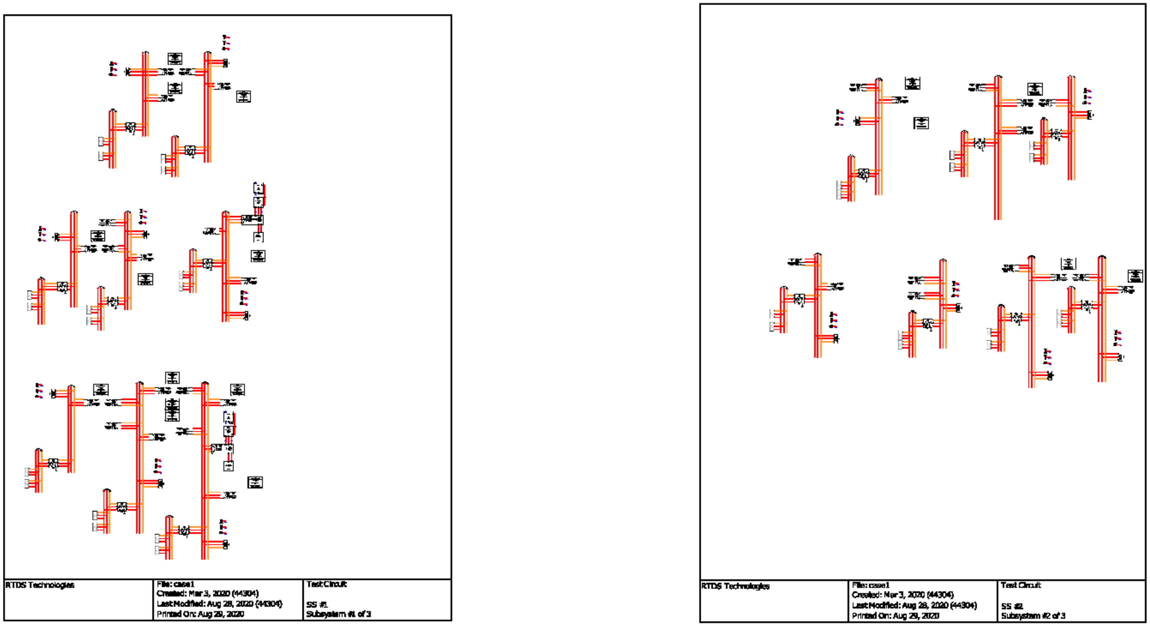


Figure 25. Single line diagram of the 2050 Danish Electricity Transmission System (400 kV)

Then, the 2050 Danish electricity system has been developed in RSCAD. The system is divided into three isolated subsystems, the simulation of which have been run simultaneously on three racks, as shown in Table 3. The three subsystems are shown in Figure 26.

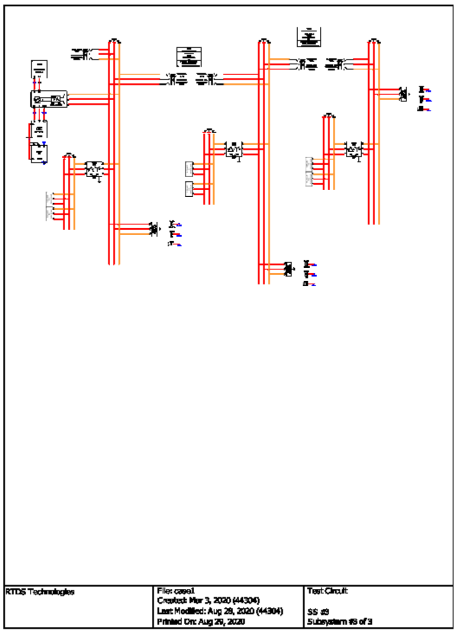
Table 3. Subsystems distributed in racks

Rack	Bus
1	1-8
2	9-15
3	16-18



Subsystem 1

Subsystem 2



Subsystem 3

Figure 26. Subsystems for the 2050 Danish electricity system in the RSCAD

Key Findings

The following conclusions can be derived based on the study in this working package:

(1) Planning for the future Danish energy systems

- The main difference between 2020 and 2035 Danish electricity systems lies in coal plant. Coal-fired power plants in Denmark will be shut down by 2035 to achieve the goal set in Energy Agreement.
- In order to reach the 2050 goal for a low-emissions society, around 7 GW more wind power will be installed compared to 2035 case. Therefore, more expansions are needed in the 2050 Danish electricity system compared to the 2035 case.
- The 2050 Danish electricity system is more dependent on the linking lines among Denmark and neighboring countries compared to the 2035 case due to the high penetration of intermittent wind power.

(2) Closed-loop test for the future Danish energy systems

- According to the closed-loop real time test results, the MPC based dispatch scheme delivered by WP5 are operationally feasible in actual power system. Therefore, the MPC based optimal dispatch and online control of the integrated energy systems for future Danish energy scenarios are verified based on the closed-loop test platform.
- There are slight differences between the dispatch results of the CHP plants in the closed-loop test and that in the MPC based dispatch scheme delivered by WP5. Since the objective of the MPC is to minimize the operational cost of the future Danish energy systems, and the operational cost of the CHP plants is much more than other power units, the CHP units are not dispatched in the MPC based dispatch scheme delivered by WP5. However, the CHP plants are dispatched in the closed-loop test to cover the system loss (e.g., losses in the windings of transformers due to resistive heating and magnetic losses caused by eddy currents, dielectric loss, corona discharge). This cases the differences.

Recommendations

The following points summarize the recommendations:

(1) Planning for the future Danish energy systems

- The expansion results of transmission lines are conservative because the flexibility from other energy vectors, e.g., natural gas system, heating system, transportation system, etc., are not considered. The electricity system can get cost effective flexibility by capitalizing on synergies and complementary advantages of the various energy systems. The expansions would be reduced by considering the flexibility, which will be studied in the future research work.

(2) Closed-loop test for the future Danish energy systems

- More and different scenarios could be used to test the integrated energy dispatch scheme, and some of the extreme conditions should also be taken into consideration.
- In the system model for the closed-loop test, only the 400kv power system has been represented. More sophisticated transmission and distribution network could be implemented, e.g., adding different electric nodes and transmission lines in the system model for the closed-loop test.

(3) Recommendations for reducing system loss

- Install reactive power compensation and improve the power factor of the electricity system. The system model in RSCAD has hardly used any compensation units. However, in actual power system, reactive power compensation devices should be installed both in the supply side and the consumption side to improve the power factor of the electricity system.

Replace the energy-cost equipment in electricity system. The resistance and reactance of the wire are inversely proportional to its cross-sectional area. Therefore, the resistance and reactance of the line with a small cross-sectional area are large, and its active and reactive power losses are considerably large under the same capacity load. Therefore, it is necessary to strengthen the grid structure and plan the transition of electric devices, e.g., replacing the old lines, small cross-section lines and high-energy-consuming transformers in the distribution network

6. Utilisation of project results

The project results can be used by the system operator, Energinet, for their future energy system planning and operation strategies. It can also be used by the decision makers for the long-term energy system roadmap for Denmark. The market design can be adopted by the Nordic market operator.

The business model can be used by the utility companies and Vestas for the operation and future product development.

Certainly, the participants made huge contributions to the research community regarding the energy system design and operation, P2G and P2H technologies, and integrated energy market design.

There are no commercial results developed in this project.

The projects results provide recommendation for realizing the future 100% renewable based energy system.

Two PhD students were educated in this project. The results of the PhD projects were disseminated through conference and ISI journal papers.

PhD student Anna Schwele participated in the teaching of the PhD course Advanced Optimization and Game Theory for Energy Systems.

PhD student Ana Turk participated in the teaching of the master course Real-Time Digital Simulation of Power Systems.

7. Project conclusion and perspective

Energy system scenarios considering P2H and P2G

The following summarises the main findings from each analysed focus area for energy system scenarios considering P2H and P2G.

Operational analyses:

Going towards increasing levels of renewable energy in the energy system results in decreasing yearly operation of the power and combined heat and power (CHP) plants, even in scenarios with a significant decrease in the CHP and power plant capacity. Even though the yearly operation of these plants is reduced, there are still hours where the full capacity of these units is needed, indicating that the value of these plants shifts from being the energy produced to instead be the capacity offered. As such, markets must adapt to this change in value, as a given capacity of CHP or power plant will require more income per amount of electric energy produced to cover the long-term marginal costs. Another option is to consider this as part of the support system or infrastructure needed in integrated renewable energy systems.

Transmission line capacity is found to be utilised more for the needs of the Danish energy system in 2050 compared to 2035, though the full capacity of the transmission lines is only utilised for needs in the Danish energy system in a small part of the year, especially in scenarios where the transmission line capacity is expanded.

Electrification:

Systems with low internal dispatchable power production capacity are more sensitive to external markets and external electricity prices. This is relevant in the discussions on future energy system electrification, as it is inherently connected to both internal electricity production capacity and transmission capacity, and as also has been the case historically it is expected that energy prices will fluctuate from year to year. Also, long-term predictions of energy prices have shown to be very uncertain, and as such, having internal dispatchable power production capacity reduces the effect of these uncertainties.

For the industry sector, direct industry electrification should be favoured over a fuel shift to hydrogen-based processes due to lower costs and higher system efficiency. Hydrogen should instead be prioritised for specific processes without alternative solutions, or where the value of local utilisation of bi-products is significant enough to make up for the extra costs for the energy system.

Electricity demand flexibility can contribute to increased integration of variable renewable electricity, though the effects of this are limited to the available capacity and electricity demand flexibility only allows the demands to be moved within a relatively short period of max. a week, and flexibility for longer periods is also needed. Uncertainties remain in relation to the actual achievable flexibility amount and the related investment costs needed; as such, there is a continued need for research on quantifying and realising this potential.

Li-ion batteries for grid-scale storage are infeasible based on hourly balancing, and should not be implemented with such a primary role. Li-ion batteries may, however, be useful for other purposes such as back-up capacity or for short-term balancing and frequency regulation, though other already utilised technologies could provide these services. From preliminary technical and economic assumptions, high-temperature rock bed storage seems feasible as a cheaper alternative to li-ion batteries for electricity storage. However, this needs to be verified in future models as improved technical data becomes available.

Heating:

Heat savings are found to be important both for reducing the total annual costs of the energy system but also to reduce the biomass consumption of the energy system. In relation to energy system costs the optimal level of heat savings was found to be approximately 32% compared with the average consumption per m^2 in 2010. This was analysed in the IDA scenario for 2050. Though the biomass consumption should also be considered in this respect, as to keep biomass consumption within sustainable levels. In the IDA scenario for 2050, going from 32% to 42% heat savings increases the total annual cost of the system by less than 0.2% of total annual costs but reduces the biomass consumption by about 3.5% of the total biomass consumption.

In relation to individual heating supply, electric-driven heat pumps should be used as much as possible for individual heating to keep the biomass consumption and the total annual cost of the energy system low. Individual solar thermal as a supplement heating supply can help reduce the use of biomass of the energy system, though its potential is limited due to its production mainly being in the summer period.

Individual heat storage technologies in connection with heat pumps and solar thermal can reduce the biomass consumption of the energy system, but only up to a certain point, depending on the amount of other flexible electricity demands in the scenario, though research has shown that from an energy system cost perspective only low-cost individual storage options should be considered.

District heating is found to be an important infrastructure in all the investigated energy system scenarios, as it allows collection and utilisation of otherwise discarded heat by distributing it to end-users. In the future district heating is expected to be mainly supplied by both large-scale heat pumps, excess heat from electrofuel production, geothermal, and CHP plants. The large-scale heat pumps and CHP plants are found to provide flexibility to the energy system, especially when heat storages are utilised.

For CHP and power plants high electric efficiency of the CCGT is found to provide the energy system with the lowest costs and lowest biomass consumption. Having internal flexible CHP or power plant capacity in the energy system makes it possible to reduce the total annual costs of the energy system, but as shown in other analyses also stabilises the total annual costs in relation to changing international electricity market prices. The use of large-scale CHP units instead of pure power plants is not a necessity for keeping the biomass consumption of the energy system at low levels, as long as the pure power plants are highly efficient and sufficient amounts of other low-cost heat sources for district heating, such as HPs, are available in the system.

Renewable fuels:

Biomass conversion technologies and electrofuels will have a crucial role in future energy systems, but it is also important that the biomass consumption is kept within the sustainable boundaries. Generally, producing any type of liquid or gaseous renewable fuels is more expensive and less efficient than electrification, so priority should always be given to electrification where possible. Electrofuels can supply the demands in the parts of the transport sector where direct electrification cannot.

Electrolysers used as part of producing electrofuels can provide a considerable potential for flexible for the electricity system, provided sufficient hydrogen storage exists. In this the optimal balance for the Danish energy system is found to be somewhere between 2.5 and 4 days of hydrogen storage combined with an electrolyser capacity of about 1.6-1.7 times the minimum needed capacity. The actual sizing depends on the need for electrofuels.

For the transport sector, it is found that liquid electrofuels provides lower energy system and fuel costs than gaseous electrofuels. Electromethanol has the lowest energy system costs, though the costs for electromethane is similar, but only until the cost of vehicles is added in the equation. Generally, methanol provides greater flexibility regarding storage and readiness to be upgraded to other fuels, namely jet fuels, which is a more complicated and energy-intensive process if it would be produced from methane. Fischer-Tropsch fuels may be an alternative if methanol-to-jet fuel pathways will not show sufficient technological maturity in the future.

Compared with producing CO_2-electrofuels, producing bio-electrofuels from biomass gasification results in significantly more biomass consumption in the energy system, but increases the efficiency of the energy system. Though both types of electrofuels are necessary for the future energy system despite the increased costs of CO_2-electrofuels as the fuels are limited by biomass availability and available CO_2-sources.

The results of the analysis indicate that syngas from biomass gasification can be a crucial fuel in combination with biogas both used for power, heat, or industrial purposes, at lower costs than electrofuels. Biogas should always have priority due to the lower cost, but since the agricultural sector outputs limit biogas, it must be complemented by syngas from biomass gasification. In addition, maximising on the use of lower-cost bio-electrofuels reduces the use of biomass for electricity generation, allowing the energy system to be more resilient to external electricity prices.

P2G and P2H technologies

In WP2 a new set of techno-economic data has been provided for the SOEC technology and the HTTES technology to be used in system models in WP1. The data was presented in Deliverable 2.1 and 2.2. Besides more basic works on understanding and improving the technologies has also been undertaken. This is detailed modelling of so-called AC-DC operation of SOECs, which is useful for dynamic operation of the technology with first results showing the opportunity to extend lifetime of the SOEC stacks with a lower cost as a consequence. Also the HTTES was modelled in greater detail in order to in the end understand partial loading and unloading better.

The next steps are to model the SOEC in connection with down stream processes to not only provide hydrogen, but other higher value products such as ammonia and methanol. The SOEC can with advantage operate even more efficiently with these technologies, outcompeting other electrolysis technologies. The potential of using the SOEC reversibly also deserves some attention as this then could be used as a giant flow battery for seasonal storage of e.g. methane. The HTTES system also need further investigation both techno-economically as well as technically. Especially the combination with mentioned SOEC flow battery and the dynamic operation of the system deserves some attention.

Market design

Existing bid formats in current forward electricity markets cannot accurately value certain types of flexible resources. To enable complicated flexible resources such as interconnected infrastructures to precisely represent their capabilities in electricity markets, WP4 proposes a new price-region bid format which allows the expression of any linearly-constrained feasible region of operation and convex piecewise linear cost function. A price-region bid can be straightforwardly derived from a linear operations model including continuous state variables. The price-region bid format generalizes existing bid formats such as price-quantity bids, as well as linear models of system assets, and is shown to be compatible with markets that rely on these mechanisms. We show that market clearing with price-region bids can be carried out as a linear program, and that important market properties hold under common assumptions.

In addition, the report of WP4 explores the capability of virtual bidding (VB) either by purely financial players (explicit VB) or by physical players like gas-_red generators (implicit VB) in improving the temporal and sectoral coordination in two-stage, namely day-ahead (DA) and real time (RT) electricity and natural gas markets under uncertainty. We use two models as benchmarks: a fully uncoordinated sequential model which achieves an upper bound for the total expected system cost, and a stochastic ideal co-optimization which provides a full temporal and sectoral coordination and yields a lower bound for the total expected system cost. The resulting models with VB are equilibrium problems, including the deterministic market-clearing problems in DA and RT in both power and gas sectors, and the two-stage stochastic optimization problems of virtual bidders, who maximize their expected profit. Our results reveal that competitive virtual bidders who have prefect insight into the probability distribution of RT prices in power and natural gas markets increase the efficiency of deterministic sequential markets, such that the resulting total expected system cost is between the lower and upper bounds. In our case study, it is illustrated that the inclusion of virtual bidding can result in an expected system cost that is very close to the lower bound. In particular, the explicit VB provides a temporal coordination of the DA and RT stages in power and natural gas markets. Moreover, self-scheduling and implicit VB by gas-fired generators bring both temporal and sectoral coordination. This implies that the sequential market with VB may approximate the stochastic ideal integrated energy system, and help reveal and exploit the existing flexibility in the systems more efficiently. The main policy implication is that a disruptive market re-design to a stochastic and integrated energy market might not be necessarily crucial for unlocking the existing flexibility. Instead, this can be done to some extent by allowing VB, while preserving the current sequential market-clearing setup.

Furthermore, this report introduces an integrated power-heat-gas dispatch accounting for the interactions of the three energy carriers and ow dynamics in an efficient manner using convex relaxations. This ideal benchmark shows the maximum potential of flexibility provided by the existing natural gas and heating infrastructure. We quantified the social value in terms of reduced total system cost that short-term operational flexibility from energy storage in district heating and natural gas networks can provide for the power system. This coordination of energy carriers is an inexpensive solution for increasing the flexibility of the system compared to investing in other storage options and grid reinforcement and interconnections.

Finally, this report provides and analyzes various local market design alternatives for local energy communities, ranging from non-cooperative to cooperative game-theoretic setups. In particular, this report explores market design alternatives that enable an access economy for energy storage systems. We observe that an access economy for such devices enhances energy communities by reducing the cost/revenue volatility of most prosumers. Each market design alternative ensures some desirable market properties, while jeopardizing some others. Therefore, there is not a certain market design that outperforms other alternatives. this report does not derive an absolute conclusion on which of the proposed market designs is more appealing. We rather provide a framework, which allows market regulators and policy makers to evaluate the implications of each market design for energy communities. The choice of a market design depends on the preference of energy community members, in particular, the magnitude of cost/revenue volatility they are willing to accept. In addition, it depends on which market properties are most attractive to members of a given energy community. Finally, the size of an energy community is a key factor in determining a market design, because the computational time significantly increases in case of cooperative market designs as the number of prosumers grows. One key finding of our analyses is that the expected community cost as well as the cost volatility of the whole community across scenarios representing uncertainty are independent of the local market design. Consequently, proposed local market designs do not affect the operational strategy of PV and energy storage systems, energy exchanges among prosumers as well as energy imports and exports to and from the energy community. However, what distinguishes various market designs is the cost allocation among energy community members, i.e., who pays to whom which amount of money. In case of non-cooperative market designs, the expected cost of each prosumer is unchanged over all non-cooperative market designs, though the cost distribution across scenarios is dependent on the market design in hand.

The cost volatility reduces when either PSRs or FSRs are available. In cooperative market designs the expected costs of individuals and the standard deviation of those costs change, depending on technologies belonging to prosumers as well as the number of energy community members. From a policy perspective we note that all proposed local market designs enable an access economy for storage systems. In all market design alternatives explored in this report, we find out that identical prosumers incur the same cost, which implies that no market participant will be discriminated. However, we hypothesize that energy storage owners may have a strong incentive for manipulating markets especially if there are only a few players in the community owning storage.

Therefore, a market mechanism should be resilient against potential market power to be exercised by storage owners. Note that exercising market power by storage owners is not a concern in the non-cooperative market design with FSRs as well as cooperative market designs. The reason for this is that in such market design alternatives energy storage systems are operated not by their owners, but by the energy community manager in favor of the whole community.

Optimal Dispatch Strategies and Online Control of Integrated Energy System

Integration of multiple energy system

The synergy of different energy subsystems achieve the most optimal economic operation with minimum wind curtailment. Integrated energy systems achieve the lowest operational costs and minimum wind curtailment compared to operation of separated energy systems. Flexibility is increased by integration of electric power system, natural gas system and district heating system Natural gas can provide higher flexibility compared to district heating system. P2G and gas storage are the main flexibility sources in the natural gas system. In contrast, the heat storage is the main flexibility sources in the district heating system. The heat and gas storage strengthen the synergy of different energy subsystems in order to provide more flexibility. The excess electricity from wind turbines can be converted to gas and heat by P2G unit which reduces the wind curtailment. P2G acts as a flexibility source in electric power system. With P2G, the flexibility of the system is increased and total system costs are lower.

Stochastic scheduling of integrated energy systems
Stochastic scheduling approach ensures the reserves are optimized and aims to reduce the expected system operational costs compared to deterministic approach. Stochastic approach in day-ahead considers larger amount of future possible realizations and leads to lower imbalance in the real-time compared to deterministic approach. With coordination and joint dispatch of the energy and reserves in the day-ahead market, system costs are minimized, the flexibility increases due to synergy between multiple energy systems and efficiency and flexibility of the energy system are increased.

Model predictive control
The model predictive control based real-time scheduling provides the cost efficient and energy efficient solution for real-time scheduling. Economic efficiency and flexibility increase is provided by taking measured state and future information of the uncertainties into account. The required computational time is acceptable with operational requirements and online application is possible. Model predictive control provides and explores the possibility of energy storages to provide balancing energy, aims to reduce the operational costs in the RT and increase flexibility while decreasing the deviation from the day-ahead planned schedule. It increases provision of reserves by P2G, electric boiler and heat pump. It is efficiently scheduling operation of integrated energy systems in the real-time while updating the measured values and predicting a few steps in the future based on the new updated measured values.

The model predictive control based real-time scheduling provides higher efficiency and flexibility to the system by introducing a higher prediction horizon taking into account larger part of future information. Moreover, systems with higher storage levels and a longer prediction horizon can provide higher economic efficiency and reduce wind curtailment. The length of prediction horizon and time resolution are of great importance for model predictive control based real-time scheduling. The length of the prediction horizon should be selected based on the required computational efficiency and storage capacity in the system. Longer prediction horizon shows higher total cost savings in an integrated energy systems with larger storages. In systems with higher storage levels, a longer prediction horizon can provide higher economic efficiency and reduce wind curtailment in the test system.

Energy system planning and closed loop test

(1) Planning for the future Danish energy systems

- The main difference between 2020 and 2035 Danish electricity systems lies in coal plant. Coal-fired power plants in Denmark will be shut down by 2035 to achieve the goal set in Energy Agreement.
- In order to reach the 2050 goal for a low-emissions society, around 7 GW more wind power will be installed compared to 2035 case. Therefore, more expansions are needed in the 2050 Danish electricity system compared to the 2035 case.

- The 2050 Danish electricity system is more dependent on the linking lines among Denmark and neighboring countries compared to the 2035 case due to the high penetration of intermittent wind power.

(2) Closed-loop test for the future Danish energy systems

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Recommendations

The following points summarize the recommendations:

(1) Planning for the future Danish energy systems

- The expansion results of transmission lines are conservative because the flexibility from other energy vectors, e.g., natural gas system, heating system, transportation system, etc., are not considered. The electricity system can get cost effective flexibility by capitalizing on synergies and complementary advantages of the various energy systems. The expansions would be reduced by considering the flexibility, which will be studied in the future research work.

(2) Closed-loop test for the future Danish energy systems

- More and different scenarios could be used to test the integrated energy dispatch scheme, and some of the extreme conditions should also be taken into consideration.
- In the system model for the closed-loop test, only the 400kv power system has been represented. More sophisticated transmission and distribution network could be implemented, e.g., adding different electric nodes and transmission lines in the system model for the closed-loop test.

8. Appendices

Project homepage:

https://coreproject-dk.com/

Technical Reports:

D1.1 Peter Sorknæs, Andrei David Korberg, Rasmus Magni Johannsen, Uni Reinert Petersen, Brian Vad Mathiesen, Renewable based Energy System with P2H and P2G

D2.1 Kabitri Chattopadhyay, Henrik Lund Frandsen, Techno-economic assessment of SOEC

D2.2 Yousif Muhammad, Kurt Engelbrecht, Henrik Lund Frandsen, Thermal Energy Storage Technologies and Cost Analysis

D3.1 Yifei Guo, Qiuwei Wu, Qing Zeng, Flexibility and Ramping Requirements

D4.1 Jalal Kazempour, Anna Schwele, Lesia Mitridati, and Niklas Vespermann, Market Framework Design and Business Model

D5.1 Ana Turk, Qiuwei Wu, Optimal Dispatch Strategies and Online Control

D6.1 Xiaolong Jin, Qiuwei Wu, Real Time Demonstration and Recommendation

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