Energistyrelsen

Slutrapport for projektet EUDP17-I: (12554) Sustainable Energy Market Integration

1. Beskrivelse af endeligt projekt

1.1 Project details

Project title	Sustainable Energy Market Integration
Project identification (program abbrev. and file)	EUDP17-I: (12554), området:Systemintegration
Name of the programme which has funded the project	EUDP
Project managing company/ institution (name & address)	Department of Sociology, Environmental and Business Economics, University of Southern Denmark, Niles Bohrs Vej 9, 6700 Esbjerg
Project partners	AAU (Aalborg University), SDU (University of Southern Denmark), DGC (Dansk Gasteknisk Center) and Rambøll
CVR (central business register)	29283958
Date for submission	30-06-2020

1.2 Short description of project objective and results

Denmark has set ambitious long-term climate and energy targets, e.g. elimination of fossil fuel in all energy sectors by 2050. In its development towards this target, the energy sectors are facing challenges to provide reliable, flexible, and competitive energy services to communities. Additional challenges involve the development and deployment of innovative, sustainable low-carbon energy technologies. One way to meet these challenges is to build on the interdependence of different energy carriers since that allows policy makers to introduce a higher share of renewable energy.

Energy system integration can provide the electrical system with more flexibility from the network perspective and more variable renewable generation can be accommodated. Meanwhile, the storages in different systems e.g. electrical, gas and heat could be further coped with each other. Existing utility-scale electrical energy storage (EES) excels in high efficiency, fast response and easy connection to the system while the gas/heat storage tanks are more cost-effectiveness and with higher energy density.

The purpose of this project is to investigate the future integrated energy system from the market perspective.

The results of the project can be found in Section 2.3 and 2.4 of the report.

1.3 Project objectives

This project is to build proper market mechanism for the wholesale market, short-term market and investment market for the efficient and sustainable operation of the future Danish energy system, concerning the resources and demand allocation, existing system infrastructure and emerging technologies, etc. This project mainly work on the wholesale market for the integrated gas and electricity systems, the short-term market for integrated energy distribution systems and the investment market for the energy system integration facilities.

Three working packages (WPs) are included. WP1 focuses on the interaction and unification of gas and electricity wholesale market. The objective of WP2 is to work on the dynamic management of flexible sources for the integrated distribution systems to participate in the short-term market. The objective of WP3 is to develop business models for the optimal investment of the emerging technologies to enhance the synergies between multiple energy systems.

Through these WPs, the major deliverable from this project will be the market models for the Danish energy system transition towards fossil-fuel free.

1.4 Executive summary

The energy market is going through a profound transition. First, the advance of energy conversion technologies facilitates the interdependency between different energy carriers, which will further enhance the interactions between the energy markets including natural gas, electricity, heating/cooling, transportation, etc. Secondly, policy incentive and public awareness on the sustainable energy promote the fast development and deployment of renewable sources across all the energy sectors. Thirdly, energy distribution systems play different roles when interfacing the transmission systems. Modern energy distribution systems act as prosumers with bi-directional energy conversion and as the new flexibility resources to support the transmission system operation.

Consequently, there is an urgent need to investigate the potential coordination of multiple energy systems under the market environment. According to the 'Single Market Progress Report' delivered by the European Commission, the integration of gas and electricity market in Europe has already delivered many positive results such as the declined electricity prices and enhanced cross-border energy trade. From Denmark's perspective, the domestic market mechanism for the future energy systems can provide energy consumers with price-competitive energy supply and encourage the consumers to participate actively in the market with demand response.

This project is a continuation of the ForskEL project “harmonized integration of gas, district heating, and electrical systems” (Project no. 12220). Mathematical tools and algorithms developed in the previous projects have been further advanced and validated in this project.

The project has been conducted as planned, and the following results have been obtained within different WPs:

- WP1.2: Individual models for electricity, natural gas, district heating system and coupling facilities have been built. Optimal operation strategies of the integrated energy system have been proposed.
- WP2.2: The core contents and the typical models for coordinating demand-side responses have been introduced. The coordination strategy of the integrated power and gas system via real-time pricing has been proposed. A two-stage stochastic optimization for the joint dispatch of energy and reserve with demand-side responses has been formulated.
- WP2.3: The integrated gas, heat and electricity system with flexible sources has been constructed. The optimal strategy of flexible source operations via real-time energy prices in the market has been proposed. An equilibrium model for simulating the behaviours of different energy system operators is proposed.
- WP3.1: Capacity optimization of the P2G plant in the integrated electricity and natural gas system has been proposed. The network expansion and co-allocation method with energy storage has been proposed.
- WP3.2: A co-expansion and planning strategy for integrated electricity and natural gas system has been proposed and validated by simulation with Western Danish power system.

It is expected that the project results can provide useful information to help policy makers and energy regulators in realizing the energy-political objective both at national and EU level. It is also expected to provide knowledge to the distribution system operators (DSOs) to optimally manage the flexible resources in their systems. With the phasing out of central power plants, DSOs are expected to provide regulation capacities to support transmission system operation. Under this circumstance, the DSOs can make profits in the regulation market with the expected results from this project. Besides, the planning tools in WP3 provide the system operators in multiple energy sectors with cost-effective ways to facilitate energy system integration.

2. Projektresultater

2.1 Overview of the project work package and their respective section reporting in the report

WP1 – Interaction and unification of gas and electricity wholesale market.	
WP1.1 – Modelling of the building blocks in the integrated gas and electricity systems.	Section 2.3.1
WP1.2 – Modelling the energy networks considering the different characteristics among gas, electricity and heating systems.	Section 2.3.1
WP1.3 – Interaction and unification of gas and electricity wholesale market.	Section 2.3.1

WP2 – Dynamic management of flexible sources for the integrated energy distribution systems to participate in the short-term market.	
WP2.1 – Identify the flexible resources in the integrated energy distribution system.	Section 2.3.4
WP2.2 – Coordinate demand responses in multiple energy systems with proper price signals.	Section 2.3.4
WP2.3 – Optimal management of the flexible sources in the integrated energy distribution systems.	Section 2.3.2 & 2.3.4
WP2.4 – Optimal bidding strategies for the integrated energy distribution systems to participate in the short-term markets.	Section 2.3.2
WP3 Business models for the optimal investment on the emerging technologies to enhance the synergies between multiple energy systems	
WP3.1 – Optimize the allocation and investment of the energy system integration facilities.	Section 2.3.3
WP3.2 – Network expansion strategy in coordination with device allocation.	Section 2.3.3
WP3.3 Comprehensive evaluation and quantification of the technical, economic and environmental cost-benefit	Section 2.3.3

2.2 Work package details

WP1 – Interaction and unification of gas and electricity wholesale market.

The gas and electricity systems are more and more coupled in recent years, with not only the increasing share of gas-fired generators but also the emerging power-to-gas technologies. Meanwhile, EU is targeting at unifying the gas and electricity market, which benefits the energy consumers with lower cost. This research aspect is to investigate the interdependency between and gas and electricity markets with emerging technologies like power-to-gas. Heating system, in this WP, will be considered as flexible demand due to its limited spatial scale compared to the gas and electricity networks.

WP1.1 – Modelling of the building blocks in the integrated gas and electricity systems.

A series of changes takes place for the building blocks of the foreseen future energy system. For example, the coal-fired central power plants (CPP) and combined heat and power (CHP) are being phased out and rebuild to biomass-fired. Technologies for wind and solar energy harvesting have been advanced rapidly in recent years. These changes will significantly influence the energy production, conversion and consumption in the future.

This task is to collect operational data from industrial demonstrations for a better understanding of the existing and emerging technologies in the IES. In addition to the technical evaluation, this task is also to further investigate the environmental performances. Current environmental management systems or criteria, such as the EU-EMAS Regulation or the ISO 14001, suggest mainly company-specific environmental indicators. In this task, the device-specific indices will be presented to quantitatively compare different technologies in the processes of energy production, transmission, conversion and consumption. Moreover, this sub-task will trace the interaction between different technologies, e.g. the carbon dioxide capture and storage (CCS) applied to CHP plants. WP1.1 enable the system design and operation to take not only economical profits but also emission into account

WP1.2 – Modelling the energy networks considering the different characteristics among gas, electricity and heating systems.

In most of the existing work, the steady-state network constraints of the energy networks are taken into account. However, such formulation neglects the distinguished characters. For example, bulk energy cannot be stored in electrical network. While in the natural gas system, the linepack storage in the pipes provides the system the majority of flexibility to ensure the secure operation. The transmission loss in the heat pipes is quite high so heating grid usually covers smaller area than gas and electrical networks. So there is a need for a unified modelling framework for different energy networks while taking their different characteristics into account.

In this task, the unified energy flow in natural gas, heating and electrical systems will be modeled considering the distinct characteristics of these networks. The gas and heating networks are modelled using quasi-steady-state models considering transient flows. Meanwhile, this task is to investigate technical issues regarding integration such as how much hydrogen could be pumped into gas pipelines according to the operating conditions of the natural gas system will be validated via field test and real-world demonstration. Regarding the power-to-heat solutions, the investigation to the thermal inertia of a district heating system will quantitatively reveal the thermal capacity and their demand from and contribution to the electrical system.

WP1.3 – Interaction and unification of gas and electricity wholesale market.

The gas and electricity systems are more and more coupled in recent years, with not only the increasing share of gas-fired generators but also the emerging power-to-gas technologies. Meanwhile, EU is targeting at unifying the gas and electricity market, which benefits the energy consumers with lower cost. At current stage, the gas and electricity systems are operated independently. And their wholesale markets are also independent.

This research task is to investigate the interdependency between and gas and electricity markets. Cooperative game and non-cooperative game between the gas and electricity market players will be investigated. The cooperative and non-cooperative gaming between the market players in gas and power system will be studied in this task. Emerging technologies like power-to-gas will be considered in the system. And the impact of significant penetration level of renewables such as wind and biomass will be investigated.

WP2 – Dynamic management of flexible sources for the integrated energy distribution systems to participate in the short-term market.

The coal-fired power plants in Denmark are phasing out in the near future. So the transmission system operator has to turn to new flexibility sources for regulation purposes. Modern energy distribution systems including gas and electricity have bi-directional energy flow with the transmission systems and can act as virtual power plants to support the secure operation of the system. So this WP mainly focuses on the distribution level of the IES to participate in the short-term market. WP2.1 is to identify the flexible resources in the integrated energy distribution system. Then WP2.2 is to coordinate demand responses in multiple energy systems with proper price signals. WP2.3 is to optimally manage the flexible sources in the integrated energy distribution systems. WP2.4 is to develop the optimal bidding strategies for the integrated energy distribution system to participate in the short-term markets in different energy sectors.

WP2.1 – Identify the flexible resources in the integrated energy distribution system.

The flexible resources in the energy distribution system is more precious and complex to manage. In power distribution system, less regulation devices such as dispatchable power plants, centralized energy storages, cross-border interconnections are no longer available. In gas and heating distribution systems, the pipes are thinner and shorter than those in transmission networks. So less capability to store energy in the pipes can be obtained.

To counter these challenges, this task is to identify the flexible resources in the integrated energy distribution system. These resources include batteries, aquifer thermal energy storage (ATES), gas storages, etc. To extend the flexibility assessment to multiple energy sectors, synergies such as electric boilers, power-to-gas, small-scale gas-compressors, etc. will also be considered. The key performance indices such as regulation capacity, response time and maximum ramping rate will be assessed under different operating conditions. With the flexibility for individual components quantitatively evaluated, this task provides the operational constraints for the management of flexible sources for the integrated energy distribution systems.

WP2.2 – Coordinate demand responses in multiple energy systems with proper price signals.

In addition to the controllable devices, the behaviours of the energy consumers in the energy distribution systems are more unpredictable. Demand-side management, or demand response has been more and more popular in recent years, especially in electricity sector. And demand response becomes the major flexibility source in the electrical distribution system. Besides, part of the heating demand can be shaded without reducing the comfort level.

This task is to coordinate the demand responses across multiple energy systems. First the consumer’s behaviour for gas, electricity and heating will be investigated respectively through historical data and questionnaires. Computational intelligence method will be used to model their behaviours and statistic models will be built. This task also takes into account the scenario with enhanced synergies that the consumers can determine themselves which energy source to use, e.g. to heat the water with electricity or gas. In order to enable the consumers to response as distribution system operators' wishes, proper price signals including electricity, gas and heating should be designed.

WP2.3 – Optimal management of the flexible sources in the integrated energy distribution systems.

With the previous 2 tasks identifying the flexibility sources and extracting consumers' behaviours, this task is to optimally manage all these flexible sources in an integrated way, considering the network constrains in different energy systems. In order to coordinate the above mentioned components providing flexibilities, the multi-time period optimization problem will be formulated for the optimal management of the flexible sources in the integrated energy distribution systems. decomposition approaches will be investigated to divide the large-scale optimization problems into several smaller ones which can be solved separately so as to enhance the applicability and scalability of the proposed methods. And the forecast errors of the renewables will be covered using robust optimization techniques.

WP2.4 – Optimal bidding strategies for the integrated energy distribution systems to participate in the short-term markets.

With proper management strategy, this task further is to propose the optimal bidding strategies for the distribution system operators in the short-term markets. Since the energy consuming pattern cannot be perfectly forecasted, a probabilistic model will be used to build the relationship between the profit and risk. The bids from other market participants will be simulated using samples from historical data. The proposed approach will be compared with assuming exogenous prices, uncontrolled flexibility sources to demonstrate the effectiveness and evaluate the market power of the aggregators.

WP3 Business models for the optimal investment on the emerging technologies to enhance the synergies between multiple energy systems

This WP investigates investment strategies and the business models for energy system integration facilities (ESIF). In coordination with the newly built facilities and devices, low-carbon network expansion strategy will be developed. Finally, the technical, economical and environmental cost-benefit will be quantitatively analysed to support policy-making.

WT3.1 – Optimize the allocation and investment of the energy system integration facilities.

This task is component oriented in the IES, mainly to decide the optimal allocation of energy system integration facilities. The revenue and operational cost (OPEX) model of ESIFs will be extracted from previous WPs. Financing and investment modelling will be investigated including capital expenditure (CAPEX) models and the associated financing schemes and investment deferral option values. Evaluation indexes will be proposed for decision making such as design indicators, operational indicators, etc.

The models of economic, financial and data flows in design and operation of an existing distribution system will be implemented for simulating the business operations in distribution grids; the interactions between the implemented models and the economic / business models of new devices and technologies to be integrated will be analyzed and modelled.

WT3.2 – Network expansion strategy in coordination with device allocation.

This task is network oriented in the IES, mainly about the network expansion planning. The existing network infrastructures have been deployed in the past following independent programs and separated ownership. Advanced coordinative approaches are needed in the IES. This task aims at the development of the next generation of network infrastructures via an integrated way across multiple energy sectors (gas, heat/cooling, electricity, etc.). A multi-objective, multi-stage, chance-constrained stochastic optimization problem will be formulated for the network expansion across the Danish energy system. The objectives include the investment cost, operational cost, energy losses, etc. Convexification and relaxation of the optimization problem will be applied to enhance the tractability. The uncertainties of the renewables will be embedded in the chance-constrains. Multi-stage optimization places different network enhancement in different years according to the future development of the Danish energy system.

WP3.3 Comprehensive evaluation and quantification of the technical, economical and environmental cost-benefit

This task is to comprehensively evaluate and quantification of the technical, economical and environmental cost-benefit. The trade-off between profit and decarbonizing will be quantitatively analysed to support policy-making in this task, taking technical constraints into account. A framework and implement a platform for low-carbon transition strategies will be suggested.

2.3 Project results and dissemination of results

2.3.1 Achieved results for Work package 1: Interaction and unification of gas and electricity wholesale market.

a. Modelling of the building blocks in the integrated gas and electricity systems.

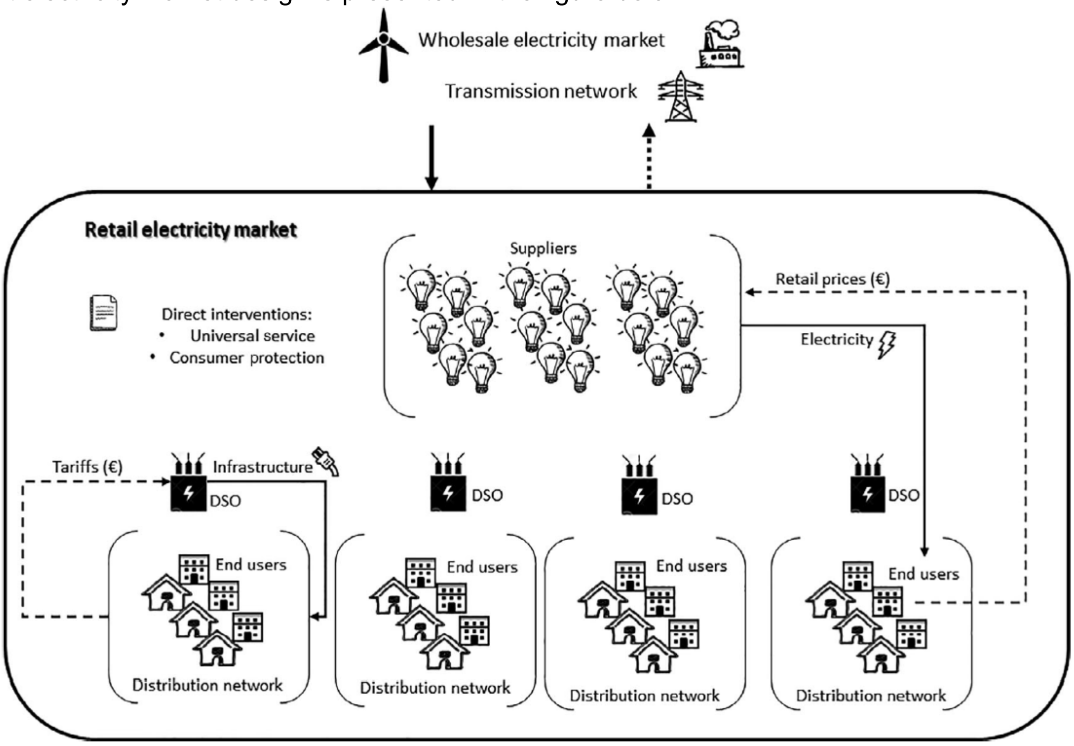
b. Modelling the energy networks considering the different characteristics among gas, electricity and heating systems

- Individual system models of electricity, natural gas and district heating system have been built respectively to characterize the operation process of each energy system.

- Models of key coupling components, including P2G facilities, CHP units, etc., have been built to integrate different energy systems.
- The dynamic optimal operation of the integrated electricity and natural gas system has been investigated to improve the wind power accommodation with the flexibilities from the natural gas system.
- The unit commitment of integrated electricity and district heating system has been solved to decrease the wind power curtailment using the flexibilities from the district heating system.

c. Interaction and unification of gas and electricity wholesale market.

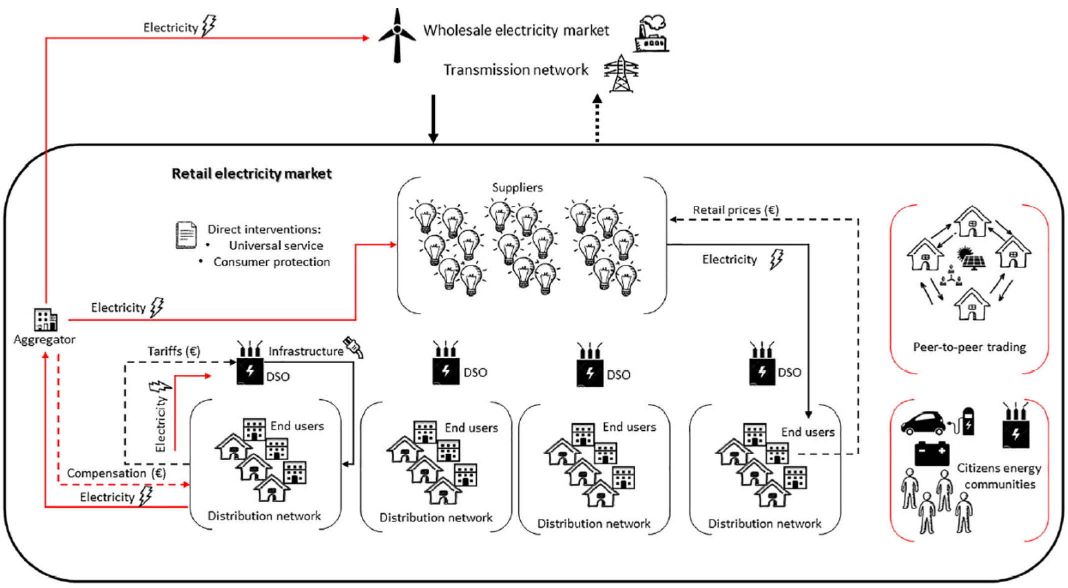
- We analyzed the EU retail market design in the context of the ongoing Green Transition toward a renewable-based energy system.
- The current electricity market design is presented in the figure below.



- The Clean Energy Package addresses the vertical–horizontal challenge as it allows traditional top-bottom transactions to coexist with bottom-up transactions, in addition to transactions between peers.
- Three conflicts arising from the implementation of the current EU retail electricity market design are identified: 1) fixed retail prices, which are allowed for in the current electricity directive, conflict with demand-side flexibility, 2) distribution network tariffs, which may be fixed, also conflict with demand-side flexibility, and 3) the introduction of retail price regulation (through direct interventions) distorts the transparency of the retail market and distorts the incentives for demand-side flexibility.
- Four conflicts arising from the joint implementation of the current EU retail market design and renewable energy policy are identified: 1) Tax and nontax levies used to fund renewable

support schemes reinforce the negative impact of fixed retail prices and fixed distribution network tariffs on demand-side flexibility, increasing the cost of integration of renewables into the market; 2) Support scheme funding—through surcharges on electricity bills—makes the business case for the electrification of mobility, heating, and cooling relative to fossil fuels less attractive for consumers; 3) Priority or guaranteed access of renewables to the distribution grid may conflict with quality of service and the equitable structure of distribution tariffs; 4) Priority or guaranteed access of renewables to the distribution grid, coupled with technological progress of storage, may challenge the economic viability of existing networks.

- Two main changes in the forthcoming electricity market directive are identified: 1) 1. Tasks of the DSO, and definition of new roles.
- A graphical summary of the forthcoming EU retail electricity market design with stylized transactions is presented in the figure below. Please note that in addition to the conventional "vertical" transactions where electricity flows from generators to end users via transmission and distribution networks, now "horizontal" transactions involving energy communities, aggregators, and peers are also present. It can be noted that large-scaled electricity customers can act as aggregators alone.



- The set of measures deals with the cooperative challenge, as it removes the legal barriers for market participants to associate and engage in mutually beneficial trades, see the figure on page 11..
- Remaining conflicts and complementarities after the forthcoming EU retail market design is Implemented are identified: 1) The conflict between fixed prices and demand-side flexibility is likely to be removed; 2) The clear framework given to Member States to assess the socioeconomic benefits of smart meter rollout continues; 3) The entitlement to a dynamic price contract and a smart meter (even if Member States do not rollout nationally) is a potential source of complementarity, as it enables customers to choose consumption efficiently; 5) An insufficiently coordinated effort in the design of distribution tariffs could still prove insufficient to enable demand-side flexibility and 6) While there is an initiative to remove price controls, Member States can choose not to remove them. Therefore, it is likely that price controls continue colliding with a more competitive and transparent retail market.

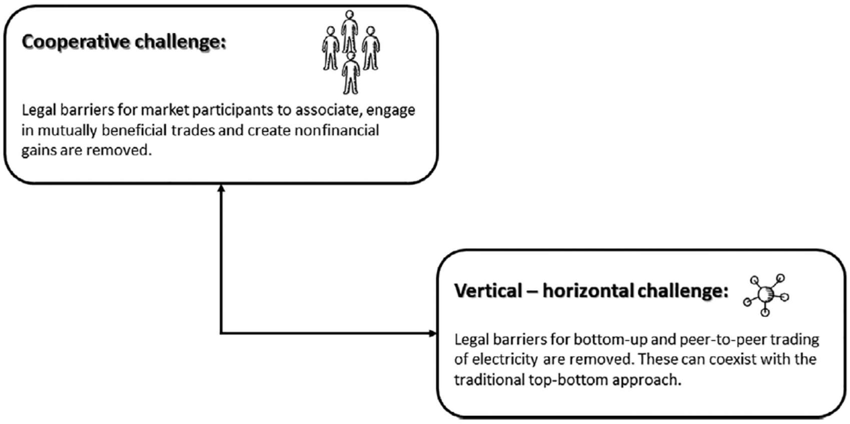


FIGURE 9 Key retail challenges addressed by the Clean Energy Package

- A dynamic game of complete but imperfect information to model the interaction and unification of Gas and Electricity Wholesale markets is proposed: 1) Game 1: Sequential market clearing (No cooperation between marketplaces) and 2) Game 2: Unified market clearing (Cooperation between marketplaces).
- In the sequential market clearing game, the two markets are cleared at different times. The order is: (1). A gas-fired power producer (Producer 2) places a bid to buy in the spot market for gas, where he obtains the gas to produce electricity. At the time of bidding, producer 2 is uncertain about an availability parameter a, which determines two things: i) how much the intermittent producer (Producer 2's competitor) can deliver to the power market, ii) how much electricity it will need to produce. (2) The gas-fired power producer places a bid to sell electricity in the electricity market. It is at this moment when the actual realization of a becomes known. Therefore, it participates in the electricity market over or under-supplied.
- In the unified market clearing (Cooperation between marketplaces) game, two markets are cleared simultaneously. (1) The supply forecast for the gas market s^g and the becomes known electricity market d^e becomes known; (2) The availability parameter a becomes also known and producer 2 becomes informed; (3) The gas-fired power producer places a bid for both electricity and gas. That is: (v_2^g, Q_2^g) in the gas market and (c_2^e, Q_2^e) in the electricity market; (4) The intermittent producer places a bid in the electricity market, i.e. $(c_1^e = 0, aQ_1^e)$; (5) A single transmission system operator runs an auction in which q_1^g, q_2^g and q_1^e, q_2^e are dispatched. This ensures that $q_1^g + q_2^g = s^g$ and $q_1^e + q_2^e = d^e$ hold. Prices p^g and p^e are determined as a result.

2.3.2 Achieved results for Work package 2: Dynamic management of flexible sources for the integrated energy distribution systems to participate in the short-term market.

a. Identify the flexible resources in the integrated energy distribution system

b. Coordinate demand responses in multiple energy systems with proper price signals

- The core contents and the typical models for coordinating demand-side responses have been introduced.
- The coordination strategy of the integrated power and gas system via real-time pricing has been proposed.
- A two-stage stochastic optimization for the joint dispatch of energy and reserve with demand-side responses has been formulated.
- The solution algorithms for optimization problems have been developed.

c. *Optimal management of the flexible sources in the integrated energy distribution systems*
- The integrated gas, heat and electricity system with flexible sources has been constructed.
- The optimal strategy of flexible source operations via real-time energy prices in the market have been proposed.
- An equilibrium model simulating the behaviors of different energy system operators has been proposed.
- The algorithms for solving optimization problems have been developed.

d. *Optimal bidding strategies for the integrated energy distribution systems to participate in the short-term markets*

- The focus for this work package is to investigate how residential dynamic taxation will be implemented in Denmark.
- 3 dynamic residential tax schemes on Danish electricity consumption are proposed.
- 2 per-unit (excise) and 1 Ad-valorem tax scheme are investigated and compared.
- Per-unit schemes respectively depend on electricity consumption and CO2 emissions.
- Assessment based on 6 categories is performed with the aid of simulation models.
- A fully dynamic excise tax depending on consumption is recommended.

2.3.3 Achieved results for Work package 3: Business models for the optimal investment on the emerging technologies to enhance the synergies between multiple energy systems

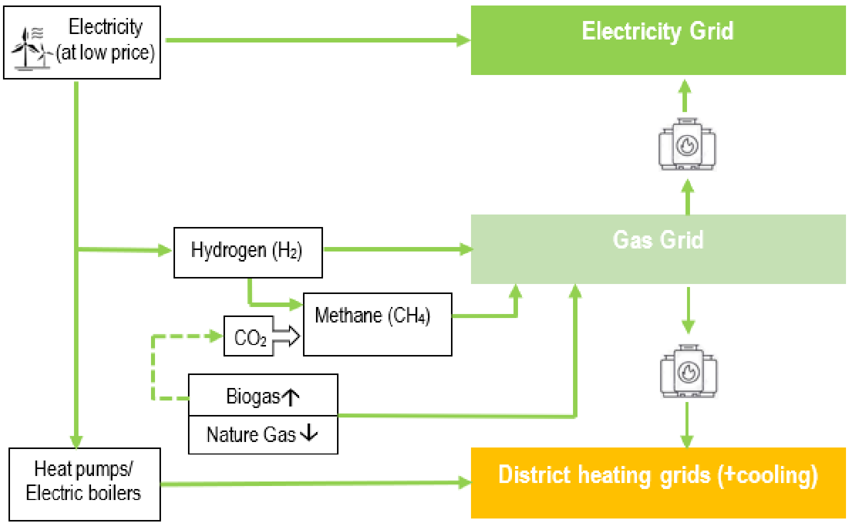
a. *Optimize the allocation and investment of the energy system integration facilities*
- An optimal allocation method of P2G plant in the integrated electricity and natural gas system has been proposed.
- The operation conditions and several important evaluation indexes of the integrated system have been compared and analyzed in the case.
- The network expansion and co-allocation with the energy storage method have been proposed with total investment and operation cost as the objective function.
- Benders decomposition method was used to decompose the problem and obtain the solution. Comparison in the case study has proven the benefit of the co-allocation with energy storage to help decrease the total cost and accommodate renewable energy.

b. *Network expansion strategy in coordination with device allocation*

- A bi-level optimization program has been formulated for the expansion and planning of the integrated electricity and natural gas system, in which the upper-level subproblem optimizes the investment cost and the lower-level subproblem optimized the operation strategy of the integrated system.
- A hybrid algorithm has been proposed to solve the bi-level programming which combined the modified particle swarm optimization (PSO) and the interior point method (IPM) to solve the upper-level and lower-level sub problems respectively.
- The proposed programming and algorithm has been validated in the integrated electricity and natural gas system in western Denmark. The results indicated that the proposed method is effective.
- Through the analysis of the results, it has been suggested that enhancing the integration of electricity and natural gas systems helps to overcome the challenges caused by the fluctuation of the increased wind power. More specifically, P2G can help to reduce the operation cost by decreasing the wind curtailment, gas fuel used and carbon emission.

c. *Comprehensive evaluation and quantification of the technical, economic and environmental cost-benefit*

- We estimated that that local district heating firms can play a significant role in maximizing the value of excess capacity of wind power when the tariff for electricity is decreased by 20%.
- If local district heating firms use the excess capacity of wind power as fuel source, the lowest annual CO_2 emission reduction for Denmark is about 20,300 tons while the highest annual CO_2 emission reduction is about 43,120 tons. However, the electrification (from wind power) of district heating sector cannot help decarbonization in the transportation sector.
- An integrated energy system towards zero carbon emission with large share of wind power is proposed, as displayed in the figure below. Please note that CO_2 in the figure can also come from waste-to-energy incineration plants and captured from atmosphere. In addition, heat from hydrogen production process can also be used for district heating and cooling.



- Cost-benefit analysis for three potential technologies to accommodating the high share of wind power in the energy system based on the technical, economic and environmental dimension were performed.
- Four geographic locations for potential power-to-gas(P2G) station using multi-criteria optimization were identified.
- A framework for implementing an integrated energy system is proposed. Results reveal that hydrogen fit the best for achieving the goal of 100% fossil fuel independent as it can contribute for decarbonization of the transport sector.

2.3.4 Integrated 4 Energy Systems for Efficiency and Sustainability

The following is a description of the work Ramboll has done in the project. In 2018 we presented a report on the integrated smart energy system together with a dataset of the Danish district heating grouped into 18 different systems. Later, in 2020, we presented an energy system model that simulates the Danish electricity and district heating system based on these data, where it was also shown how flexible taxes and tariffs can help integrate more renewable energy in the integrated system.

a. *The Integrated Energy System*

In [2], the relevant energy markets and technologies are described, together with their developments and need for new flexible energy services. An illustration of an integrated energy system is shown below, whose key concepts are explained next.

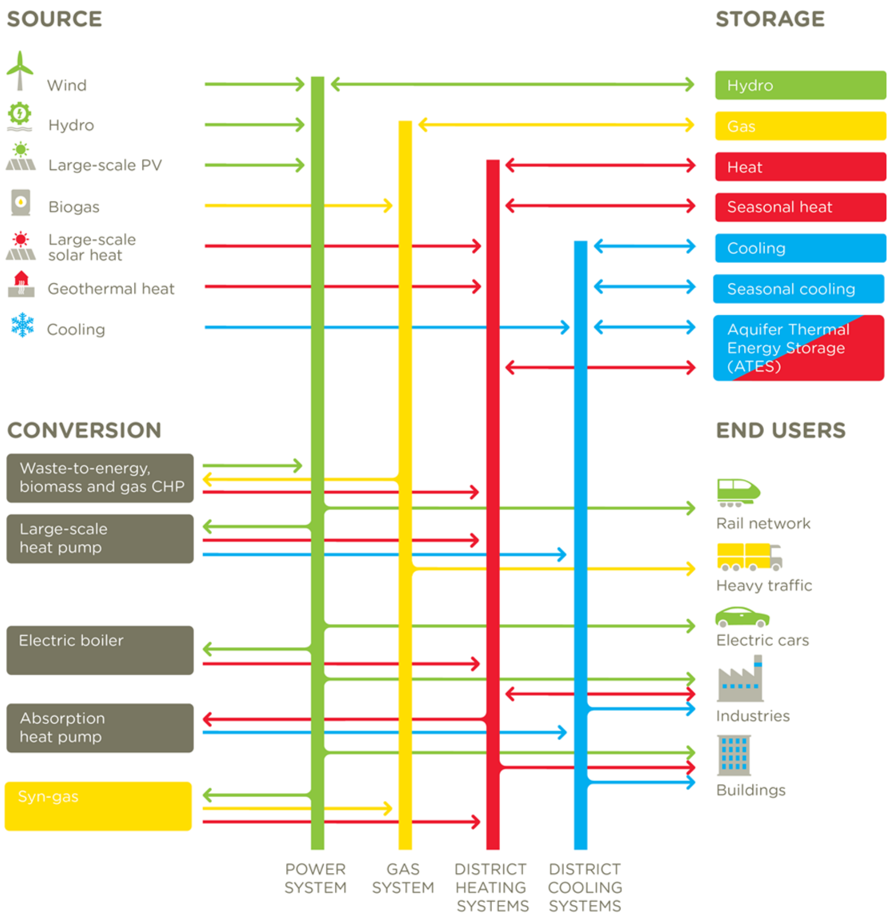


Figure 2-1: The integrated smart energy system

- **District heating system and the heat market in each network**
  A continuous development of district heating is required to achieve carbon neutrality in a cost-effective way. All district heating systems are operating and acting on the power and gas market on behalf of all the consumers, a technical aggregation, and striving to minimize

cost of operation and thereby maximizing the benefit (or profit) to the consumers n tems of lower prices. Inside each network there is a natural market place for heat production: for long-term contracts with private producers and for hour by hour operation taking into account costs from producers, and from purchase of fuels and electricity and sale of electricity (from own CHP). Moreover there is a market for capacity from peak boilers, as utilities purchase or rent available capacity in case it is profitable compared to investments in capacity.

Due to the ability of the district heating store heat efficient and to use electricity in electric boilers and heat pumps and to generate electricity with CHP, there is and can be a subatantial interaction between the district heating and electricity systems. This will increase VRES integration and efficient use of any surplus heat, which otherwise would be wasted. Moreover the ability to disrupt at any time using gas as back-up can reduce the need for investments in capacity in the power grid. Additionally, tank and pit thermal energy storages can be relatively inexpensive energy storage solutions. The expectation is that natural gas areas will be converted to district heating or individual heat pumps, biomass boilers or a hybrid solution. In summary, the following trends are foreseen: 1. Central coal-fired power plants are converted to biomass or mothballed; 2. Large solar thermal plants with heat storage pits is developed in small and medium-sized cities; 3. Large heat storage in the large cities; 4. Development of heat pumps, that co-produce cooling; 5. Geothermal heat delivering low temperature heat to heat pumps, but it may turn out that waste heat from data centers will be more competitive.

The district heating systems have traditionally been operated efficient as non-profit companies with the aim to minimize heat prices for consumers, which is the natural regulation as the companies are owned by the consumer and the municipalities acting on behalf of the citizens. Yet, there has lately been an ongoing discussion on how to regulate the district heating sector. While in a larger market such as the electricity market it can be argued that there are several advantages from liberalization, the same benefits will not necessarily happen in a district heating system, as the important parts of the market for which there is a market is liberalized. The utilities benefits form the market for all services for which there is a market, such as consultancy services, contractors, service companies, fuels, electricity and financing. The most prevalent idea is to co-optimize the operation of the district heating and electricity market in order to increase the VRES integration by utilizing the district heating systems more optimally. The technologies to improve the integration with the electricity system are heat pumps, electric boilers and CHP´s. Integration of renewable energy in the district heating system has so far predominantly been biomass and some solar heating. The fossil fuels continue to be replaced by biomass but the amount of electricity for heat pumps and electric boilers will presumably also increase. It is important to emphasize that the integration with the electricity system is dependent on how the electricity markets develop. Electricity markets, taxes and distribution tariffs need to be designed so that any electricity consumer/producer can be flexible in case it is profitable for the society. The district heating companies have the potential to act as very efficient flexible consumers.

- **District cooling system as an attachment to district heating**
  Although there are some operating small district cooling systems and projects undertaken in the major cities, district cooling is still at a preliminary development stage so it can be considered a part of the district heating sector. It was estimated that there is a cooling potential of 4,000 GWh-c in Denmark to be developed. From this, surplus heat can be produced and used in a nearby district heating system. Heat pumps can also use other heat sources when they do not deliver cooling and produce more heat. In addition to the economic gain, the advantage of developing district cooling is the integration of large-scale electric heat pumps in the district heating system, as investment and operating costs are shared between district heating and district cooling companies.

  The district cooling market is not regulated as a non-profit market (the supplier can therefore set the cooling price, so that it makes a profit), but the costs for the consumer are lower than for alternative individual cooling production. Because the district cooling market is small, there is not an ongoing discussion about changing any framework conditions. As the cooling market and the electricity markets are liberalized and strongly integrated with the district heating market, these two can be seen from the district heating market perspective. To sell electricity, the district heating company can for example invest in a gas engine. To sell cooling, the district heating company can similarly invest in a heat pump, a chilled water storage and district cooling grid. Thus, district heating and district cooling should be fully integrated.

- **Natural gas system and the gas market**
  Denmark has historically been self-sufficient with natural gas from the North Sea, but with few reserves left and with the upcoming renovation of the Tyra field, imports of natural gas from other countries are necessary for the first time. The amount of renewable gas is expected to increase slightly. This is biogas or synthetic natural gas. The gas system, with existing storages in Lille Thorup and Stenlille, can in the future act as a storage for VRES by power-to-gas (P2G) technologies. Yet, according to the forecast, there is still a significant need for fossil natural gas in 2040. In terms of the natural gas market coupling, the European Union is working towards creating an internal energy market (IEM) that connects all member states into a single liberalized natural gas market. A different approach from looking solely at the natural gas markets is to focus on energy system integration. It is particularly interesting from the electricity system to use the natural gas system to store renewable energy because the natural gas system does not require a constant balance between demand and supply. It is possible to use the gas cavern storages, line packing and transfer of gas to other areas. The most promising technology to enable this ability is P2G, where electricity is used to produce synthetic natural gas. Hydrogen (H_2) is produced from electrolysis, Carbon Dioxide (CO_2) is stripped from a source (say a biomass CCS plant) and by a methanation process synthetic natural gas (CH_4) is produced. The surplus heat from the CCS and the electrolysis can be used in the district heating system – the high-temperature part directly, the low-temperature part via heat pumps. Due to the CO2. Therefor the location of the P2G plants has to take this into

account. Location could e.g. be at the waste to energy plants, at which there is a constant emission of CO_2 and access to power grid, district heating grid and gas grid.

Producing electricity back from natural gas can be done using gas-fired power plants or a fuel cell technology. Furthermore, it is discussed that integrating the operation of the electricity and natural gas markets/systems in the future can lead to lower operational costs, better VRES integration and improved system operation by coordinating the two markets considering VRES production (uncertainty), system constraints, production facilities, gas storage and line pack and demand. The approach may be more interesting when P2G is developed and VRES production is much higher, instead of the current sequential market structure.

- **Electricity system and the electricity market**
  The Danish electricity system is changing from a central system with conventional thermal condensing- and CHP plants to a decentralized system based on wind and solar power and smaller CHP plants. To ensure a high security of supply when domestic conventional production capacity is reduced, and to develop a common European electricity market, new power cables are built. According to the Danish Energy Agency's expectations, the increased electricity consumption from heat pumps, electric boilers, data centers and electric vehicles must be covered by higher output from VRES. The Danish Energy Agency's expectation is conservative based on the existing framework conditions. Therefore, the production from VRES may well be higher. In summary, the following trends are foreseen: 1. Large central power plants are decommissioned, mothballed or converted to biomass with reduced power capacity; 2. Wind turbines and solar cells gradually replace the conventional power plants; 3. The number of individual heat pumps and large-scale heat pumps and electric boilers increases and enables a more flexible electricity consumption: 4. Several large data centers are being built and according to Energinet.dk will be responsible for about 10% of the electricity demand by 2025; 5. Electrification of the transport sector is stagnant; 6. New transmission lines will be built and the existing ones expanded.

  Developing the electricity markets so more VRES can be integrated is a hard task. So far, the development has been focused on liberalizing and coupling electricity markets across countries in the EU. Yet, the markets are still developing. To integrate VRES, a change in the market framework conditions may also be needed. From an energy system integration perspective, not only electricity markets are needed, but also variable distribution tariffs and changes in tax payments. All evidence suggests that instead of sectoral suboptimal solutions, system integration is preferable. Electricity markets are required, but the sectoral focus must be shifted to an energy system perspective.

We also introduced and discussed the need for changes in the structure of taxes, subsidies and distribution tariffs for the energy carriers, as the structure of the markets may be changed, but the development will likely still be driven by politically agreed changes in the framework conditions. The question is how to design the framework conditions for the cheapest renewable energy transition.

Lately, the discussion has been on changing the electricity tax to incentivize large-scale heat pumps and electric boilers. Likely, it will be just another temporary solution before, yet another tax or subsidy must be adjusted. Instead, the solution may be that the socio-economic preferences are reflected in the markets. For the energy sector, the best solution is to tax emissions (and maybe land-use) and not tax or subsidize technologies. For example, a CO_2-tax that is high enough to spur a development that puts on track to keep global mean temperature at a reasonable increase. In that regard, it is easy to conclude that the existing CO_2-quota system is not working. Instead, a CO_2-tax that continuously can be adjusted is better than a CO_2 quota system. Were the CO2-tax high enough, the development of wind and gas would presumably happen by market forces.

Another question is how the electricity distribution tariffs should be adjusted. The electricity grid is and will be the main distributor of energy. Thus, it is important that the right price signals are sent to consumers and producers of electricity. The electricity tariffs should provide a good signal of how much load is on the local distribution grid and wind in the system. Currently, the tariffs are typically fixed over the day, but the future demand patterns may not follow that of today. Electric vehicles, heat pumps and electric boilers can react more flexibly in relation to VRES production, but also the local grid congestion. Thus, the right price signals not only come from electricity markets but also from smart tariffs.

b. *Energy System Model Simulation*

Building on the energy integration measures listed in [2], in [3] a new approach is taken to model the combined electricity and district heating systems in more detail. It is recognized that the main interaction is between electricity and district heating in the Danish context, while district cooling is of second priority but still important as electricity for district cooling can respond to market prices and paves the way for large heat pumps for combined heating and cooling. Although the gas will play a minor role for supply of energy for heating, the gas infrastructure will still play an important role to provide back-up capacity for heat and power.

A model that simulates the optimal operation of the integrated electricity and district heating system in Denmark has been developed. It is based on a unit commitment mathematical formulation. The Danish heating system is grouped into large, medium and small towns, with a total of 18 zones. The electricity system is represented by the two electricity market zones in Denmark; DK1 and DK2. The system is simplified by a DC model with each zone being a copperplate. Historic demand profiles and solar and wind profiles are scaled for future projections of annual demand and installed renewable energy capacity. The following input data is included in the model: 1. Generation unit data (efficiency, capacity, O&M cost, fuel, etc.); 2. Network data (transmission capacities between electric zones); 3. Hourly electricity and district heating demand profiles; 4. Renewable energy electricity production profiles; 5. Fuel prices, taxes, CO_2 quota prices, tariffs, etc.

A selected investigation of flexible taxes and tariffs was presented. The modelling analysis showed how flexible electricity tariffs and taxes may help to better integrate renewable energy by allowing heat pumps and electric boilers to operate more. The result of the analysis demonstrates how the district heating system alone and in particular together with the natural gas system can integrate the fluctuating wind energy as if it was a huge electric battery – a virtual battery. The result also demonstrates how to improve the resiliency of Denmark in a smart way by combining flexible demand on a large and cost-effective scale via district heating and district cooling systems and with back-up from the gas system.

To improve the results and the model, the following can be included: 1. Inclusion of neighboring countries; 2. Include modelling of the district cooling and the natural gas system with storage capacity; 3. Include individual hybrid heating solutions (heat pump + natural gas boiler); 4. Integration of additional heat storages, chilled water storages, heat pumps and electric boilers; 5. Inclusion of P2X, taking into account use of surplus heat for district heating and storing methane in the natural gas system for later use in CHP plants.

2.4 Project dissemination

The project results have been disseminated in several ways. Detailed information are presented below.

2.4.1 Project meetings

During the project period, kick-off meetings, regular project meetings, project operational meetings were held to ensure the progress of the project, disseminate the research project and get feedback from academic and industrial partners. The meetings have been held at Department of Sociology, Environmental and Business Economics, University of Southern Denmark; Aalborg University and Rambøll in Copenhagen.

A project advisory board (PAB) were formed at the beginning. Members of the project advisory board include Syd Energi A/S, Gaspoint Nordic, Offshore Danmark, Accelerace, Energginet, Aalborg University, Danish District Heating Association and SDU RIO. On the same day of annual project meeting, PAB meeting was held. The PAB meeting is to report the project status, discuss the completed project results as well as obtain feedback from the PAB members.

2.4.2 Publications

A. Journal articles

1. Shu K, Ai X, Fang J, Yao W, Chen Z, He H, Wen J, “Real-time subsidy based robust scheduling of the integrated power and gas system,” *Applied Energy*, vol. 236, pp. 1158-67, Feb. 2019.
2. W. Gan, X. Ai, J. Fang, M. Yan, W. Yao, W. Zuo, J. Wen, “Security Constrained Co-planning of Transmission Expansion and Energy Storage,” *Applied Energy*, vol-239, pp. 383-394, Apr. 2019.
3. Y. Xi, Q. Zeng, Z. Chen, H. Lund and A. J. Conejo, “A Market Equilibrium Model for Electricity, Gas and District Heating Operations,” *Energy*, May. 2020.
4. Albertsen, L. H., Andersen, M., Boscán, L. R., & Santos, A. Q. (2020). Implementing dynamic electricity taxation in Denmark. Energy Policy, 143, 111543. doi:https://doi.org/10.1016/j.enpol.2020.111543

5. Boscán, L. R. (2020). European Union retail electricity markets in the Green Transition: The quest for adequate design. WIREs Energy and Environment, 9(1), e359. doi:10.1002/wene.359

B. Conference papers

1. J. Fang, Q. Zeng, X. Ai, Z. Chen, J. Wen, "Dynamic Optimal Energy Flow in the Integrated Natural Gas and Electrical Power Systems," *IEEE Power and Energy Society General Meeting*, Portland, OR, USA, AUG. 2018.
2. K. Shu, X. Ai, J. Wen, J. Fang, et al, "Optimal Energy Management for the Integrated Power and Gas Systems via Real-time Pricing," *IEEE Power and Energy Society General Meeting*, Portland, OR, USA, Aug. 2018.
3. K. Hu, J. Li, X. Xu, W. Hu, Q. Huang, S. Xu, D. Xu, Z. Chen, "Optimal Planning of P2G Plant in Integrated Electricity and Natural Gas System," *IEEE Innovative Smart Grid Technologies-Asia (ISGT Asia)*, Chengdu, China, May. 2019.
4. Y. Xi, J. Fang, Z. Chen, H. Lund, et al, "Integrated Flexible Resources and Energy Markets in the Danish Multi-energy System," *IEEE Innovative Smart Grid Technologies - Asia (ISGT Asia)*, Chengdu, Sichuan, China, May. 2019.
5. Y. Xi, J. Fang, Z. Chen, H. Lund, et al, "Integration and Coordination of Flexible Resources in Multi-energy Systems," *IEEE PES General Meeting*, Montreal, Canada, Aug. 2020.
6. X. Wu, Z. Chen, J. Fang, "Unit Commitment of Integrated Electricity and Heat System with Bi-directional Variable Mass Flow," *IEEE Power and Energy Society General Meeting*, Montreal, Canada, AUG. 2020.

C. Workshop presentations

1. Boscán, L. "Reconciling Renewable Electricity subsidies with flexibility amid the Green Transition", Workshop on Present Energy Transitions: The multiple dimensions of energy scarcity and current risks, Oso, Norway, 23-25 Apr. 2018
2. Yang, Y. "How can wind farms maximize the value of excess capacity? A case study from Denmark", Workshop on Future Energy Transitions in the Nordic states and beyond, Temper, Finland, 18 – 20 Oct. 2018

D. Reports

1. Yang, Y. "Evaluation of the technical, economic and environmental cost-benefit of integrated energy system in Denmark". University of Southern Denmark, 2020
2. Thomsen, S., Dyrelund, A. Energy Market and Technologies, Report for EUDP sustainable energy market integration, Rambøll, 2018.
3. Thomsen, S., Dyrelund, A., Juarez, V. Integrated 4 energy system for efficiency and sustainability.

E. Papers under review

1. Ma. L., Yang, Y. Solgaard, H. & Yu, J. "When wind blows too much - an investigation on integrating excess capacity of wind energy", Energy Research and Social Science.

3. Project conclusion and perspective

Modeling of integrated energy systems has been proposed with the characterization of the operation process of each energy system. The coordination strategy of demand response and the optimal management of flexible resources with real-time pricing have been investigated. Besides, the integrated expansion and planning scheme have been proposed to build a more integrated energy system.

This project facilitates energy system integration and brings economic benefits to DSOs, TSOs, consumers, etc. Meanwhile, it promotes social awareness with disseminations. The applicants intend to apply for further funding to carry out site demonstration.

Dato: 29 June 2020	Underskrift:

Underskrives af den der tegner virksomheden, der hermed bekræfter rigtigheden af ovenstående oplysninger.