Towards Fully Renewable Energy Systems - Experience and Trends in Denmark

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***Abstract*—Deployment of renewable energy generation capacities and integration of their power production into existing power systems has become a global trend throughout the world, with a common set of operational challenges stemming from variability and limited predictability of power generation from, e.g., wind and solar. Denmark is a country that invested early in wind energy, rapidly proposing very ambitious goals for the future of its energy system and global energy usage. While the case of Denmark is specific due to its limited size and good interconnections, there may still be a lot to learn from the way operational practice has evolved, also shifting towards a liberalized electricity market environment, and more generally going along with other technological and societal evolution. Our aim here is to give an overview of recent and current initiatives in Denmark which contribute towards a goal of reaching a fully renewable energy system.**

***Index Terms*—Renewable energy integration, Energy markets, Flexibility, Coordination, Integrated energy systems.**

I. INTRODUCTION

RENEWABLE ENERGY deployment and integration can be seen as a global phenomenon, as numerous countries around the globe are investing massive efforts to support this trend, with motivations ranging from abating climate change's negative effects, security of energy supply, etc. Renewable energy is often seen as a cornerstone in our move towards a more sustainable future [1]. The literature on challenges related to the integration of renewable energy generation is vast and growing at a rapid pace, covering a wide range of technical topics ranging from power system operation and control, to more economical, environment and societal topics in connection with the economics of change, life cycle assessment of renewable energy projects and social acceptance of distributed energy generation projects. A good starting point to have an overview of challenges related to wind power in power systems is [2]. In contrast, it might be more difficult to find literature that tells about how renewable energy integration is seen in practice and supported with a number of initiatives, from adaptation of electricity markets to deployment of new components in the power system, but also of regulatory nature. A notable exception of an overview of wind power integration studies is that in [3] (and follow-up publications), also aiming to propose best practice guidelines when designing and reporting on such complex system studies. In this context, we place emphasis here on the case of Denmark, a Scandinavian country with long-lasting experience in integrating wind power generation into its energy system, also with very ambitious objectives of having its energy supply (for electricity, industry, transport and heating) fully covered by renewable energy by 2050 [4]. Recently, the IDA Energy Vision 2050 was published to provide an extensive coverage of scenarios and projections for residential electricity, industry, heating and cooling, as well as transport [5].

The Danish situation is often seen as propitious to the integration of renewable energy generation in view of its limited peak load (app. 6.5GW), substantial installed generation capacities (nearly 15GW) and a strong interconnection to neighboring countries (7.2GW as of 2015), with additional interconnection projects in the pipeline (e.g., with two new links to Germany and the UK, agreed upon in Spring 2016). An overview of such interconnections is given in Fig. 1 as of 2014, with the Skagerrak link to Norway upgraded to 1.7GW in 2015. A complete description of the current electricity and gas systems in Denmark, as well as plans for their future development, is available in [6]. This situation contrasts with the opposite case of the Iberian peninsula for instance, with a substantial peak load to be satisfied (up to 49.3GW) and limited connection to the remainder of the European power system, through the 2.8GW France-Spain interconnector.

However, reaching a fully renewable energy system is not only a matter of electric infrastructure, and we place here emphasis on these other aspects that matters, from market mechanisms that adequately support renewable energy integration, to stimulating and operating available flexibility (demand response, electric vehicles and storage, synergies with gas and electricity systems), and finally to having a more holistic view of energy production and consumption in a smart city context. After first giving a brief overview on history and current status with deployment of renewable energy generation capacities in Denmark in Section II, the paper describes in Section III the electricity market and power system operational framework allowing to run the Danish power system with high shares of renewable power generation. Current challenges and foreseen changes are discussed. Subsequently in Section IV, emphasis is placed on the idea of getting the demand side to contribute to the integration of renewables, by motivating, operating and rewarding flexibility in consumption, the so-called demand response. Initiatives to promote demand response were naturally generalized to smart cities considerations, since having

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Fig. 1. Interconnection to the Danish power system as of 2014. In 2015, the Skagerrak transmission facility connecting Denmark and Norway was upgraded to 1.7GW. (source: Energinet.dk).

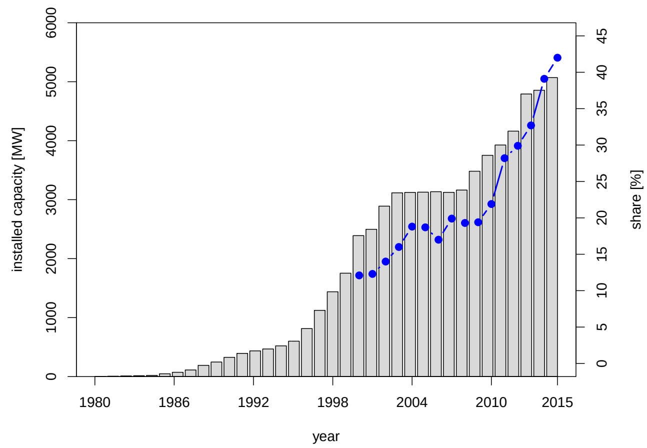

Fig. 2. Evolution of installed wind power capacities as well as wind power penetration in Denmark (source: Energinet.dk).

to look more broadly at varied types of electric consumption and their specifics e.g. for transportation, as well as opportunities provided by dense urban environments. Eventually, this leads to think of synergies between energy carriers or energy systems, which we present in Section V. There, the case of gas and heat are discussed in the Danish context. Other recent considerations relate to the case of hydrogen and synthetic gas. We present our concluding remarks and perspectives in Section VI.

II. Brief History and Status of Renewable Energy in Denmark

When thinking of renewable energy in Denmark, one clearly has wind power in mind, since that country pioneered in using wind energy to meet its electric power consumption. This originates from a choice in the 1970s to invest in this solution to support abatement of CO_2 emissions. The Danish model is fairly unique, as it has historically been one of the most successful countries in terms of supporting deployment of wind power generation capacities. Starting from 1979, the capacity increased steadily, only halted for a little period in the early 2000s, see Figure 2. Looking towards the future, major wind power developments are planned mainly in the form of medium to large offshore wind farms (several hundreds of MWs each) and through the repowering of older onshore wind farms. As of today, wind power is supplemented by non-negligible solar power capacities, nearly reaching 800MW at the end of 2015.

The successful deployment of capacities and subsequent integration of renewable energy generation is part of a broader evolution from a centralized to a decentralized setup for power generation in the country. This decentralization process means that, while Denmark had a limited number of relatively large power plants in the 1980s and 1990s, the power generation landscape rapidly evolved with the deployment of distributed generation capacities, obviously including wind turbines, more recently solar panels, but also Combined Heat and Power (CHP) plants. These latter ones have the additional advantage of coupling heat and electricity systems which, as will be discussed later in this paper, also brings opportunities to accommodate renewable energy generation, with its fluctuations and limited predictability.

For those interested in an exhaustive analysis of the Danish energy system and its evolution over the last two decades, the latest (i.e., for 2014) overall statistics about the Danish energy system are available in [7], giving a broad overview of generation mix, evolution of capacity by type, consumption by sector, etc.

III. From Electricity Markets to Power System Operation

A. The Liberalization Process and Current Market Conditions for Renewable Energy Sources

Scandinavia was one of the first regions of the world to liberalize its electricity sector (both generation and retail), after The Energy Act of 1990 which layed the ground for the deregulation process in the region. We mention Scandinavia and not Denmark only, since the electricity market is a regional one. With the deregulation of electricity markets also happening in other European countries, all those markets are getting fully integrated yielding a number of operational and financial benefits, see e.g., [8]. The market operator for Scandinavia, now also covering other countries, e.g., UK and the Baltic countries, is Nord Pool[1].

European electricity markets, such as the Scandinavian one, are primarily composed of a forward allocation mechanism, the day-ahead market, and of a balancing mechanism allowing to settle deviations from day-ahead schedule. Day-ahead markets are organized as zonal markets, hence only considering transmission capacity limitations between market zones. These

[1]nordpoolspot.com

are to be seen as financial markets anyway, while the link to power system operations is made by communicating energy production and consumption schedules to the various system operators. When reaching the balancing stage eventually, market-based operation is taken over by the system operators over their respective balancing areas. Accommodating renewables in such a deregulated environment is known to yield a number of operational problems (see, e.g., [9]) while support mechanisms and market designs should evolve accordingly [10].

Wind power producers were originally remunerated based on feed-in tariffs in the 1990s, i.e., a fixed price per MWh generated. They eventually got to participate in the electricity market as conventional power producers. This triggered a number of studies on the impact of wind power generation on market prices and market dynamics, see e.g., [11], [12]. Those concluded that, due to very low marginal costs and inherent variability, wind power generation induces a downward pressure on wholesale electricity prices. However, it is not as much the energy actually produced that impact prices than generation forecasts. This is since the day-ahead market is cleared long before operations (12 to 36 hours), hence requiring wind power offers to be based on predictions. An extensive overview of the policy measures, as well as their impact, to support wind power in the Danish electricity market, can be found in [13]. While wind power is the dominant renewable energy source in Denmark, solar power generation is now becoming non-negligible. Support conditions, as well as impact on electricity markets, are qualitatively similar to the case of wind energy, though with a time delay.

If jointly looking at day-ahead and balancing market mechanisms, these penalize renewable energy producers since day-ahead revenues are eventually decreased due to balancing costs stemming from deviations from day-ahead schedule (in connection with forecasting errors). However, this penalization can also be seen as an incentive for renewable energy producers to improve their forecasts, since intuitively, a decrease in forecast error should readily lead to higher revenues. In practice, the situation is quite more complex as originally hinted by [14]. In Denmark a two-price imbalance settlement is used, meaning that only those that contribute to the system imbalance are to be penalized. As an example, a wind power producer who produce more than expected, while the overall system requires extra power to get back to balance, will not be penalized and receive the day-ahead price for each and every MWh in surplus. This asymmetry in balancing penalties may then work as incentives for renewable energy producers to offer in a more strategic manner, even though understanding and predicting system balance and related penalties naturally is a difficult task. In addition, owing to the significant renewable energy penetration in Denmark, offering strategies may definitely affect market outcomes, either since a single producer is a price-maker, or through population effects as actual production, information and its processing, are necessarily dependent for those renewable energy producers. For a discussion on those aspects, the interested reader is referred to [15]. Finally, while these market mechanisms act as an incentive to decrease energy imbalances on a per-market-unit basis, i.e., hourly, these do not concern the sub-hourly fluctuations in power delivery, which may eventually yield increased needs for ancillary services to accommodate these power fluctuations. Some have recently argued for mechanisms that would allow for a transparent attribution of these ancillary service costs to all actors of the power system, including renewable energy producers, hence laying the ground to support new business cases for flexibility providers, e.g., storage and demand response [16].

B. Links to Operational Aspects and Foreseen Challenges

Electricity markets, both day-ahead and balancing, function based on energy blocks to be delivered or consumed over hourly market time units. Since a constant balance between generation and consumption is needed, schedules obtained through electricity market clearing cannot give a complete overview of power system operational schedules. In practice, the hourly schedules from Nord Pool are translated into 5-minute operational schedule to be transmitted to the TSO [17]. In addition, in order to insure reliable and economic operation, the TSO is to purchase ancillary services, e.g., reserves, which may then be activated to accommodate imbalances. These are purchased before energy is traded through day-ahead market, to prevent conflicts between short-term capacity reservation for system services and energy exchanges. With increased renewable energy penetration, this approach to operation is challenged. One may intuitively think of co-clearing reserve and energy, and to generalize market mechanisms in a stochastic optimization framework, so as to accommodate variability and uncertainty in renewable power generation [9]. Already, the Danish TSO, in concert with other Scandinavian TSOs, has taken a proactive stance when it comes to balancing operation, since power system reserves are deployed preventively and in a regional coordination framework. In practice, provided that transmission capacity is available, the Danish TSO may for instance readily profit of flexible and relatively inexpensive hydro capacities in Norway to balance the power system in Denmark.

Still, as for the case of many system operators worldwide, flexibility and consideration of a finer resolution in operation is a key to accommodating high-frequency fluctuations from both wind and solar power generation. Large Danish offshore wind farms may have power swings in the order of 100MW within a few minutes, hence requiring availability and adequate operation of flexible balancing units. Flexibility in power system operations is a general concern in relation to renewable energy integration, see e.g., [18], [19].

Both in markets and in operations, forecasting of renewable energy generation is of utmost importance. Denmark was one of the first country to invest heavily in developing forecasting methodologies and to integrate forecasts in operational practice, already from the early 1990s. While renewable energy forecasting attracted little interest worldwide at that time, the literature is expanding steadily, with many new proposals with novel models and usage of new data types (remote sensing, weather forecast information, etc,) being proposed every year. For recent state-of-the-art in wind and solar power forecasting, the reader is referred to [20], [21] and [22], respectively. These developments are generally directly translated to operational solutions made available on a commercial basis, by some of the numerous forecast providers that flourish around the globe. Still today, many challenges remain in renewable energy forecasting, stemming from the increasing quantity of data being collected, number of sites to be considered, variety of data to assimilate in forecast methodologies (e.g., from lidars and weather radars for wind energy, and from sky imagers for the case of solar power), etc. An overview of these challenges as well as proposals for better integration of forecasts in power system operation is given in [23]. Maybe the most relevant of these challenges is to optimally estimate forecast uncertainty, in a dynamic and conditional manner, and to then account for such uncertainty information in operational problems.

IV. Flexibility in Electric Power Consumption

Higher shares of wind and solar energy in the energy mix translate to increased needs for backup generation, or storage, for those times with low power generation, as well as increased flexibility to cope with variability in power generation, and re-dispatch in case of forecast errors. Flexibility in power system operation is high in Denmark, thanks to those interconnections, but also thanks to those CHP plants, whose level of flexibility was improved over the years through various technology upgrades. Consequently, in principle, Denmark may not be seen as a country where flexibility in electric power consumption, and hence demand response, is the most necessary and most valuable to power system operation. However, flexibility in electric power consumption is seen as a potentially new degree of freedom in power system operation, being also relatively cheap or at least competitive with other flexibility options in terms of operational costs, while requiring limited investment costs. In addition, integration of renewables has supported a move towards electrification of, e.g., transportation (electric vehicles) and heating sectors (heat pumps). Therefore, it might be beneficial to optimize flexible operation of new consumption patterns in a market environment. Deployment of new electric consumption means embracing renewable energy policy is an important component of a future fully-renewable energy system, see e.g., [24], [25].

Demand response presents a large number of opportunities and challenges, which would be too many to discuss here. For an overview of those, the reader is referred to [26] and references therein. In order to learn about the deployment process, market design, operational aspects, as well as social aspects of demand response, one of the world largest demand-response research and demonstration experiments was initiated in 2011 on the Danish island of Bornholm, located nearly 40 kms off the South coast of Sweden. The EcoGrid EU[2] project involved nearly 2000 households and small businesses, to take part in a market-based demand response experiment. The hypothesis of the project was that electricity markets could evolve so as to issue prices that would optimally support and control demand response, by taking advantage of the dynamic and conditional elasticity of demand. In practice, this conditional dynamic elasticity links to thermal inertia of buildings, flexibility in charging patterns of electric vehicles, etc. An overview of the EcoGrid EU market architecture is given in [27], while it is illustrated in Figure 3.

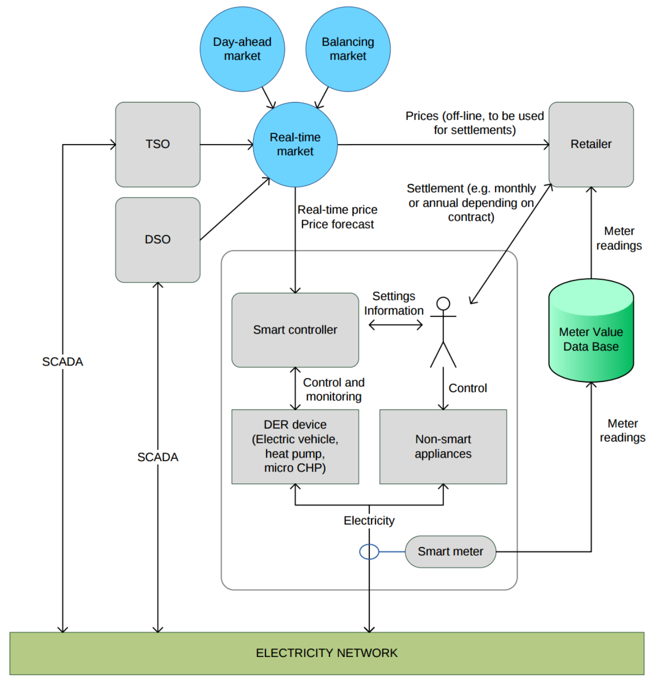

Fig. 3. Complete architecture of the EcoGrid EU experiment, combining control aspects to emulate demand response, market concepts to operate it, as well as metering and settlement aspects (taken from [28]).

The real-world experiment was organized in several phases. The first one was to be seen as an open-loop experiment to basically assess if and how the control systems deployed (and aggregators) were being responsive to modulation of electricity prices. This revealed to be a difficult task, though allowing to validate the price-responsiveness of most of electric loads involved, while providing a first quantification of the balancing that could be providing by demand response through such a market [29]. Subsequently, the second phase consisted in a closed loop experiment, where the market would be regularly cleared based on forecasts of the conditional elasticity of the electric loads, then accounted for in the market clearing algorithm. This second phase ran for a period of nearly 9 months and permitted to gain practical experience on market-based demand response. An extensive analysis of the market setup and results, also considering remaining challenges in underlying concepts and implementation, is gathered in [30]. Some key figures include achieving a peak flexibility of 21.6%, as well as a 8.6% increase in integration of wind power generation. In parallel, the most important conclusions related to the need to improve forecasts to be used as input to market clearing, as well as to the thorough consideration of cross-elasticities (i.e., temporal dependence) in demand response. Finally, a third phase of the experiment concentrated on evaluating the possibility to support congestion management with market-based demand response. That part revealed that, even though demand response could help, difficulties to pre-

[2]eu-ecogrid.net

dict localized demand response potential for small groups of electric loads, combined with the inherent uncertainty in such response, was potentially tampering the viability of demand response as a practical solution.

V. Smart Energy and Smart Cities

Further than flexibility in electric power consumption only, an approach to accommodating further renewable energy relates to a more holistic view of the energy system, flexibility in interfacing with e.g. heat and gas, as well as its role in the more general context of smart cities. These acknowledge the fact that an increasing share of the population live in cities, while modern means of data collection, communication and processing, allow for better control, operations and planning of energy, transportation, etc. also in a more integrated manner. For the specific case of Denmark, we first consider synergies between electricity and gas, then with the heating system, while finally describing and discussing a real-world smart city development in Copenhagen, its capital city.

A. Potential Synergies with Gas

Gas-fired power plants (GFPPs) comprise one of the main power generation technologies nowadays and they are expected to have an even more prominent role in the future energy system. One of the main reasons for that will be the transition to an environmental friendly energy system. GFPPs are characterized by fast ramping ability, as well as better efficiency and reduced emissions compared to other thermal power plants. These characteristics make them an ideal choice for the transition to a green energy system, especially if we take into account the potential of using green gases (e.g., biogas and synthetic gas) in the following years. For this reason, the interaction among the energy systems and especially between the electrical and gas networks is expected to increase. On top of that, the utilization of power-to-gas technologies will help this interaction to flourish.

Loose coupling among the electricity, gas and heat systems already exist, as many players (e.g., GFPPs, CHP plants etc.) interact with more than one of them. In countries and regions where these interactions have been noticed, some initial steps towards the coordination of the individual systems were made, but as the interaction increases, more issues have to be solved. For example, ISO New England that depends heavily on GFPPs to cover heat and electricity demand faced significant difficulties to operate the power system in days with high heat and electricity demand [31]. This made necessary to examine the system and market dynamics between natural gas and electricity. Additionally, the need for coordinated operation of natural gas and electricity systems with high shares of renewables, like in the case of Spain, is discussed in [32]. It is stated that market designs have to be reformulated and that interdependency of the networks has to be studied under the uncertainty introduced by intermittent renewable energy.

In that vein, Denmark is placing a significant focus on the development and coordination of energy systems with increased shares of renewable energy sources, with the gas system playing an important role. As the shares of wind and solar power are expected to dominate power production, the GFPPs will mainly serve as peak-load generation, ensuring security of supply. For this reason, operation of the gas system has to be optimized and economically adapted under this new setup.

Increasing the interaction among the energy systems will also reveal the potential for energy storage in the gas (and heat, at different temporal and spatial scales) systems. The Danish system operator Energinet.dk owns two gas storage facilities with a capacity of 11 TWh methane gas and an additional capacity of 15-20 GWh in the gas network, which may be seen as large storage capabilities. An important peculiarity for the Danish case is the existence of a common system operator for electricity and natural gas (Energinet.dk) that readily permits a coordinated operation and cost effective investment decisions for both systems. Such a setup with common system operator can be also found in other European countries, e.g., Estonia, Luxembourg and Portugal.

The large-scale integration of renewables in the energy systems can be facilitated by designing a coherent energy system that will be operated optimally under new market structures [48]. Electricity markets are the most mature and already undergoing massive changes due to the increased penetration of renewables in the power system [9]. Substantial changes are also been made in the natural gas market. A gas exchange, Gaspoint Nordic, has been established so that the players have the necessary marketplace to trade natural gas. Historically, the gas market was based on long-term contracts and bilateral agreements. However, a significant shift of the traded volume from the bilateral market to Gaspoint Nordic has been noticed lately. Traded volume in Gaspoint Nordic was 8.3 % of the total traded volume in 2010, while in 2015 this number increased to 58.2 %, showing a transformation of the gas market towards a more liquid and competitive model [34]. These new market models are expected to facilitate the coordination of the energy systems and raise new opportunities for players participating in them.

There are various sources of flexibility that the system operator can utilize in order to keep the system physically balanced. In Denmark, flexibility services can be procured from the available line pack in the pipeline network, storage facilities that are controlled by the system operator and by varying the production from the North Sea. However, the combination of line pack and storage facilities are the most commonly used ones due to their abundance. The interaction between electricity and gas systems is highly increasing in real-time operation that strengthens the need for changes in the design of the gas balancing model. The limited speed that gas travels compared to electricity makes the flexibility in the gas system to be location and time dependent [35]. The usual balancing period used for gas system is one day and it is common that imbalances within predefined limits are not charged. In recent years, though, the optimal definition of these limits is of high importance as imbalance charges need to reflect the actual balancing costs [36]. Denmark, like most European countries, is putting a lot of focus to build an efficient balancing model, described in [37], that will optimally adjust the trade-off among exploiting the available flexibility of the gas system, ensuring security of supply and reflecting the imbalance costs.

Denmark is also highly investing in transforming the gas system in getting greener. This can be accomplished by producing biogas from renewable energy sources, such as from biomass by thermal gasification or wind power by electrolysis. Biogas production was 7 PJ in 2015 and is expected to increase up to 14 PJ in 2020 [34]. Additionally, upgrading biogas and injecting it into the natural gas network will set biogas producers in a better and more competitive marketplace that will help the development of this technology in the future. It is foreseen that 10 % of the expected Danish gas consumption will be covered by upgraded biogas in 2020 [34].

The focus placed by various countries, including Denmark, on the coordination between electricity and natural gas systems is highlighted in a number of research studies. Initially, the impact of natural gas infrastructures on power systems is examined in [38]. Although the study focuses on the interdependency of the two networks on the U.S. setup, it demonstrates the impact of natural gas infrastructure contingencies and natural gas prices on electric power generation scheduling. In order to accomplish an efficient operation of an integrated system, new operational models have to be developed. On that scope, the coupling model presented in [39] indicates a strong interdependence between the two networks pointing out a high potential in using a global model for operating the two systems. The study was performed in a realistic test case of the Greek electricity and gas systems showing that applying such models in reality is feasible. Additionally, different coordination scenarios between the two networks are studied in [41] quantifying the economic and technical benefits of coupling the electric power and natural gas infrastructures. The increased integration of renewables in the energy system has reinforced the link between the two systems close to real-time operation. For that reason, the proposal of short-term operational models is vital. For instance, a model of simulating the integrated electricity and natural gas systems in short-term operation is presented in [40]. In this work, the systems are coupled by taking also into account the dynamics of gas. It is shown that gas travel velocity and the capacity of gas storage in the network play an important role in short-term operation and need to be modeled in order to get the maximum benefit from the system coordination. As previously mentioned, the gas balancing problem has both a temporal and a spatial dimension making the development of short-term models important. In the same direction, an integrated model with wind power variability is proposed and studied in [42], showing that GFPPs would facilitate the integration of wind energy into power systems. Finally, the effects of utilizing power-to-gas in Denmark are examined in [43]. Test case results show a reduction in total system cost and wind power curtailment highlighting the benefits of investing in this new technology that will allow the bidirectional interaction of the systems to prosper.

These innovative insights will enable and facilitate the coordination of electricity and natural gas systems. Models applied to realistic case studies show a great potential to capture the existing synergies and build up new ones that will assist the progress towards a sustainable energy system in the future.

B. The Case of Heating in Denmark

The development of district heating in urban areas has been identified by the Heat Roadmap Europe as a key recommendation for a low-carbon heating sector in Europe [44]. DH has a central role in Denmark's energy strategy to meet the ambitious target of reaching a fully renewable energy system by 2050 [45], [46]. Indeed, 46% of Danish net heat demand is currently covered by district heating, mainly produced by Combined Heat and Power (CHP) plants.

Interactions with the district heating system can provide additional flexibility in electric power system operation, by generating heat from CHP plants during high electricity price periods, or from heat pumps and electric boilers during low electricity price periods. In addition, heat storage in the form of water tanks, combined with relocation technologies, can provide cost effective energy storage capacity [48]. Exploiting the existing synergies between these systems can improve the efficiency and flexibility of the overall system, as well as facilitate the penetration of renewable energy sources in the power system.

Denmark has long been a leading country in the development of DH and has developed many initiatives to introduce competition and increase the efficiency of the DH system. In the Greater Copenhagen area, the day-ahead heat dispatch is prepared by Varmelast.dk, an independent market operator owned by the three major heat distribution companies. Although supply and retail heat prices are fixed, heat producers compete on their heat production costs and are dispatched based on a merit-order and a least cost principle. Figure 4 shows the sequence of decisions for heat and electricity dispatch.

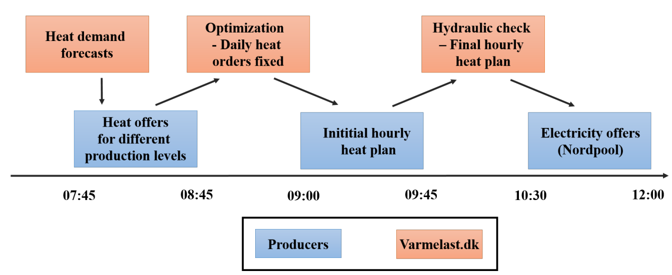

Fig. 4. Procedure for preparing heat plans in the Copenhagen area (inspired by [49]).

For CHPs, heat production costs are calculated as total production costs minus expected revenues from electricity sales. This approach ensures that the most efficient units are dispatched at each hour, and implicitly accounts for the interactions with the power sector. However research is still needed to increase the flexibility in the heat system and model interactions and uncertainties from other energy systems. Indeed, as the heat dispatch is determined before the opening of the electricity market, and due to the constraints on their joint feasible operating regions, CHPs have a limited flexibility when participating in the day-ahead electricity market. Hence they are exposed to the risk of low prices and financial losses when participating in the electricity market eventually. In addition the work in [50] showed that the inflexible heat-driven dispatch of CHP plants can have a negative impact on the power system and increase wind curtailment.

Additionally, over the last decades, due to the large penetration of wind power and the increasing number of hours with low electricity prices, CHP plants have become less profitable in the power market [47]. This has led to an increase in the use of oil boilers. In that context, large-scale heat pumps, electric boilers and heat storage have been investigated as sustainable alternatives to CHPs. In particular, HOFOR (utility in Copenhagen area) is currently installing in Copenhagen its first large-scale heat pump that will participate in the heat and electricity markets.

Literature on the integration and management of flexible heat sources is profuse. Ref. [51] showed that exploiting existing heat storage capability of heat networks could provide operational flexibility and allow higher wind penetration in systems with insufficient ramping capacity. In parallel, Ref. [52] showed the benefits of integrating electric boilers, heat pumps and heat storage in the Danish energy system. By producing heat when electricity prices are low and decoupling the strong linkage between heat and power outputs of CHPs, these technologies can increase the flexibility of the overall system, and again reduce wind curtailment. And, by lowering balancing costs and the number of hours with low electricity prices, these technologies increase the value of wind production. Figure 5 (inspired by [50]) illustrates the virtually relaxed feasible operating region of an extraction CHP coupled with flexible heat sources. In addition, power-to-heat technologies such as residential heat pumps and electric boilers, can provide additional flexibility to the system. And, in order to harness this flexibility from end-users, novel retail approaches are needed and are integrated in the scope of the Energylab Nordhavn project.

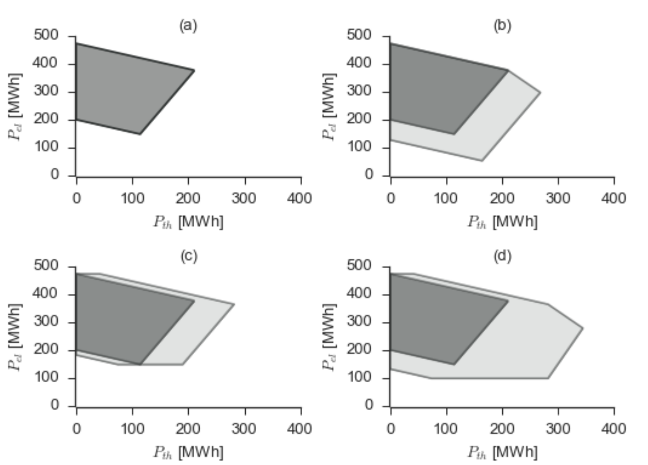

Fig. 5. Joint feasible operating region of an extraction CHP (inspired by [50]). (a) CHP only; (b) CHP and electric boiler; (c) CHP and heat storage; (d) CHP, electric boiler and heat storage

However major challenges remain for the large-scale development of these technologies. Ref. [53] showed that current taxes on electricity-based heat producers in Denmark reduced the profitability of electric boilers and heat pumps. In Copenhagen and Odense (thord largest city in Denmark), flat heat tariffs for producers and consumers have also been challenged as they do not reflect actual heat production costs. In addition, the introduction of dynamic heat prices could be an additional argument for the development of large-scale heat pumps. In Aarhus (second largest city in Denmark), the heat market operator, Varmeplan Aarhus, has already implemented dynamic heat wholesale prices. Based on the experience in Aarhus, the CITIES project is investigating alternative heat supply tariffs [54].

Additionally, due to the large penetration of stochastic renewable energy sources, it is essential to model the growing uncertainty from the power sector for optimal heat dispatch. Ref. [55] introduced uncertainties on heat demand and electricity prices and recast the joint heat and electricity dispatch of CHPs and heat storage in the Copenhagen area using piecewise linear decision rules. This approach showed improvement in terms of robustness of the solution with minimum financial losses. In Ref. [53] the heat and electricity dispatch of CHPs is formulated as a two-stage stochastic optimization problem. This approach showed that traditional deterministic models tend to overestimate the benefits of installing heat pumps and electric boilers.

The aforementioned studies proposed a co-optimization approach for heat and electricity dispatch. These approaches showed improvements in terms of flexibility of the overall system and wind penetration. However they are difficult to implement in the current Danish market framework. Ref. [56] proposed a novel approach for heat dispatch constrained by electricity dispatch. The day-ahead heat dispatch problem is modeled as a hierarchical stochastic optimization problem, where the lower-level problems represent electricity market clearing scenarios. This method allows independent heat market operators, such as Varmelast.dk, to dispatch optimally heat sources while anticipating the impact of the participation of CHPs in the day-ahead electricity market.

These studies hinted at the fact that the development of flexible heat sources and a better modeling of the interactions with the power sector could increase the flexibility of the overall system. While stochastic and robust optimization models showed improvement in flexibility, heat market operators in Denmark seem reluctant to adopt such methods. In order to better dispatch this potential flexibility in a deterministic market framework, new trading mechanisms incorporating flexible products for heat and electricity should be investigated.

C. The EnergyLab Nordhavn Smart Living Lab

As for many other countries, there still remain a gap between all those studies in the literature and actual deployment of operational and transparent solutions of practical value. Those should also be supported by viable business models, for existing and new actors of the energy system to engage in proposal new operational practice. With that objective in mind, many initiatives for large demonstration projects were started throughout Europe. These are most often deployed in a smart city context, hence taking part of a general momentum for improving infrastructures and their usage in urban environments.

In Denmark, Copenhagen aims to be a frontrunner sustainable city, an objective that was formulated in connection with the 2009 United Nations Climate Change Conference. It consists in becoming a carbon-neutral city by 2050. In practice, a relevant initiative is the development of the Nordhavn neighborhood in Copenhagen, to extend with housing and office space for 40.000 inhabitants and 40.000 office spaces in the long term. This extension of the neighborhood is to become a smart living lab for energy and its connection with other infrastructures. The EnergyLab Nordhavn[3] project started in 2015, placing emphasis on energy system integration, interaction with the transportation system, development of ICT- and storage-based management solutions for increased flexibility in power system operation, active distribution network planning etc. It comprises an interesting and ambitious large-scale public-private partnership to support relevant research and transfer of relevant technologies to a urban environment. A strong focus is also on new business models, in order to rethink the relationship of customers to energy usage and its utility, e.g., by pricing indoor temperature and comfort instead of the usage of primary energy carriers like electricity and district heating. Such an initiative illustrates the strong commitment of Denmark to new models for research and initiative, seen as a cornerstone to the further integration of renewables into the energy system.

VI. Conclusions and Perspectives

Denmark, supported by a strong political will, is a country that aims to fully meet its energy needs with renewable energy, hence with substantial penetration of wind and solar power generation means. While starting from a favorable standpoint, with good interconnections and existing flexibility on the supply side, it still faces a number of challenges before to reach those goals. With a strong commitment to research and development, as well as a proactive attitude towards demonstration and real-world implementation, the country has invested in grand projects that will support renewable energy integration, with particular focus on gaining and steering new flexibility in the system. Besides the role of interconnectors, such flexibility originates from electric demand response and more generally coupling with transportation (through electric vehicles), heating (through, e.g., heat pumps and CHP plants) but also with the gas system (also through generation means). While most of these developments have focused on technology and infrastructure, it is clear that future steps ought to focus on the social and market components of the renewable energy transition problem. The same way this transition has triggered a number of important changes in the system itself, it may also be an opportunity for changing the way people perceive energy production, exchange and consumption.

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