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# Heat Pumps in Denmark: Current Situation in Providing Frequency Control Ancillary Services

Menglin Zhang, Qiuwei Wu, *Senior Member, IEEE*, Theis Bo Harild Rasmussen, Xiaodong Yang, *Member, IEEE*, and Jinyu Wen, *Member, IEEE*

*Abstract*—**The Danish government set an ambitious goal to achieve a fully renewable-based energy system by 2050. In this context, the integrated electricity and heating system is undergoing rapid development in Denmark as a promising way to accommodate the ever-growing renewable energy sources (RESs). The electric heat pumps (HPs), coupled with the power and heat sectors, can propagate the flexibility on the heat consumer side to the power system operations, playing an important role of improving system flexibility and balancing the variability of the RES. In this paper, the current development situation of HPs in Denmark is analyzed, including both the large-scale HPs in the district heating system and individual HPs on the residential side. The possibility of using HPs to provide frequency control ancillary service (FCAS) is analyzed according to the market and technical requirements of the FCAS in the Danish transmission system and experimental results of representative demonstration projects of HPs. A comprehensive analysis of the advantages, barriers, future prospects, and challenges for using HPs to provide the FCAS are carried out from the perspectives of different entities.**

*Index Terms*—**Danish energy system, frequency control ancillary service, individual heat pumps, integrated electricity and heat system, large-scale heat pumps, power to heat.**

## I. INTRODUCTION

THE Danish energy and climate policies have set ambitious goals of achieving a fully renewable-based energy system and low-emission society by 2050 [1]. The widespread use of district heating (DH) and the rapid development of wind power generation are the cornerstones to achieve these goals [2]. Today, around 64% of the Danish households are supplied with DH for space heating and hot water [3]. In 2019, about 47% of the electricity consumption in Denmark was from wind energy [4]. The integrated electricity and heat system (IEHS) makes it possible to utilize the flexibility of DH to accommodate the fluctuating wind power [5]. Such balancing contributions are necessary to accommodate increasing wind energy integration in Denmark and decreasing the number of central power plants currently in operation [6].

In this context, flexible power-to-heat technology, such as electric boilers (EBs) and heat pumps (HPs) are politically encouraged and widely deployed to support an efficient integration of large amounts of wind power in Denmark [7]. Compared to EBs, HPs are a more expensive investment but may save considerable operational costs due to higher energy efficiency.

At present, HPs can be divided into two categories, i.e., large-scale HPs in the district heating system (DHS) and individual HPs on the residential side. Both categories are expected to play an important role. Reference [8] indicates that the introduction of large-scale HPs in Denmark has positive socioeconomic potential, bringing a potential benefit of around 100 M€/year in 2025 with the optimal thermal capacity in the range between 2 and 4 GW. Reference [9] concludes that individual HPs can reduce the power system peak capacity investments of about 300–600 MW for the Danish energy system by 2030, corresponding to the size of a large power plant. Reference [10] analyses the influence of individual HPs on the future Danish energy system until the year 2050 by optimizing both investments and operational costs, indicating that individual HPs on the residential side will supply around 25% of the total residential heating demand after 2035.

In previous research on HPs, the focus is primarily placed on the extent to which HPs can facilitate wind power utilization and improve economic efficiency. In these studies, HPs are usually scheduled as day-ahead to operate during periods of high wind energy or low electricity prices. However, the ever-increasing penetration levels of fluctuating renewables, such as wind and solar energy, are intensifying the need for additional grid services to guarantee the power balance and voltage stability. New research is being used to explore the benefits of HPs providing grid services. The existing grid services provided by HPs primarily involve frequency control ancillary services (FCAS), such as reserve provisions [11], and non-frequency control ancillary services (NFCAS), such as voltage control [12], and some other services such as congestion management [13] and peak reduction [14]. Reference [11] studies the technical and financial feasibility of utilizing residential HPs to provide frequency restoration

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reserves. Reference [12] integrates voltage droop control into the air-to-water HPs to reduce the critical states in the distribution grid in residential areas caused by high penetration of PV plants. Reference [13] mitigates the distribution network congestion through coordinated management of the HP and electric vehicle loads. Reference [14] indicates that the system operator can reduce the peak load substantially by utilizing the combination of HP demand response and thermal storage tanks with a small compensation for consumers. Reference [15] reviews the advances and challenges in controlling HPs to provide grid services in the electricity markets of the United States, including frequency regulation, load following, and reserve provisions. Reference [16] reviews the applications and control methods of HPs in a smart grid context, focusing on the voltage control, congestion management, spinning reserve, and non-spinning reserve.

Despite the various grid services, this paper only focuses on the FCAS, which can be used to maintain a short-term balance between supply and demand in an electricity system. These services utilize operational reserves that can respond to disturbances to achieve the precise control of the system frequency [17]. Generally, these services differ greatly in technical definitions and trading rules in different parts of the world due to the structural and development progress differences in the underlying power systems [18], [19]. Although academic research shows the capability of HPs providing FCAS, the accumulated experience of operating HPs in actual FCAS markets is still very limited around the world. There are still many aspects that need to be explored and verified in practice, including the future development prospect of HP technology, technical feasibility for HPs providing FCAS, requirements of market entry for HPs owners, legislative amendment for aggregators of HPs, etc.

The organization of the FCAS markets and the development prospects of HPs vary from country to country. This research only focuses on the HPs and FCAS in Denmark due to its advanced technology in developing renewable energy and heating supply. The main contributions of this paper are summarized as follows,

- Review the current situations of the large-scale HPs connected to the DHS for collective heating and individual HPs on the residential side; and
- Analyze the possibility of using HPs to provide the FCAS according to the market and technical requirements of the Danish FCAS and carry out a comprehensive analysis of the advantages, barriers, and future challenges for using HPs to provide the FCAS.

The logic overview of this paper is shown in Fig. 1. First, the basic operational principle of HPs is presented in Section II as a foundation of the whole paper. Then, the current development status of large-scale and individual HPs in Denmark is separately introduced in Section III. On this basis, the possibility, advantages, and barriers of using HPs to provide the FCAS are analyzed in Section IV. After that, the application and future challenges of using HPs to provide the FCAS are summarized in Section V. Finally, a conclusion is presented in Section VI.

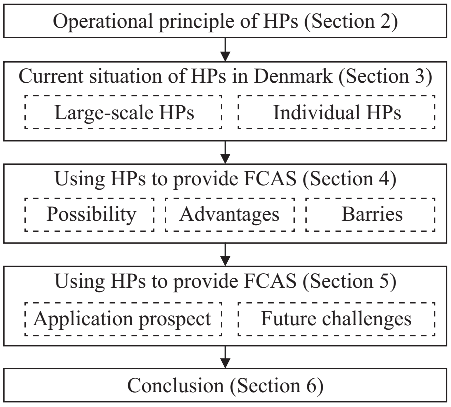

Fig. 1. The logic overview of this paper.

## II. ELECTRIC HPS IN BRIEF

The thermal energy from a low-temperature heat source can be transferred to useful high-temperature heat with the use of an HP. A HP has four main components, i.e., evaporator, compressor, condenser, and expansion valve [20]. Fig. 2 shows the operating principle of an electric HP device for heating purposes, which is based on the physical property that the boiling point of a working fluid increases with pressure. The working fluid, namely the refrigerant, cycles through all the components.

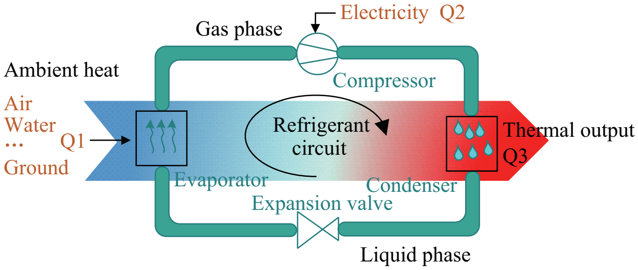

Fig. 2. Operating principle of a HP.

In the evaporator, the refrigerant heats up and boils by absorbing heat from the low-temperature heat sources through the first heat exchanger. In this process, liquid refrigerant is turned into a gaseous state. In the compressor, the input electrical energy is converted to mechanical energy that compresses the refrigerant gas into a high pressure, which then by consequence, reaches a desired high temperature. Then the hot and high pressurized vapor arrives at the condenser, delivering heat to the heating system or the consumer through the second heat exchanger. By condensing, the refrigerant turns into a liquid state. After passing through the pressure-lowering device, i.e., the expansion valve, the low-pressure refrigerant can evaporate at a low temperature. At last, the liquid refrigerant returns to the evaporator, where the cycle starts again.

The heat sources of HPs can be the air, seawater, sewage water, lake or river water, industrial waste heat, geothermal sources, flue gas, solar heat storage, and a combination of multiple sources, etc. [21], [22]. These heat sources cause HPs to have different operating characteristics, and may be limited to the geographical conditions for the installation.

The refrigerant, is an essential component of an HP. Its low boiling point characteristic allows the HP to make use of low-temperature heat sources. A major focus of the refrigerants is their impact on the environment when they are leaked from the HPs. Reference [23] describes the evolution process of deployed refrigerants in reducing environmental impacts. The chlorofluorocarbon and hydrochlorofluorocarbon are early refrigerants which are being phased out due to the high potentials in ozone depletion and global warming [24]. The development of future HP technologies is focusing on natural working fluids, such as propane, ammonia, and $CO_2$.

Among the four components, the compressor is the heart of an HP [25]. According to the working principle of the compressor, the HPs can be divided into fixed speed HPs and variable speed HPs [26]. The former operates with a fixed electric demand and controls the thermal output in an on-off manner. In contrast, the latter allows continuous regulation of the compressor speed, which offers higher operational flexibility due to the adjustable electric consumption.

The efficiency of an HP is denoted by its coefficient of performance (COP), defined as the ratio between the amount of thermal output Q3 and the electricity input of the compressor Q2. A high COP value represents high efficiency. The COP of different HPs usually ranges between 3 and 5 [27]. In energy system analyses and technology assessment, a seasonal or annual average COP is normally applied [28].

## III. OVERVIEW OF HPS IN DENMARK

The HPs in Denmark originated from the international energy crisis in the 1970 s. Over the past few decades, the development of HPs has experienced several stages, which were reviewed in [29]. The HPs in Denmark did not step into a period of rapid growth until 2013 when they became the political darling of the government. In order to reach Denmark's goal of fossil energy independence by 2050, electricity from wind energy is increasingly used for heating purposes in the form of HPs.

HPs are expected to increasingly displace other heating technologies up to 2030 due to relaxations of the tax on electric heating and will amount to 16% of energy consumption for heating in 2030 [1].

The Danish heat supply is distinguished by its collective and individual heat supply [30]. The large-scale HPs are usually connected to the DHS for collective heat supply, while the individual heat pumps are connected to households in rural areas and small towns. The Danish Transmission System Operator (TSO), Energinet.dk, expects that the large-scale and individual HPs will compromise a significant part of the Danish electricity demand by 2030 [31].

### *A. Large-scale HPs*

There is no uniform definition for large-scale HPs. Reference [32] reviews the applications, performance, economic feasibility, and industrial integration for large-scale HPs with heating capacity more than 50 kW. In [33], large-scale HPs are defined as units with a heat power capacity greater than or equal to 1 MW. In this paper, large-scale HPs primarily refer to those connected to DH for collective heat supply, with heating capacity ranges in Denmark between 0.2 MW and 10 MW [34]. Those large-scale HPs usually use natural refrigerants to reduce greenhouse gas emissions. Different large-scale HP projects differ in thermal capacity, heat source, inlet and outlet temperatures, and COP. These different factors result in different investment costs, around 0.8 million €/MW to 1.1 million €/MW [35]. Reference [36] investigates how the investment costs vary depending on capacity, heat sources, etc.

In 2017, there was an accumulated thermal capacity of over 50 MW for large-scale HPs [34]. In early 2018, the Danish Energy Agency announced it would support 13 large-scale HP projects targeted at replacing fossil fuels at some DH plants and utilizing a variable RES, such as wind power [37]. Denmark's support for electric HPs is to avoid price rises for DH customers when the subsidy for natural gas-based combined heat and power (CHP) plants expires. These large-scale HPs would be installed at 11 CHP-based DH plants and have a combined electricity capacity of 29.7 MW, which would cover 29,000 households across Denmark. According to Denmark's energy and climate outlook in 2019, the heat supply from large-scale HPs and EBs will increase from 1% of the DH consumption in 2017 to 11% in 2030 [1].

A survey map of large-scale HPs for DH made by PlanEnergi is shown in Fig. 3 [38]. The planning of large-scale HPs involves the optimal sitting, optimal capacity to be installed, and the optimal choice of heat sources to be used [39]–[41]. The planning of large-scale HPs regarding optimal sitting and sizing is investigated in [39] for the Nordhavn district in Copenhagen. In the planning, a number of optional connection points of HPs are provided in the 10 kV distribution network. The planning aims to minimize the capital expenditure and operating expense for both the EPS and DHS. In addition, the benefits of the operational flexibility of large-scale HPs are also integrated into the planning process. In [40], the planning of large-scale HPs regarding optimal sizing and optimal choice of heat sources minimizes investment and operational costs

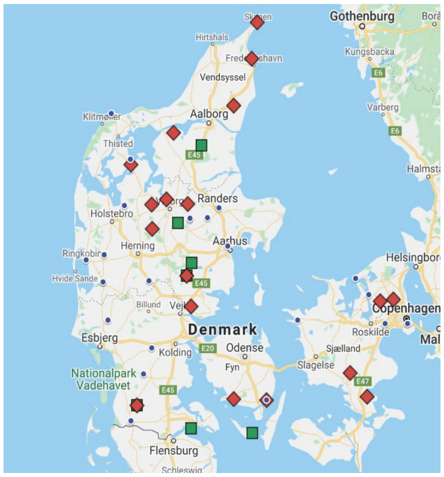

Fig. 3. Road map for large-scale HPs in the DHS of Denmark. (Red diamonds and green rectangles represent planned and commissioned HPs by PlanEnergi, respectively; blue points represent other commissioned HPs.).

of the DHS, while considering the seasonal variations of the heat source temperatures, capacity limitations, COP, as well as technical constraints. In contrast, the optimal sizing and placement of large-scale HPs consider the detailed operational constraints of both heating and electricity networks in [41].

In the power sector, large-scale HPs can be connected to the medium-voltage distribution network. In the heat sector, the large-scale HPs can be connected to both the distribution and transmission networks of the DHS. Since there is a big difference for the forward temperature in the two networks, approximately 100 °C in the heat transmission network and 60°C in the heat distribution network, the large-scale HPs connected to the heat distribution network give a higher COP due to lower temperature lift compared with HPs connected to the heat transmission network. However, connecting the large-scale HPs into the heat transmission network is not limited to the local heat demand for heat production. For example, many large-scale HPs are located near the sea to use sea water as low-temperature sources, and it is possible to fully utilize these HPs to supply the inland areas if they are connected to the heat transmission networks. Reference [42] compares the performance difference of large-scale HPs connected to either distribution or transmission networks in the DHS of Greater Copenhagen.

The flexible operation of large-scale HPs depends on the capacity of the connected thermal storage tank. In Denmark, the thermal storage capacity in CHP plants can supply two days to a full week of heat demand during the cold season [32]. In addition, the investment for a large-scale thermal storage tank is relatively cheap, providing favorable conditions for the flexible operation of large-scale heat pumps.

### B. *Individual HPs*

Individual HPs, generally small-scale capacity, are usually used for single-family houses or apartments, installed at places where heat densities are lower and district heat distribution is not feasible [30].

In Denmark, the small electrically driven compression HP is the only type of HP for individual heating. According to the methods used to collect heat from the heat source and methods used to distribute the heat in the house, individual HPs are differentiated as air-to-air HPs, air-to-water, brine-to-water HPs (ground-source HPs), and ventilation HPs. The number of these four types of HPs installed in Denmark in early 2014 are 120,000 to 160, 000, 17,000 to 22,000, 25,000 to 35,000, and 17,000 to 22,000, respectively [27]. The typical heating capacities are 3–8 kW for single air-to-air HPs, 3–4 kW for air-to-water and brine-to-water HPs, and 3 kW for ventilation HPs [43]. The main reasons for the large share of air-to-air HPs are their low investment cost and easy installation.

The Danish Energy Agency predicts that the individual HPs will consume 4 TWh thermal energy per year by 2040 [44]. According to the estimation of the Danish distribution network operator, there will be around 0.5–0.6 million houses with individual HPs by 2050 [45]. The total electricity capacity of individual HPs will be around 1–2 GW by 2050, based on the typical electric power of individual HPs rating of 2 kW.

The individual HPs are integrated into the low-voltage grid and will be transported through the higher voltage levels. The individual HPs will change the profile of electricity usage, increasing the power demand during peak cooking hours between 17.00 and 20.00, when people come home from work.

Being different from the large-scale HPs, the individual HPs can utilize different heat storage options to achieve flexible operations, including building structures and thermal storage tanks. Most HP systems in Europe are connected to a thermal storage tank [46]. The individual HPs for one-family houses are typically installed, combined with a roughly 200 liter tank for hot water and a small buffer tank of around 40–80 liters [47]. However, the limited volume of the tanks is not large enough to achieve flexible operations in an hourly time resolution. Additional flexibility can be achieved by installing heat accumulation tanks. Tanks of up to 1,000 liters are realistic for installation in one-family houses [48].

Even though the individual HPs have higher energy efficiency than other individual heating technologies, they have more expensive investment costs that create difficulties of affordabilty for end-users and may hinder their own development. The new emerging business model for individual HPs in Denmark has avoided this situation. In the new business model, heating from HPs becomes a service that is provided by the operator who owns the HPs and is responsible for the installation, operation, and maintenance of the HP system [49]. Under this scenario, the end-users can enjoy and pay for the service and save the investment cost. The practice in Denmark has validated the potential of this new business model for individual HPs. For example, homeowners who live in the rural areas of Lolland-Falster in Denmark can subscribe to an annual heating service from the local energy company while avoiding the installation and maintenance cost of HPs [50].

## IV. FCAS FROM HPs

The majority of the energy balance between generation and consumption is traded in the day-ahead and intraday markets in Denmark. However, there is still a difference between traded volume before the hour of operations and actual consumption in the hour of operations, therefore, additional balance is provided by the FCAS. Fig. 4 illustrates the sequential energy balance via different markets.

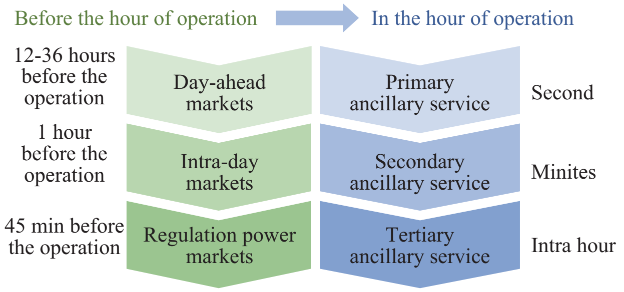

Fig. 4. Sequential energy balance by different markets.

Generally, ancillary services are divided into two categories, i.e., the FCAS and non-frequency control ancillary service (NFCAS). The FCAS is used for the instantaneous balance between power production and consumption. The NFCAS is a compulsory system service, used to maintain system stability. This paper only focuses on the FCAS. In Denmark, the TSO is responsible for procuring most of the FCAS, which can be supplied by the electricity producers or consumers.

### *A. FCAS in Denmark*

The Danish transmission system is divided into two non-synchronous areas, i.e., Western Denmark (DK1) and Eastern Denmark (DK2), which are linked by a direct current link under the Great Belt [51]. DK1 is synchronous with Germany and is part of the European continental electricity system, while DK2 is coupled with the Nordic grid. This situation causes the FCAS in two areas to be slightly different due to their affiliation respectively to DK1 and DK2.

Table I summarizes the classification of the FCAS in DK1 and DK2 [52]. The FCAS are generally designated as primary, secondary, and tertiary reserves. In the Danish context, the primary reserve is adopted as the frequency containment reserve (FCR) in DK1 and frequency containment reserve for disturbance (FCR-D) and for normal operation (FCR-N) in DK2. The secondary and tertiary reserves are respectively adopted as the automatic frequency restoration reserve (aFRR) and manual frequency restoration reserve (mFRR).

TABLE I
FCAS CLASSIFICATION IN DK1 AND DK2

| Areas | DK1 | DK2 |
|---|---|---|
| Classification of FCAS | Primary reserve: FCR<br>Secondary reserve: aFRR<br>Tertiary reserve: mFRR | Primary reserve: FCR-D, FCR-N<br>Secondary reserve: aFRR<br>Tertiary reserve: mFRR |

### *B. Market and Technical Requirements for FCAS*

The different categories of FCAS in DK1 and DK2 are compared in Figs. 5 and 6, respectively, from aspects of market entry rules and technical requirements [53]–[55].

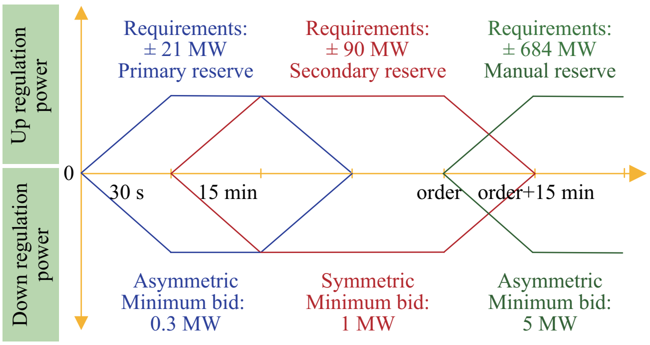

Fig. 5. FCAS in DK1.

As can be summarized from Figs. 5 and 6, the key factors that the TSO requires for several types of FCAS include the following aspects,

- The total volume requirements.
- The response time for the partial and full delivery of the required amount of FCAS.
- The direction of FCAS (upward or downward, symmetrical or asymmetrical regulation).
- The minimum volume of a bid to enter into the market.

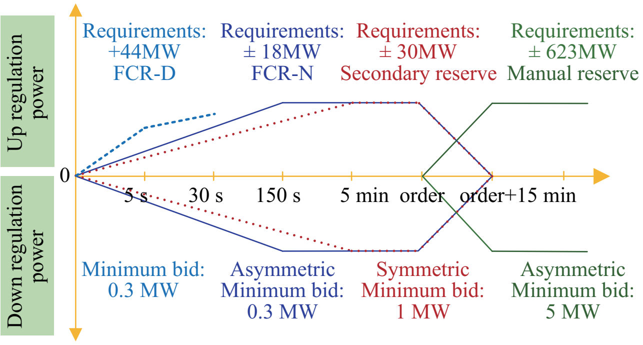

Fig. 6. FCAS in DK2.

In DK1, the primary reserve, i.e., FCR, is used to restore the balance between production and consumption of electricity, stabilizing the grid frequency at close to but deviating from 50 Hz. The full delivery of FCR must be within 30 s and should maintain the regulation at least 15 min until the secondary and manual reserve services can take over. The FCR is automatically regulated depending on the grid frequency deviations. The requirement published by Energinet is ± 21 MW in 2020 [54]. The upward and downward regulation of FCR can be asymmetric. A minimum of 0.3 MW is necessary for players to enter the bid.

The secondary reserve (aFRR) in DK1 serves two purposes, releasing the primary reserve and restoring any imbalances on the interconnections. The required amount of aFRR in 2020 was ± 90 MW. The aFRR suppliers must be capable of delivering the requested reserve within 15 min and submitting a bid for a minimum of 1 MW. The upward and downward regulation of aFRR should be symmetric.

The tertiary reserve (mFRR) in DK1 is used to relieve the aFRR in the event of substantial imbalances and ensures balance in the event of outages of production and transmission facilities. The tertiary reserve is activated by the Energinet's control center and is purchased in the mFRR capacity market [55]. The mFRR suppliers must be capable of delivering a full response within 15 min once receiving the activation order and offering a bid of minimum 5 MW.

In DK2, the primary reserve includes the FCR-N and FCR-D. The FCR-N is used to restore the power balance and stabilize the grid frequency close to 50 Hz. It must be delivered linearly within 150 s. In addition, the FCR-N is symmetrical, requiring the upward and downward regulation reserve to be procured together. The required amount of FCR-N was ± 18 MW for Energinet in 2020. The FCR-D is a fast reserve to follow substantial frequency drops caused by the outage of major plants or lines. The players of FCR-D must supply 50% of the response within 5 s and supply the remaining 50% of the response within an additional 25 s. The total volume requirement is +44 MW. The minimum volume of a bid for FCR-N and FCR-D is the same as the FCR in DK1.

Being different from the aFRR in DK1, the aFRR suppliers in DK2 are required to provide a full response in a shorter time, i.e., 5 min. The response time and minimum volume of a bid for the manual reserve in DK2 are the same as those in DK1.

### C. Possibility of HPs to Provide FCAS

As large-scale and individual HPs have different characteristics, the Energinet has launched different demonstration projects to test the possibility of these two types of HPs to provide the FCAS.

#### 1) Large-scale HPs in EnergyLab Nordhavn Project

In Denmark, the large demonstration project Energylab Nordhavn is a typical example of the application of large-scale HPs. This project started in 2015, located in Copenhagen's Nordhavn, one of the largest development districts in Europe. It commits to exploring smart solutions for the sustainable and cost-efficient integrated energy system that provides intelligent control of subsystems and components for efficient utilization of renewable energy [56]. It utilizes large-scale public-private partnerships to support relevant research, and it is seen as a cornerstone for transferring new technologies and new models to the real world. In 2019, HPs are listed as one of the new technologies that have the potential to deliver ancillary services in Denmark, by taking the experimental results of the Energylab Nordhavn as an example [57].

In the demonstration project, a two-stage ammonia HP with a thermal capacity of approximately 800 kW and an electric power of 250 kW is installed in the Nordhavn harbor area, which is the main supply unit of a small-scale DH grid. The large-scale HP system has installed a large heat storage tank with a volume of 100 $m^3$ to allow for the flexible operation of the large-scale HP [58]. The two compressors of the HP have variable speed drive, enabling a part-load operation mode of the HP. In addition, the control system has been rebuilt to enable the fast ramping of the large-scale HP.

According to the demonstration tests, the feasible and infeasible situations when utilizing HPs to provide different types of FCAS are summarized in Table II.

According to the summary in Table II, the large-scale HP will be more compatible with the secondary and tertiary reserves from the perspective of response time. However, the minimum bid volume may hinder them from becoming a player in the market.

#### 2) Aggregation of Individual HPs

At the current stage, individual HPs do not show as high potential as large-scale HPs in providing FCAS due to their limited regulation capability and high cost of installing control and communication equipment. However, there are still some exploratory projects in Denmark to promote the positive role of individual HPs in providing grid services. Due to technical requirements, the individual HPs in households need to be aggregated to participate in the grid service.

Two companies in Denmark, Insero and Neogrid, have participated in a pilot project based on the aggregation of the flexibility of a pool of small-scale HPs totaling 315 kW electric power [59], [60]. Neogrid Technologies has developed an aggregation platform that can forecast the electricity consumption, optimize the operation of HPs in relation to various inputs, such as price, wind and weather, and provide control to the pool [61], [62].

Even though the purpose of the pilot project was to make the pool available on the existing Nordic regulating power market, the two companies have planned to cooperate further with this project for offering the FCAS with the aggregation of small HPs [58]. For future development, the FCAS capabilities of residential HPs should be assessed by comparing the technical capability of the HPs with the required capability to provide the FCAS product. The technical capabilities are determined by ramp rate, allowed number of starts and stops, minimum start and stop time, size of unit, heat storage size, etc. [63].

Two other projects in Denmark, intelligent remote control of individual HPs [64] and HPs in a smart grid future [65], focus on the aggregate control of thousands of individual HPs. In these two projects, a virtual power plant (VPP) server was developed, which can collectively and remotely control when HPs can be turned on or off. With this aggregation, the VPP server can act as a one stand-alone controllable unit in the grid. At present, the VPP server control has been applied to the grid constraints in the distribution grids, communication scenarios, grid measurements, and market design for conges-

TABLE II
FEASIBLE AND INFEASIBLE SITUATION FOR HPS PROVIDING FCAS

| FCAS | Test | Results |
|---|---|---|
| FCR-D | Feasible situation | The large-scale HP can provide equivalent upward regulation for the power system by shutting down immediately. The shutdown operation takes approximately 30 s, satisfying the time requirement for full delivery of FCR-D. |
| | Infeasible situation | The large-scale HP cannot deliver 50% of the regulation within the first 5 s and the remaining regulation within an additional 25 s. The large-scale HP needs approximately 26 min to restart the system and it cannot satisfy the requirement of restoring the regulation capability within 15 min. |
| | Need to improve | The limitation to recovery time needs to be revised to make the large-scale HP play a role. |
| FCR-N | Feasible situation | In most cases, the large-scale HP can deliver partial load regulation within 3 to 5 min. The rebuilt control can deliver the regulation within 1.5 min, within the required 150 s for FCR-N service. |
| | Infeasible situation | The upward regulation is more preferred for the large-scale HP. It is hard for them to provide symmetric upward and downward regulation. |
| | Need to improve | Future large-scale HPs are expected to be designed based on the same control principles. If the required time for FCR-N can be increased to 3 to 3.5 min, the large-scale HPs will have a higher possibility to be suppliers in the market and be able to deliver higher capacity. |
| aFRR and mFRR | Feasible situation | The large-scale HP can provide these two services to a large extent, since the response time of the large-scale HP is no more than the required time, 5 min in aFRR service and 15 min in mFRR service. |
| | Infeasible situation | It is hard for all large-scale HPs to satisfy the minimum bid volume for aFRR and mFRR due to their limited power capacity when they operate on the markets as a stand-alone unit. |
| | Need to improve | Reduce the volume limit of bids will be beneficial to increase the possibility of HPs entering the markets. |

tion management. Even though it has not been applied to the FCAS, previous experiences have laid a foundation for the FCAS provision of HPs in aspects of aggregate control, building modeling, and integration of software and hardware.

### *D. Advantages of HPs to Provide FCAS*

HPs have flexible operational modes, enabling them with the capability of providing the FCAS. All HPs can change their power consumption by switching on/off states. For example, an individual HP in operation is able to stop immediately to provide an upward reserve and a stopped individual HP can reach full power consumption within 1 min to provide a downward reserve [27]. In addition, HPs can provide reserves by capacity regulation, which can be achieved by variable-speed HPs or the aggregate control of a pool of HPs.

Using HPs to provide the FCAS has huge socio-economic and environmental benefits, manifested as,

- Denmark has an ambitious goal to achieve a fully renewable-based energy system, translating to increased needs for the FCAS to cope with the variability of wind and solar power generation. However, due to the integration of renewables, traditional central power plants as providers of the FCAS will be gradually phased out. Alternative sources of the FCAS must be established. The HPs on the demand side are seen as a potential new technology to change the power consumption profiles, providing also relatively cheap or at least competitive FCAS compared with other options, such as energy storage systems and flexible generators. Additionally, HPs support a transition towards heating electrification to reduce $CO_2$ emissions.
- Denmark has long been a leading country in heating supply, processing a high level of heat demand and thermal inertia. HPs as coupling devices linking the power and heat sectors can harness the huge thermal inertia of buildings to propagate the flexibility on the heat consumer side to the power system operation. Additionally, by combining with thermal storage tanks, HPs have less impact on users' comfort and fewer operational restrictions when providing the FCAS, contrasting with other resources on the demand side. In addition, the flexible operation of HPs can benefit power system operators. The identified potential of reducing investment in the power system peak capacity is around 300–600 MW by using individual HPs in Denmark by 2030 [9].

### *E. Barriers of HPs to Provide FCAS*

The participation of HPs in FCAS markets involve the interaction with multiple entities, as summarized in Fig. 7. The barriers from these entities involve multiple aspects including regulatory, technical, economic, and market, etc.

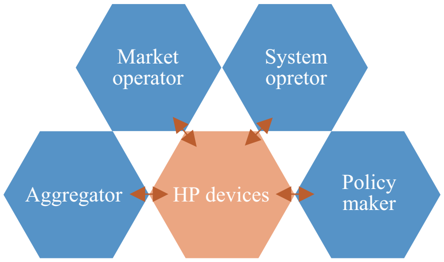

Fig. 7. Barriers from different entities.

Current barriers that may hamper HPs from being a player of the FCAS markets primarily originate from the following aspects,

#### *1) Market Side*

The technical and market requirements for the FCAS were largely generation-oriented and not for resources on the demand side. The market entry condition needs to be redesigned to secure the HPs as the players of the markets. The changes primarily reflect on one or more of the following: response direction, response time, and minimum bid volume. However, any change of these parameters must be agreed upon in the Danish Energy Act, and a revision of the agreement is a complicated and long-lasting process.

At present, the majority of the secondary reserve in Denmark is provided by Norway through the interconnection between Denmark and Norway [66]. In addition, the secondary reserve needs the suppliers to equip themselves with online measurements, which is costly. These two aspects prevent the HPs from barely having a chance to join this market. Although the HPs have the technical potential to participate in the tertiary reserve, the participation needs a control center operating 24/7, which represents a cost challenge. In addition, FCR-N and aFRR require symmetric bids for upward and downward regulation. However, it is hard for HPs to provide equal amounts in both directions.

#### *2) Aggregator Side*

The HPs will join in the FCAS markets as resources of the demand side. A third-party independent aggregator is necessary to enable the HPs to enter the market, which can aggregate a pool of small size individual HPs to satisfy the minimum bid volume requirement and dispose of HPs' electricity consumption. The demand response aggregation is allowed in Denmark [67], however, today there are no independent aggregators in the Danish market and the aggregation takes place only through the balance responsible party (BRP) [68]. To enable independent aggregators to enter the market at scale, it is important to clearly define their roles and responsibilities and clarify their distinguishment from the BRPs [69]. More details are given in [70] regarding the barriers to independent aggregators.

To satisfy the requirement for minimum bid volume, the aggregators will face the challenge of operating several large-scale HPs or a pool of small-size individual HPs. This includes forecasting the baseline of the aggregated HPs, optimizing the bidding strategy, and coordinating the control of a large group of HPs. A baseline of HPs is analogous to a generator setpoint and must be determined ahead of time. However, due to the uncertainty and disturbances of heat usage, the baseline of HPs is difficult to predict, which in turn influences the accuracy of available capacity to participate in the market. To optimize the bidding strategy and achieve the coordination control, the aggregator may face a huge calculation burden.

### *3) Policy Maker Side*

The weak business case for demand-side resources brings economic barriers for HPs entering FCAS markets. At present, the demand response is very limited in Denmark. The payments in the market are too low to reward the aggregators and customers and to include the high levy on electricity and costs of installing control and measurement equipment. Denmark is one of the countries with the highest electricity prices in Europe, second only to Germany [71]. Tax makes up 64.4% of the total price in 2019 [72]. The energy taxation is the highest in all the EU countries. Such a situation makes it hard to create a positive business case and attract large amounts of HP customers to contribute to a pool.

### *4) Device Side*

The primary reserve market requires that the HPs have a short delivery time and can respond to the frequent activation call. However, current HPs have not been designed for flexible operation. On the one hand, the flexible operation of HPs generally requires investment in two-way communication systems being connecting with the power system [73], smart thermostats for ensuring comfort of heat users [74], and a capacity expansion of the heat accumulation tank for heat demand shifting [31], [46]. On the other hand, the response speed of an HP is limited by the maximum allowed change rate of the compressor over a certain time. A minimum run and pause-time is required in most HPs. In addition, the frequent start-ups may cause mechanical wear [22], [33], reduce the lifetime of the HP devices, and influence the COP performance [75].

In addition, the flexibility of HPs is not constant during the course of the year. During the non-heating season, typically May to October in Denmark [76], the heat storage potential of individual HPs will be limited to the small storage capacity of the hot water tank, instead of the whole building in the heating season. Moreover, the available heat storage capacity for the flexible operation of individual HPs is very limited in the cold season, where the heat users will force the HP to operate at its full power for several hours.

### *5) System Side*

Being different from the diversity of electricity demand, the heat demand is highly simultaneous in the cold season [77]. When HPs are largely deployed, peak demand induced by HPs is expected in winter. Additionally, unlike the control to the single generator, the aggregators need to coordinate large amounts of HPs in a pool to react to the same regulation signal from the grid or the market, where overloading or the low voltage of the distribution grids could be amplified [78]. In addition, the demand response of HPs has a rebound effect [79], [80], which may create new voltage or bottleneck problems in the power system. These problems further influence the planning and reliability evaluation of distribution networks with a large share of HPs [81], which has been considered in a few studies [82], [83]. Reference [82] considers collaborative planning of distributed wind power generation and rural distribution networks, utilizing the operational flexibility of individual HPs to reduce the upgrade investment of the distribution network. Reference [83] proposes a novel reliability evaluation method for the electricity-heat integrated energy system with HPs, which considers the load-point and system-level reliability indices and the maximum output heat power of HPs for ensuring the security constraints of the distribution network.

## V. APPLICATION PROSPECT AND FUTURE CHALLENGES

As for the case of many other countries, the development of HPs is also receiving massive financial and policy support. In Europe, all EU countries encourage the use of more sustainable heating technologies by national legislation. HPs as one of the best candidate technologies that are becoming widely deployed, which enables the EU to achieve its future energy and climate policy target [84]. The implementation of HPs in Lithuania and European countries is overviewed in [25]. The operational experience of large-scale HPs in Sweden is summarized in [33], showing the environmental benefits of HPs and their competitiveness on other options. In North America, HPs show continuing growth as an efficient electric heating alternative to fossil fuel heating systems [85]. In China, the national policy also supports and subsidizes renewable heating technology, such as HPs. The development of HPs in different regions of China is shown in [86]–[88].

In summary, there is massive support for HP development. According to the aforementioned Danish operational experiences on the use of HPs to support the FCAS, there are still many aspects that need to be improved to enable HPs to be players in the markets. Future challenges that need further research are as follows,

- Develop more advanced HP technical performance design that satisfies the technical requirements of the FCAS;
- Implement demand-side oriented market rule designs to operate HPs in different FCAS markets;
- Establish new business models with reasonable and sustainable incentive policies that can promote revenue of stake owners when operating HPs in the FCAS markets;
- Realize accurate baseline prediction and decentralized optimization and control for a pool of individual heat pumps;
- Design a joint bidding strategy for the energy and FCAS of HPs owners considering the operational characteristics of HPs and their impact on heat users' comfort; and
- Conduct comprehensive analysis of social, economic, and environmental benefits for operating large-scale and individual HPs in different FCAS markets.

## VI. CONCLUSION

The future Danish energy system is characterized by substantial penetration of wind power and widespread use of heat supply, where HPs will play an important role in providing flexibility. With strong political and financial support for the development of HPs and their pilot demonstration, both large-scale heat pumps in the DH and individual HPs on the consumer side are expected to make up a large share of the electricity demand in the future. Single large-scale HPs have been experimentally tested for providing responses in the order of seconds to minutes, thereby demonstrating the potential in providing different types of FCAS. The aggregate control to a pool of individual HPs is technically feasible, but has not been tested for proving FCAS. Although using HPs to provide the FCAS has huge socioeconomic benefits, barriers from different entities still exist that may hinder the HPs to be a player in the FCAS markets. Future steps need to focus on the advanced HP technical performance design, demand-side market rules, new business models with reasonable and sustainable incentive policy, decentralized optimization and control of a pool of devices, joint bidding strategy of the energy and FCAS for device owners, and comprehensive benefit analysis.

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