WHEN TRUST MATTERS

QUANTIFICATION OF DEMAND-SIDE FLEXIBILITY POTENTIAL IN DENMARK IN 2030

EWII A/S

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WHITEPAPER

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Table of contents

EXECUTIVE SUMMARY

Executive Summary

EWII has asked DNV to quantify the value of demand-side flexibility in Denmark in 2030. The purpose of this study is therefore to provide insights into the potential value of demand-side flexibility in the electricity system in Denmark. To that end, DNV has quantified the benefits in the wholesale market related to grid investments and in balancing markets.

DNV finds that by unlocking Denmark's demand-side flexibility potential, the integration of renewables will be improved and both the cost to serve final load and the cost to generate will be reduced. The rate of customer connections can be accelerated in congested areas, and balancing costs can be reduced. The study also finds that:

- Biomass can be completely removed from the Danish energy mix. However, to ensure security of supply, a high participation of demand-side flexibility is needed. The avoided CO_2 emissions from biomass-fired generation account for 7,2 million tonnes CO_2 equivalents.
- Direct benefits for consumers who own flexible assets range from DKK 480 million for smart charging and vehicle to grid, to DKK 31 million for battery energy storage systems behind the meter.
- All consumers will profit from the indirect benefit of lower cost to serve final load, which is reduced by about DKK 94 million annually. Largely caused by reduced cost of generating power and heat (82 million DKK annually).

- Demand-side flexibility can reduce cost of imported electricity by 335 GWh. This is mainly due to less curtailment, more waste incineration and lower electric heating demand from e-boilers and heat pumps.
- Deployment of demand-side flexibility can reduce 1.2 MW or 12% of the peak demand from 60 kV to 10 kV transformers by 2030. When these transformers are congested, or if these transformers are affected by congestion on higher grid levels, freed-up capacity can be used to connect additional customers, adding an estimated value of DKK 2.2 million per year per congested transformer, or DKK 220-900 million per year for Denmark, even higher than the benefits expected from savings in the wholesale market. Cost related to grid connection approval times are not included and dynamic effects from employment or taxes are included and as result the real benefits might be underestimated.
- DNV's quantification of balancing energy shows the TSO will face an increased cost to buy energy or a decrease in revenues from selling energy of DKK 4.5 million in 2030. The additional benefits from balancing are therefore small compared to wholesale and grid benefits.

DNV recommends the sector increase incentives for demand-side flexibility in the Danish energy system and remove the regulatory barriers hindering companies from utilizing demand-side potential. More transparency about the anticipated grid congestion levels could also incentivize mitigation measures. New grid investments are needed, but increased demand-side flexibility will accelerate grid connection and reduce or postpone some of the grid investments required for the electrification and green transition of the Danish energy system.

1 INTRODUCTION

1. Introduction

Denmark has an ambition to scale up both production and consumption of wind and solar energy, targeting significant renewable electricity consumption growth from 2025 to 2030, with growth accelerating towards 2040. The rapid development of wind and solar is a challenge for DSO's and for the controlling Danish TSO. Accommodating such peak load increases will require significant investment in Denmark's grid capacity, and the Danish TSO has raised concerns over the challenge this could present to Denmark's energy security. Concurrently, Denmark aims to reduce the amount of biomass utilized in the Danish energy system. In this study, DNV has therefore assumed biomass will be fully phased out by 2030.

In the absence of biomass, demand-side flexibility is understood as a cost-efficient way to increase the electrification of the energy system with wind and solar. It is commonly held that grid reinforcements, especially at the TSO level, cannot keep pace with the energy transition. This results in grid congestion and long wait times for new (or upgraded) grid connections (both in HV and MV grids), slowing the pace of energy transition and hindering economic growth. Demand-side flexibility can directly address this issue by supporting the acceleration of grid connections in congested areas and by reducing peak demand.

EWII has asked DNV to quantify the value of demand-side flexibility in Denmark in 2030. Thus, the purpose of this study is to provide insights into the potential value of demand-side flexibility in the electricity system in Denmark.

In this study DNV has,

1. **Quantified the benefits** of demand-side flexibility in the wholesale market
2. **Quantified grid benefits** based on accelerated grid connections
3. **Quantified the benefits** for the balancing market

The analysis has been performed using DNV's power market model with data from the Danish Energy Agency's AF24 (Analyse Forudsætninger) and load profiles from five transformer stations owned by Trefor El-net. The methodology of the analysis and the results regarding the benefits for the wholesale market, grid, and balancing market are described in this report.

1.1 What is demand-side flexibility?

Demand-side flexibility describes the technological capability of changing when energy is consumed by a product or system. This could mean reducing energy consumption during peak consumption hours, or increasing energy consumption when renewable energy generation in the system is high. Demand-side technologies such electric vehicles chargers, large industrial heat pumps, electrical boilers connected to district heating systems, large industrial heat pumps, or battery energy storage systems can incorporate this kind of flexibility, thereby reducing peak load in the energy system and shifting demand load when needed. (In this study, electrolyzers and utility scale BESS are not included in the definition of demand-side flexibility.) With the incorporation of greater demand-side flexibility, grid capacity can be used more evenly throughout the day. This results in a reduced need for immediate grid capacity investment, allowing for the postponement of necessary upgrades and/or expansions.

1.2 Purpose of this study

Towards 2030 and 2040 an increasing amount of the energy produced and consumed in Denmark will come from wind and solar. Massive investment in the Danish power grid will be necessary to properly integrate this growing share of wind and solar power. The purpose of this report is to investigate how renewable energy can be integrated in a biomass free electricity system, how to increase the affordability of such an energy system, and how to accelerate grid connections in an already congested grid.

1.3 Our Approach

To quantify the value of demand-side flexibility (DSF) in Denmark, two scenarios have been explored:

- **High DSF - High flexibility scenario:** In this scenario the Danish market has incorporated the maximum possible demand-side flexibility.
- **Low DSF - Counterfactual with low demand-side flexibility:** In this scenario the Danish market has incorporated certain demand-side flexibility beyond what is already available.

DNV's scenarios are based on a forecast of generation capacity, demand, and interconnector capacity in the Danish Energy Agency's analytical assumptions (Analyse Forudsætninger, AF24). However, DNV has assumed that biomass generation will not be a part of the power system in 2030. For the analysis of grid investments, DNV has used the load profiles of five transformer stations owned by Trefor El-net. As with other forecasts, DNV's analyses are subject to uncertainty, which increases in the longer term.

Electricity wholesale market benefits have been assessed by including the demand-side flexibility options available in each scenario. The capacity of DSF available in both scenarios is the same, yet the flexible operation of these resources is unlocked and exposed to the relevant markets in different proportions. The comparison of results from the two scenarios has been used to quantify the wholesale benefits by using DNV's European Market Model. This market model simulates the day-ahead spot market by optimizing the unit commitment and economic dispatch of electricity generation, based on its marginal cost. The above scenarios are only applied to Denmark. The rest of European countries remain unchanged in both simulations, with a middle level of DSF deployment.

2 AVAILABLE DEMAND-SIDE FLEXIBILITY IN 2030

2. Available demand-side flexibility in 2030

To quantify the potential benefits of demand-side flexibility in Denmark, DNV has identified the technologies in the Danish power system with a potential to provide flexible power. Table 2-1. Demand-side flexibility technologies. Table 2-1 the technologies DNV has used to model the flexibility potential are listed.

TABLE 2-1

Demand-side flexibility technologies.

Demand-side flexibility technology	Assumption and explanation
Industrial demand-side response	Industrial demand-side response is when plants or industries with large energy consumption reduces its consumption above a given power price.
Behind-the-meter BESS	Battery energy storage systems behind the meter provide flexibility through charging and discharging daily when prices show a sufficient spread to cover their efficiency and operational costs. The battery is optimized behaviour against wholesale market.
Smart charging by electric vehicles	Batteries in electric vehicles are included in the analysis and considered as demand-side flexibility technology that can provide flexibility by shifting their load. The electric vehicles will do smart charging when the vehicles are connected to the grid.
Vehicle to grid	Batteries in electric vehicles are used as a battery when they are connected to the grid. This is called bidirectional charging or vehicle-to-grid (V2G). V2G enables the EV battery to feed as well as charge power from the grid. V2G is modelled as a behind-the-meter battery whose charging and discharging is limited by the EVs that are connected to the grid.
Residential and commercial electric heating	Flexible residential and commercial electric heating is assumed to be provided by heat pumps and is considered a shiftable load within 12-hour periods.
District heating – CHPs, Heat pump and e-boilers	CHP generators, heat pump and e-boilers can provide heat based on their technical characteristics and the hourly heat demand of Denmark. There is a heat storage for each DK bidding zone, equivalent to their average daily heat demand. Flexibility is provided through the use of the storage and the possibility of using multiple technologies to provide heat.

TABLE 2-2

Additional assets in DNV's European Power Market Model.

Technology	Assumption and explanation
Front-of-the meter BESS	Battery energy storage systems in front of the meter are directly connected to the grid rather than being located behind the meter. The battery can provide ancillary services or buy electricity when prices are low, store it, and sell when prices are high. Front-of-the meter BESS is modelled in the same way in both scenarios.
Electrolysers	Load from electrolysers is considered curtailable, and shiftable. Minimum and maximum annual load need to be fulfilled (minimum=maximum), but it can shift the load across the hours based on the power prices. Max and min monthly consumption defined has to be met to avoid large shifts of electrolyser consumption from one month to another, yet the conditions include certain flexibility to shift part of the demand across months. Electrolyser's load can be curtailed when power prices rise above the input bid price, and the max/min consumption conditions can be violated at a very high cost (4000-90000EUR/MWh). Electrolysers are not considered DSF technologies and are modelled in the same way in both scenarios.
Rooftop Solar PV	Rooftop solar PV is not allowed to be curtailed.

2.1 Demand-side flexibility - Available power in 2030

Table 2-3 summarizes the available flexible power per technology, on average in 2030. It shows both upward flexibility corresponding to increasing generation or reducing demand, and downward flexibility corresponding to decreasing generation or increasing demand. In 2030, DNV estimates a total of 3.5 GW of upward flexible power and a total 6.3 GW of downward flexible power.

TABLE 2-3

Available power, upward and downward flexible power.

	Upward flexible power [MW]			Downward flexible power [MW]		
Technology	**DK 1**	**DK 2**	**DK**	**DK 1**	**DK 2**	**DK**
Industrial DSR	100	0	100	0	0	0
BESS Behind-the-meter	150	50	200	150	50	200
Smart charging	46	41	81	188	160	271
V2G	242	211	453	242	211	453
Residential electric heating	287	157	405	1,062	478	1,112
District heating - CHP	712	249	961	678	337	1,015
District heating - HP & e-boilers	924	398	1,321	1,977	1,274	3,251
Total	**2,461**	**1,106**	**3,522**	**4,297**	**2,510**	**6,302**
BESS Front-of-the meter	250	250	500	250	250	500

2.2 Demand-side flexibility - Activated flexibility in 2030

Using the market model and the amount of available demand-side flexibility power, DNV has calculated the activated flexibility in 2030. The amount of flexibility that is activated is a result of the 2030 electricity wholesale market simulation where system behavior is optimized, such as generators unit commitment, and economic dispatch. Table 2-4 shows the amount of activated flexibility. DNV's power market model identifies a total of 5.6 TWh upward flexibility and 5.4 TWh downward flexibility. BESS front-of-the-meter is not included in the total as it is not considered DSF as it does not add extra flexible capacity in the high flexibility scenario compared to the low flexibility scenario. The utilization of BESS front of the meter only changes because of changed market conditions, not because it is modelled differently.

TABLE 2-4

Activated power, upward and downward flexibility power.

	Upward flexibility [GWh]			Downward flexibility [GWh]		
Technology	**DK 1**	**DK 2**	**DK**	**DK 1**	**DK 2**	**DK**
Industrial DSR	0	0	0	0	0	0
BESS Behind-the-meter	102	32	134	107	34	141
Smart charging	324	285	609	324	286	610
V2G	608	481	1,089	700	553	1,253
Residential electric heating	1,979	1,035	3,014	1,979	1,035	3,014
District heating – CHP	154	81	235	93	40	133
District heating - HP & e-boilers	349	193	541	179	85	263
Total	**3,515**	**2,108**	**5,623**	**3,382**	**2,032**	**5,414**
BESS Front-of-the meter	331	313	644	349	330	679

3 THE BENEFITS FOR THE POWER SYSTEM

3. The benefits for the power system

A full deployment of demand-side flexibility in the Danish power system will provide benefits for both consumers and the society through savings in the wholesale market, grid benefits and balancing energy savings.

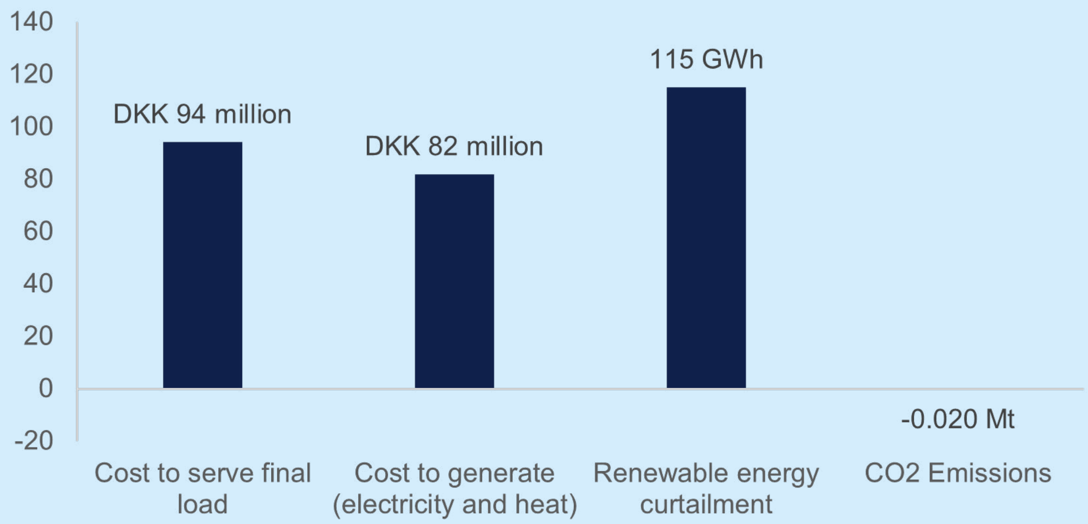
3.1 Wholesale market and adequacy

DNV identifies a range of benefits for the energy system in Denmark if the potential for demand-side flexibility is fully unleashed. For the Danish wholesale market, the following results are found in 2030:

- 82 million DKK are saved in 2030 due to lower cost to generate electricity and heat compared to the low demand-side flexibility scenario.
- All consumers would benefit from the indirect benefit of lower cost to serve final load which is reduced by about DKK 94 million annually in comparison to a low demand-side flexibility scenario
- Renewable energy curtailment will be 115 GWh less.
- 0.02 Mt more of CO2 would be emitted by the power sector, due to an increase in waste generation in comparison to the low demand-side flexibility scenario. Yet, the avoided CO2 emission from biomass-fired generation account for 7.2 Mt CO2 equivalents using emission numbers from Statistic Denmark's and forecast of biomass consumption by the Danish Energy Agency.

FIGURE 4.1

Annual benefits on the wholesale market.



DNV has also performed an adequacy assessment as part of the analysis. This analysis shows that Denmark does not present unserved energy in the base analysis of the Danish power market. However, in the cold-spell sensitivity analysis, then the Danish bidding zone DK2 shows unserved energy under the low demand-side flexibility scenario. A cold-spell is a short period where the temperature is significantly lower compared to a similar period and region. Unserved energy is not observed in the scenario with high demand-side flexibility as the flexibility will allow the system to maintain security of supply by compensating for the lack of biomass generation capacity. It is important to mention that DNV has just done one model run based on one climate year (1985). The amount of wind varies from year to year, as well as temperatures, and import and export changes with various factors in the surrounding countries. DNV has not investigated any extreme situations and an investigation into system adequacy in greater detail would require multiple model-runs using different climate years and stochastic simulations.

When all biomass generation is assumed to be phased out by 2030, DNV's results show that the maximum amount of unserved energy is 146 MW (338 MWh) in the cold-spell sensitivity analysis. DNV's calculation of indicative adequacy benefit of DSF has been done by comparing the investment required for installing 146 MW of peak generation capacity, and the costs of enabling 146 MW of demand-side flexibility. The difference between these numbers is defined as the DSF adequacy benefit.

DNV assumes that additional generation capacity will not come from carbon-free technologies. Therefore, the price of gas peaking plants is considered. The costs of industrial demand-side flexibility are considered, as these are likely to play a dominant role in scarcity situations. This is limited to the annualised enablement costs of demand-side flexibility. Typically, industrial customers also require annual capacity payments for participating in services with low activation frequencies. Because these payments are direct benefits for consumers, they are not considered as additional costs to consumers. Given these assumptions, the adequacy benefit of DSF in Denmark in 2030 is DKK 49 million.

The difference between scenarios is not significant. The difference between the scenarios is based on the flexible capacities that are assumed to be exposed to the market. The Low DSF scenario already has significant volumes of flexibility, which likely prevent high prices to occur.

The additional flexibility especially saves on costs to import electricity. DNV's analysis show 335 GWh less net import and this implies savings on "cost to generate" in other countries. In the high flexibility scenario, this less imported electricity is mainly compensated by more waste incineration, wind generation (curtailment reduction is mainly in wind) and less electric heating demand from heat pumps and e-boilers.

Curtailment of wind and solar in the low flexibility scenario is 0.7% of available renewable energy and in DNV's view this is quite low. In the high flexibility scenario curtailment is decreases by 115 GWh. Therefore, there is little opportunity for demand-side flexibility to facilitate renewable integration, reducing curtailment and decreasing prices, as the curtailment levels are already low.

3.2 System balancing

The energy system must be in balance. Different actors supply ancillary services to ensure this is always the case. In the ancillary service market for aFRR and mFRR, the TSO must buy energy when the system is short on real-time supply and sell energy when there is a real-time energy oversupply.

The quantification of system balancing benefits considers the difference in energy balancing costs in the high flexibility scenario and the low flexibility scenario in 2030. To calculate the system balancing benefits, DNV has used the following assumptions:

- **Balancing capacity data** is taken from the expected 2030 capacity in the Energinet Outlook for Ancillary Services 2024-2030.
- **Balancing energy utilisation** is assumed to remain the same as 2024 (source: ENTSO-E transparency).
- **Balancing energy costs** are determined by the marginal costs of technologies technically capable of providing the different balancing services. Marginal costs are calculated based on the inputs and the results from the DNV power market model. The merit order, assumptions about activation price and available capacity are in the appendix of this report.

DNV's power market model indicates the average available energy and its activation price per technology in both the low-flexibility and the high-flexibility scenario.

Combining these energy activation needs, the availability per technology and the activation price per technology, DNV concludes that the high-flexibility scenario results in either an increase in costs or decrease in revenue of DKK 4.5 million for balancing energy compared to the low flexibility scenario.

In the low flexibility scenario, the model results show that there is sufficient balancing energy available from BESS, reducing wholesale curtailment of renewables such as wind, solar, and district heating system assets (CHP, heat pumps and e-boilers) to fulfil the balancing energy needed.

The average activation prices of these assets are slightly more favourable in the low flexibility scenario compared to the high flexibility scenario.

DNV has not considered day-ahead capacity procurement costs. DNV has only assessed which technologies are likely to be needed to fulfil the capacity requirement by 2030 as expected by Energinet in their outlook for ancillary services.

For 2030, DNV finds that district heating prices are slightly lower in the high flexibility scenario. This increases the marginal cost and the willingness to pay (i.e. activation prices) for heat pumps, district heating and e-boilers but lowers marginal cost (i.e. activation costs) for combined heat and power.

In the low flexibility scenario, downwards (i.e. charged) electricity can be sold back for higher prices (because of more and higher high priced hours), while upwards (i.e. discharging) can be recharged for lower prices (because of more low-priced hours).

More flexibility improves the integration of wind and solar by reducing curtailment. However, this fewer curtailed energy can then not be re-activated for balancing services, resulting in less cheap upward balancing energy.

The results show slightly higher balancing costs in the high demand-side flexibility scenario.

As indicated in Table 3-1 district heating, heat pumps and e-boilers, curtailment of wind and solar, combined heat and power (CHP) and BESS front-of-the-meter are expected to provide the bulk of the balancing energy. The extra capacity from smart charging of electric vehicles, V2G, behind the meter BESS and household heat pumps are expected to be priced out of the market.

TABLE 3-1

Benefits for system balancing. DH HP= District Heating Heat pumps, CHP= Combined Heat and Power, BESS= Battery Energy Storage System, DH–e-boiler= District Heating electric boilers, RES= Renewable Energy Sources.

	Costs 2030 High flex (MDKK)	Costs 2030 Low flex (MDKK)	Cost difference High-Low DSF (MDKK)	Technology providing the service - High flex	Technology providing the service - Low flex
aFRR down	-112.8	-114.3	1.5	DH HP, CHP, BESS	DH HP, CHP, BESS
aFRR up	1.5	1.5	0.0	RES, DH e-boiler, HP	RES, DH e-boiler, HP
mFRR down	-282.4	-285.4	3.0	DH HP, CHP, BESS	DH HP, CHP, BESS
mFRR up	25.4	25.4	0.0	RES, DH e-boiler HP, BESS	RES DH e-boiler, HP, BESS
Total	**-358.6**	**-363.0**	**4.5**		

3.3 Grid infrastructure

In 2030, DNV's wholesale analysis results show a potential upward-flexibility capacity in Denmark of 1.24 GW, which is available for transformers at 10kV level or lower.

This capacity can support 60kV to 10kV voltage transformers by reducing peak load. The reduction can allow additional customers to be connected, when the 60kV to 10kV transformer or the higher-level voltage network is congested.

In our analysis, the number of customers that can be connected is determined by the maximum peak load day. DNV has analysed the load profiles of the peak load days for five transformers. DNV has estimated the 2030 peak load day profile based on these 2024 load profiles and the DNV wholesale model results for 2030.

The results show a potential to reduce the peak load by 1.2 MW or 12% per 60kV to 10kV transformer, which could be used to connect additional customers.

To calculate the additional value these customers would bring, DNV assumed a societal benefit of DKK 1.94 million per MW per year. This price is based on the next best alternative solution for these customers, which is to rent and install a gas or diesel engine. This calculation results in an added value of DKK 2.24 million per year per congested transformer in 2030.

To extrapolate this to the whole of Denmark, DNV assumes that 100-400 comparable transformers will be congested by 2030, about 10%-40% of the total 60 kV substation fleet in Denmark.

This results in a potential societal benefit of DKK 220-900 million per year for Denmark. This quantification does not consider that a diesel engine or other fossil fuel-based generation may not necessarily possible due to climate regulation. Cost related to grid connection approval times are not included and dynamic effects from employment or taxes are included with the result the benefits quantified above might be much higher.

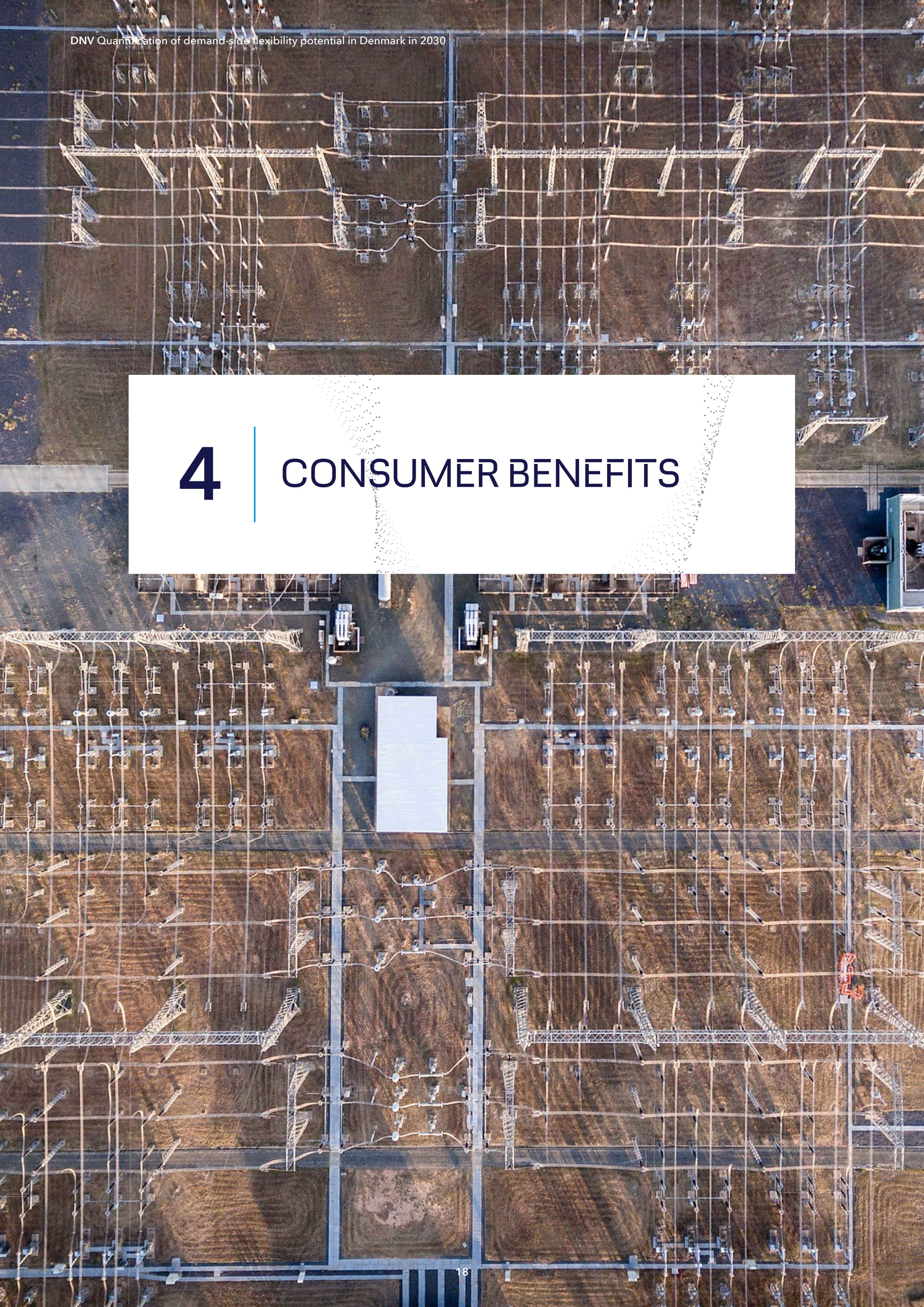
TABLE 3-2

Transformer (TF) statistics and results from DNV grid model. Source: DNV calculations

Transformer	Rated capacity of transformer [kW]	Max in 2030 [kW]	Curtailable load [kW]	Potential shifting [kW]	Possible shifting [kW]	% peak reduction
10kV average	14,060	9,663	108	1,225	1,225	**14%**
TF1	15,200	11,794	123	1,405	1,405	**13%**
TF2	15,200	9,590	86	985	985	**11%**
TF3	15,200	14,184	157	1,792	1,792	**14%**
TF4	15,200	8,525	77	872	872	**11%**
TF5	9,500	9,870	96	1,096	1,096	**12%**

DNV has not found data on how many transformers will be congested by 2030 as Danish grid operators do not provide numbers for the future congestion of the electricity grid. No in-dept analytics could be performed on the number of congested transformers and therefore had to rely on assumptions from experts in TREFOR El-net. By "congested", we mean that either the transformer or substation itself reaches its rated capacity, or there is congestion on higher grid levels that restricts the DSO from connecting more customers. In several other countries, it can be observed that congestion on TSO level is the main barrier, as grid reinforcement on higher voltage levels typically takes many years to complete.

Some of these substations would be in solar- and wind-dominated areas and not in demand-dominated areas. Since our analysis focuses on demand-driven congestion, DNV assumes that 100-400 medium-voltage transformers will be congested by 2030, corresponding to 10%-40% of the substations in Denmark.



4 CONSUMER BENEFITS

4. Consumer benefits

DNV finds that direct benefits for consumers who own flexible assets range from DKK 480 million for smart charging and vehicle-to-grid, to DKK 31 million for batteries behind the meter.

All consumers would benefit from the indirect benefit of lower cost to serve final load, which is reduced by about DKK 94 million annually in comparison to a low demand-side flexibility scenario as shown in Figure 4.1.

FIGURE 4.1

Direct benefits for consumers distributed on smart charging + V2G, space electric heating and BESS.

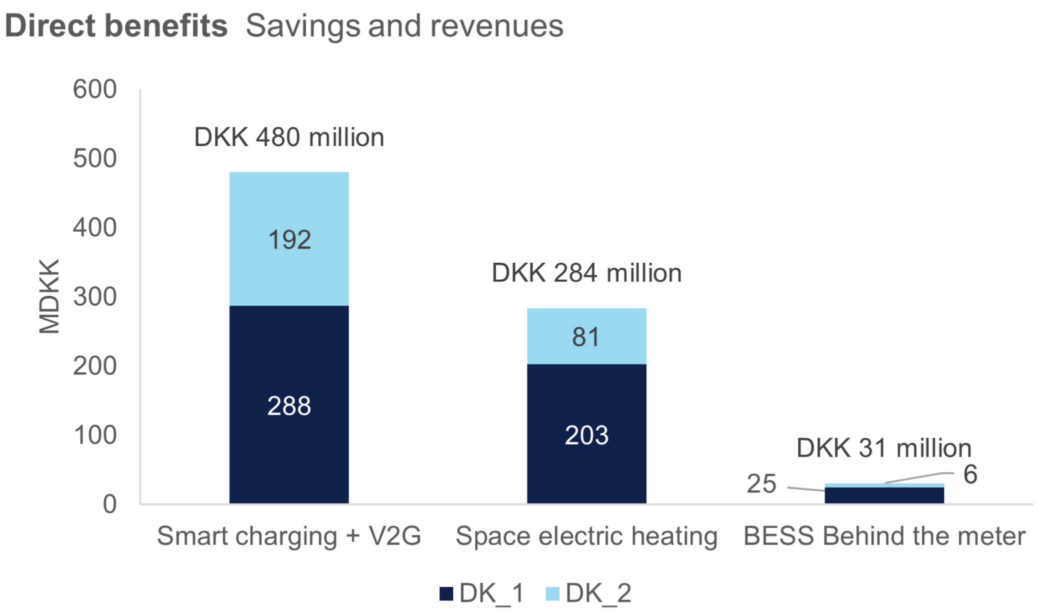
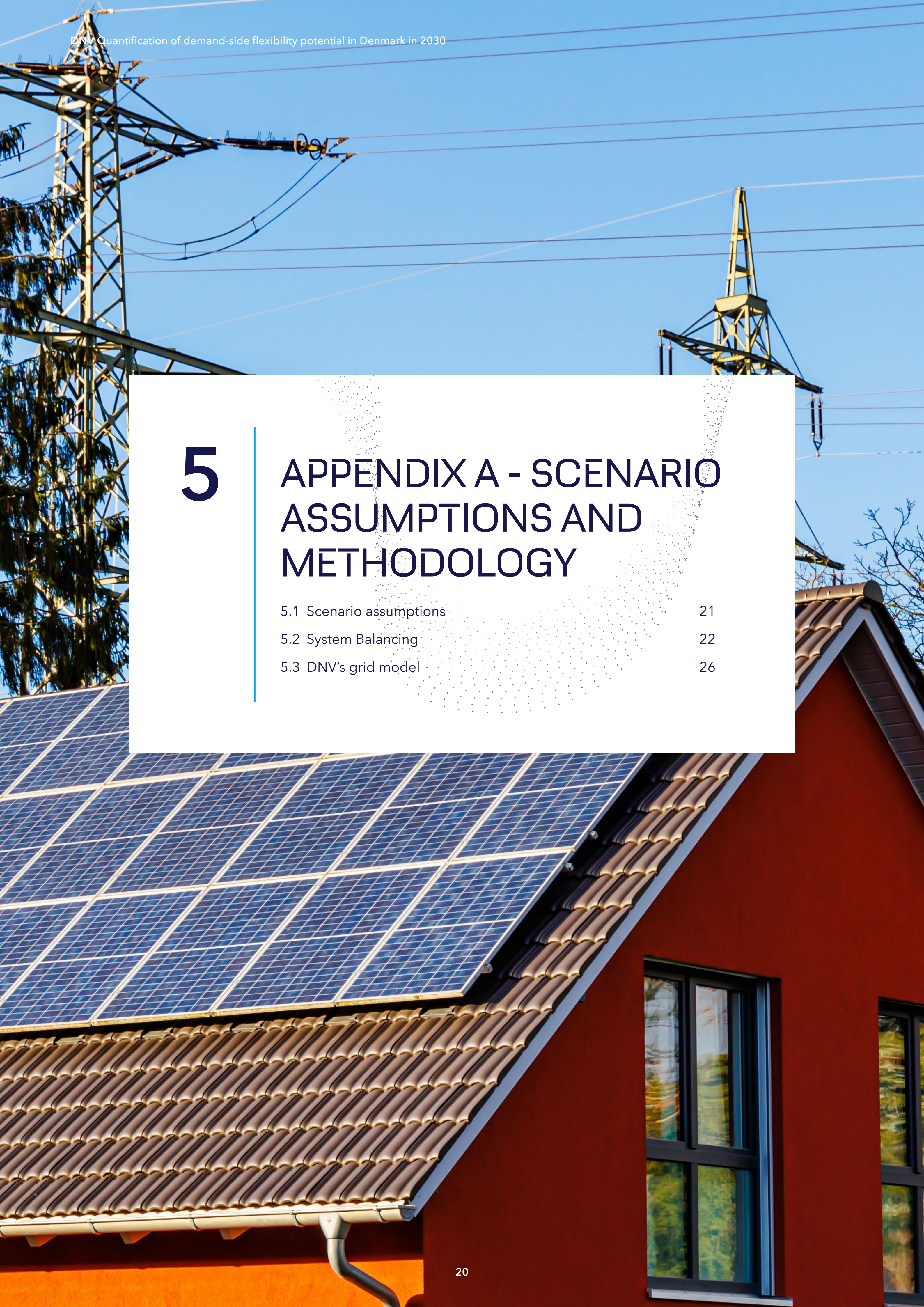


TABLE 4-1

Direct benefits for consumers distributed by bidding zone.

Direct benefits	Relative to cost in low flexible scenario (% savings)			Average saving/revenue per kWh (DKK/kWh)		
	DK1	**DK2**	**DK**	**DK1**	**DK2**	**DK**
Smart charging + V2G	44%	32%	38%	0.21	0.16	0.18
Space electric heating	12%	7%	10%	0.07	0.05	0.06
BESS Behind-the-meter	32%	22%	29%	0.25	0.19	0.23



5 APPENDIX A - SCENARIO ASSUMPTIONS AND METHODOLOGY

5. Appendix A - scenario assumptions and methodology

5.1 Scenario assumptions

DNV's market model is based on the forecast of AF24 from the Danish Energy Agency with the exception that biomass is phased out in 2030 and the electrolyzer capacity is set to 100 MW in DK1. The figures below present the numbers used. DNV has used its European Power Market Model, a fundamental market model that simulates the day-ahead spot market by optimizing the unit commitment and economic dispatch of electricity generation, based on marginal cost.

FIGURE 5.1

Installed generation capacity in 2030, source: AF24.

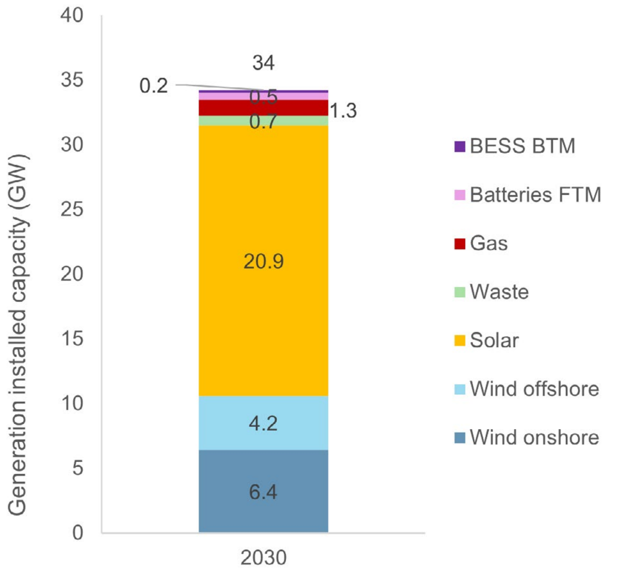


FIGURE 5.2

Electricity demand in 2030, source: AF24, and power market model results.

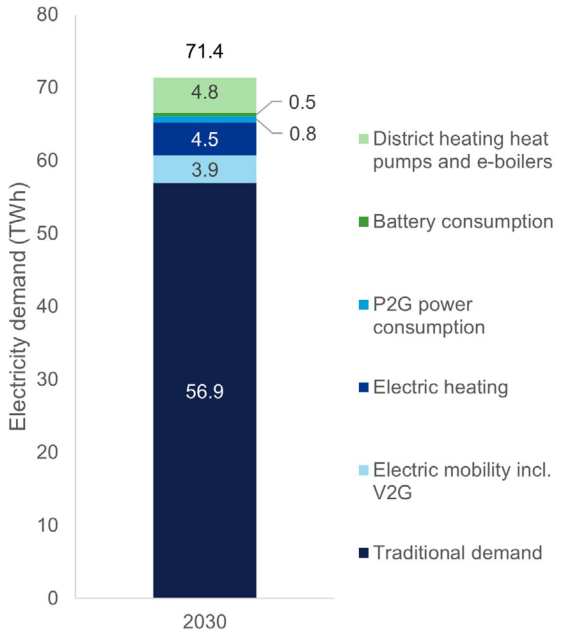
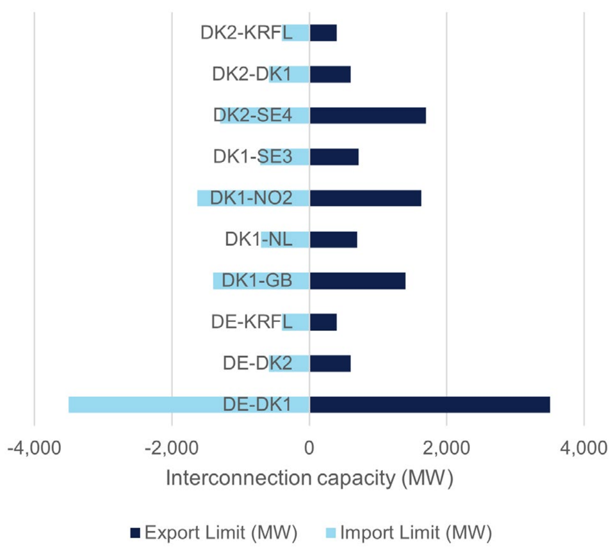


FIGURE 5.3

Interconnection capacity in 2030, source: AF24.



5.2 System Balancing

FIGURE 5.4

DSF benefits for system balancing: methodology map.

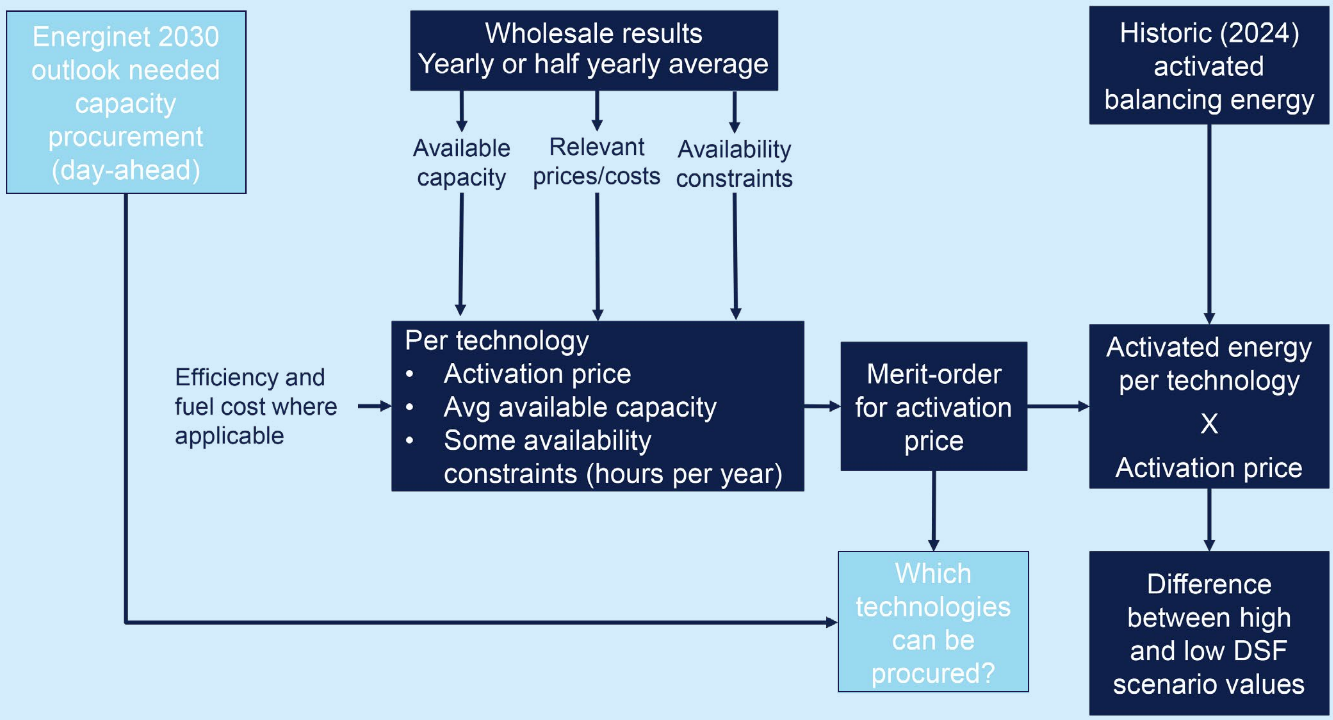
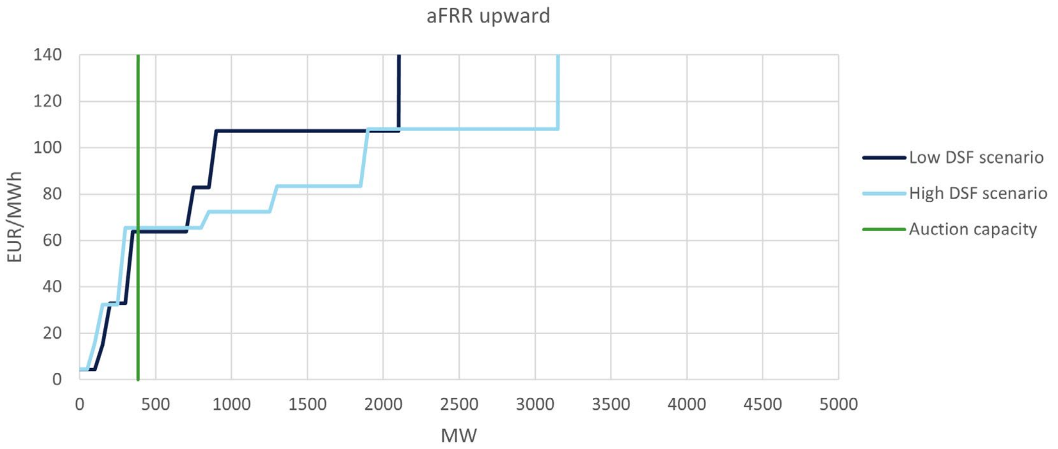
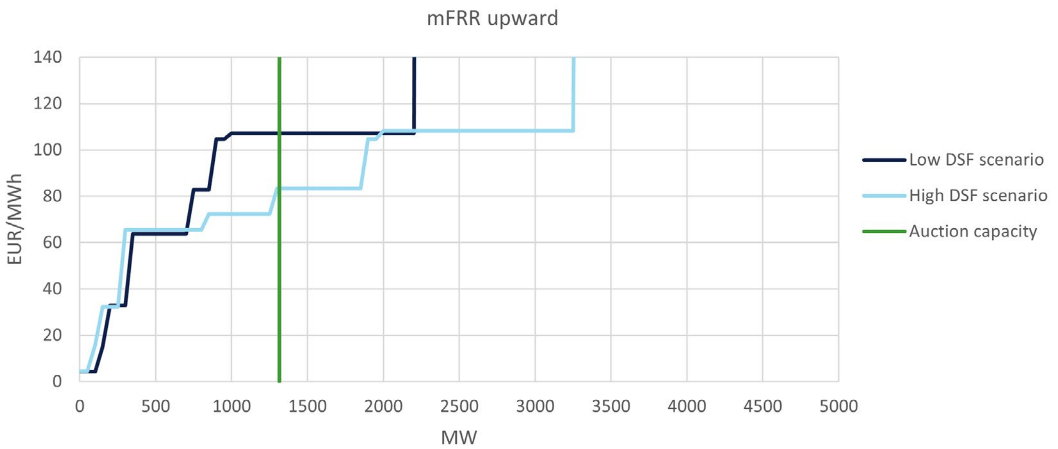


FIGURE 5.5

Upward merit order. Source: DNV calculation.



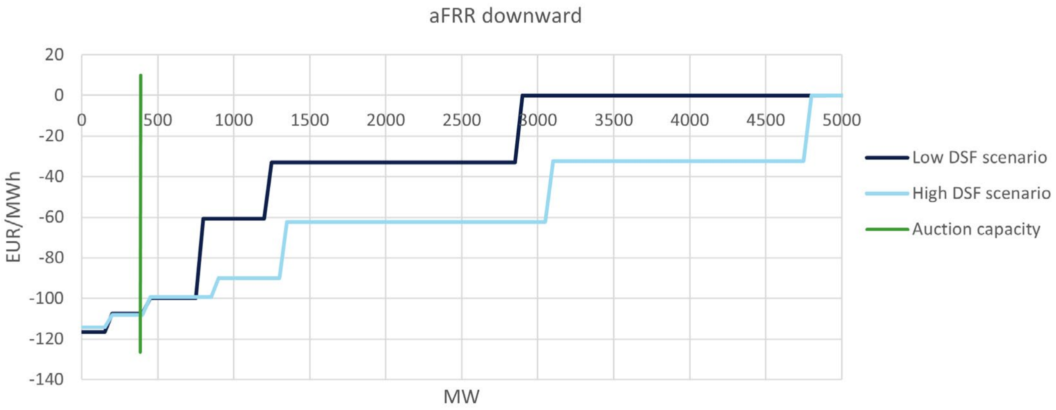


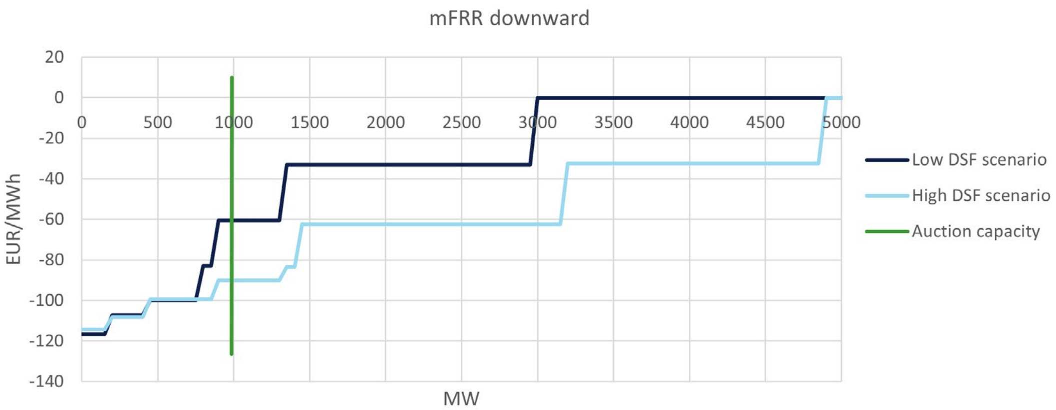
For upward balancing energy, DNV has determined the marginal cost per technology as the average annual price the TSO must pay for activation. Using wholesale curtailed wind and solar is the cheapest technology. However, it is only available for a few hours at a time. After that, district heating e-boilers and heat pumps can temporarily reduce their load, opting to produce heat at a non-peak hour. BESS front-of-the-meter is considered the next cheapest technology with its re-charging costs at periods when power prices are low. Combined, these technologies are likely capable of providing all necessary upward balancing energy. The light blue line (high demand-side flexibility scenario) indicates that these technologies are slightly less available than in the low demand-side flexibility scenario (dark blue line). Their activation price is a bit higher in the high demand-side flexibility scenario as well, resulting in higher costs for balancing energy.

The additional flexible capacity from demand-side flexibility has a higher activation price than the technologies that already provide the necessary balancing energy. Given this, demand-side flexibility technologies are likely not used, or used sparingly. The green line indicates that the demand-side flexibility technologies might be used for the procurement of capacity. However, the benefits of this are not quantified here, as they would have very different (opportunity) price behaviour than indicated in the merit order.

FIGURE 5.6

Downward merit order curve. Source: DNV calculations.





For downward balancing energy, DNV has determined the willingness to pay per technology as the average annual bid price market parties must pay to the TSO to generate less or consume more. District heating heat pumps that can produce more heat and natural gas CHPs that can produce less are likely to place the highest bids for the downward balancing energy. BESS front-of-the-meter is considered the next cheapest technology. The bid price from BESS fron–of-the-meter represents the availability of discharging at an expensive moment.

Combined, these technologies likely provide all necessary downward balancing energy. For these technologies, there is very little difference in available capacity between the high flexibility scenario (light blue line) and the low flexibility scenario (dark blue line). The bid prices in the low flexibility scenario are slightly higher, resulting in higher revenue for the TSO. The additional flexible capacity has a lower bid price than the technologies that already provide the necessary balancing energy. The DSF technologies are likely rarely used, if at all.

The green line indicates that the flexible technologies might be used for the procurement of capacity. However, the benefits of this are not quantified here, as they would have very different (opportunity) price behavior than indicated in the merit order.

TABLE 5-1

DSF benefits in system balancing - Downward (aFRR, mFRR, RR)

Upward

Merit order technologies	Marginal cost – High flex (EUR/MWh)	Marginal cost – Low flex (EUR/MWh)	Marginal cost reasoning	Available capacity High flex (MW)	Available capacity Low flex (MW)	Capacity source
Wind OFFSH	0	0	Marginal cost	1,855	1,530	Average curtailed capacity
Wind ONSHO	0	0	Marginal cost	1,735	1,884	Average curtailed capacity
PV	0	0	Marginal cost	956	871	Average curtailed capacity
DH electric boiler	4	4	Average Summer (Apr-Sept) value of heat * efficiency	140	151	Average load in summer (Apr-Sept)
DH Heat pump	16	15	Average Summer (Apr-Sept) value of heat * efficiency	91	100	Average load in summer (Apr-Sept)
e-boiler winter	32	33	Average Winter (Oct-Mar) value of heat * efficiency	244	274	Average load in winter (Oct-Mar)
Battery FTM	65	64	Marginal cost: cost of charging at another time = average market price 50% lowest hours / efficiency (95%).	426	422	Average available upward capacity based on wholesale dispatch from simulation results
Battery BTM	66	64	Marginal cost: cost of charging at another time = average market price 50% lowest hours / efficiency (95%).	152	-	Average available upward capacity based on wholesale dispatch from simulation results
EV - V2G	72	70	Marginal cost: cost of charging at another time = average market price 50% lowest hours / efficiency (86%).	453	-	V2G installed capacity*average availability profile
EV	83	83	Cost of purchasing electricity in another moment: average market price	189	133	Average upward flexible power
Heatpump	83	83	Cost of purchasing electricity in another moment: average market price	405	-	Average upward flexible power
Electrolyzers	105	105	Maximum electricity price at which the electrolyser consumes, based on modelling results to fulfil 3000FLH	100	100	Installed capacity market model
NGAS CHP	108	107	Short-run marginal cost (electic CHP efficiency minus average heat revenues of co-produced heat in winter)	1,283	1,283	Installed capacity market model
Industrial DSR - 24 hr	207	207	Input data, equivalent variable O&M of DSF	16	-	Installed capacity market model
Industrial DSR - 4 hr	323	323	Input data, equivalent variable O&M of DSF	9	-	Installed capacity market model
Industrial DSR - 8 hr	500	500	Input data, equivalent variable O&M of DSF	30	-	Installed capacity market model
Industrial DSR - 1 hr	1000	1000	Input data, equivalent variable O&M of DSF	10	-	Installed capacity market model
Industrial DSR - 2 hr	1097	1097	Input data, equivalent variable O&M of DSF	35	-	Installed capacity market model

TABLE 5-2

DSF benefits in system balancing - Upward (aFRR, mFRR, RR)

Downward

Merit order technologies	Marginal cost – High flex (EUR/MWh)	Marginal cost – Low flex (EUR/MWh)	Marginal cost reasoning	Available capacity High flex (MW)	Available capacity Low flex (MW)	Capacity source
DH Heat pump	-114	-117	Average Winter (Oct-Mar) value of heat * efficiency	330	317	Remaining capacity in winter - Oct to Mar
NGAS CHP	-108	-107	Short-run marginal cost (electic CHP efficiency minus average heat revenues of co-produced heat in winter)	898	898	Installed capacity market model, which is operating * (1 minus minstable level)
Battery FTM	-99	-100	Willingness to pay: average market price 50% highest hours * efficiency (95%). It will be willing to pay the revenue of discharging at high prices later.	313	311	Average available downward capacity based on wholesale dispatch from simulation results
Battery BTM	-99	-100	Willingness to pay: average market price 50% highest hours * efficiency (95%). It will be willing to pay the revenue of discharging at high prices later.	125	-	Average available downward capacity based on wholesale dispatch from simulation results
EV - V2G	-90	-90	Willingness to pay: average market price 50% highest hours * efficiency (86%). It will be willing to pay the revenue of discharging at high prices later.	453	-	V2G installed capacity*average availability profile
Electrolyzers	-83	-83	Willingness to pay: average electricity market price (cost to purchase electricity). Due to its condition of annual generation equivalent to 3000FLH, it would have already utilised the cheapest price hours to consume.	100	100	Installed capacity market model
EV	-62	-61	Willingness to pay: average market price 50% lowest hours. It will be willing to pay the lowest cost that it would have to pay to charge.	631	442	Average downward flexible power
Heatpump	-62	-61	Willingness to pay: average market price 50% lowest hours. It will be willing to pay the lowest cost that it would have to pay to charge.	1,112	-	Average downward flexible power
DH electric boiler	-32	-33	Average Winter (Oct-Mar) value of heat * efficiency	3,365	3,335	Remaining capacity in winter - Oct to Mar
Wind OFFSH	0	0	Marginal cost	1,994	1,989	Average generating capacity
Wind ONSHO	0	0	Marginal cost	1,657	1,650	Average generating capacity
PV	0	0	Marginal cost	2,355	2,353	Average generating capacity

5.3 DNV's grid model

FIGURE 5.7

DNV grid model - Highest load profile days and isolated traditional load. Source: Transformer data from TREFOR El-net.

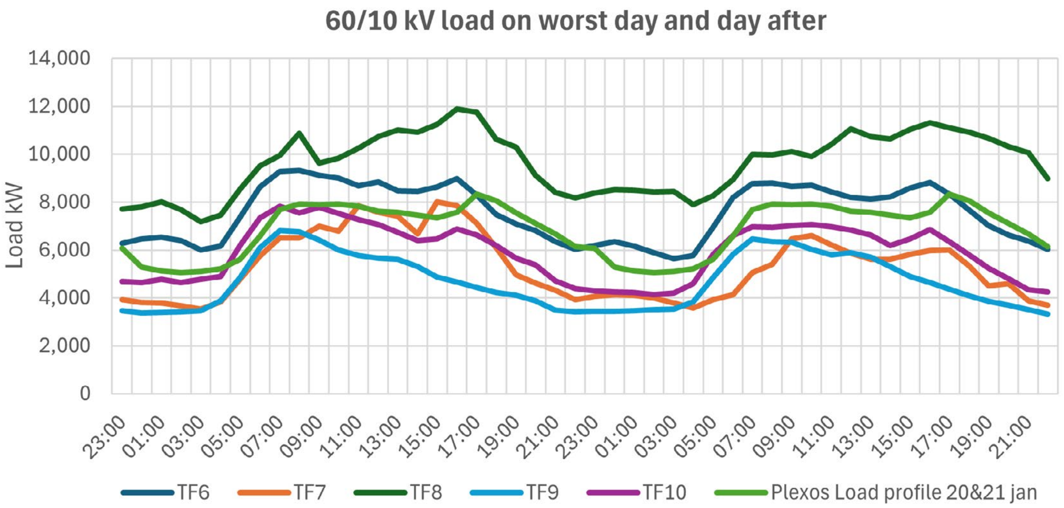
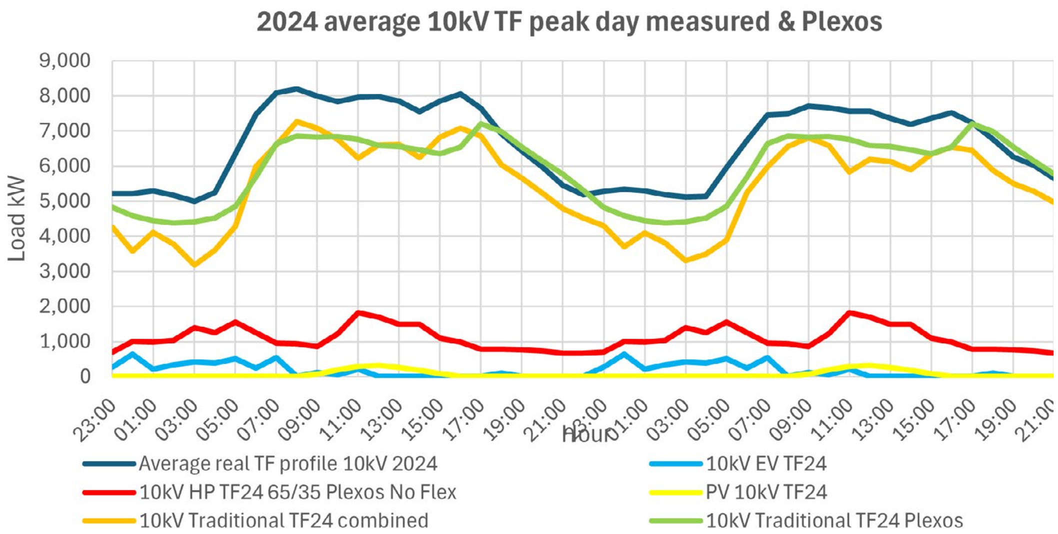


FIGURE 5.7

Source: DNV calculations, HH = Households, TF = Transformer, HP = Heat pump, EV = Electric Vehicle smart charging



The 2030 profiles that are used in the DNV grid model are based on:

1. Measured 2024 TREFOR El-net transformer load for 60kV to 10 kV. First top graph.
2. AF24 annual data for 2024 and 2030 (especially on demand types such as EV, heat pumps and solar PV)
3. DNV power market model profiles for the two highest load days 20th January and 21st January (green line in both graphs)

6 LIMITATIONS OF THE APPROACH

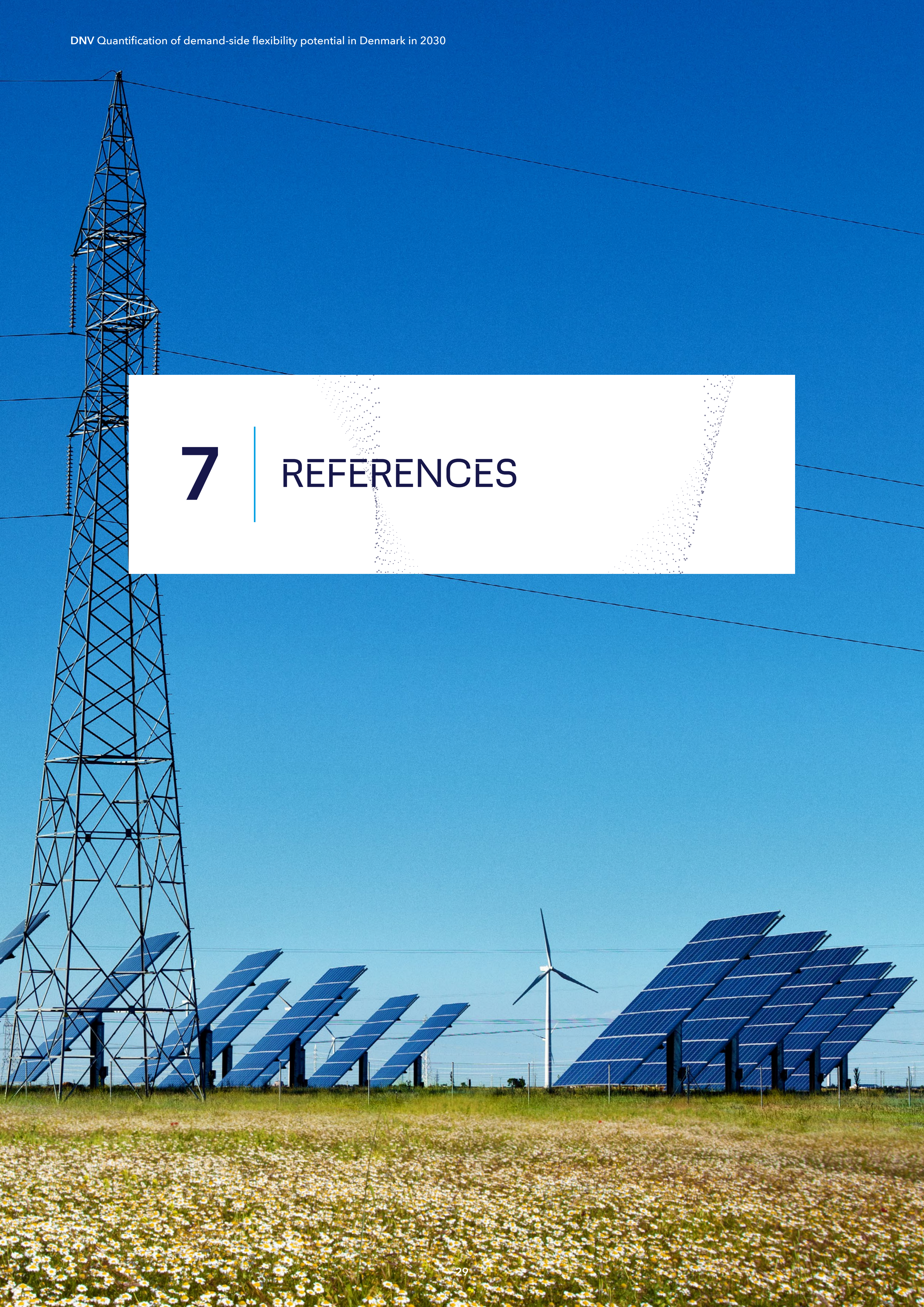
6. Limitations of the approach

The following approach to quantifying the value of flexibility in different segments includes certain limitations. The main ones are listed below:

- Potential flexibility from public charging points is not included.
- Apart from EVs, other means of electric transport such as electric buses or trucks are not modelled. This is due to data unavailability.
- The renewable curtailment presented in this report refers to the curtailment due to higher available generation than load and considers the possible congestion of the interconnectors. However, congestion in national distribution and transmission networks is not considered in DNV's European power market model.
- Investment costs for enabling DSF are not considered for either scenario.
- DNV has not performed a detailed adequacy assessment. An adequacy study requires stochastic modelling to draw statistically valid conclusions. The modelling used for this study was deterministic, and therefore not sufficient. Hence, the results presented are a lower bound, as actual benefits could emerge when a complete adequacy assessment is performed.
- The merit order built for technologies providing balancing services is based on marginal costs of the different technologies only. Other costs such as opportunity costs (e.g., the missed revenue for not selling their flexibility in other markets such as congestion management) are not included.

Abbreviations

DSF	Demand-side flexibility
BESS	Battery Energy Storage System
FTM	Front the Meter
FTM BESS	Front the Meter Battery Energy Storage System or Utility Scale BESS
BTM	Behind the Meter
DH HP	District Heating Heat Pumps
CHP	Combined Heat and Power
DH e-boiler	District Heating electric boilers
V2G	Vehicle to Grid
EV	Electric Vehicle
DSR	Demand-side Response
AF24	Analyseforudsætninger 2024
aFFR	Automatic frequency reserve market
mFFR	Manual frequency reserve market



7 REFERENCES

7. References

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/2/ Demand-side flexibility: Quantification of benefits in the EU. DNV report for smartEn – Smart Energy Europe

/3/ Energinet Outlook for Ancillary Services 2024-2030

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DNV is an independent assurance and risk management provider, operating in more than 100 countries, with the purpose of safeguarding life, property, and the environment. As a trusted voice for many of the world's most successful organizations, we help seize opportunities and tackle the risks arising from global transformations. We use our broad experience and deep expertise to advance safety and sustainable performance, set industry standards, and inspire and invent solutions.

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We provide assurance to the entire energy value chain through our advisory, monitoring, verification, and certification services. As the world's leading resource of independent energy experts and technical advisors, we help industries and governments to navigate the many complex, interrelated transitions taking place globally and regionally, in the energy industry. We are committed to realizing the goals of the Paris Agreement, and support our customers to transition faster to a deeply decarbonized energy system.

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