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BUSINESS CASE FOR FLEXIBLE RESIDENTIAL HEAT PUMPS

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WP5.4. Flexibility Business Case Methodology [iPower WP5.4 2013]

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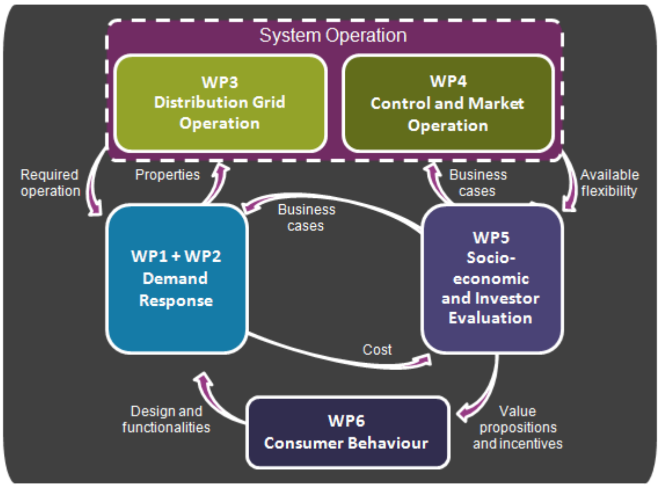
PREFACE

References

References are marked with [ ] (e.g. [Author Year]) referring to the full reference list found in Chapter 8

The iPower project

The analysis is part of iPower WP5.5 'Business cases for flexible consumption'. The relationship between WP5 and the remaining iPower project is illustrated in figure below:



Interaction between work packages in iPower project [iPower WP2 2012]

The results in this report are based on assumptions from previous studies of residential heat pump as well as technical and economical estimations from heat pump experts. However, this analysis could be updated with possible new findings from iPower WP1 demonstrations of heat pump control as well as new assessment of value of heat pump flexibility.

The final dissemination of iPower WP5 is scheduled in November 2015.

Disclaimer
This analysis has been prepared and quality assured internaly by the Danish Energy Association.
The Danish Energy Association cannot be held responsible for economic losses resulting from the use of information or data in this analysis.

NOMENCLATURE

Aggregator	Controller of many smaller DERs, e.g. many residential heat pumps. The aggregators perform intelligence control of units in the portfolio, e.g. optimises towards one or more electricity markets.
Air-to-water heat pump	Heat source is the surrounding air
Ancillary services markets	Primary, secondary and tertiary reserve reservations
Balancing markets	Intraday trading and Regulating power market
Balmorel	The linear power system model Balmorel is used to calculate e.g. power prices and investments in the energy system 2020-2035
BRP (Balance Responsible Party)	Commercial actor that is responsible for portfolio of power consumption and power production. Provides bid to the markets on behalf of their customer. Imbalance costs are settled according to BRP portfolio.
Building category	The Danish one-family houses with radiator heating are divided into different categories based on three categories of insulation year (House building year) and three categories of heat capacities.
Business case	In this analysis the word 'business case' is used to describe the economic rationale behind flexible heat pumps, both from a private economic perspective (customers, commercial actors) and a societal perspective.
Business model	An attractive business model might have to enable several sub-business cases to fulfil the requirement (risk, economic profit) of all stakeholders. The generic business model of flexible consumption is investigated in coming iPower WP5.5 report
Capacity mechanism	Economic mechanisms beyond power price and ancillary service prices that will secure reliable capacity. Three main capacity mechanisms exist: Strategic reserve, Capacity market and capacity payment.
CCGT	Combined cycle gas turbine
COP	Coefficient of performance. The total efficiency of the heat pump (including electric heater) specified as heat production divided by power consumption. The modelling of COP is described in Appendix 7.1.6
Cost of flexibility / cost of flexible heat pump	The cost of 1) additional control of a heat pump and 2) Heat storage
Day-ahead market	Trading of power Day-ahead. Balmorel simulates prices on the Day-ahead market.
Demand response	"Changes in electric usage by end-use customers from their normal consumption patterns in response to changes in the price of electricity over time, or to incentive payments designed to induce lower electricity use at times of high wholesale market prices or when system reliability is jeopardized." [Balijepalli 2011]
DER	Distributed Energy Resource, flexible consumption or production unit located in the distribution grid, i.e. PV, EV, residential heat pump
Electric heater	Auxiliary electric heater that can produce heat with efficiency of =0,99. The heat capacity of the electric heater is part of the heat pump heat capacity.

Energy-only market	Energy-market where power prices together with ancillary services are the only income for power producers, i.e. no payment for power capacity.
EV	Electric Vehicle
Flexible heat pump	A heat pump that is controllable, i.e. a user or third party operator can control the heat pump and possibly also the temperature requirement (via the thermostat settings) in the house with the purpose of minimizing the cost of electricity and/or reduce the required peak demand. Further, a flexible heat pump has a heat storage that allows the heat to be produced during periods with low power prices and thus switch the power consumptions away from peak load periods
Ground source heat pump	Liquid-to-water based heat pump. Heat source is the surrounding ground temperature
Heat capacity of building	The energy needed to changce the temperature of the building structure and indoor air (Wh/C/m2)
Heat pump heat capacity	The heat pump is dimensioned to a given maximum heat effect at outdoor temperature of e.g. -12 C, which in this analysis is referred to as the heat capacity. The possible heat effect increases with higher outdoor temperature (see Figure 75)
Heat storage	A buffer where heat production from heat pumps can be stored. The heat storage can be A). an additional accumulator tank or B). heat stored in the building structure and indoor air
House building year	The building year is a measurement of the insulation level of the house, i.e. older buildings have in general worse insulation compared to newer houses
Individual heating	Heating in buildings outside district heating areas, i.e. residential heat pumps, natural gas boilers, wood chip pellets boilers, oil and natural gas boilers
Non-flexible heat pump	A heat pump that is operated to maintain the indoor comfort level given by a required constant indoor temperature (similar to constant thermostat setting). This means the heat pump does not have heat storage and hence the heat has to be produced when needed independent of the power price
O&M	Operation and maintenance cost consist of Fixed O&M (EUR/kW/year) and variable O&M (EUR/kWh)
OCGT	Open Cycle gas turbine.
Peak power capacity	The maximum value of the residual power production. This capacity is needed to provide power in all hours. In reality the required peak power capacity is determined based on desired Security of supply in the electricity system. The capacity value of e.g. interconnectors, power plants and wind power contributes to the required peak power capacity.
Private economic profit of flexible heat pumps	The profit of customers due to flexible heat pump operation In the day-ahead market calculated as reduction in electricity cost minus investments cost of flexibility
PV	Photovoltaic
Radiator and floor heating	Water based heat distribution systems in houses.
Residential heat pumps	Only heat pumps in one-family residential houses are included in the analysis. The heat pumps are either ground source or air-to-water heat

	pumps
Residual power production	The power production from controllable power plants and import needed to cover the difference between consumption and uncontrollable production (wind and solar).
Socioeconomic value of flexible heat pumps	The created system value in Denmark due to flexible heat pumps. The calculation of the system cost in the day-ahead market is defined in Table 7.
System cost	The total cost in Balmorel of power and heat production including new investments in the system, i.e. the countries included in the model
System service contract/market	A contract/market between TSO/DSO with suppliers of system services. The ancillary service markets are existing examples of these markets. Future Danish contract/market could involve TSO sourcing of reliable peak power capacity and DSO sourcing of voltage regulation.
Thermal Building module	Module to Balmorel that calculates the heat balance and hence building structure temperature and indoor air temperature based on the thermal properties of the building, outdoor air temperature etc.
ToU grid tariff	Time-of-Use grid tariff. The tariff is variable during the day with predefined levels in different time periods

EXECUTIVE SUMMARY

The political targets in Denmark aim for a CO2-neutral power and heat sector by 2035. This gives residential heat pumps the potential to become a key technology in the future Danish energy system as a replacement for existing residential oil and natural gas boilers outside district heating areas. Prognosis suggest ~400.000 residential heat pumps could be installed in Denmark by 2035 (corresponding to electricity consumption of 1,8 TWh). Residential heat pumps will significantly increase the electricity demand in the households which can lead to challenges in the local distribution grid and increase the national demand for peak power capacity. However, flexible operation of heat pumps can influence this demand and hereby create value for both customers and society.

The Non-flexible heat pump is defined as a heat pump that is operated to maintain the indoor comfort level given by a required constant indoor temperature (similar to constant thermostat setting). The Flexible heat pump is defined as a heat pump that is controllable, i.e. a user or third party operator can control the heat pump and the temperature requirement (via the thermostat settings) in the house with the purpose of minimizing the cost of electricity and/or reduce the required peak demand. By varying the temperature the flexible heat pump can utilize the house as a heat storage that allows the heat to be produced during periods with low power prices and thus switch the power consumptions away from peak load periods.

The objective of this analysis is to investigate the Business case for flexible residential heat pumps in Denmark from 2020-2035 from a private economic and socioeconomic value perspective, respectively. The business case consists of different value pools where flexible heat pumps (controllable according to prices and control signals) can create economic profit compared to non-flexible heat pumps:

- Day-ahead market
- Variable distribution tariffs
- New market opportunity: Balancing and ancillary service markets
- New market opportunity: Capacity mechanism

Model of flexible heat pumps in Balmorel

The Danish flexible heat pumps in the day-ahead market 2020-2035 are simulated in the energy system model Balmorel that calculate future power prices and investments in the Northwest European power markets. The residential heat pumps are modelled via a Thermal Building Module in Balmorel, where different building categories (insulation and heat capacity) are used to calculate the aggregated heat demand and via a variable COP model calculate the aggregated power demand. The heat pump flexibility is modelled via different heat storage investment options, where heat storage in the building structure proved to be more cost-efficient compared to additional hot water accumulator tanks. Thus, the costs of flexibility in the model consist of additional control of heat pump and thermostats in the houses to control the indoor air temperature within the customer's heat comfort boundaries.

Consequently, the power price and investments in Balmorel is affected by optimization of the power consumption of the residential heat pumps. The model is used to quantify the value of flexible heat pumps with variable indoor temperature (variable thermostat setting) compared to non-flexible heat pumps with constant indoor temperature (constant thermostat setting).

Socioeconomic value

The total Danish socioeconomic value of the flexible consumption of residential heat pumps is estimated in Balmorel at ~400 million DKK/year in 2035 via change in Danish system costs. The value primarily comes from Danish fuel cost savings as flexible heat pumps move power consumption to off-peak hours with cheaper power production. Further, the marginal value of wind production is increased by flexible consumption which makes an additional ~180 MW offshore investment profitable from 2020-2035.

The reduction in peak power capacity investments by 500-750 MW corresponding to ~150 million DKK/year in 2035 is a contribution to the total socioeconomic value. Non-flexible residential heat pump will increase the peak power capacity requirement, when high heat demand is coinciding with a period with high conventional power consumption and low wind production. However, flexible heat pumps can reduce the peak power capacity by shifting the power consumption away from this period. This is illustrated via Balmorel results of non-flexible and flexible residential heat pump power consumption in figure A below:

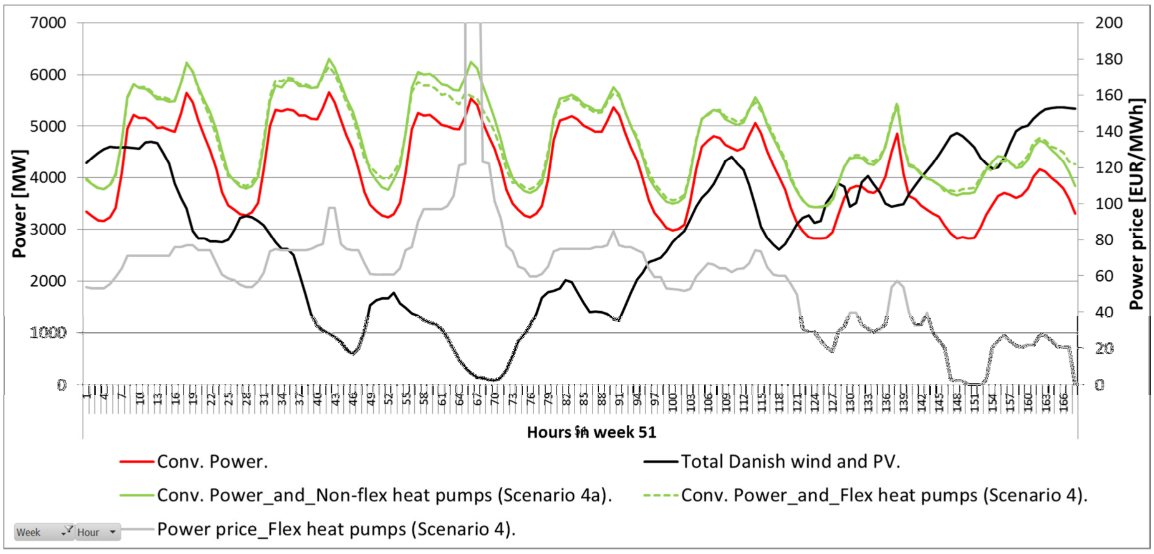


Figure A. Balmorel results of Danish spot market power prices (gray), power consumption and wind power production during one week in 2035. The power consumption of non-flexible (full green) and flexible (dotted green) heat pumps during a period with low wind production (black) and high conventional power demand (red).

The economically attractive investment in flexible heat pumps from a power system perspective is investigated in different scenarios in Balmorel. The results show that more fluctuating power prices due to increased wind power production as well as tighter capacity margins due to power plants closures are the main drivers for increased value of flexibility from 2020 to 2035. This is shown in figure B below via the number of houses with flexible heat pumps in different scenarios:

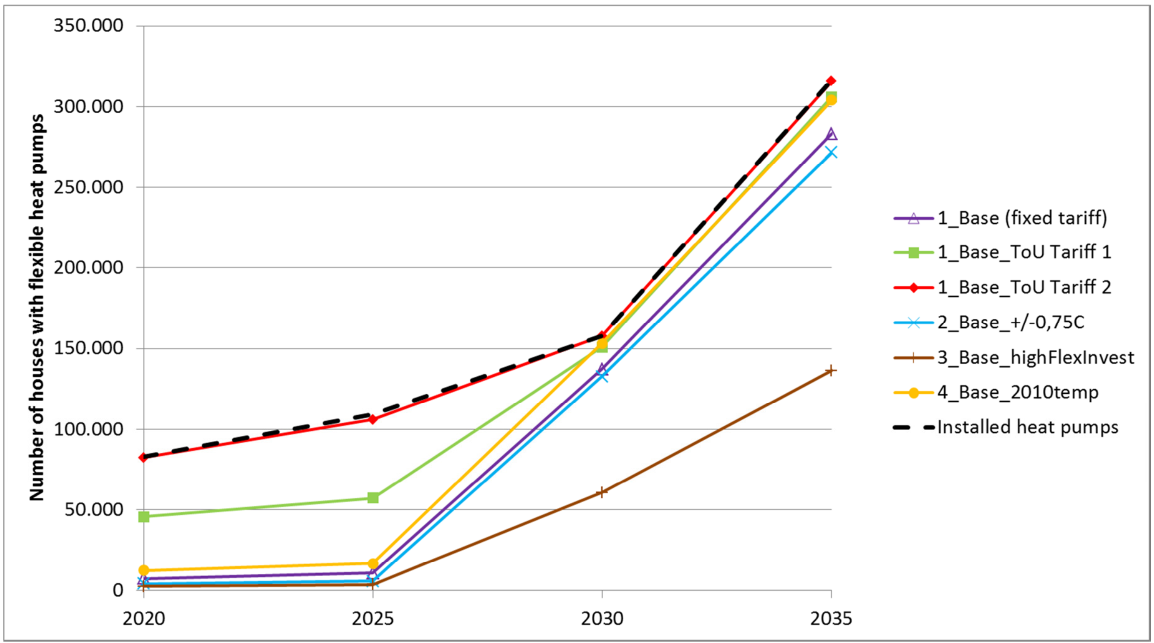


Figure B. Investment in flexible heat pumps in different scenarios in Balmorel. The development of variation in power prices and the required peak power capacity lead to higher investments in flexible heat pumps in 2035 compared to 2020. Scenarios with Time of Use tariffs (green and red) lead to higher investments in 2020 and 2025 compared to remaining scenarios with fixed tariffs.

The installation of residential heat pumps (dotted black) is the upper limit for investments in flexible heat pumps. The investment in different scenarios shows how the changes between the different scenarios affect the attractiveness in flexible heat pumps. Variable tariffs have a significant influence on flexibility investments in Balmorel in 2020 and 2025 compared to scenarios with fixed tariffs.

Reduction in distribution grid reinforcement costs and ancillary service costs could increase the estimated socioeconomic value of flexible heat pumps, but have not been included in this analysis.

Private economic business case

The private economic profit (including investment in flexibility) in the day-ahead market due to reduced electricity costs is estimated in Balmorel at ~200-700 DKK/year per average flexible heat pump in 2035. The profit spread is due to scenarios with different outdoor temperature profiles (heat demand) that have a significant influence on the profit potential of flexible heat pumps. In all scenarios the result showed that houses with higher power consumption (low insulation) have the highest absolute flexible consumption profit. As a secondary effect within houses with same heat demand the profit is larger in houses with higher heat capacity.

The day-ahead market profit per flexible heat pumps is significantly higher from a socioeconomic perspective compared to private economic perspective (via reduction in electricity costs). This indicates that the societal value of flexibility is higher than the customer will experience through reduced electricity cost of flexible heat pump compared to non-flexible heat pump. The spot price variation does not send a signal to the consumers that reflect the full socioeconomic saving potential of flexible consumption.

The other contributions to the private economic business case of flexible heat pumps are summarized in figure C below. All estimates are based on assumptions that are explained in the analysis together with drivers and risks regarding the different contribution to the business case:

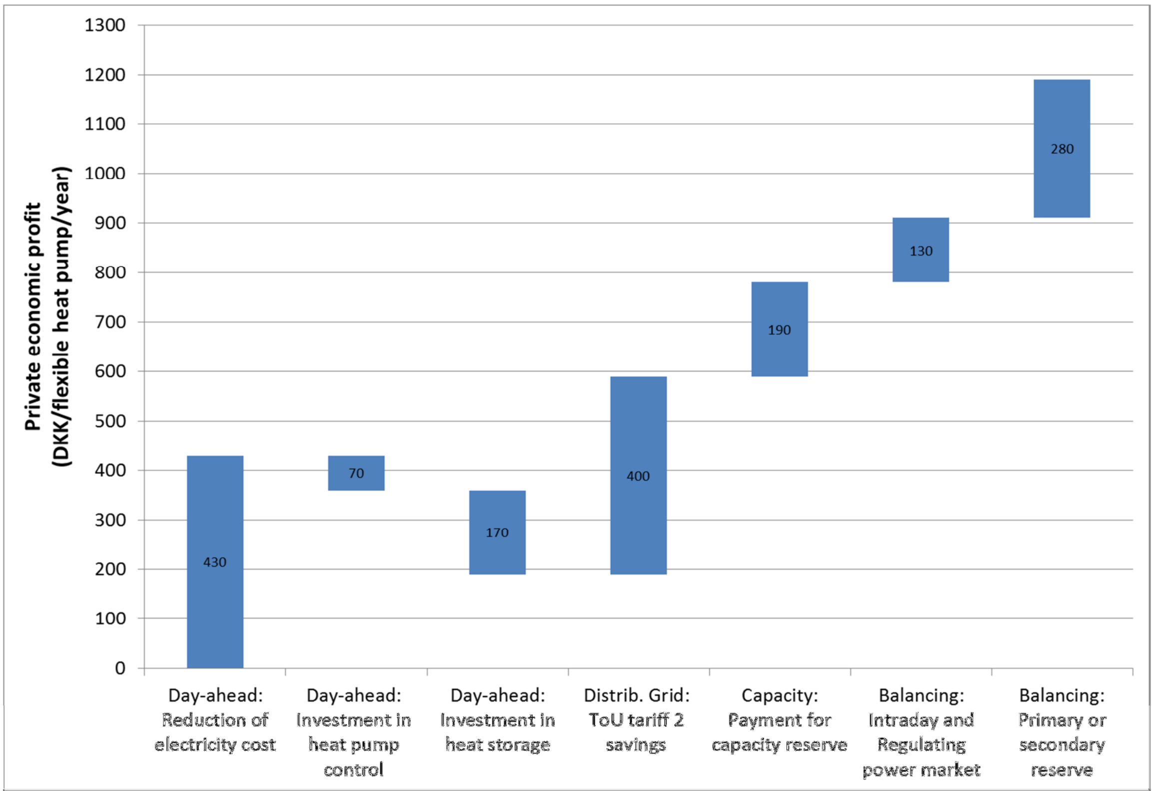


Figure C. The private economic profit of flexible heat pumps compared to non-flexible heat pumps.

Distribution system operators (DSOs) are facing increased grid reinforcement costs due to residential heat pumps. Variable tariffs can be used by the DSO's to increase incentive for off-peak power consumption and hereby delay investments in additional grid capacity. Balmorel was used to assess the impact of variable tariffs on heat pump power consumption and average tariff cost. The variation in tariff cost provides additional profit for flexible heat pumps compared to fixed tariff. Two different time-of-use (ToU) tariffs were applied and the power consumption was optimized towards both spot market prices and variable tariffs. As shown in figure B above the investments in flexible heat pumps are significantly increased in 2020 and 2025 due to the additional profit from variable tariffs. The net private economic profit of ToU tariff 2 was estimated at ~400 DKK/year per average flexible heat pump. Flexible heat pumps could provide DSO products like voltage control to secure voltage quality in the grid.

The flexible residential heat pumps have the potential to provide ancillary services as part of an aggregated portfolio due to the size of the heat storage in the houses and the control capabilities. The future value of the Danish ancillary services is difficult to assess, because the market design, volume and suppliers are likely to change in the future. However, assuming constant 2014 reservation prices of primary and secondary reserves the potential private economic profit is estimated at ~280 DKK/year per flexible heat pump with additional control capabilities. Further, flexible heat pumps can create profit from participation in Intraday and Regulating Power market. The demand for balancing is expected to increase in the future due to more fluctuating power production. The private economic profit of participation in Intraday and Regulating Power market is estimated at ~30% additional profit compared to spot market optimization only ([Biegel et al 2013] and [Holmberg 2014]). Based on the results from the day-ahead optimization this corresponds to additional profit of ~130 DKK/year per average flexible heat pump.

The requirement for reliable power capacity investments is expected to increase in the future due to increased wind power production and decommissioning of existing power plants. Capacity mechanisms could be needed in Denmark to secure reliable power capacity (maintaining existing power capacity, attract new power capacity and demand response). The capacity mechanism put a value on reliable capacity reserves that can be provided by both production and flexible consumption. The analysis presents development of capacity mechanisms in other European countries [IHS CERA 2013]. A suggestion for flexible heat pumps participation in a capacity mechanism is given in the analysis that takes the characteristics of heat pump and heat storage operation into account. The private economic profit of flexible heat pump as capacity reserve is estimated at ~190 DKK/year per average flexible heat pump.

The electricity bill including revenues of flexibility services (revenue of capacity reserve and ancillary services) of non-flexible and flexible heat pumps is compared in the figure below. The investment in flexibility is not shown in figure D below:

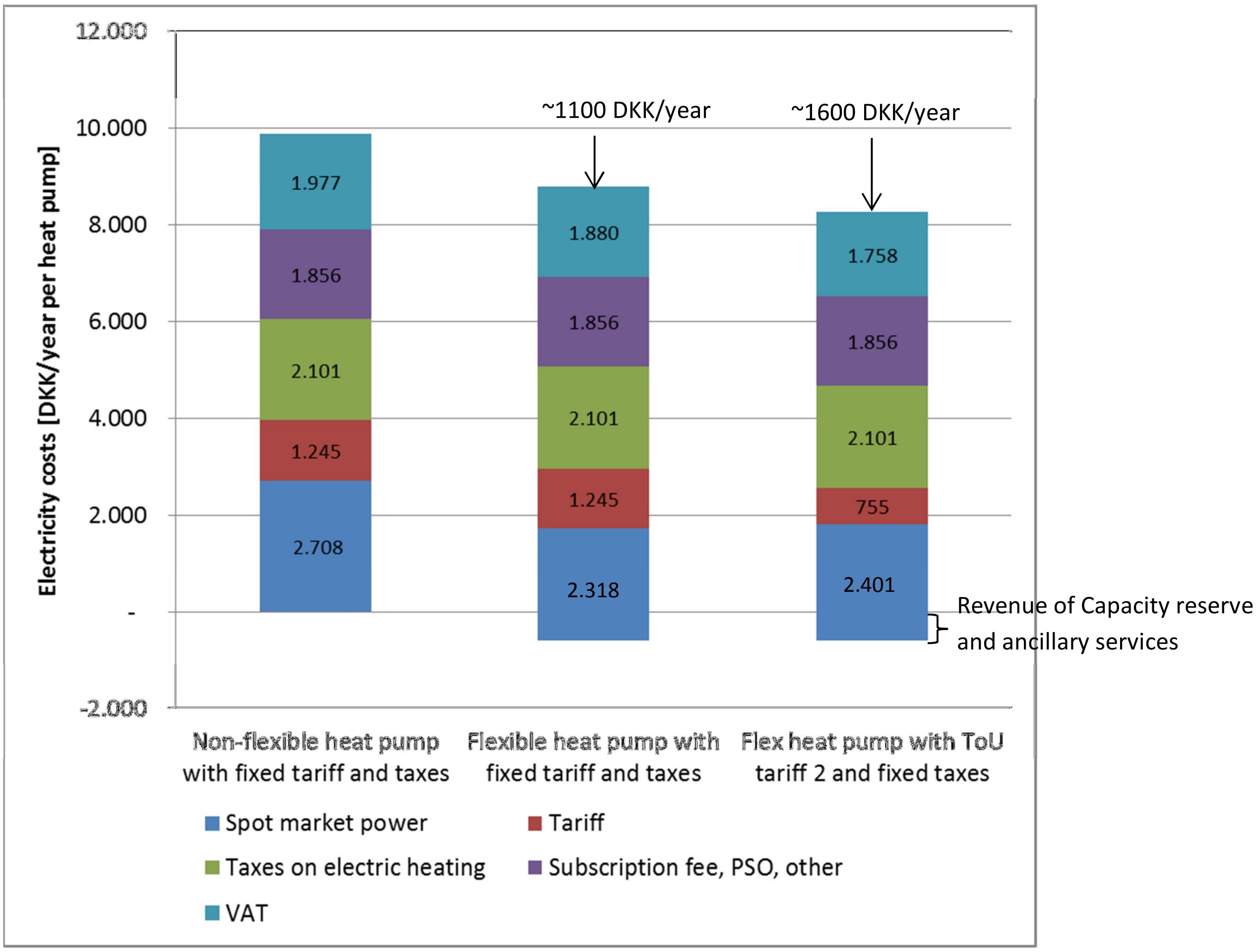


Figure D. The electricity cost, tariffs and revenue of flexibility services (Capacity Reserve, TSO and DSO balancing) of non-flexible and flexible heat pumps with different tariff scenarios.

The results show that the private economic profit of flexible heat pumps depends on the number of ways the flexibility is used to create additional profit. On a short term optimization towards spot market is possible with individual intelligent meters. Variable tariffs could increase the profitability of flexible heat pump. On longer term market based products to TSO and DSO could contribute to the business case of flexible heat pumps.

The possible development of the business case is discussed in Chapter 6.3.1.

1 INTRODUCTION

The political targets in Denmark aim for a CO2-neutral power and heat sector by 2035. This gives residential heat pumps the potential to become a key technology in the future Danish energy system as a replacement for existing residential oil and natural gas boilers outside district heating areas. The heat pumps can use the increasing fluctuating renewable power production from wind and solar to reduce the energy consumption and CO2 emission from individually heated houses in Denmark.

Residential heat pumps will significantly increase the electricity demand in the households which can lead to demand for additional peak power capacity and challenges in the local grid. However, flexible operation of heat pumps can influence this demand and hereby create value for both customers and society. Further, previous smart grid studies (e.g. [Energinet.dk et al 2012]) have estimated flexible consumption can lead to reduced cost of power production and ancillary services in the future.

The **Non-flexible heat pump** is defined as a heat pump that is operated to maintain the indoor comfort level given by a required constant indoor temperature (similar to constant thermostat setting). This means the heat pump does not have heat storage and hence the heat has to be produced when needed independent of the power price.

The **Flexible heat pump** is defined as a heat pump that is controllable, i.e. a user or third party operator can control the heat pump and the temperature requirement (via the thermostat settings) in the house with the purpose of minimizing the cost of electricity and/or reduce the required peak demand. Further, a flexible heat pump has a heat storage that allows the heat to be produced during periods with low power prices and thus switch the power consumptions away from peak load periods.

An illustration of the power consumption from non-flexible and flexible heat pumps is shown in Figure 1

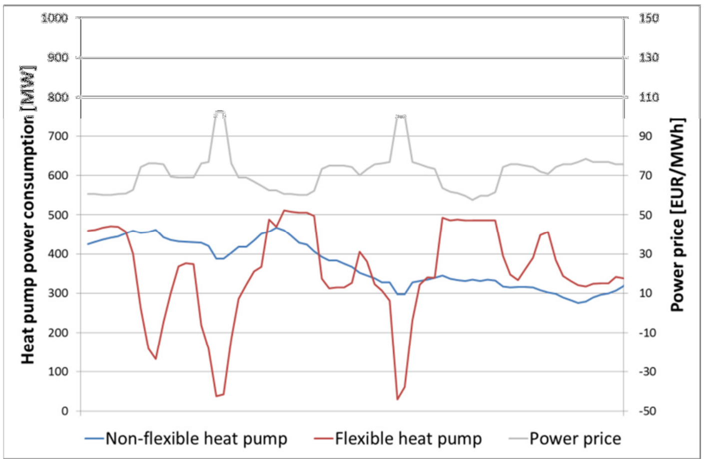


Figure 1. The power consumption of flexible heat pumps compared to non-flexible heat pumps calculated with the Balmorel model (see Chapter 2.1.3).

The analysis is part of iPower WP5.5 'Business cases for flexible consumption'. The relationship between WP5 and the remaining iPower project is illustrated in Figure 2

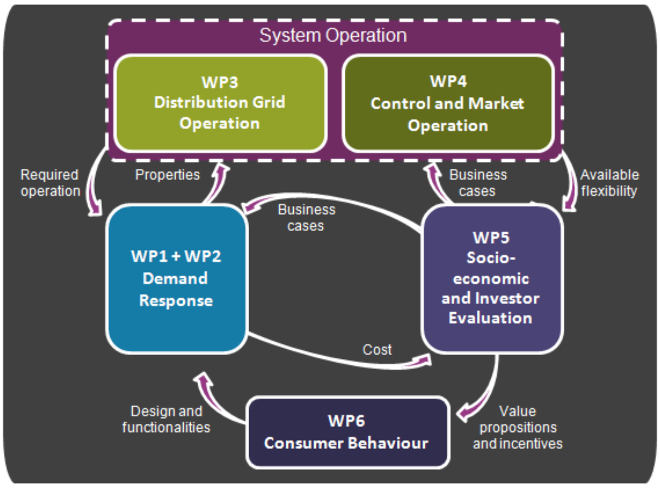


Figure 2. Interaction between work packages in iPower project [iPower WP2 2012]

A later iPower WP5.5 report will focus on a more generic business model for flexible consumption that should balance the economic requirement of demanders and suppliers (commercial actors like Aggregators/BRP) of flexibility.

Intelligent control of residential heat pumps is a key area in both research and business innovation of residential demand response. The iPower project WP1 is developing and testing control of household consumption to demonstrate the possibility to develop flexible consumption. Two different methods to control the heat pumps are tested:

- *Develco* is demonstrating control of heat pumps through a smart meter.
- *Greenwave Reality* is demonstrating control of heat pumps through a Home automation system

The vision in iPower is that Distributed Energy Resources (DER) flexibility including residential heat pumps can play an important role in the future energy system. The different areas where flexible consumers can create economic profit are illustrated in Figure 3:

- Cheaper power consumption
  - Day ahead market (Elspot) and Intraday market (Elbas)
- Cheaper regulating power and power reserves
  - Regulating power market
  - Ancillary service markets
- Cheaper investments
  - Reduce demand of peak power capacity

- Reduce investments in grid reinforcements (enabled via tariffs and DSO products)

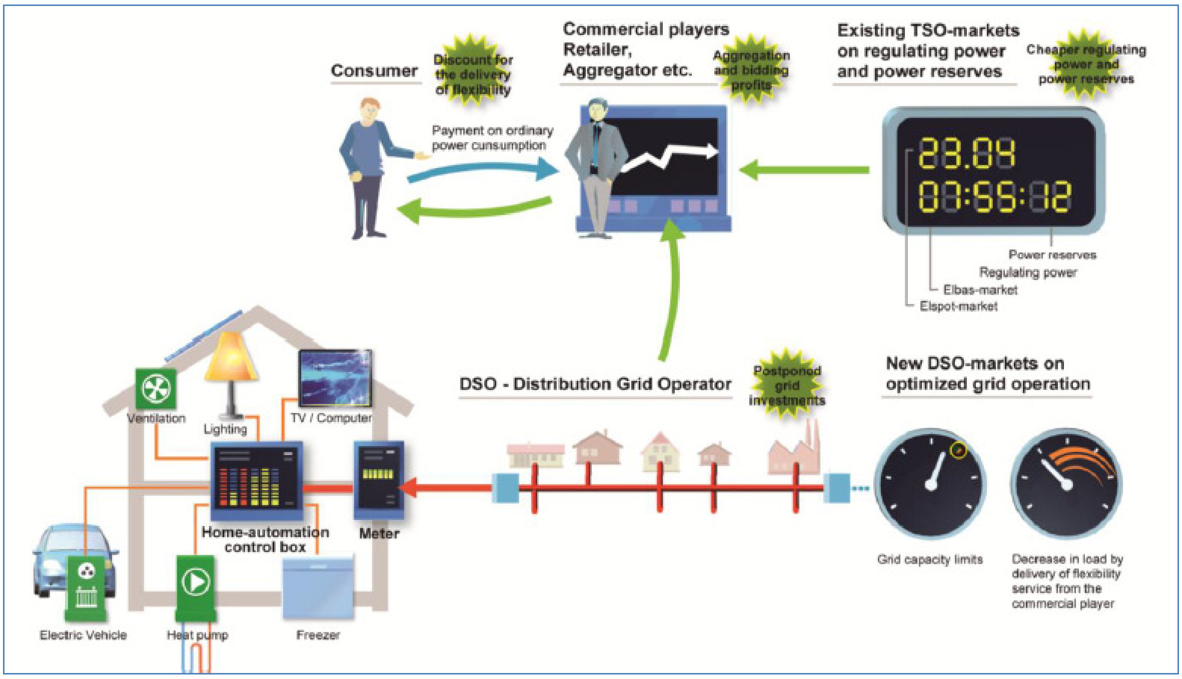


Figure 3. Illustration of the consumer involvement in trading flexibility [Energinet.dk et al 2012].

In this analysis the **'business case'** is used to describe the economic rationale behind flexible heat pumps, both from a private economic perspective (customers, commercial actors) and a societal/socio economic perspective. The overall business case for flexible heat pump consists of several sub-business cases in the areas where flexible heat pumps create economic value.

This business case will only focus on the potential monetization of heat pump flexibility and not on how flexibility can be incorporated in products to customers.

1.1 OBJECTIVE

This analysis will investigate the impact of large scale installation of residential heat pumps on the power markets and in the distribution grids and asses how flexibility can change this impact.

Based on these findings the private economic profit and socioeconomic value of flexible residential heat pumps compared to non-flexible residential heat pumps will be quantified.

Hence, the objective of the analysis is to investigate:

- The Business case for flexible residential heat pumps in Denmark from 2020-2035 from a private economic and socioeconomic value perspective, respectively.

The goal of the business case is to help the stakeholders reduce the uncertainty regarding flexible heat pumps, by presenting the economic profits made possible by investment in new technology, new market design etc. This business case analysis should also highlight areas of special interest for further work with the purpose of reducing risk and providing more thorough economic value estimations.

1.2 BUSINESS CASE METHODOLOGY

The analysis follows the definition of roles and responsibilities in the future power market described in the "Dangrid" work [Energinet.dk et al 2012]. Commercial actors like Balance Responsible Party (BRP) and Aggregators will enable flexibility from DERs (including residential heat pumps) and provide market based products to the demanders of flexibility.

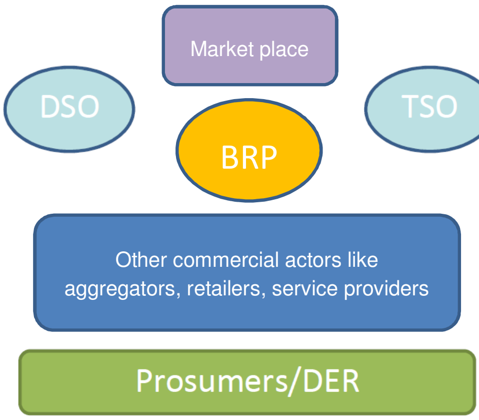


Figure 4. Actors involved in demand and supply of flexibility products to the market places (existing TSO-markets and future DSO market "FLECH") [Energinet.dk et al 2012].

The demanders of flexibility from residential heat pumps are:

- Transmission System Operators - TSOs (secure sufficient security of supply, i.e. sufficient capacity and ancillary services)
- Distribution System Operators - DSOs (reduce grid reinforcement cost)
- Private customers (reduce electricity costs).

This analysis will focus on the flexibility demander's value creation to construct the business cases for flexible heat pumps. The business case methodology used in iPower WP 5.5 is described in [iPower WP5.4 2013]. A cost-benefit method is applied to identify and quantify the benefits and costs of flexible heat pumps compared to non-flexible heat pumps.

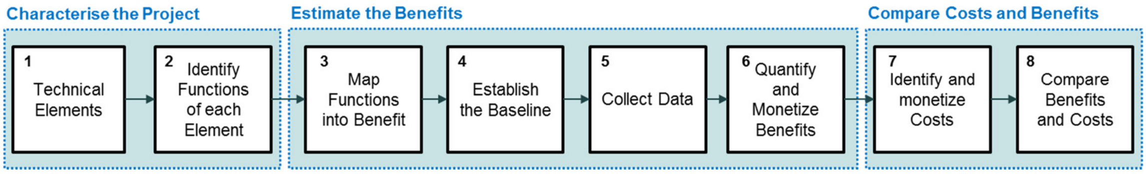


Figure 5: Methodology of cost-benefits analysis to quantify the flexible heat pump business case.

The ‘technical elements’ are the applications where flexible heat pump affects the future energy market and grid development compared to the baseline (non-flexible heat pumps):

- Chapter 2. Flexible heat pumps in the day-ahead market
- Chapter 3. Flexible heat pumps impact on distribution grids
- Chapter 4. Flexible heat pumps in balancing and ancillary service markets
- Chapter 5. Flexible heat pumps participation in a capacity mechanism

In Chapter 6 the value creation in the four chapters are collected to the business case of flexible heat pumps from a private economic and socioeconomic perspective, respectively.

The different methods to monetize the benefits and costs in each technical element are shown in Table 1:

Technical element	Benefit and cost estimation method	Chapter
Day-ahead market	Private economic benefit: -Annual benefit of electricity cost reduction with flexible vs. non-flexible heat pumps calculated in Balmorel -Cost of flexible heat pump control and heat storage Socioeconomic value: -Difference in total Danish power and heat costs in Balmorel with non-flexible vs. flexible heat pumps	Chapter 2
Distribution grid	Private economic benefit:-Variable tariffs impact on power consumption of flexible heat pump in Balmorel. Profit of flexible heat pump with variable tariffs compared to non-flexible heat pumps with fixed tariff. Socioeconomic value: -Variable tariff impact on total tariff revenue -Illustration of flexible heat pump impact on grid reinvestment costs	Chapter 3

Balancing and ancillary service markets	Private economic benefit: -Profit based on prices of Intraday/Regulation power market and ancillary services (primary, secondary and tertiary reservation payment) in Denmark and neighboring countries -The annual heat pump revenue is calculated via the expected kW or kWh per heat pump that can participate in the market as part of a portfolio multiplied with the expected market price per kW or kWh: Yearly heat pump revenue = kW * price/kW/year or kWh * price/kWh/year Socioeconomic value: Not assessed in this analysis	Chapter 4
Capacity mechanism	Private economic benefit: - Description of capacity mechanism in other countries (UK, USA, Sweden). Suggestion to flexible heat pump participation in capacity mechanism -The annual heat pump revenue is calculated via the expected kW per heat pump that can participate in the market as part of a portfolio multiplied with the expected market price per kW: Yearly heat pump revenue = kW * price/kW/year Socioeconomic value: - Shadow-price of new power capacity	Chapter 5

Table 1. The elements that contributes to the business case for flexible residential heat pumps.

Each chapter contains:

- Methodology and key assumptions.
- Results.
- Sub conclusion

The sub conclusion includes a table with summary of findings in the chapter regarding:

Demander of flexibility	
Market requirement of participation	
Socioeconomic cost	
Socioeconomic benefit	
Private economic cost	

Private economic benefit	
Risks	
Drivers for Danish business opportunities	

1.3 ACKNOWLEDGMENTS

The Thermal Building Module that is used in this report was developed by Karsten Hedegaard in the Ph.D. project “Wind power integration with heat pumps, heat storages, and electric vehicles” [Hedegaard 2013]. The authors would like to thank Karsten Hedegaard for the advice with the use of the module and the input to the research methodology in this analysis.

Further, iPower WP1 (Develco, Green Wave Reality and Danish Technological Institute) and Bosch Thermotechnic have provided valuable input to the technical assumptions for heat pump modeling in this report.

2 FLEXIBLE HEAT PUMPS IN THE DAY-AHEAD MARKET

The main objective of this chapter is to quantify the value of flexible heat pump operation compared to non-flexible operation in the day-ahead market.

2.1 METHODOLOGY AND KEY ASSUMPTIONS

This subchapter explains the modeling of flexible heat pumps and the modeling of the impact on the Danish energy system

2.1.1 MODELING OF BUILDINGS HEAT DEMAND AND HEAT STORAGES

The residential heat pump converts power to heat with a variable efficiency (COP, Coefficient of Performance) to meet the space heating demand and hot water demand in the building. The space heating demand is dominating during the winter season. The heat is transferred via a water based system, i.e. radiator or floor heating.

A Thermal building module [Hedegaard 2013] is used to calculate the heat balance and temperature variation in indoor air and building structure based on the thermal properties of the different building categories (cf. Table 3) as well as the profiles of outdoor temperature, hot water demand etc. An illustration of the Thermal Building module is shown in Figure 6.

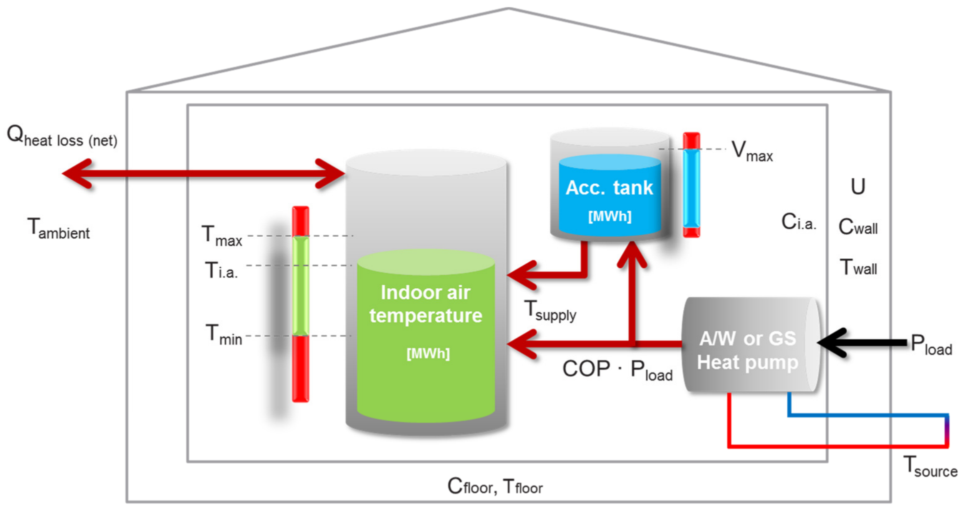


Figure 6. Illustration of the Thermal building module. The heat demand (Qheat loss(net)) in the building is based on outdoor air temperature. The heat transfer coefficients (U-values) and heat capacities (C-values) are used to calculate the temperature variation of indoor air (i.a.) and building structure. The heat storage is modelled via allowed indoor temperature variation and/or additional heat accumulator tanks. The COP of air-to-water (A/W) and ground source (GS) heat pump, respectively, is modelled as a function of supply temperature (Tsupply) and source temperature (Tsource).

The mathematical description of the Thermal building module is presented in [Hedegaard 2013] and [Hedegaard et al 2013]. The applied thermal properties of different buildings (heat capacity and heat transfer coefficients) are explained in Appendix 7.1.4.

Heat pump flexibility

Two heat storage options are available in the Thermal building module:

- accumulator tank with a volume of Vmax (maximum 1000 L) that can store the heat (water)
- heat storage in the building structure and indoor air

The flexibility of the heat pump depends on:

- **Heat storage size** (MWh)
  - Heat storage in accumulator tank (Volume Vmax and assumed ΔT=15 °C)
  - Heat storage in building structure and indoor air
    - Allowed indoor temperature variation (Tmax and Tmin)
    - Thermal property of the building (Heat capacity)
- **Heat loss to surroundings** (MW)
  - Thermal property of the building (insulation)
- **Heat pump heat capacity** (MW), i.e. thermal effect the heat pump can produce
- **Shift to other heat sources** (e.g. hybrid heat pump) – not part of this analysis

The ratio between the heat storage size and the heat loss to the surroundings determines how long time it is possible to delay or bring forward the power consumption of the heat pump before the heat storage boundaries is reached. The heat pump heat capacity is determining how fast the heat storage can be filled. The heat capacity is dimensioned to supply heat equal to the heat loss at a given outdoor temperature, in the analysis assumed -12 C. At this outdoor temperature, the heat pump will only be able to maintain the indoor temperature and not fill the heat storage.

2.1.2 INVESTMENTS COST OF FLEXIBLE HEAT PUMPS

Flexible operation of the heat pump requires investment in equipment: Additional heat pump control capability and heat storage (option A and/or B). The cost of the flexible heat pump investment is [Hedegaard 2013]:

- The cost of control of heat pump is 130 EUR/house
- Heat storage option A. The cost of additional accumulator tank 1260 euro for 1000 L tank.
- Heat storage option B. To invest in digital thermostat, i.e. make it possible to overaccumulate heat in the building structure and indoor air by controlling the set point on the radiator. This makes it possible to control the indoor temperature between T_{max} and T_{min}. The cost of digital thermostats is set to 310 EUR/house; it is assumed an average of 5 new digital thermostats are needed (40 EUR/heater) in each house plus installation cost[1].

The different investment options are presented in Figure 7 together with the respective investment costs.

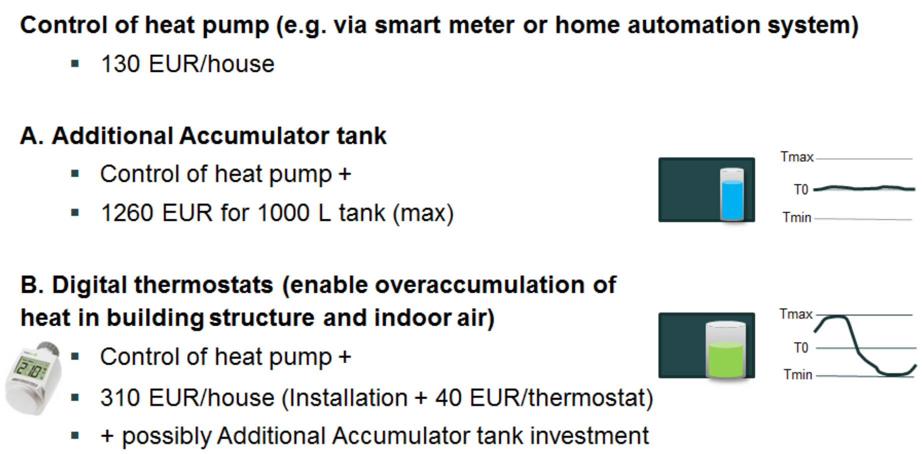


Figure 7. Illustration of the two heat storage options and the associated investment costs in the analysis.

'Control of heat pump': Estimation by Develco indicates a future control of heat pump (gate-way cost incl. support of digital thermostats) at around 70 EUR/house [Eriksen 2014].

'Digital thermostats': Today companies like Danfoss and Nest Lab produce digital thermostats.

[1] The following operation costs are not included: A). The power consumption of gateways of 1-2 W [Jensen 2014], i.e. 0,0015kW *8760h/year*2,2DKK/kWh ≈ 30 DKK/year. B). A digital thermostats ('Danfoss Living') consume 2 x 1,5 V AA batteries with an expected lifetime of 2 years [Jensen 2014]. The battery cost is 1 battery/year/thermostat*~5DKK/battery*5 thermostats ≈ 25 DKK/year.

A comparison of the two heat storage option cost is shown below. The different flexible heat investment options are evaluated in the analysis.

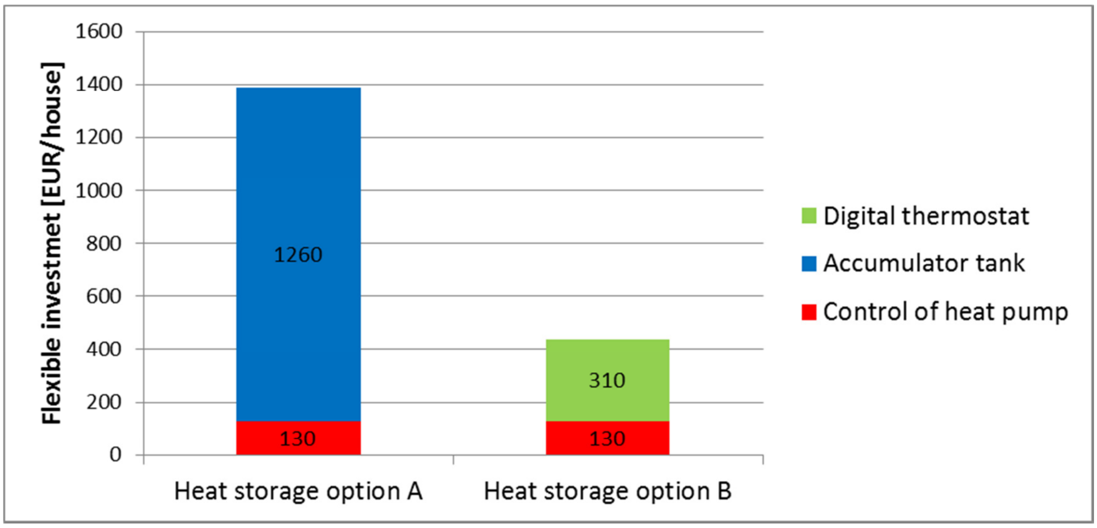


Figure 8. The flexible investment cost of the heat storage options A (1000 L tank) and heat storage option B [Hedegaard 2013].

2.1.3 ENERGY SYSTEM MODEL BALMOREL

The linear energy system model Balmorel [Balmorel] is used to simulate the power prices in the Day-ahead market in the North European power and district heating systems from 2020-2035 under different scenarios. The model's scope is the green coloured countries in Figure 9. The model minimizes hour-by-hour the cost of producing power and district heating in the modelling area. Each country is divided into regions, which again can be divided into areas. The existing and expected future interconnector capacity is used to describe the transmission capacity between regions in the model. The power production and consumption is balanced hour-by-hour in each region including power transfer with other regions. In each district heating area the heat production and consumption is balanced hour-by-hour.

Balmorel has a number of power and heat restrictions that has to be fulfilled in each simulation hour in the different regions and areas based on the profiles of wind, consumption, heat demand etc. In the model the fuel cost and efficiencies of production units are specified. The model calculates the hourly power price in the Day-ahead market as the marginal cost of production that fulfills the specified restrictions with the lowest total system cost.

The simulation is performed on 13 representative weeks each with 168 hours for the years 2020, 2025, 2030 and 2035. In each simulation year old production units are exogenously decommissioned (e.g. nuclear power plants) and new capacity is exogenously added (e.g. onshore wind, PV) based on expected national development. A number of available investment options in new heat and power technologies (e.g. offshore wind, biomass CHP etc.) are used in Balmorel to calculate which additional investments can reduce the overall system costs:

- The cost of producing power in the system (given the restriction in interconnector capacity) and the cost of producing heat in the regions/areas.
- The cost of providing sufficient peak power capacity (called *reserve power capacity*) to meet the power demand in all hours

The model simulates the Day-ahead power market as an energy-only power market, where peak power capacity is secured only via power price revenue, i.e. there is no separate payment for providing sufficient power capacity.

This means the power prices in the model will increase in one or few hours to make peak power capacity investments profitable. The simulations are performed with maximum power price of 10^6 EUR/MWh, which lead to the Danish peak power price is ~12.000 EUR/MWh in one hour. Key simulations are repeated with maximum power price of 3000 EUR/MWh (similar to 2014 Value of lost load (VOLL) in Nordpool), which lead to four hours with Danish peak power price of ~3000 EUR/MWh; in general, the results are not changed significantly by reducing the maximum power price in the simulations.

Due to the low investment cost Open Cycle Gas Turbine (OCGT) represents investments in Balmorel that are made only to provide sufficient peak power capacity. Thus, the shadow-price of additional peak power capacity is determined by new OCGT unit's investment and maintenance cost shown in Table 2:

Investment cost OCGT: 0,45 million EUR/MW = 450 EUR/kW

- Annuity cost OCGT: 33,1 EUR/kW/year (with 4% investment rate, 20 years)
- Annuity cost OCGT: 45,8 EUR/kW/year (with 8% investment rate, 20 years)

Fixed O&M cost OCGT: 8,1 EUR/kW/year

Table 2. Investment and Fixed O&M cost of Open Cycle Gas Turbine (OCGT) [Danish Energy Association 2013].

In Balmorel flexible demand like heat pumps can affect the required peak power capacity and/or the power prices by moving the consumption to other hours. Thus, heat pump flexibility is therefore attractive as long as the marginal investment cost of additional heat storage is lower than reduction in system costs.

The key input and output of the Balmorel model is shown in Figure 9.

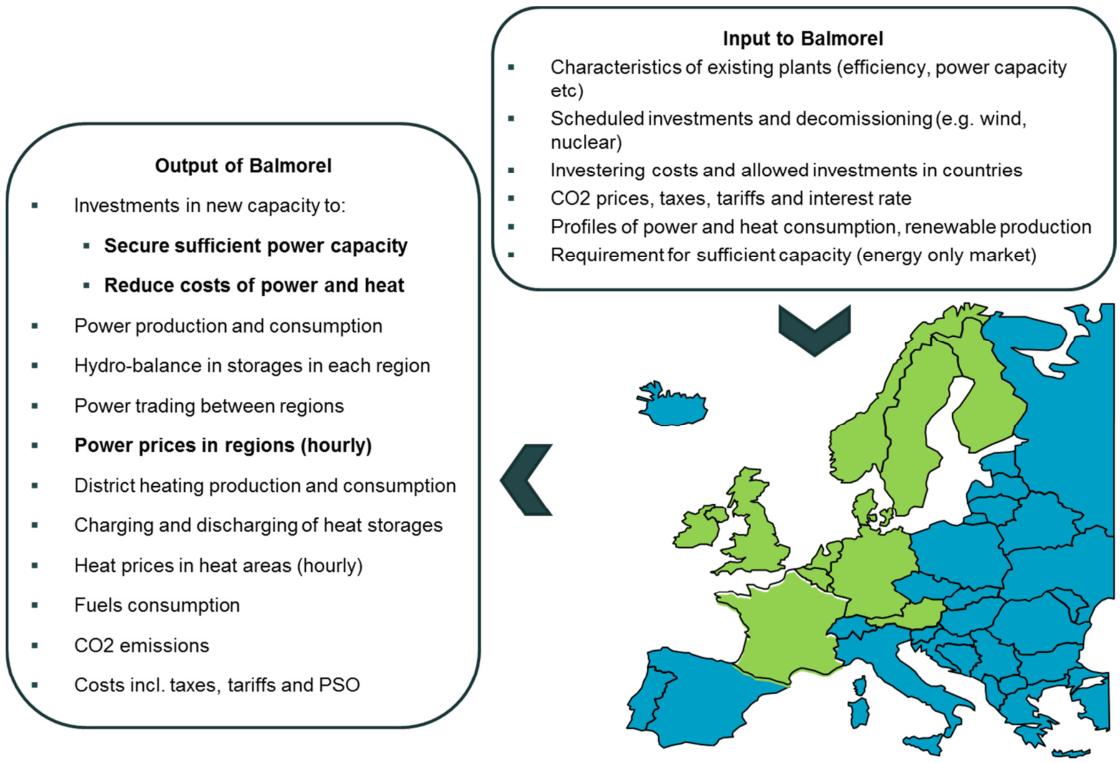


Figure 9. Methodology for investments - input and output of the model.

The applied CO2 price and EV charging profile in Balmorel is seen in Appendix 7.1.1. Further, a more elaborate description of assumptions for the Danish energy system 2020-2035 in Balmorel is found in [Danish Energy Association 2013].

2.1.4 ELECTRICITY CONSUMPTION OF DANISH RESIDENTIAL HEAT PUMPS

The prognosis of the number and energy consumption of Danish residential heat pump [Energinet.dk 2013a] is shown in Figure 10. According to the forecast approximately 120.000 and 430.000 heat pumps is expected in 2020 and 2035, respectively. These heat pumps are divided into four categories seen in the figure. It is expected that the majority of electricity demand from heat pumps will come from conversion of existing buildings with oil fired boilers and natural gas boilers.

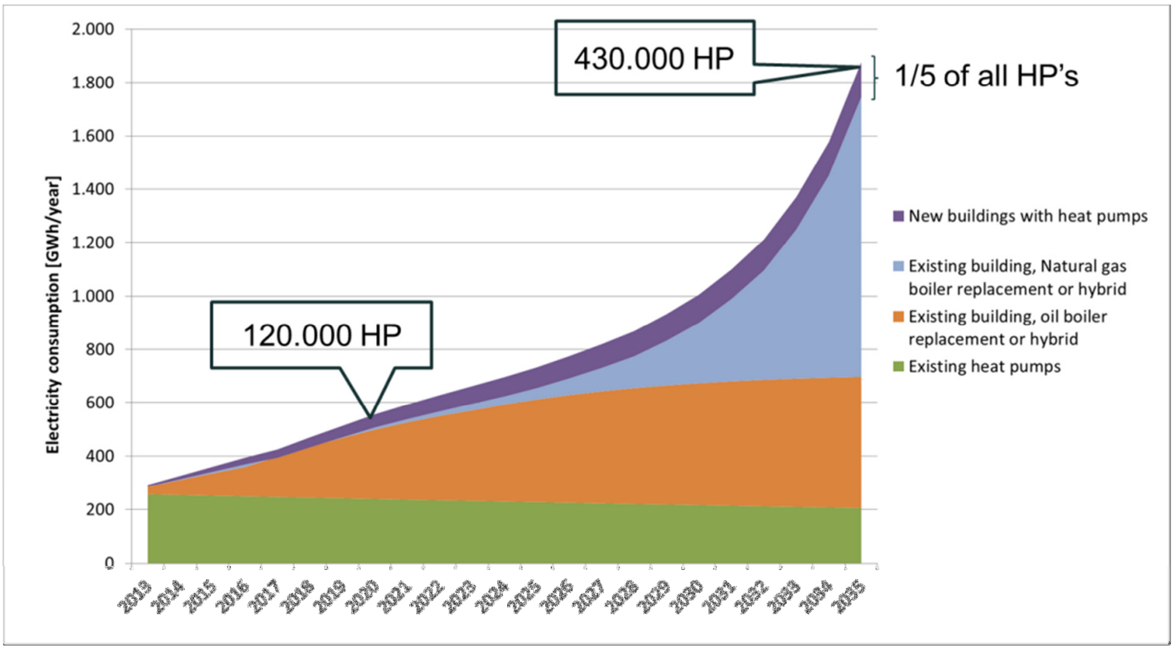


Figure 10. Prognosis of the number and energy consumption of Danish residential heat pump [Energinet.dk 2013a].

Despite the expected high number of heat pumps in new houses (~1/5 of all heat pumps in 2035) the impact from these heat pumps on the electric grid and on power prices will be significantly less than from heat pumps installed in existing buildings due to the low heat consumption in new houses. Thus, *heat pumps in new buildings (built after 2005) are not included in the analysis*.

2.1.5 MODELING OF THE HEAT DEMAND IN BUILDING CATEGORIES

The heat pumps in existing houses are modelled in Balmorel in 20 separate areas (10 in DK-East and 10 in DK-west) [Hedegaard 2013]. Each area represents one category of aggregated residential houses with similar thermal property. Buildings are divided into different categories based on Insulation level (building year of the house, different U-values per category), Heat capacity (C_{wall}-values) and Floor heating or radiator heating. The modelled building categories are highlighted with green in Table 3.

Increasing heat demand

Increasing heat capacity

Heated area / number of buildings	Insulation level (building year of houses)			
Heat capacity (C) (Wh/m2 floor area/°C)	1. 1850-1960	2. 1961-1978	3. 1979-2005	2006-2035
Radiator (C=60)	RAD_1_C60	RAD_2_C60	RAD_3_C60	
Radiator (C=100)	RAD_1_C100	RAD_2_C100	RAD_3_C100	
Radiator C=140)	RAD1__C140	RAD_2_C140	RAD_3_C140	
Floor heating			FLO_3	

Table 3. Building categories given by 3 heat capacity levels and 3 insulation levels.

In Appendix 7.1.3 it is explained how the total heat demand of all individually heated buildings 2006-2035 is used to estimate the <u>heat demand and number of heat pumps</u> in the different building categories 2020-2035. In Figure 11 the number of houses in the different building categories in the simulations is shown:

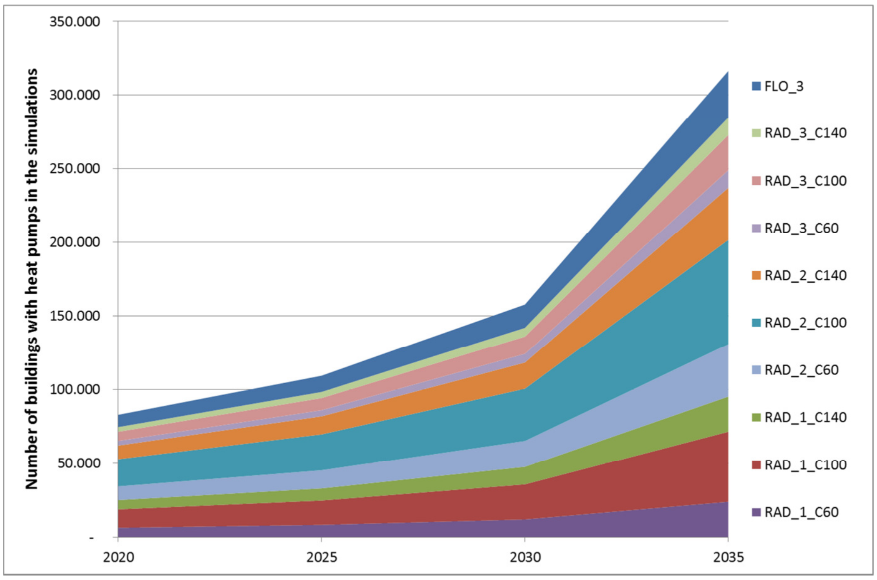


Figure 11. The number of buildings with a heat pumps in the different building categories.

The number of heat pumps in the categories also represents the *maximum number of flexible heat pumps*.

2.1.6 INVESTMENT IN FLEXIBLE HEAT PUMPS IN BALMOREL

The Thermal building module (cf. Chapter 2.1.1) is implemented in Balmorel which means the power consumption of the heat pumps influence the energy system optimization. Balmorel finds the share of heat pumps in each building category that it is attractive from a system costs perspective to make flexible by investing in control and heat storages, i.e. the investment options described in Chapter 2.1.2. Thus, heat storage investments are attractive in the model as long as the marginal reduction of the total system costs (power production and peak power capacity) is larger than the investment cost of additional heat storage.

An overview of input to the Thermal building module and the output of Balmorel regarding flexible heat pumps are presented in Figure 12:

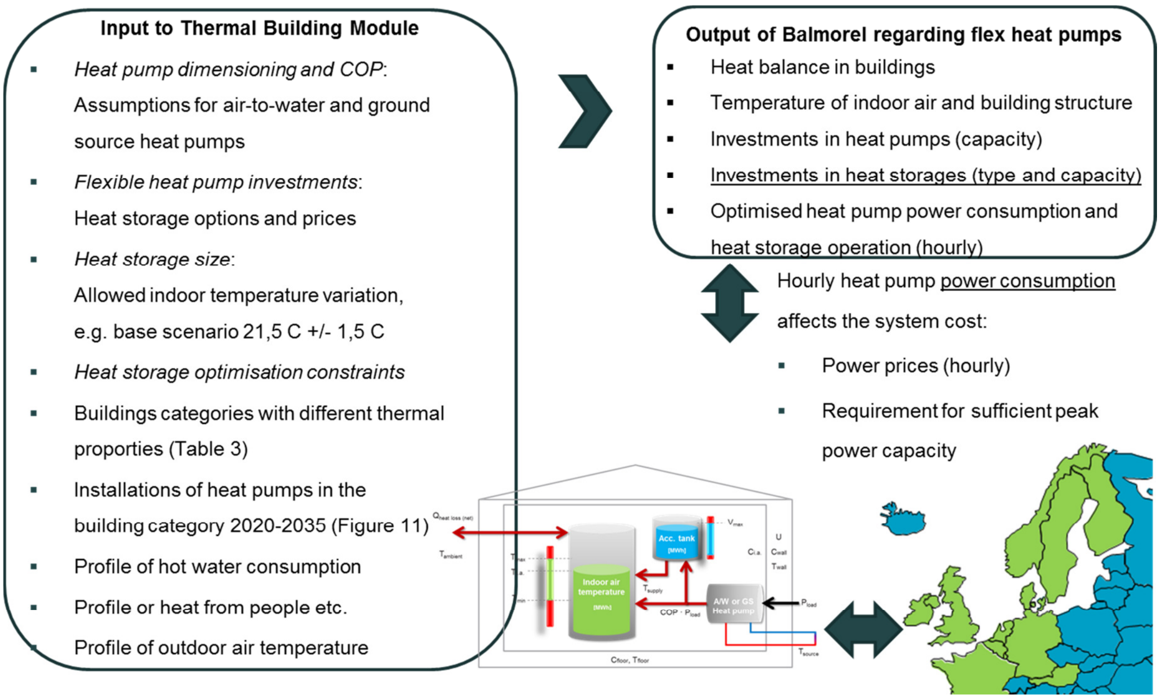


Figure 12. The input to the Thermal Building Module and output of Balmorel regarding flexible heat pumps.

Heat pump dimensioning and COP

The heat capacity of the heat pumps is dimensioned to cover the space heating and hot water demand at -12C. The electric heater makes up part of the heat capacity.

Two types of heat pumps are modelled in the Thermal Building module: Air-to-water heat pumps and ground source heat pumps. The power consumption of the heat pumps is calculated via an hourly variable

COP. The COP is depending on the reservoir and supply temperature for both air-to-water heat pumps and ground source heat pumps.

Further assumptions are found in Appendix 7.1.5 Heat pump dimensioning criteria and Appendix 7.1.6 Modeling of heat pump COP.

Flexible heat pump investments

The applied methodology to handle investment in flexible heat pumps in Balmorel is described in Appendix 7.1.2. The power consumption of non-flexible heat pump is used as input to the investment decision.

The heat storage investment costs options are presented in Figure 7 in Chapter 2.1.2. Investments in heat storages are made in each building category (Table 3).

The cost of communication of power consumption (for settlement purpose) is assumed to be similar between flexible and non-flexible heat pumps in the power market. By 2020 all Danish household will have individual meters. Hourly settlement is a necessity for flexible consumption profitability. It is assumed that the additional fee of hourly settlement is very small (20-50 DKK/year) in the future and therefore neglected [Biegel et al 2013].

Heat storage size

In the case of investment in additional accumulator tanks (option A) the heat storage size increases proportional to the tank volume, which is allowed an arbitrary value between 0 and 1000 L. The allowed ΔT=15 °C which corresponds to ~17,4 Wh/L.

In heat storage option B the heat storage size is equal to the amount of heat that is needed to change the indoor temperature from T_{min} to T_{max}. Thus, the relative heat storage size is dependent on the heat loss of different building categories.

The non-flexible heat pumps are operated to maintain an indoor temperature of 21,5 °C (constant thermostat setting) which means without a heat storage.

For flexible heat pumps the high and low indoor temperature boundaries (variable thermostat settings) is +/- 1,5 °C in the base scenario. The influence of +/- 0,75 °C is also investigated in a scenario. [Danish Technological Institute 2012] estimates that the allowed indoor temperature variation is +/- 1-2 °C, and that the allowed variation in some rooms may be +/- 2-3 °C.

Heat storage optimization constraints

Applied constraint for Heat storage option B: Flexible heat pumps has to maintain minimum 21,5 °C in average during the optimization horizon (one week).

The constant means that flexible heat pumps can increase heat production compared to non-flexible heat pumps to raise the indoor temperature above 21,5 °C in some hours, but then has to decrease the heat production compared to non-flexible heat pumps in other hours to lower the indoor temperature below 21,5 °C.

The constraint makes it able to compare heat production costs of flexible and non-flexible heat pump, because the heat demand is then roughly similar (results show +/- 1% difference) for non-flexible and flexible heat pumps during the optimization horizon.

The Thermal Building Module includes the effect of thermal inertia of the building structure on the change in indoor air temperature. In the module the heat loss to the surroundings increases or decreases based on the actual temperature of building structure.

2.2 RESULTS

2.2.1 OVERVIEW OF SCENARIO ANALYSIS

The objective of the scenarios analysis is to study the effect of changes in certain assumptions on the results, i.e. to understand e.g. the effect of the temperature profile on the attractiveness of flexible heat pumps.

An overview of the scenarios is presented in Table 4. Only changes compared to Base scenario (Scenario 1) are listed for scenario 2-9.

Number	Scenario name	Interest rate and taxes	Outdoor temperature profile	Allowed indoor temperature interval	Flex heat pump investment cost	Electric heater % of heat capacity
			Socioeconomic scenarios			
1.	Base	4%, no tax	2011	21,5 +/- 1,5 °C	Normal	20%
1a.	Base_**NoFlex**			Fixed 21,5 °C		
2.	Base_+/-0,75C			+/- 0,75 °C		
3.	Base_0,75C_highFlexInvest			+/- 0,75 °C	High	
4.	Base_2010temp		2010			
4a.	Base_2010temp_**NoFlex**		2010	Fixed 21,5 °C		
5.	Base_2010temp_ OnlyACCinvest		2010	Only accumulator tank invest		
			Private economic scenarios (P.E.S)			
6.	P.E.S	8%, with tax				
6a.	P.E.S_**NoFlex**	8%, with tax		Fixed 21,5 °C		
7.	P.E.S_+/-0,75C	8%, with tax		+/- 0,75 °C		
8.	P.E.S_2010temp	8%, with tax	2010			

8a.	P.E.S_2010temp_**NoFlex**	8%, with tax	2010	Fixed 21,5 °C		
9.	P.E.S_highEH	8%, with tax	2010			35%
9a.	P.E.S_highEH_**NoFlex**	8%, with tax	2010	Fixed 21,5 °C		35%

Table 4. The scenario investigated in Balmorel. Non-flexible heat pumps have fixed indoor temperature.

The base scenario contains a number of assumptions regarding the development of the energy system 2020-2035, e.g. wind profile, water inflow profiles to hydro storages, interconnection capacities etc. These assumptions are constant in all scenarios. Key assumptions regarding CO2 price and EV charging is described in Appendix 7.1.1.

Hence, the main focus of the scenarios is to quantify the effect of five *sensitivity parameters*:

- Interest rate and taxes. The interest rate of investments affects the relative attractiveness of different technology investment options, also investment in flexible heat pumps. In the socioeconomic scenarios no taxes on fuels used for heating purposes are applied and the interest rate is 4%. The economic lifetime used to calculate the annuity is assumed to be 20 years. Taxes on fuels are included in the private economic scenarios and the interest rate is 8%.
  Constant distribution tariffs and electricity tax is included in scenarios 1-9. The influence of variable tariffs is investigated in Chapter 3.2.1.
- Outdoor temperature profile. The outdoor temperature profile determines the building's heat demand, i.e. the periods where a high peak heat demand is required. 2011 is a 'normal' Danish temperature profile and 2010 represents a winter season with several very cold weeks.

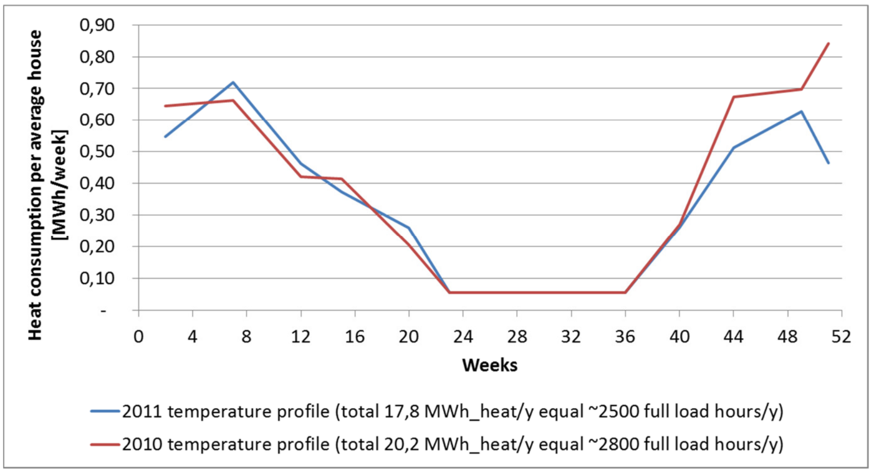


Figure 13. The weekly heat consumption in an average house in 2020 for temperature profiles of 2011 and 2010, respectively, calculated in Balmorel with the Thermal building module. The corresponding total yearly heat consumption and full load hours of the heat pump is shown in the legend for the two profiles.

- Allowed indoor temperature interval. The interval states allowed T_{max} and T_{min} in the buildings with flexible heat pumps. In the base scenario +/- 1,5 C is assumed. A reduction to +/- 0,75 C lead to half heat storage size in all building categories.
- Flex heat pump investment. The investment options and costs are explained in the previous chapter 2.1.6. In scenario 3 the influence of double as high Digital thermostat investment cost is investigated.
- Electric heater % of heat capacity. The dimensioning criteria of the electric heater affect the average COP, because the electric heater is used more when the electric heater's share of the total heat capacity is increased. In scenario 9 the electric heater covers 35 % of the heat capacity compared to 20% in all other scenarios.

Table 5 shows the impact of the dimensioning of the electric heater on the electric heater share of the total power consumption:

Scenario		Electric heater dimensioning (% of total heat capacity)	Electric heater power consumption (MWh/y)	Heat pump power consumption (MWh/y)	Electric heater (% of total power consumption)
8	NoFlex	20	8.159	460.539	1,7
8	Flex	20	4.034	455.939	0,9
9	NoFlex	35	56.957	446.675	11,3
9	Flex	35	33.621	447.851	7,0

Table 5. The dimensioning of the electric heater impact the share of the total power consumption.

The effect of the sensitivity parameters is measured via three key results:

- Flexible heat pump investment
  - E.g. flexible investment in % of installed heat pumps (Figure 19)
- Private economic profit
  - E.g. Average Private economic profit (EUR/flex house) (Figure 31)
- Socioeconomic value
  - E.g. Socioeconomic cost savings (million DKK/year) (Figure 35)

2.2.2 OVERVIEW OF DANISH ENERGY SYSTEM DEVELOPMENT 2020-2035

The key drivers for the development of the energy system in Denmark and North Europe like fuel prices, technology costs, decommissioning, and CO2 prices are similar in all scenarios. This makes it possible to observe the impact of non-flexible and flexible heat pumps in Denmark in the scenarios. However, the sensitivity parameter 'Interest rate and tax' determines different energy system developments in the socioeconomic scenarios compared to the private economic scenarios. In Figure 14 and Figure 15 the Danish electricity production by fuel is used to illustrate the difference.

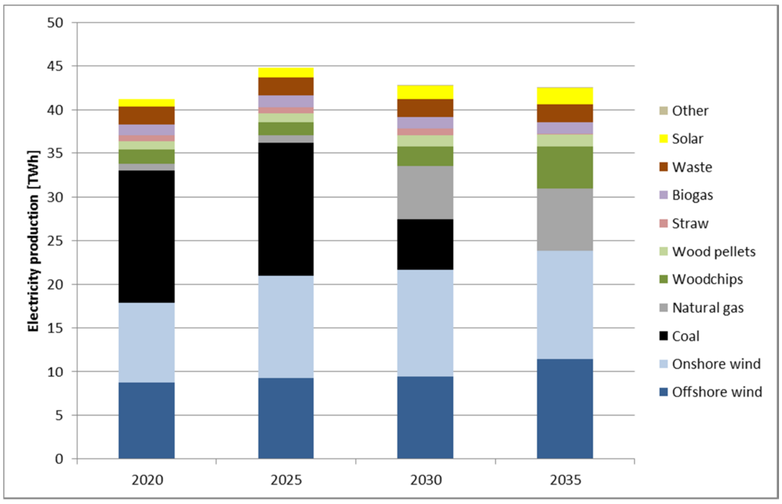


Figure 14. The power production in the socioeconomic scenarios without tax leads to increased natural gas use. Scenario 1a is shown

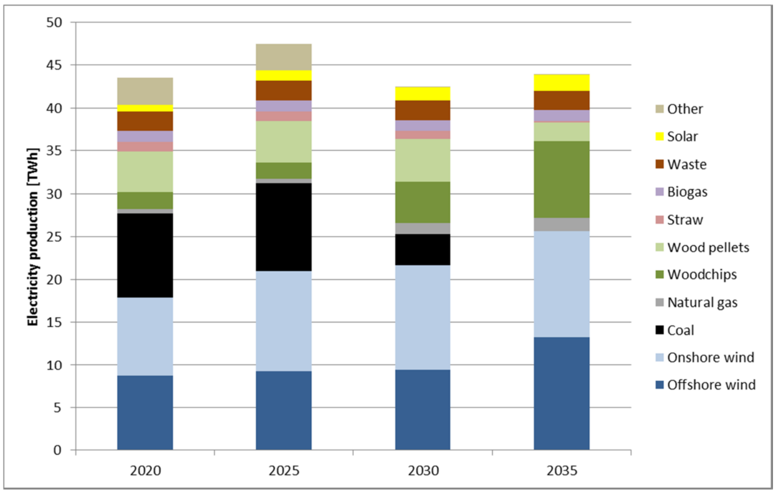


Figure 15. The power production in the private economic scenarios with tax leads to increased use of biomass and more export. Scenario 6a is shown.

The overall trend is a continuous increase in offshore and onshore wind production together with a phase out of coal fired production. In the socioeconomic scenarios the no fuel tax condition leads to an increased use of natural gas. In the private economic scenarios the inclusion of fuel taxes lead to a more dominant use of biomass (wood chips and pellets) to supplement the wind production.

The increased integration of especially wind production lead to higher fluctuation in power prices, which is a key driver for the economic value of flexible consumption. In Figure 16 the change towards more hours with both high and low prices is illustrated via duration curves in 2020, 2025, 2030 and 2035:

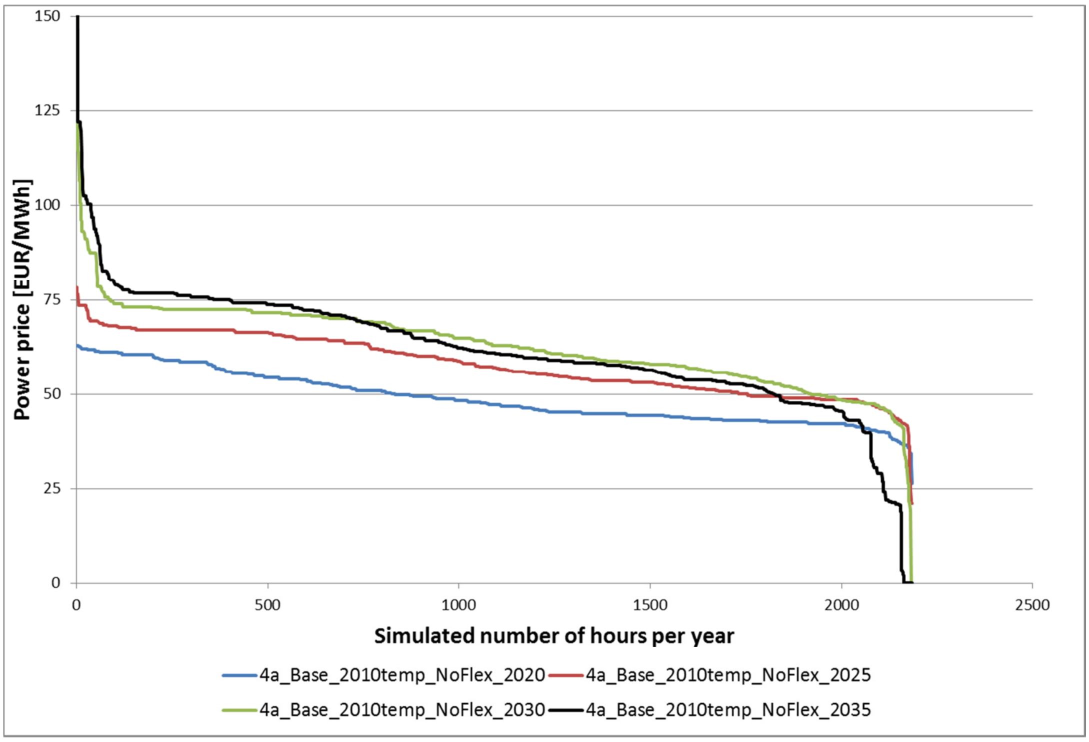


Figure 16. Duration curve of power prices 2020-2035. Periods with both higher and lower power prices occur more frequently with higher share of wind production.

2.2.3 INSTALLED HEAT PUMP HEAT CAPACITY

The total heat capacity of the residential heat pumps is determined by the installed number of heat pumps (Figure 11) and the heat capacity dimensioning criteria per heat pump (Appendix 7.1.5). The total heat capacity in the different building year categories is shown in Figure 17:

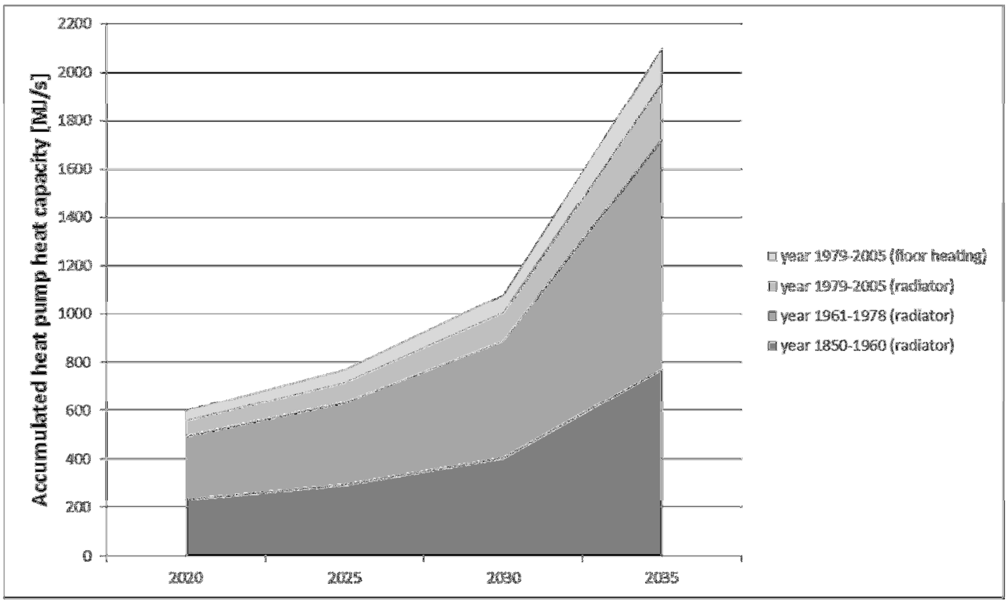


Figure 17. The total heat capacity of the residential heat pumps in the different building year categories from 2020 to 2035. The majority of the heat pump heat capacity is installed in houses before 1979.

The installed heat capacity is similar in all scenarios.

2.2.4 FLEXIBLE HEAT PUMP INVESTMENTS

In each building category the optimal investment in flexibility regarding heat storage type and size is calculated in the model for 2020, 2025, 2030 and 2035. The optimization methodology in Balmorel is described in Appendix 7.1.2.

In all scenarios investments in heat storage option B (heat storage in building structure and indoor air) is more cost efficient compared to heat storage option A (additional accumulator tanks).

The reason is due to the cost per MWh of storage in option A and B. The total heat storage (kWh/house) and heat storage annuity cost (EUR/kWh) is shown Figure 18.

- For option A the maximum ΔT=15 °C which corresponds to ~17,4 Wh/L.
- For option B the maximum heat storage is calculated as:

Maximum heat storage = $\Delta T_{max} \cdot A \cdot C_{wall}$, where the following values are used:

ΔT_{max} = Tmax-Tmin = 3 °C, heat area A = 150 m2, heat capacity C_{wall} = 60-140 Wh/C/m2.

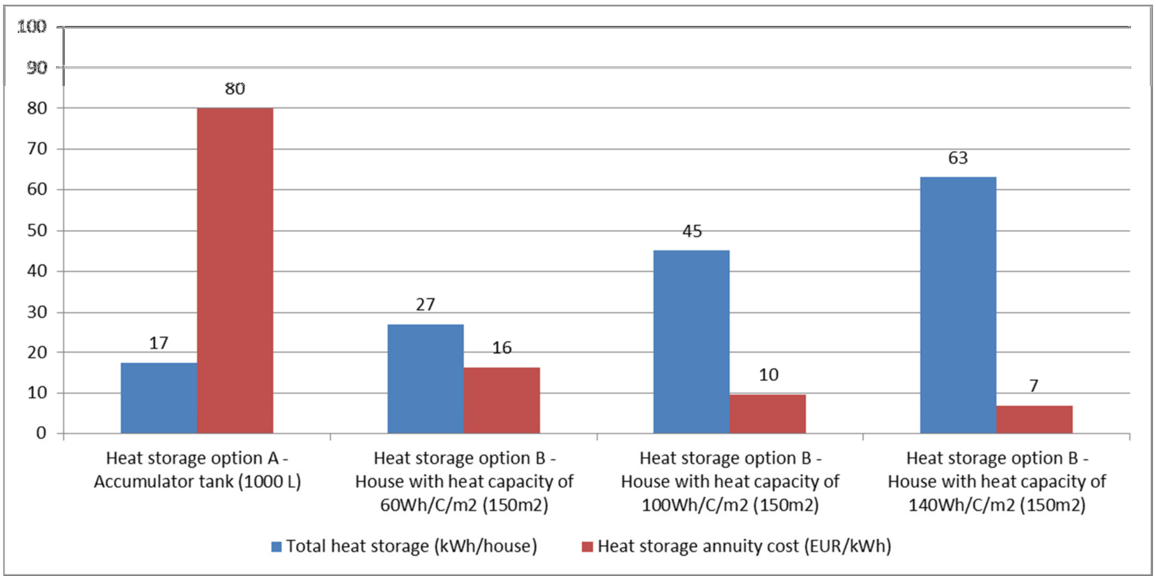


Figure 18. The total heat storage (kWh/house) of accumulator tank and building construction with C_{wall} = 60, 100, 140 Wh/C/m2 and the annuity cost of the heat storage options (EUR/kWh). The allowed indoor air temperature variation is +/- 1,5 °C in option B.

In a large accumulator tank (1000 L) the possible stored heat is less than in a house with low heat capacity (~60 Wh/m2/C) and significantly less than a house with high heat capacity (~140 Wh/m2/C). The heat storage size vs. heat demand determines the time period where the heat pump can be switched off. If the peak heat demand is e.g. 7 kW/house, this corresponds to max period of ~2,5 hours and ~9 hours for heat storage option A and heat storage option B - heat capacity 140 Wh/C/m2, respectively, assuming for option B that the indoor temperature of the house is highest allowed (e.g. 23 °C) when the heat pump is stopped.

Due to the lower investment cost the heat storage cost per kWh becomes less in heat option B compared to A. Thus, the following results mainly concern flexible heat pump investment in option B (heat storage in building mass+indoor air).

The investment in four different scenarious of flexble heat pumps (i.e. with investment in heat storage option B) is shown aggregated for all building categories in Figure 19. Due to change in e.g. power price-variation, wind production and required peak capacity the attractiviness of flexible heat pump investment changes from 2020 to 2035:

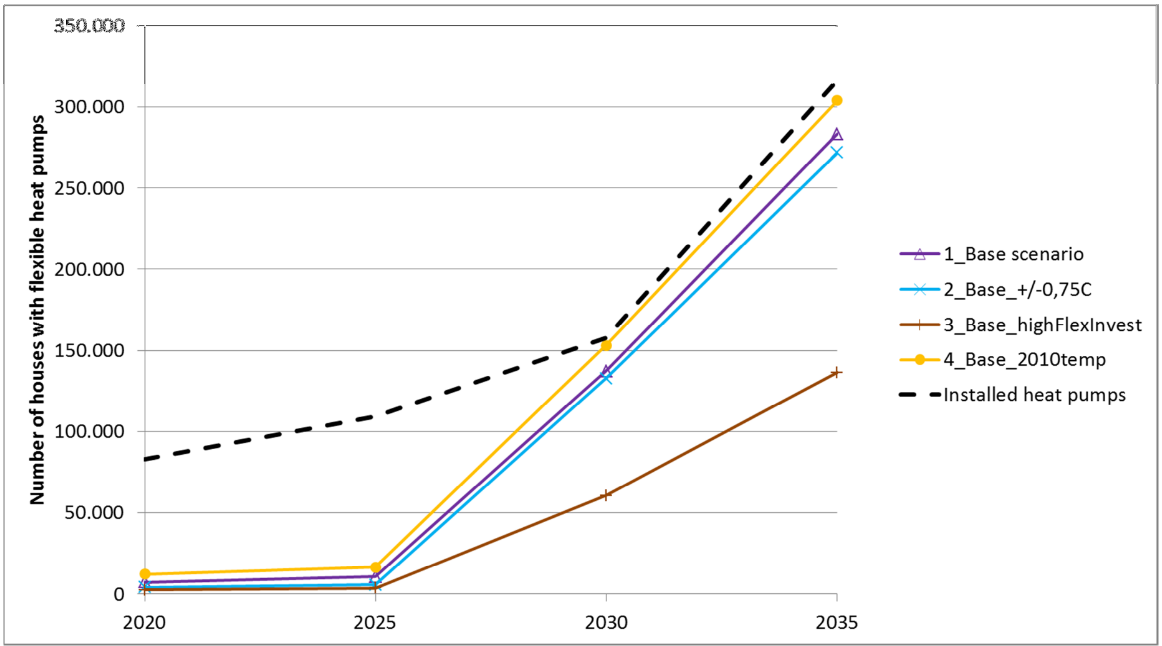


Figure 19. Investments in flexibility in selected scenarios compared to the maximum number of heat pumps.

The figure illustrates that in 2030 and 2035 investment in heat pump flexibility is attractive from a system perspective. The number of flexible heat pump is close to maximal potential (i.e. installed heat pumps) in 2030 and 2035 in three of the scenarios. The reduced heat storage size (+/-0,75 C) only has a small impact on the investment in 2030 and 2035, because the majority of the system value can be obtained with the smaller heat storage size. The scenarios with double investment cost in flexibility lead to significant reduction in flexibility investment.

In Appendix 7.2.3 the investment in flexible heat pumps in each building category is shown in the Base scenario and the High flexible investment cost scenario.

2.2.5 ILLUSTRATION OF FLEXIBLE HEAT PUMP OPTIMISATION

The simulated heat production and power consumption of non-flexible and flexible heat pumps is shown for scenario 4 in Figure 20:

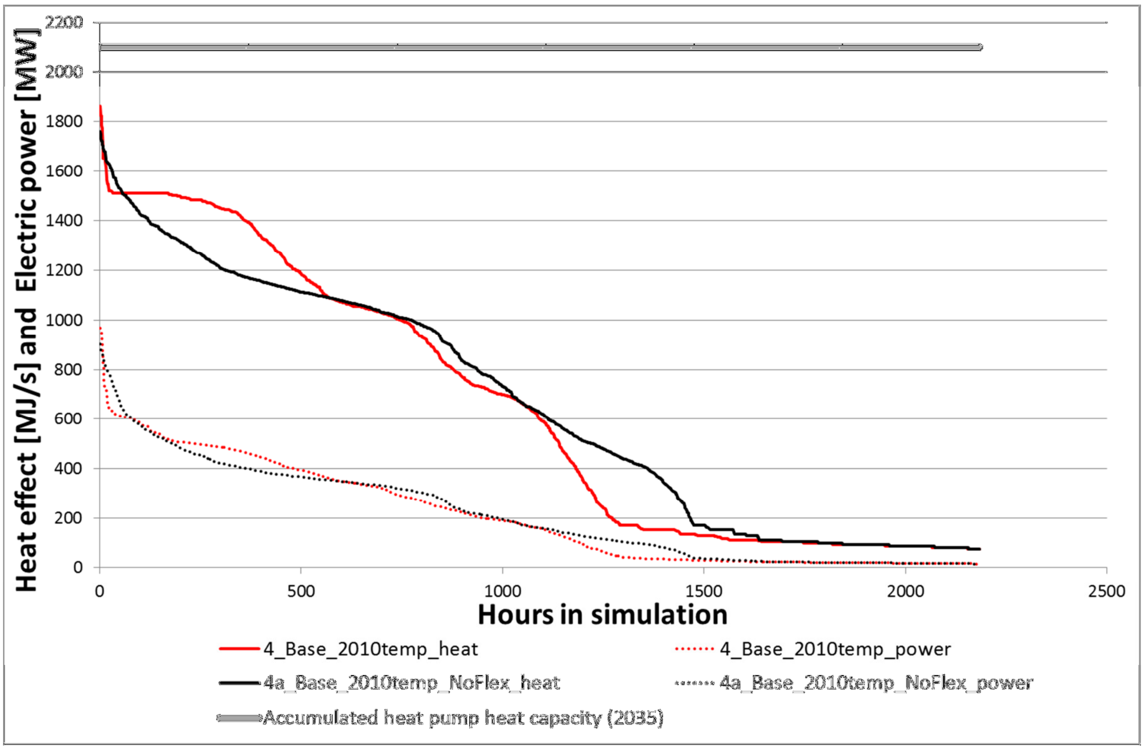


Figure 20. Duration curve in Scenario 4a in year 2035 of heat and power consumption of non-flexible and flexible heat pumps.

The duration curves show that flexible heat pumps have more hours with high heat production and low heat production, respectively, compared to non-flexible heat pumps. With flexible heat pumps the heat storage is used to produce the heat in hours with low power price and reduce the consumption in hours with high power prices.

The optimization of heat pump's power consumption according to power prices and indoor temperature restrictions is shown in Appendix 7.2.2. Further, this appendix also shows the influence of the electric boiler power consumption during periods with high heat demand.

The electric power of residential heat pumps is a model to the simultaneousness power consumption of all residential heat pumps, i.e. not the sum of installed power capacity in each heat pump. For further use in this analysis the following key characteristics of heat pump power consumption and yearly energy consumption in 2035 will be used:

Max 900 MW / ~300.000 heat pumps = average max 3 kW per heat pump Average consumption (2011 temperature profile) = 1.560.000 MWh/year / ~300.000 heat pumps = ~5,1 MWh/year per heat pump Average consumption (2010 temperature profile) = 1.870.000 MWh/year / ~300.000 heat pumps = ~6,2 MWh/year per heat pump Average hourly consumption during the heat season = 5,1 MWh/year / ((8760h/year) *½) = 1,2 kWh/h

Table 6. The max power, yearly consumption and hourly consumption during the heat season of an average residential heat pump in 2035 according to the Balmorel simulations. Heating season is approximately 6 month = 8760 * ½ h/year.

2.2.6 INFLUENCE OF FLEXIBLE HEAT PUMP ON INVESTMENT IN WIND POWER AND PEAK POWER CAPACITY

The explanation for the investment in flexibility is largely due to the impact on required peak power capacity and additional investment in wind power in the model. In the total investment 2020-2035 in OCGT capacity, CCGT capacity and offshore wind power in Denmark is shown in two scenarios:

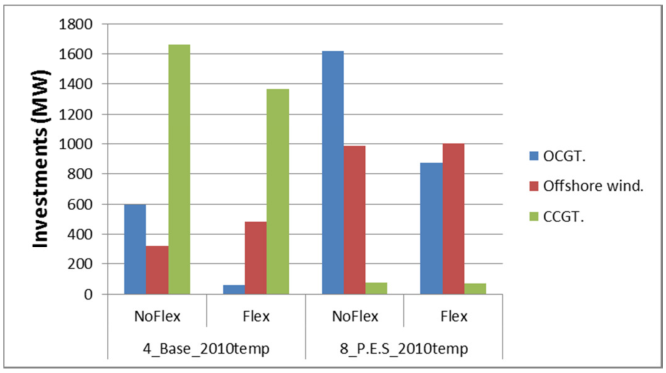


Figure 21. Investments in Denmark in OCGT, CCGT and offshore wind during 2020-2035 in scenarios with and without flexible heat pumps.

The accumulated 2020-2035 change in investments in peak load capacity and offshore wind power capacity between scenarios with flexible heat pumps minus investments in non-flexible heat pumps is shown in Figure 22. The results show that in all scenarios less investment in peak power capacity (OCGT plants) and CCGT plants (cheap power capacity which also contribute to peak power capacity) is needed with flexible heat pumps. Further, the wind power investments are increased in the socioeconomic scenarios 1-4 due to flexible heat pumps.

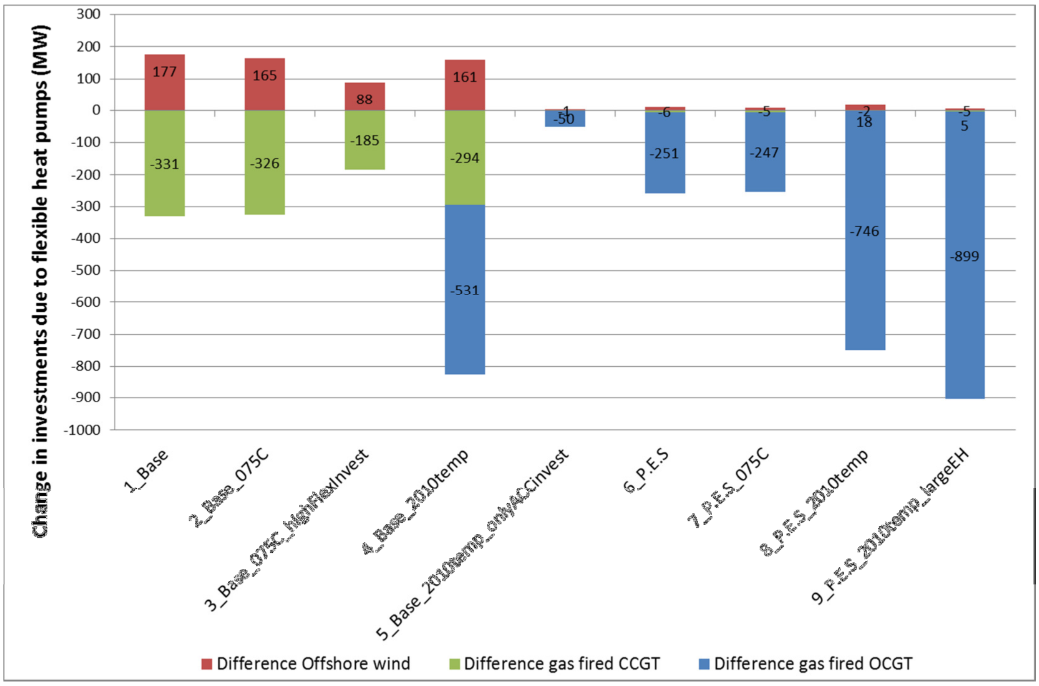


Figure 22. The difference in investment in offshore wind, OCGT and CCGT capacity between non-flexible and flexible heat pumps.

Based on Figure 22 the following conclusions are drawn:

- The reduction in OCGT peak power capacity is between ~500 MW (Scenario 4) and ~750 (Scenario 8) with the 2010 temperature profile.
- The reduction in OCGT peak power capacity is ~250 MW with the 2011 temperature profile (Scenario 6), i.e. the temperature profile has a high impact on the demand for peak capacity.
- Dimensioning of the electric heater to 35% of the total heat effect increases the potential of OCGT peak power capacity reduction to ~900 MW (Scenario 9)

The relationship between the flexible heat pump and the change in these investments is explained below:

Wind power capacity is added to the model if the power price (including CO2 price and subsidy) is sufficient to make offshore wind investments profitable. However, the marginal revenue of wind decreases with increasing wind power volume, which at some volume destroys the business case for additional offshore wind investment. Flexible consumption will shift consumption to hours with low prices when the wind power production is high and the conventional consumption low. The additional demand from flexible heat pumps in off peak hours lead to higher marginal prices for wind power production which will increase the volume of offshore wind power that is profitable. The results show up to ~180 MW additional offshore wind capacity is profitable due to flexible heat pumps in the socioeconomic scenarios.

The additional Peak power capacity is determined by the hour(s) with highest residual power production (difference between consumption and wind production) minus the existing available power capacity. Thus, the dimensioning criteria of peak power capacity is during a peak consumption period with very low wind and solar production, i.e. where the required residual power production is as high as possible. Thus, the consumption of non-flexible and flexible heat pump during the peak load hour(s) influences the required peak capacity.

It is clear from Figure 22 that scenarios with 2010 temperature profile leads to higher peak power capacity (OCGT) investments compared to scenario with 2011 temperature scenarios. This result is explained via two examples of simulated weeks in 2035, where different profiles of temperature, consumption and wind power are used to illustrate the required peak power capacity.

In Figure 23 the Danish power consumption without heat pumps (red) is shown during one week (week 7) together with the heat pump power consumption with 2010 temperature profile (green) and 2011 temperature profile (blue), respectively. Due to the difference in temperature profile the non-flexible heat pump power consumption is much higher around hour 150 (night to Sunday) with the 2011 temperature profile compared to 2010 temperature profile. However, this peak consumption of non-flexible heat pump power is during a period with medium wind production and low total consumption which means the residual power production is relatively low.

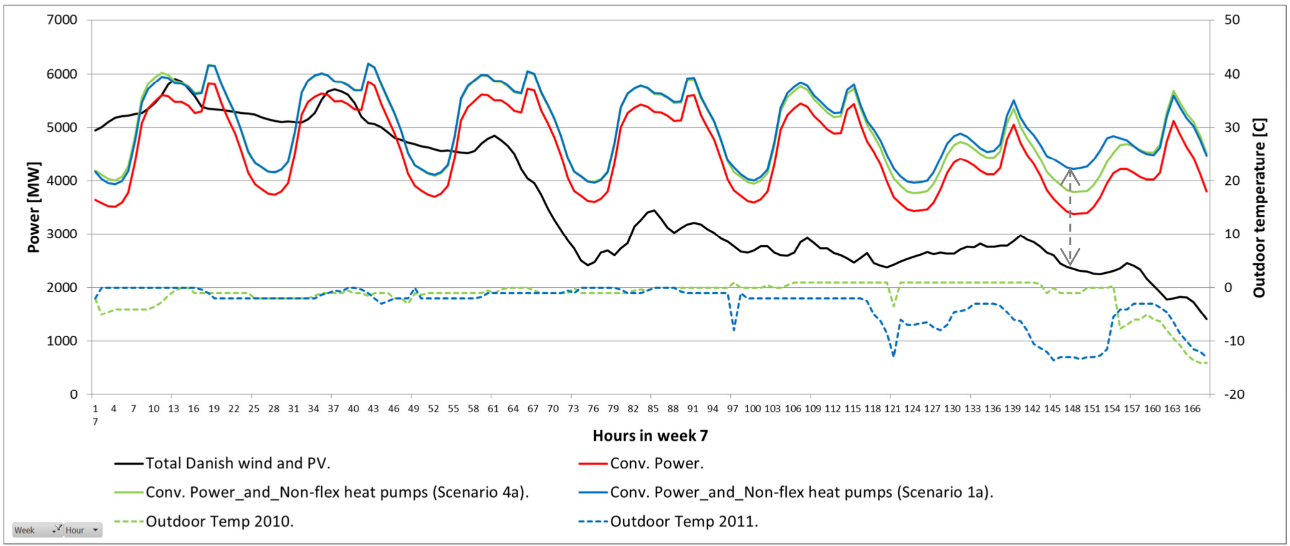


Figure 23. The power consumption of non-flexible heat pumps with 2010 and 2011 temperature profile. During the period with high heat pump consumption (2011 temperature) around hour 150 the residual power production is relatively small.

In Figure 24 the same parameters are shown for another cold week (week 51). Around hour 66 (Wednesday at 18:00) the non-flexible heat pump power consumption with 2010 temperature profile (green) is very high during a period with peak demand and very low wind production. Thus, the non-flexible heat pump consumption will increase the required peak load capacity because the required residual power production is increased.

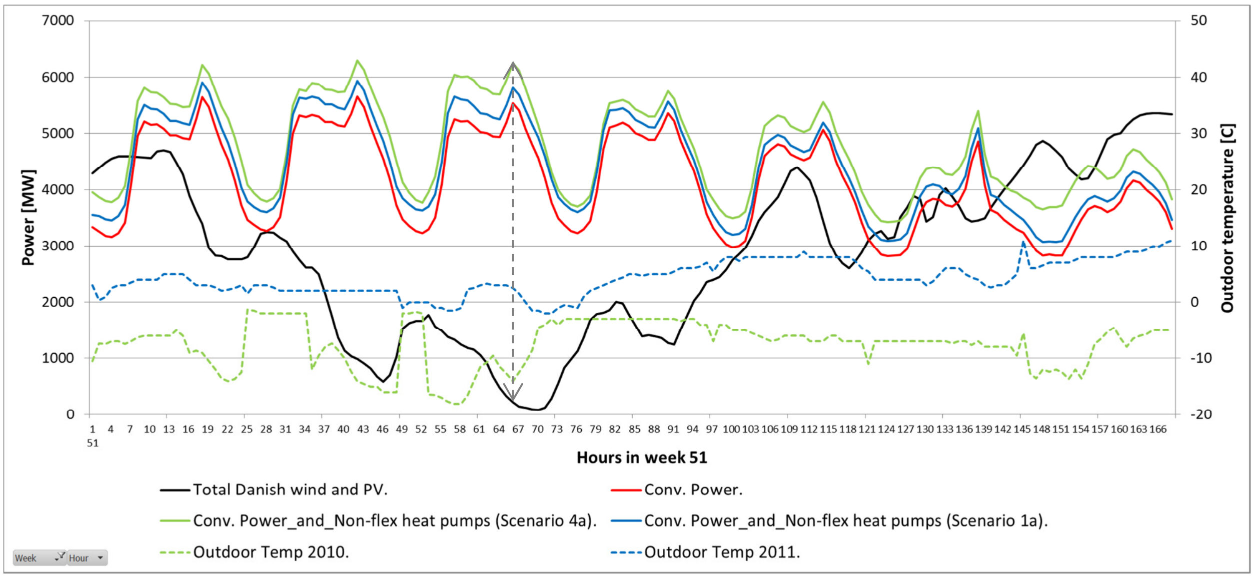


Figure 24. The power consumption of non-flexible heat pumps with 2010 and 2011 temperature profile. During the period with high heat pump consumption (2010 temperature) around hour 66 the residual power production is very high.

In Figure 25 the power consumption of flexible heat pumps (dashed green) is shown together with the non-flexible heat pumps (green) and the power price (gray). In Figure 26 a zoom (marked with the blue line on the x-axis in Figure 25) shows the change of power consumption from non-flexible and flexible heat pump of approximately ~750MW.

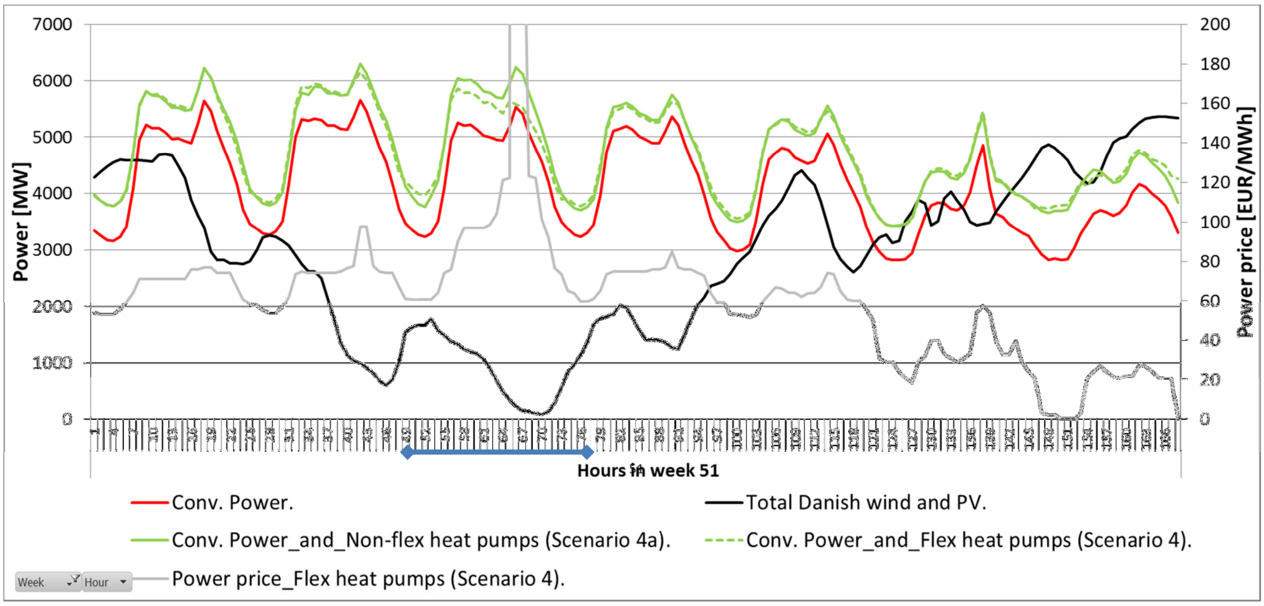


Figure 25. The power consumption of flexible heat pumps is changed compared to non-flexible heat pumps due to power prices and peak power capacity requirement.

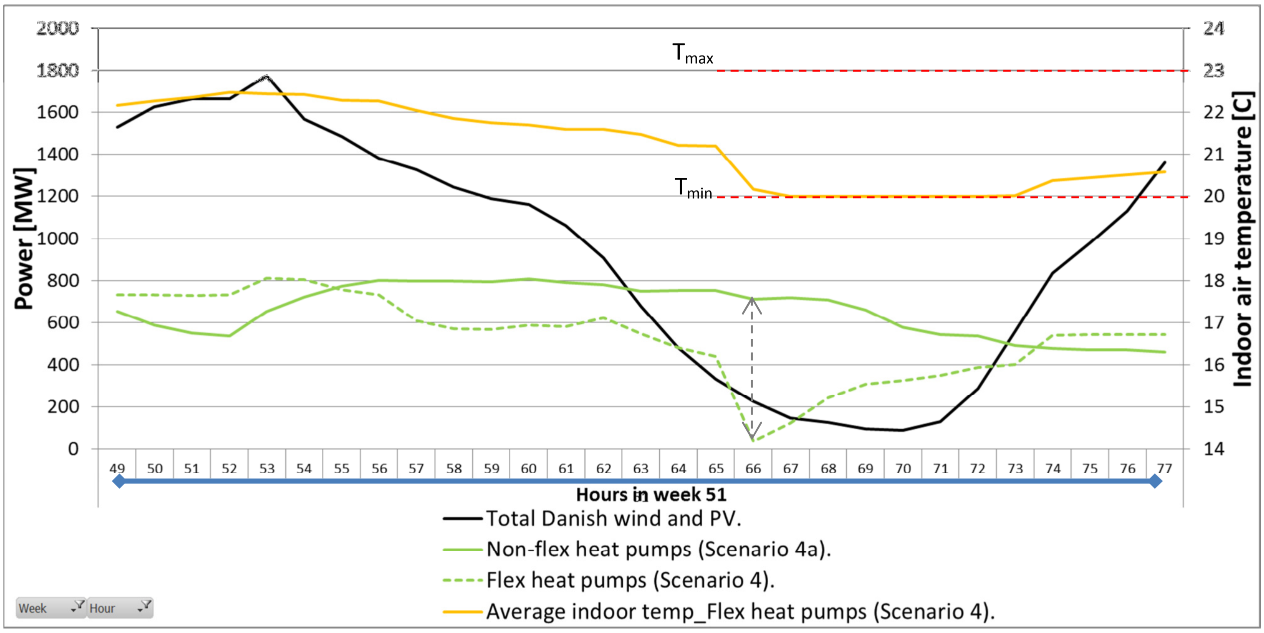


Figure 26. The power consumption of non-flexible and flexible heat pumps is shown together with the average indoor air temperature for flexible heat pumps.

As seen in Figure 25 the flexible heat pump reduces the power consumption to avoid the high power price and minimizes the required peak power capacity. The heat storage in the building structure and indoor air is used to reduce the power consumption for longer periods of time. The indoor air temperature is a measure of the level in this heat storage. When a reduction in power consumption of the flexible heat pumps is needed, the average indoor temperature (dotted yellow) decreases from close to the maximum level (Tmax = 23 C) to the minimum level (Tmin = 20 C) and is maintained there for several hours.

The ability to increase the indoor air temperature (i.e. store heat) depends on the buildings heat demand compared to the heat pump capacity. The foresight in the model allows the indoor temperature to be optimized according to the future demand, i.e. the indoor temperature is high before periods where reduction in power consumption is needed. However, if the foresight is short during a period with heat demand a higher heat pump capacity could be needed to increase the indoor air temperature sufficiently. The increased capacity would represent an additional cost of flexible heat pumps but at the same time allow better optimization according to the power prices. This question is not part of this analysis since both flexible and non-flexible heat pumps have been assigned same capacity (to cover heat demand at -12C).

2.2.7 PRIVAT ECONOMIC PROFIT OF FLEXIBLE HEAT PUMP

In the Day-ahead market the difference between the power price for non-flexible and flexible heat pumps is the only economic driver for a private economic business case. In Figure 27 and Figure 28 the average power prices of non-flexible and flexible heat pumps is shown together with the average consumption weighted power price (power price of average Danish consumption) with 2011 and 2010 temperature profile, respectively. According to Figure 19 investment in flexibility is mainly in 2030 and 2035, hence the average power price of flexible heat pumps is only shown for 2030 and 2035.

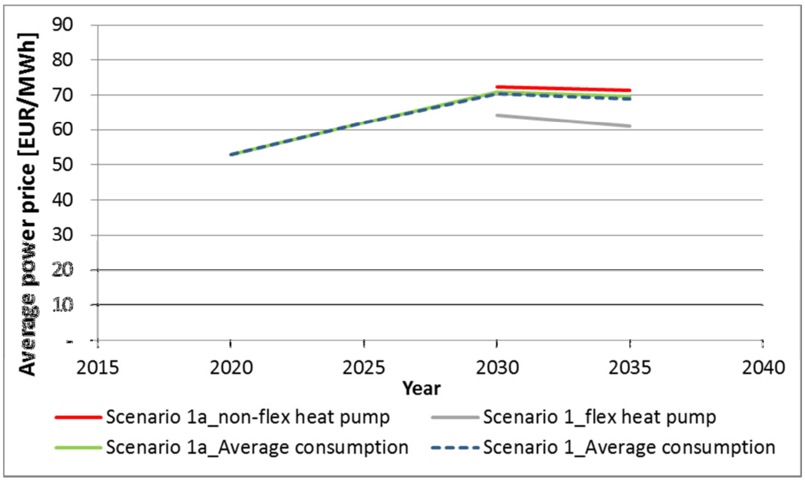


Figure 27. The average consumption weighted Danish power prices in scenario 1 (2011 temperature profile) with non-flexible heat pumps (green) and flexible heat pumps (blue dotted) compared to power price of non-flexible (red) and flexible heat pumps (gray).

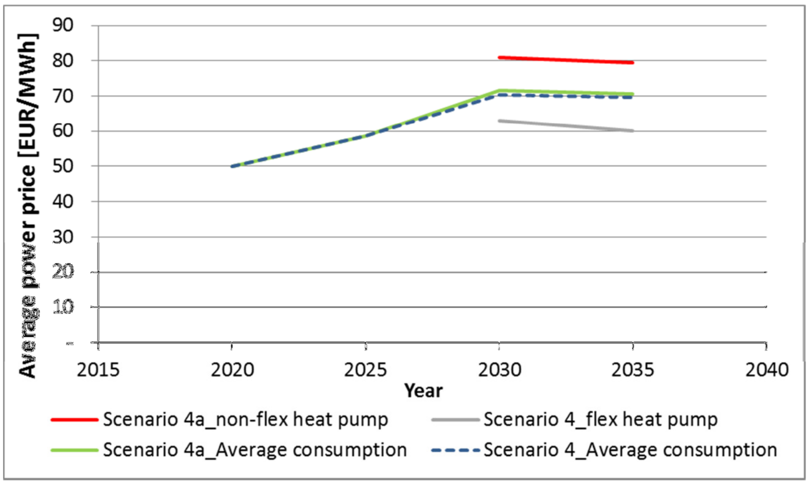


Figure 28. The average consumption weighted Danish power prices in scenario 1 (2010 temperature profile) with non-flexible heat pumps (green) and flexible heat pumps (blue dotted) compared to power price of non-flexible (red) and flexible heat pumps (gray).

A breakdown of the total private economic electricity costs savings is shown for Scenario 1 and 4 in Figure 29.

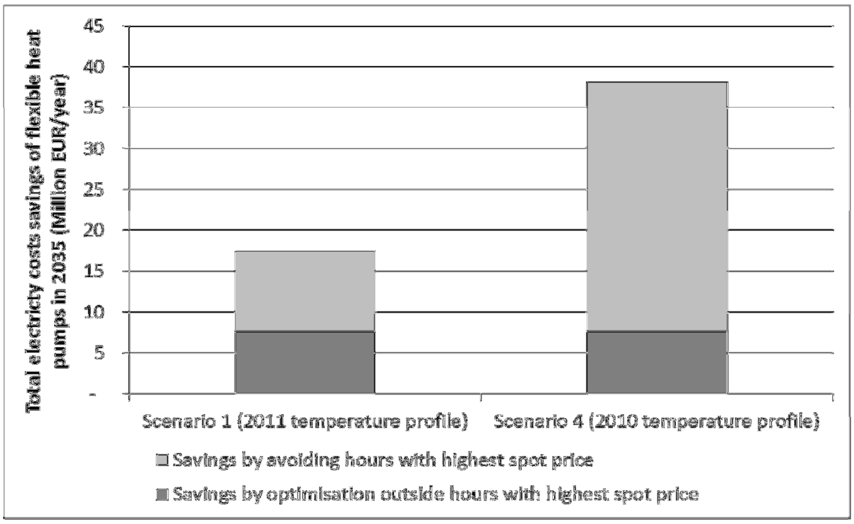


Figure 29. The electricity costs savings in the hours with the highest power prices and savings in remaining hours.

The savings by optimization outside hours with highest spot price is almost similar for 2011 and 2010 temperature profile.

The savings by avoiding hours with highest spot price:

- With 2011 temperature profile, ~50% of the electricity cost savings of flexible heat pumps are created by avoiding hours with highest spot prices.
- With 2010 temperature profile, the similar number is ~80%. This indicates that the correlation between heat demand (outside temperature) and hours with peak prices is important for the electricity costs saving potential. This correlation is extremely high with 2010 temperature profile, which means the most realistic electricity cost savings potential is found with the 2011 temperature profile.
- Assuming the maximum allowed power price is 3000 EUR/MWh (similar to 2014 Value of lost load (VOLL) in Nordpool) the Balmorel results corresponds to 14-15 hours per year with the highest power price. This indicates that a large share of the electricity cost savings can be ‘captured’ by moving consumption few hours.

The average power price is higher for non-flexible heat pumps compared to the average Danish power price, because the majority of the heat pump power consumption is during the winter period where the power prices are generally higher. Due to optimization of the residential heat pump consumption the average power price of the flexible heat pump is lower than the average Danish power price.

The private economic profit of flexible heat pumps is calculated in each scenario as the saving in electricity cost minus the investment in flexible technology

a. [2]Savings in electricity cost of flexible heat pumps = Electricity cost of non-flexible heat pumps – Electricity cost of flexible heat pumps
b. Profit of flexible heat pumps = Savings in electricity cost of flexible heat pumps - Investment cost of flexibility

The investment cost of flexibility is 440 EUR/house for heat storage option B including additional control of heat pump. The annuity cost is:

4% interest rate: 0,074*440 = 32EUR/year = ~240 DKK/year.

8% interest rate: 0,102*440 = 44 EUR/year = ~330 DKK/year

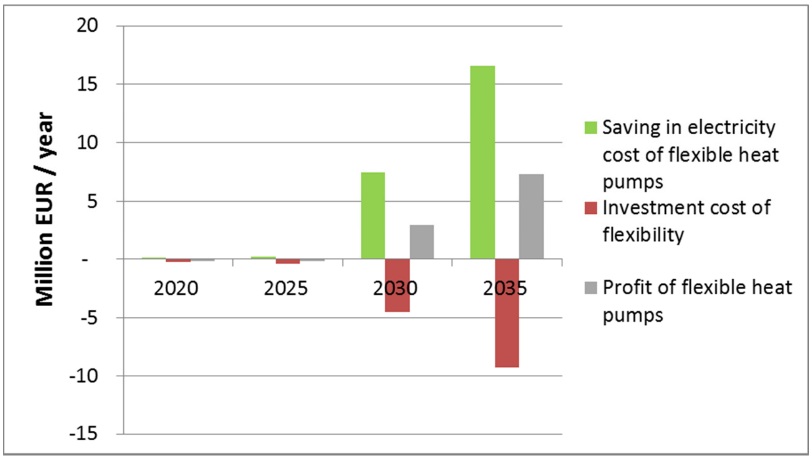


Figure 30. The profit of flexible heat pumps calculated via savings in electricity cost minus investment in flexible equipment.

The average profit per flex house (all building categories) is calculated for each scenario:

c. Average private economic profit per flex house = Total private economic profit of flexible heat pumps (all building categories) / number of flexible heat pumps

In Figure 31 the profit is shown for all scenarios in 2035:

[2] There are minor differences (+/- 1%) in the heat production between non-flexible and flexible heat pump in the scenarios. The electricity cost of flexible heat pump has been calculated by adjusting the heat production to be equal to non-flexible heat pumps, i.e. using the average electricity price of flexible heat pumps to calculate the cost of the adjusted heat production.

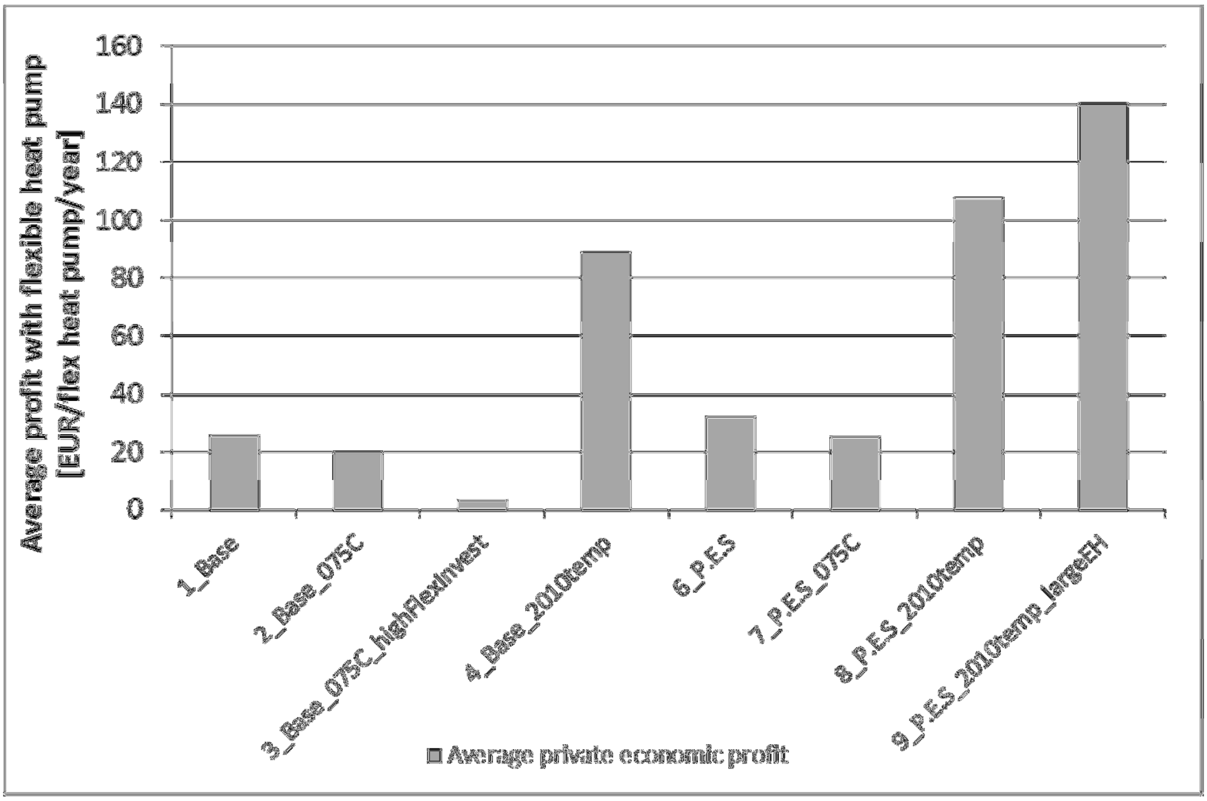


Figure 31. The average private economic profit wih flexible heat pump in 2035 in the different scenarios.

Some important observations in Figure 31 are:

- The average profit (including flexibility investment) in Scenario 1 is 26 EUR/year = ~200 DKK/year. The electricity cost saving (excluding flexibility investment) is ~440 DKK/year. The saving corresponds to ~16% of the total non-flexible heat pump spot market cost.
- The average profit (including flexibility investment) in Scenario 4 is 89 EUR/year = ~700 DKK/year. The electricity cost saving (excluding flexibility investment) is ~940 DKK/year. The saving corresponds to ~25% of the total non-flexible heat pump spot market cost.
- The profit is significantly higher with 2010 temperature profile compared to 2011 profile, which is due to the higher variation in average power prices between the non-flexible and flexible heat pump illustrated in Figure 28.
- The profit due to flexible heat pumps is slightly higher in the private economic scenarios compared to socioeconomic scenarios.
- An increase of the electric heater from 20% to 35% of the heat pump capacity lead to an increase in the potential flexible heat pump profit by average 30%.

The profit of flexible heat pumps in Figure 31 is the average of all building categories. The private economic profit of spot market optimization in 2035 in different building categories (see Table 3) is displayed in Figure 32 together with the corresponding simple payback period from Day-ahead market:

d. Payback period (years) = Total Investment cost of flexibility per category / Day-ahead market Profit per category per year

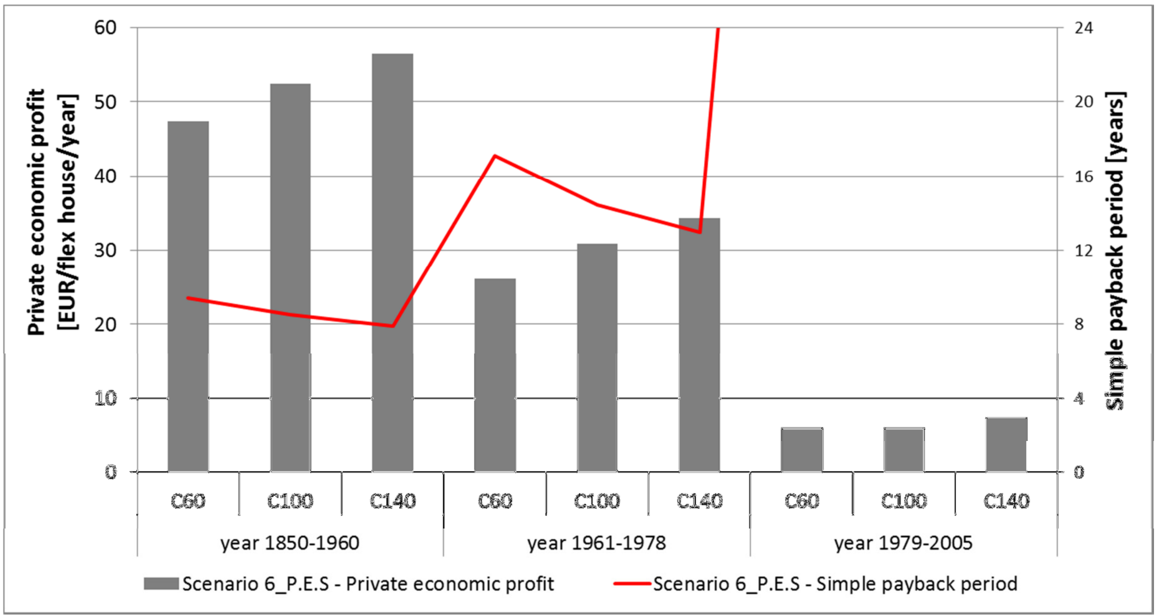


Figure 32. Private economic profit and simple payback period of flexible heat pumps in Day-ahead market in houses with radiator heating and different heat capacity (C60-C140, see Chapter 2.1.5) and building year categories.

The observations in Figure 32 are:

- The profit of flexible heat pumps is highest in older building categories (high yearly consumption) and lowest in the newest building category (low yearly consumption). Due to the increased electricity consumption in the older buildings the revenue of moving the consumption is higher. The flexibility cost is similar per house in all building categories which lead to higher profits and lowest payback period in older building categories.
- The influence of reducing the heat storage size from +/- 1,5C to +/- 0,75 C only leads to a minor reduction in profit. This means the majority of the potential profit of moving consumption according to power prices is already captured with half the heat storage size.
- The heat capacity (C60, C100, C140) only has a minor impact on the profit. As expected houses with high heat capacity has a higher profit than houses with lower heat capacity. However, this indicate the majority of the potential profit of moving consumption according to power prices is already captured in houses with heat capacity of C=60 Wh/C/m2.

2.2.8 SOCIOECONOMIC VALUE OF FLEXIBLE HEAT PUMP

The Danish socioeconomic value of electricity and heat production is measured via the system costs:

Danish system costs =
+ Fixed O&M cost + Variable O&M cost + Fuel consumption cost + CO2 cost
+ Accumulated annuity investment cost ex. Flex heat pumps
+ Accumulated annuity investment cost Flex heat pumps
- Net export income (i.e. Export – import)
- ½ Bottleneck income (i.e. Bottleneck income out + bottleneck income in)

Table 7. Calculation of the Danish system costs of power and heat production. The bottleneck income is divided between the TSO's in Denmark and the neighboring country (e.g. Germany, Sweden, Norway), i.e. only ½ is included in the Danish system costs.

The total socioeconomic costs of heat and electricity production in 2035 are shown in Figure 33 for scenarios with non-flexible heat pumps and flexible heat pumps, respectively:

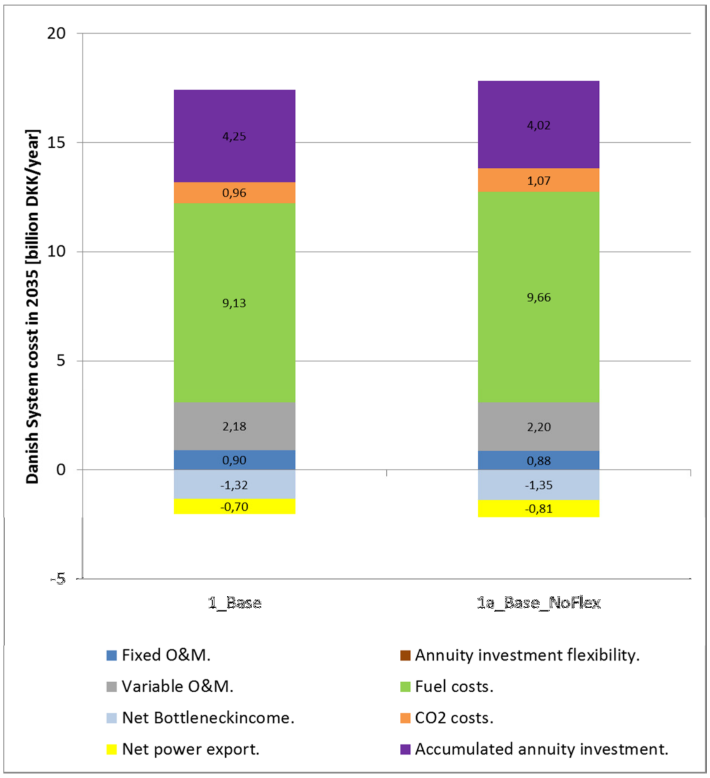


Figure 33. Example of the Danish socioeconomic cost with flexible heat pumps (left) and non-flexible heat pumps (right) in scenario 1

The development of Danish system costs savings due to flexible heat pumps is shown in Figure 34:

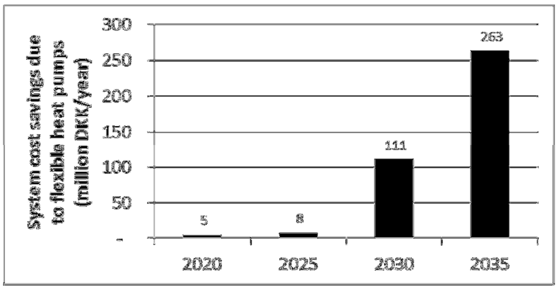


Figure 34. Development of Danish system costs savings due to flexible heat pumps in Scenario 1 from 2020-2035.

The Danish socioeconomic value due to flexibility is calculated as the difference between the parameters for non-flexible compared to flexible heat pumps. The result for the scenarios in 2035 is shown in Figure 35:

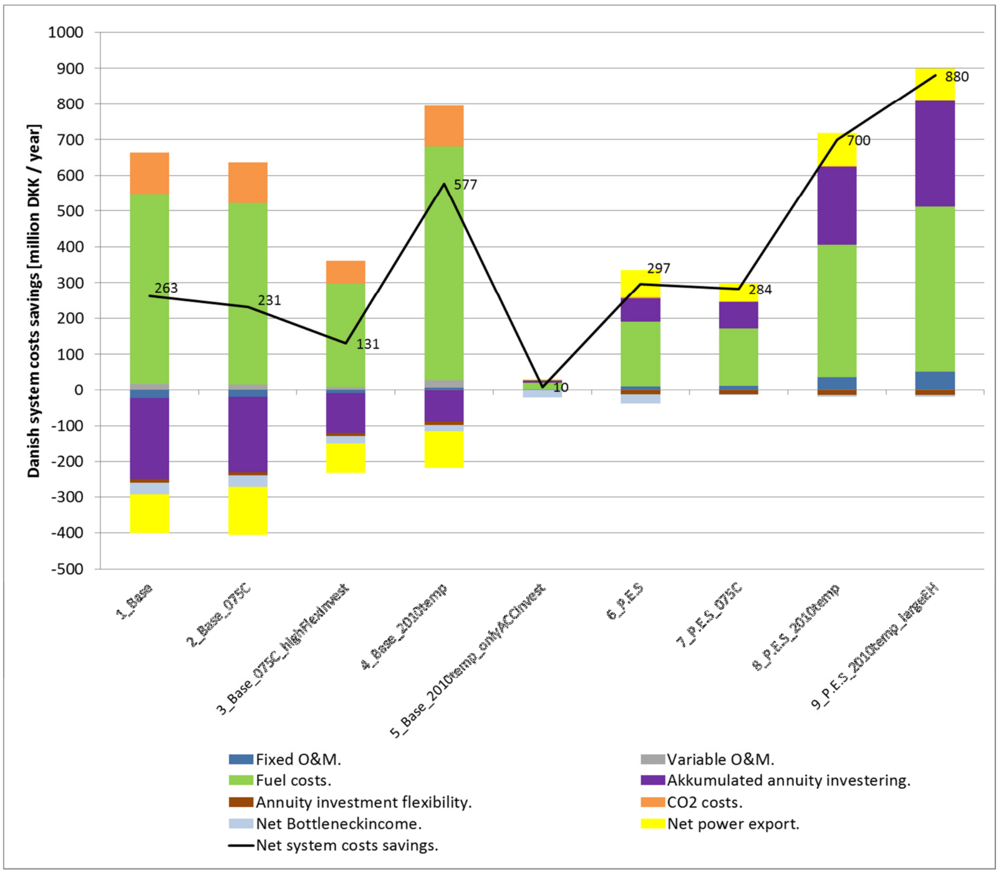


Figure 35. The difference in Danish system cost in each scenario between flexible heat pumps compared to non-flexible heat pumps. A positive value indicates cost savings of flexible heat pump compared to non-flexible heat pumps.

The following observations are made:

- The impact of fuel cost reduction is the dominant contribution to socioeconomic value from flexible heat pumps. When the power demand of heat pump is switched to periods with more wind production and off-peak periods the fuel consumption on power plants is reduced due to increased use of wind production and lower requirement for peak load plants production.
- The investment costs are mainly influenced by additional investment in offshore wind power and reduced investment in peak power capacity (cf. Figure 22).
    - In the socioeconomic scenarios (1-5) the additional cost of wind turbines surpasses the reduction in peak power capacity, which leads to a net increase in annualised costs. However, the additional wind power investment give rise to higher fuel cost reductions.
    - In the private economic scenarios (6-9) the reduced peak load capacity lead to a net decrease in annuity investment cost.

The average socioeconomic value per flex house in the different scenarios is shown in Figure 36 together with the average private economic profit per flex house (cf. Figure 31):

a. Average socioeconomic value per flex house = Total socioeconomic value of flexible heat pumps (all building categories) / number of flexible heat pumps

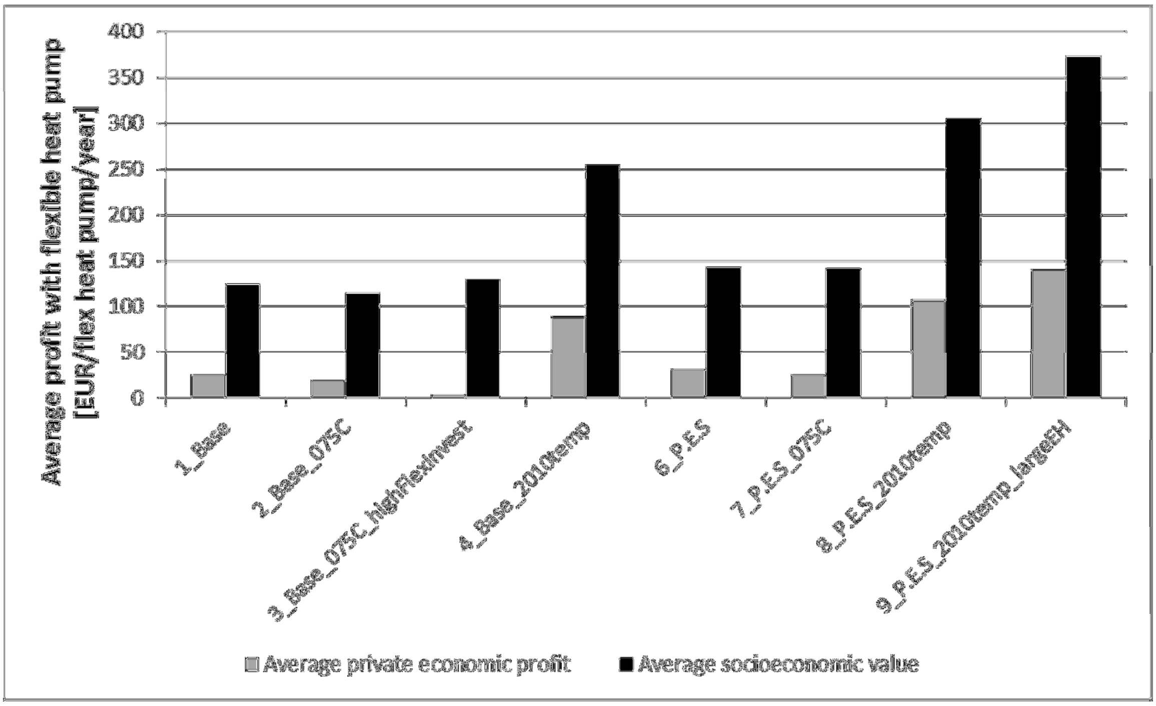


Figure 36. The Danish socioeconomic value in 2035 in the different scenarios compared to the private economic profit.

The socioeconomic value per flexible heat pump is higher than the private economic profit per flexible heat pump in all scenarios. This is due to flexible heat pumps reduces average spot prices and peak power capacity investments for all consumption ('the society') at the same time as the average spot price of flexible heat pumps is reduced. Non-flexible consumption receives a free-rider benefit due to flexible consumption. If all consumption was flexible the socioeconomic and private economic savings per consumer would be more equal.

This indicates that flexible heat pumps create a higher value for the society than the customer experiences through savings in electricity cost. The spot price variation does not send a signal to the consumers that reflect the full socioeconomic saving potential (the "public good") of flexible consumption. Thus, the incentive to invest in flexibility is stronger from a society compared to a private economic perspective.

From a society point-of-view it would be an advantage to increase the signal to customers regarding flexible consumption. This increase in signal could involve variable tariff and taxes.

Value of peak power capacity reduction

The required peak power capacity should be determined based on the worst case scenario. According to chapter 0 scenarios with the 2010 temperature profile are close to worst case because maximum non-flexible heat pump production occurs similar with a period without wind production. Hence, the additional value of flexible heat pumps with 2010 temperature due to reduced investment in peak power capacity should be added to scenarios with 2011 temperature profiles.

The reduction in accumulated annuity investment in OCGT-plants is calculated below according to investment and fixed O&M cost given in Table 2.

Scenario 4_Base_2010temp

- OCGT saving (4% interest rate): 531.000 kW * 41,2 EUR/kW/year * 7,45 DKK/EUR / 10^6 = 162,8 mio DKK/year
- OCGT saving % of total Danish system costs savings in scenario: 162,8 / 577 = 28%

Scenario 8_P.E.S_2010temp

- OCGT saving (8% interest rate): 746.000 kW * 53,9 EUR/kW/year * 7,45 DKK/EUR / 10^6 = 299,5 mio DKK/year
- OCGT saving % of total Danish system costs savings in scenario: 299,5 / 700 = 43%

Table 8. The value of reducing the OCGT investment in socioeconomic scenario (#4) compared to private economic scenario (#8) with 2010 temperature profile.

The reduction in OCGT investment makes up 28-43% of the total Danish system costs savings according to Table 8. The value of reducing the CCGT investments is not similar straightforward, since CCGT plants have significant production of power and heat, which has to be produced by other technologies.

The simplified[3] system costs savings of flexible heat pumps in Scenario 1 and 4, respectively, is shown in Figure 37.

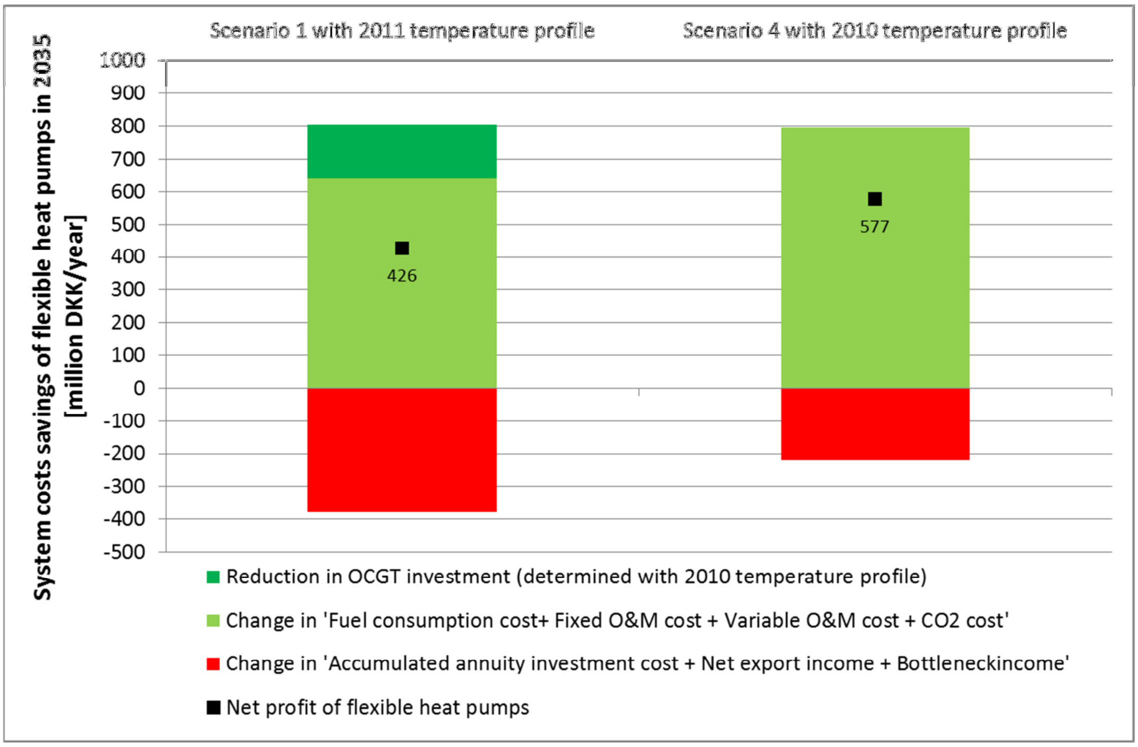


Figure 37. The socioeconomic value of flexible heat pumps is estimated at ~400 mio DKK/year in 2035 in Scenario 1. The OCGT savings in Scenario 4 are added to Scenario 1.

Hence, the calculated range of the Danish socioeconomic value of flexible heat pumps is ~400 million DKK / year in 2035.

[3] The OCGT-savings in Scenario 4 is added to Scenario 1. In Scenario 4 the similar OCGT-savings are shown via 'Change in net export, investment in offshore wind and peak power capacity etc.' (red)

2.3 SUBCONCLUSION

The chapter has presented a methodology to assess the influence of non-flexible vs. flexible heat pump in the Danish energy system 2020-2035 applying a energy system-wide model, Balmorel. The implemented Thermal Building Module allows flexible demand of residential heat pumps to impact the power prices and investments in Balmorel, which makes it possible to quantify the value of flexibility.

The key findings of flexible heat pumps in the Day-ahead market were:

- Flexible heat pumps require investment in additional control and heat storage. Heat storage in the building structure is more cost-efficient (EUR/MWh) compared to accumulator tanks.
- The expected ~400.000 residential heat pumps in Denmark 2020-2035 are divided into different building categories depending of house age (insulation level) and heat capacity. Further, division between houses with radiator and floor heating has been applied.
- The majority of the power demand from residential heat pumps is expected in existing houses due to higher heat demand per house, i.e. new houses built 2005-2035 are not included in the analysis
- Balmorel has optimized investment in flexible heat pumps in each building category:
    - The dominant effect on investment in flexible heat pump is the heat demand of the building, i.e. older buildings have a higher electricity consumption which give absolute higher electricity costs savings.
    - Heat capacity has a secondary effect on the investment in flexible heat pumps within each house age category.
- The peak demand of residential heat pumps is estimated at ~900 MW in 2035
- The correlation between wind profile and outdoor temperature profile (2011 and 2010, respectively) has large impact on the requirement for peak power capacity investment. It was concluded that the impact of flexible heat pump should be based on the impact in the worst case scenario (2010 temperature profile)
    - The reduction in peak power capacity is ~500-750 MW
- A reduction of heat storage size (+/- 0,75 C) has low impact on the potential profit of flexible heat pump in the day-ahead market

Further, the socioeconomic value per flexible heat pump is higher than private economic profit per flexible heat pump (via electricity cost savings). This indicates the societal value of flexibility is higher than the customer will experience through reduced electricity cost of flexible heat pump compared to non-flexible heat pump. The spot price variation does not send a signal to the consumers that reflect the full socioeconomic saving potential of flexible consumption. In Figure 38 the private and socioeconomic saving per flexible heat pump is shown for scenarios with different temperature profiles (the peak power capacity savings is added to socioeconomic value in Scenario 1):

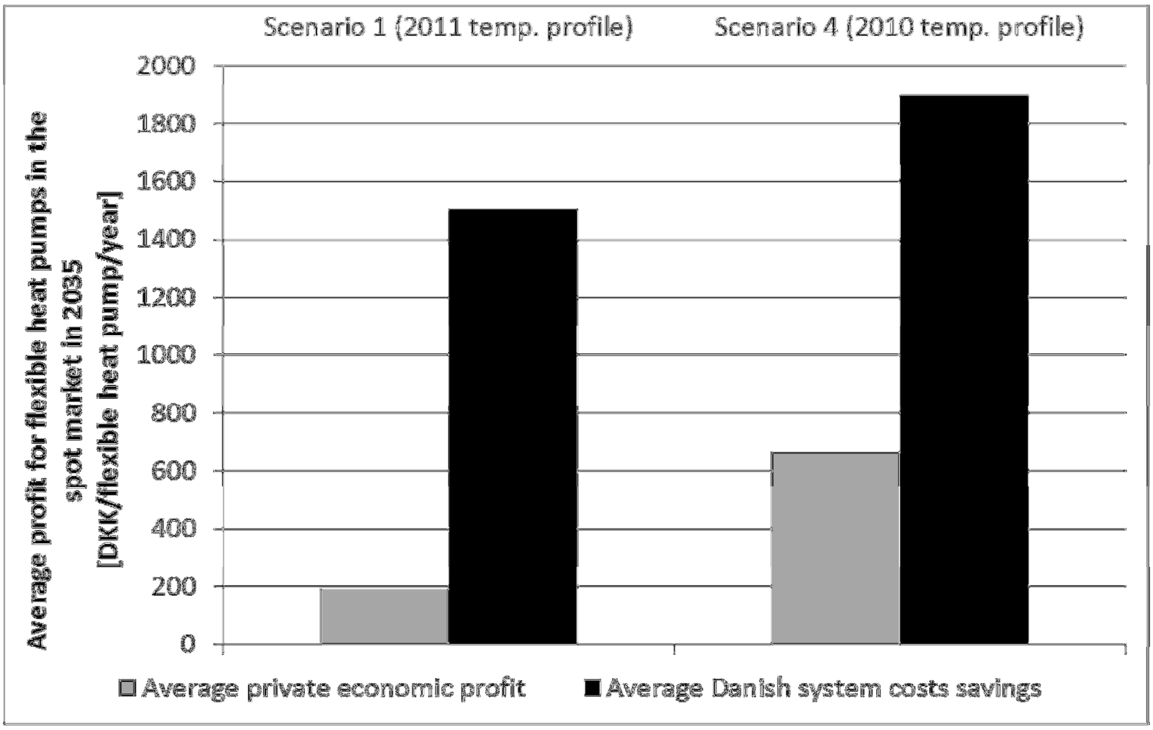


Figure 38. The private economic profit and Danish system costs savings per average flexible heat pump in 2035 according to Figure 36. The peak power capacity savings of 163 million DKK/year found in Scenario 4 is added to the Danish system costs savings in Scenario 1.

The Business case of flexible heat pump in the Day-ahead market is summarized in the table below:

Demander of flexibility	-End-user – optimisation of total electricity cost in Day-ahead market Society – reduced cost of power and heat production due to flexible consumption
Market requirement of participation	-Hourly read meter – mandatory in Denmark by 2020
Socioeconomic cost	-Investment in control of heat pump -Investment in controllable thermostats in the house
Socioeconomic value	-Improved marginal value of wind power, additional ~180 MW installed by 2035 according to Balmorel simulations -the net Danish system costs savings in 2035 ~400 million DKK/year (Scenario 1) according to Balmorel. -Flexible heat pump mainly influence the system cost via fuel cost savings, because demand is moved to off peak periods and periods with more wind production -Reduced investments in peak power capacity, ~150 million DKK/year by 2035
Private economic costs	-Investment in control of heat pump

	-Investment in controllable thermostats in the house Socioeconomic scenarios: The total investment per house is ~440 EUR=0,074*440=32EUR/year=~240 DKK/year.
Private economic profit potential	-Profit found in Socioeconomic scenarios: According to Balmorel results the total electricity cost saving including investment is ~200 DKK/year per average flexible heat pump with 2011 temperature profile. With 2010 temperature the similar number is ~700 DKK/year. Hence, the average profit excluding investments is: ~440 DKK/year per flexible heat pump (2011 temperature profile) - Profit found in Private economic scenarios: A slightly higher profit per average flexible heat pump is found in the scenarios with tax and higher interest rate. The payback period regarding Day-ahead revenue of flexible heat pumps vary between different house categories (flexibility provide higher savings in houses with higher power demand, older houses have a more attractive business case)
Risks	-Customer acceptance of variable indoor temperature -Standardisation of control of heat pumps towards third party operator (Aggregator/BRP) -Lack of residential heat pump installations -Electricity costs savings split between customer and several commercial actors
Drivers for Danish business opportunities	-Proof-of-concept of decreased heat/power cost with optimised residential heat pump

Table 9. Summary of the Business case of flexible heat pumps in the Day-ahead market.

3 FLEXIBLE HEAT PUMPS IMPACT ON DISTRIBUTION GRIDS

The chapter will examine the impact of variable grid tariffs (0,4 kV) on the private economic profit of flexible residential heat pumps.

The impact of flexible heat pumps on distribution grid investments is briefly illustrated in the end of the chapter. The impact of flexibility on both 0,4 kV and 10 kV grids will be examined more closely in a following iPower WP5.5 report.

3.1 METHODOLOGY AND KEY ASSUMPTIONS

3.1.1 COMPOSITION OF DANISH ELECTRICITY PRICE

The composition of the Danish electricity price is shown in Figure 39 [Danish Energy Association 2014b]. In 2014 the total electricity price/kWh for a one family household is approximately 183 øre/kWh = 1830 DKK/MWh excluding VAT.

- However, electric heating including residential heat pumps receives tax reduction (42,1 øre/kWh excl. VAT) for the electricity consumption if the electric heating is registered as the primary heating source.
- The spot market price is the average retail price for customers.
- The Local grid tariff and the subscription fee vary significantly between DSO areas. The average consumption weighted local grid tariff in Denmark was ~25 øre/kWh (2013) for households with yearly electricity consumption below 4000 kWh/year [Danish Energy Association 2014b].

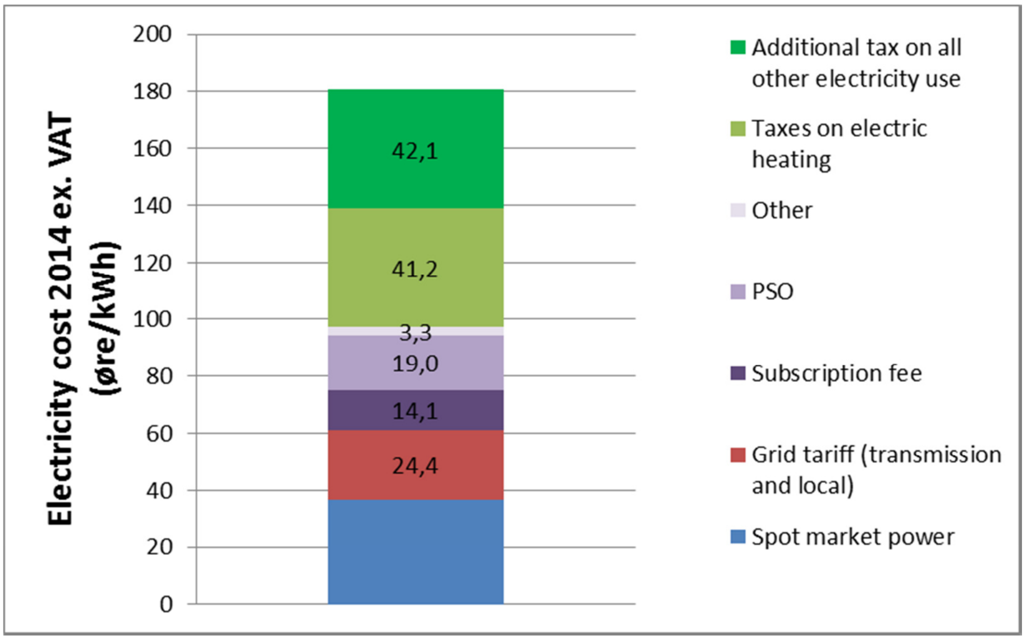


Figure 39. The composition of the electricity price In Denmark 2014. Taxes are reduced for residential heat pumps. Spot market power price and grid tariff are average Danish values. PSO (publice service obligation) mainly consists of support to renewables and small combined heat and power plants [Danish Energy Association 2014b].

Each of the ~50 DSO's in Denmark determines the grid tariff and subscription fee for different customer segments in their grid area. The total tariff consists of:

- Subscription fee
- Grid tariff (consumption weighted average 2013: 24,4 øre/kWh = 244 DKK/MWh)
    - Transmission system tariff (2013: 6,9 øre/kWh = 69 DKK/MWh)
    - Regional grid tariff (transport of electricity)
    - Local grid tariff (transport of electricity and energy service management)

The allowed DSO income is regulated (covers cost of depreciation, interest, OPEX etc.) which influence the allowed Local tariff and subscription fee. Thus, the tariff and fee is used to allocate the DSO cost on the customers depending on their consumption.

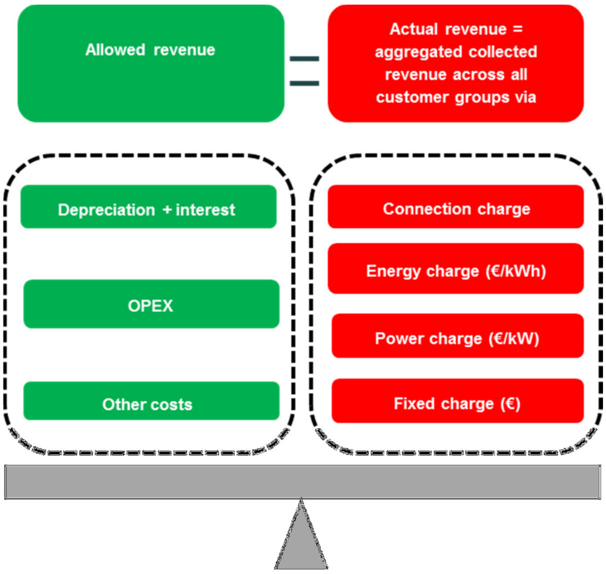


Figure 40. The tariffs affects the actual revenue of the DSO and it has to balance the allowed revenue [Eurelectric 2012].

3.1.2 GRID TARIFFS IMPACT ON FLEXIBLE DEMAND

The variable tariff is a mean to achieve a change in customer behavior (consumption profile) which will lead to savings in grid investments etc.

The variable tariff levels can be designed to:

- Maintain tariff revenue, i.e. increased payment from non-flexible consumers to finance savings from flexible customers
- Decrease tariff revenue, the desired change in demand pattern lead to similar/larger savings in e.g. grid investments

Further, the grid tariffs can be used to make demand response more profitable. The idea is to increase the tariff during peak demand hours and reduce the tariff during off-peak periods. This will create economic incentive to shift the consumption to off-peak periods which can have positive effect on grid investment and operation cost:

- Reduce requirement for new grid investments due to less peak demand
- Reduce losses in peak load periods

An overview of different tariffs types is given in Table 10. In Figure 41 the different type of tariffs are evaluated towards smart energy criterias, i.e. impact on peak load, energy savings, network cost reduction and regulatory trade-off:

Network tariff type	Options within this approach:
Volumetric tariffs (€/kWh)	1. Flat (fixed price for a fixed amount of energy) 2. Fixed (fixed price per unit of energy/kWh) 3. ToU (price per kWh depends on time of consumption) 4. Event driven including critical peak pricing (higher prices if peak occurs) 5. Dynamic including real time (dynamic prices e.g. depending on wholesale prices)
Capacity tariffs (€/kW)	1. Flat (fixed price for a predefined capacity) 2. Variable – e.g. two capacity levels (different capacity levels defined, one price for each level) 3. ToU (price per kW depends on time of consumption)
Two part tariffs (€/kW) + (€/kWh)	Combination of the above options (for example ToU, event driven, dynamic options possible within the energy component)
One of the above + System services contracts	1. Interruptible tariff options (e.g. lower network tariffs for giving the option to control a predefined amount of load) 2. Other

Table 10. Types of different Grid tariff [Eurelectric 2012].

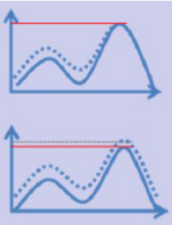
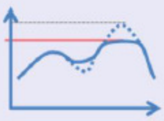
Network Tariff Type	Incentive	Possible Effects on Load	Impact on overall energy consumption reduction	Impact on network costs reduction (losses excluded)	Regulatory trade-off criteria
A. Fixed volumetric (€/kWh)	Reduce overall consumption, regardless of the time		✔ Medium to high – provides incentives for reducing overall consumption, but price signal is lower than time-of-use tariffs	✘ Low	✔ Intelligibility / Acceptability ✘ Economic efficiency ✘ Cost reflectiveness ✘ Revenue adequacy (for DSOs with no ex post adjustment)
B. Capacity based (€/kW)	Reduce peak usage (e.g. not switching multiple appliances at the same time) Shift consumption to off-peak hours		Medium* – incentive is for reducing customer's peak demand, which may also induce reduction of overall consumption *Medium to high for ToU capacity based tariffs		✔ Intelligibility / Acceptability ✔ Economic efficiency ✔ Cost reflectiveness ✔ Revenue adequacy (for DSOs with no ex post adjustment)
C. Time-of-use volumetric • High €/kWh (peak hours) • Low €/kWh (off-peak hours)	Reduce consumption during peak-hours Shift consumption to off-peak hours		✔ Medium to high – allows for higher prices during peak-hours which encourages higher overall consumption reduction	✔ High – peak demand (consumption during peak-hours) is the major driver for network costs	✔ Economic efficiency ✔ Cost reflectiveness ✘ Revenue adequacy (for DSOs with no ex post adjustment) ✘ Higher tariff complexity
D. Two-part tariff • Power component (€/kW) and • Energy component (€/kWh) (with flat or ToU energy charge)	Reduce peak usage/ Reduce consumption during peak-hours Shift consumption to off-peak hours				✔ Economic efficiency ✔ Cost reflectiveness ✔ Revenue adequacy (for DSOs with no ex post adjustment) ✘ Higher tariff complexity

Figure 41. Influence on different types of grid tariff on smart energy criterias. Capacity and Time-of-use tariffs show improvements compared to Fixed volumetric tariffs [Eurelectric 2012].

In Denmark in 2014 fixed volumetric tariffs is the dominant type of tariffs for residential households. The advantage is it is easy to understand and gives incentive for energy savings, but provides no incentive for demand response and peak load reductions.

The dimensioning of distribution grids is driven by the expected peak load. The DSO investment and operation cost is dominated by the required dimensioning of the grid. Thus, a cost-true tariff should depend on the customers load (kW), i.e. a capacity tariff. However, this capacity tariff provides no direct incentive for energy savings. Demand response can benefit by moving the demand to off-peak periods.

Time-of-use (ToU) volumetric tariffs can also provide incentive to reduce the peak demand. However, the impact of ToU tariffs on short peak loads (e.g. 5 minutes interval) is presumably small if the tariff is hourly basis.

A dynamic tariff does not have fixed levels (EUR/MWh or EUR/MW) and/or time periods. The dynamic tariff could be:

- an online price/tariff signal from the DSO
- a published Day ahead ToU tariff based on:
    - expected spot price or wind production
    - expected peak load

To achieve the required demand response a combination of variable tariffs and System service contracts (e.g. DSO products regarding voltage control and bottleneck management) could be required.

3.1.3 ONE-BILL MODEL IMPACT THE INFLUENCE OF VARIABLE TARIFFS

In 2015 Denmark will change from two-bill to one-bill model (Engrosmodel) which means the supplier (retail contract with end-customer) will determine the end-customer's electricity price including taxes and tariffs. The supplier can choose to follow tariffs from TSO and DSO and national taxes or decrease/increase the incentives for demand response by tailor-made power price variations for different customers.

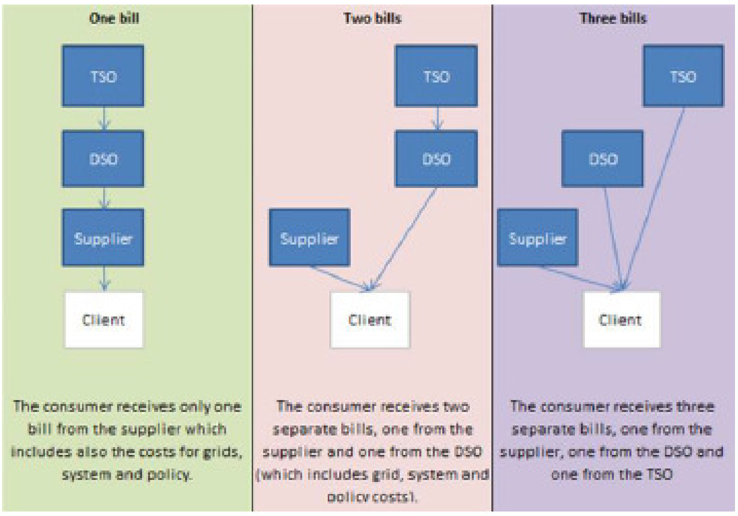


Figure 42. Market models for settlement of customers with either one, two or three different bills [Eurelectric 2012]. Denmark is changing from two bills to one bill ('Engros-modellen').

3.2 RESULTS

3.2.1 TIME-OF-USE TARIFFS APPLIED IN BALMOREL

The impact of variable Local grid tariff on the consumption pattern and profit of flexible heat pumps is investigated in Balmorel. Scenario 1 in Table 4 is re-calculated with two different local Time-of-Use tariffs applied for residential heat pumps. The tariff profiles and impact on demand profiles is shown in Figure 43:

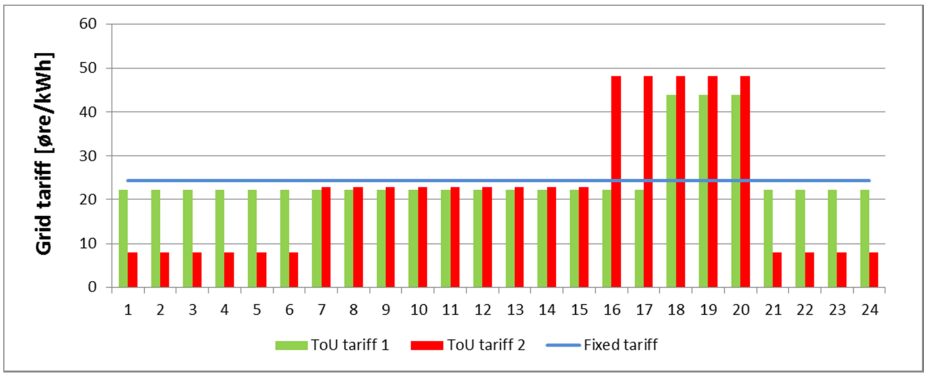


Figure 43. Input to Balmorel: Three different tariff profiles (fixed, ToU tariff 1 and ToU tariff 2)

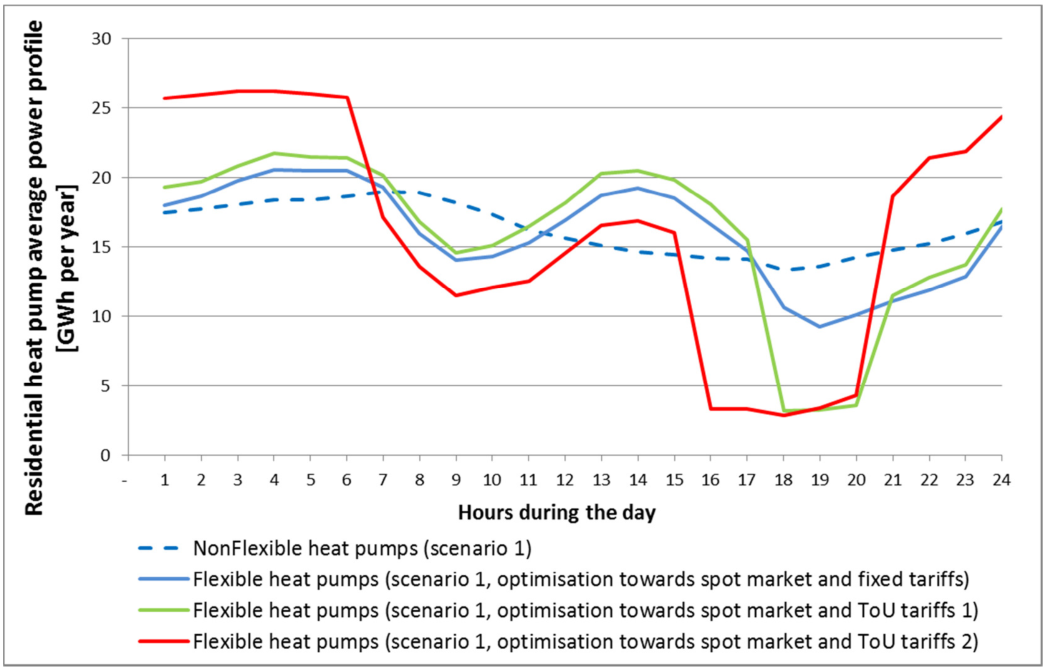


Figure 44. Output of Balmorel: The average consumption profile of residential heat pumps with the different tariffs.

The demand profile of flexible heat pumps in Balmorel is clearly influenced by the variable tariff, because the consumption in Balmorel will move as long as a cost saving is obtained no matter how small it is. In reality, the actual change in demand profile depends on a number of factors, not only the potential economic profit.

The applied tariffs make it cost optimal for residential heat pumps to shift consumption away from peak load periods. Further, the ToU tariff 2 increases the electricity consumption during the night.

A separate power meter could make it possible to settle power consumption of residential heat pump (and possible also EV) according to a special tariff (and tax) compared to the remaining household power consumption with a 'normal' tariff. The cost of an additional heat pump power meter (one phase, wireless connected to the main power meter) is ~500 DKK [Eriksen 2014]. Alternatively, the special tariff must apply to all household consumption; further, customers with heat pumps (or EV) should actively choose the special tariff.

The advantages of targeted ToU tariff (and taxes) to residential heat pumps are:

- providing stronger economic incentive for flexible consumption than (revenue neutral) tariff for all type of 'conventional consumption', e.g. similar to ToU tariff 1
- promoting controllability of residential heat pumps, which is needed for market based services
- promoting development and operation of heat storage, which is needed for market based services
- Does not impact existing revenue from 'conventional consumption' of DSO.
- DSO has approximately no marginal costs of the initial added residential heat pumps (because existing grid capacity is sufficient), which mean reduced average tariff for residential heat pumps does not reduce the existing total tariff revenue.
- easy to estimate profit of flexibility compared to uncertainty of emerging market products

Individual meters would also make it possible to sell power separate to the residential heat pump, and might be required to validate balancing and capacity reserve services to the grid.

3.2.2 PRIVATE ECONOMIC PROFIT OF TIME-OF-USE TARIFFS

The ToU tariffs impact the investment in flexible heat pumps as seen in Figure 45

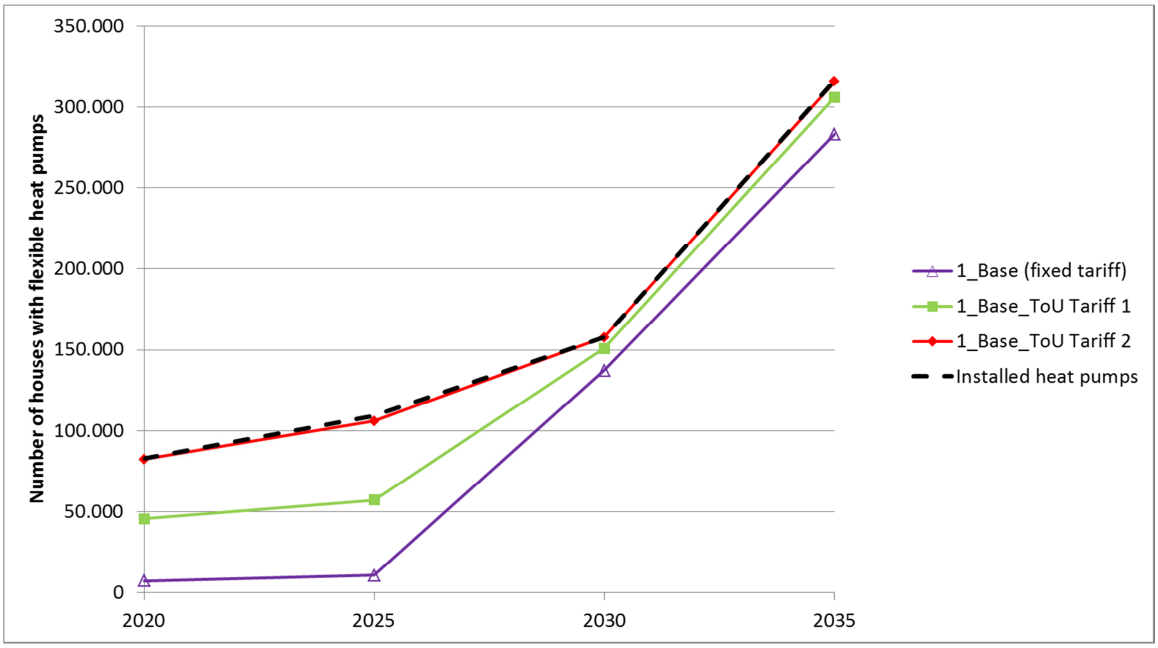


Figure 45. Investment in flexible heat pumps is increased with ToU tariffs compared to fixed tariffs

The investment in flexible heat pumps in the different building categories (cf. Table 3) with ToU Tariff 1 is shown in Figure 46. The investment in flexible heat pump is highest in the oldest building category (year 1960-1850) with higher heat and electricity consumption. The heat capacity has a minor impact of flexibility investment in the building category year 1961-1978:

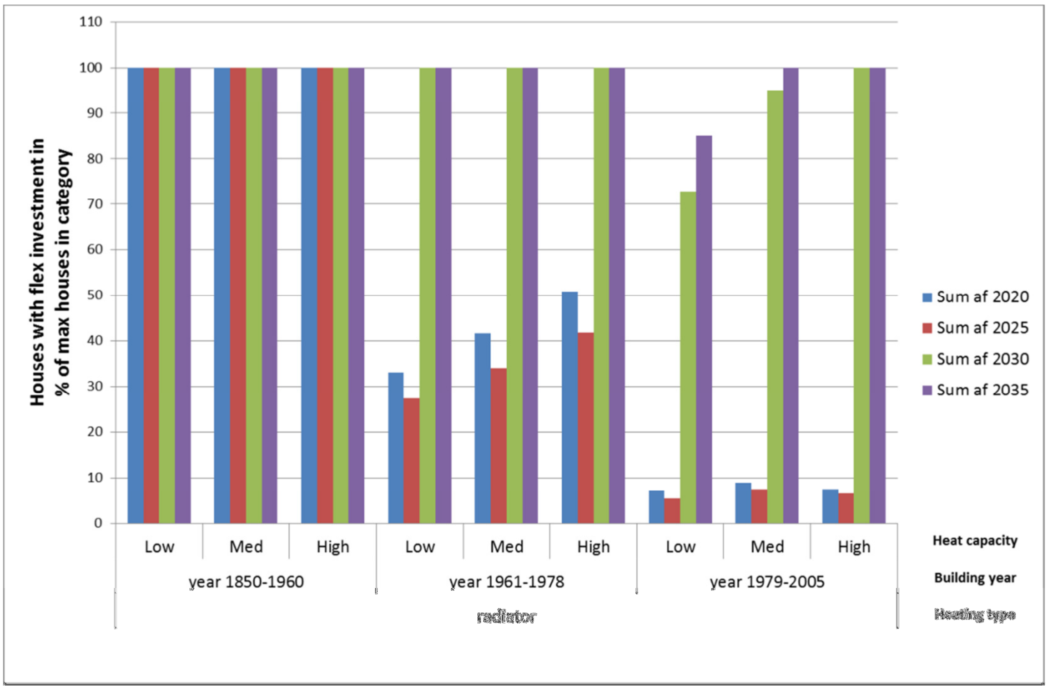


Figure 46. Investment of flexible heat pumps in different building categories 2020-2035 with ToU tariff 1.

The total tariff revenue, average tariff and yearly profit are calculated in Table 11 for fixed and ToU tariffs in 2035.

	Total tariff costs of residential heat pump in 2035 (mio DKK/year)	Average tariff (DKK/MWh)	Yearly tariff profit* (DKK / year / flexible heat pump)
-Non-flexible heat pumps (with fixed tariff)	95	244	
-Non-flexible heat pumps (with ToU tariff 1)	95	244	-1
-Non-flexible heat pumps (with ToU tariff 2)	82	209	179
-Flexible heat pumps, optimization towards spot market and ToU tariff 1	**88**	**227**	**87**
-Flexible heat pumps, optimization towards spot market and ToU tariff 2	58	148	490

Table 11. The tariff revenue, average tariff and yearly profit of flexible heat pumps in 2035 are shown in the table. The average tariff is reduced to 148 DKK/MWh with ToU tariff 2 compared to 244 DKK/MWh with fixed tariffs.

*) The profit is based on yearly heat pump power consumption of 5,1 MWh and compared to Non-flexible heat pump with fixed tariff.

The profit of flexible heat pumps is different with ToU tariff 1 compared to ToU tariff 2. The flexible heat pumps are optimized towards both spot market and ToU tariff 2 experience an average tariff of 14,8 øre/kWh compared to fixed tariff of 24,4 øre/kWh. This corresponds to a yearly profit of 490 DKK/year/flexible heat pumps due to ToU tariff. The similar profit with ToU tariff 1 is 87 DKK/MWh.

The demand profile and yearly heat demand of non-flexible and flexible heat pumps is almost similar from 2020 to 2035, which means the private economic profit of flexible heat pumps due to ToU tariff will also be constant.

In Figure 47 the profit of flexible compared to non-flexible heat pumps is shown in the base scenario with fixed tariff and Time-of-use tariff, respectively. The profit from spot market optimization is reduced due to simultaneous tariff optimization. Due to ToU tariff optimization the profit in the spot market is reduced with ~11 EUR/flexible heat pump/year in 2035. However, the total profit per flexible heat pump increases significantly in the base scenario with ToU tariff.

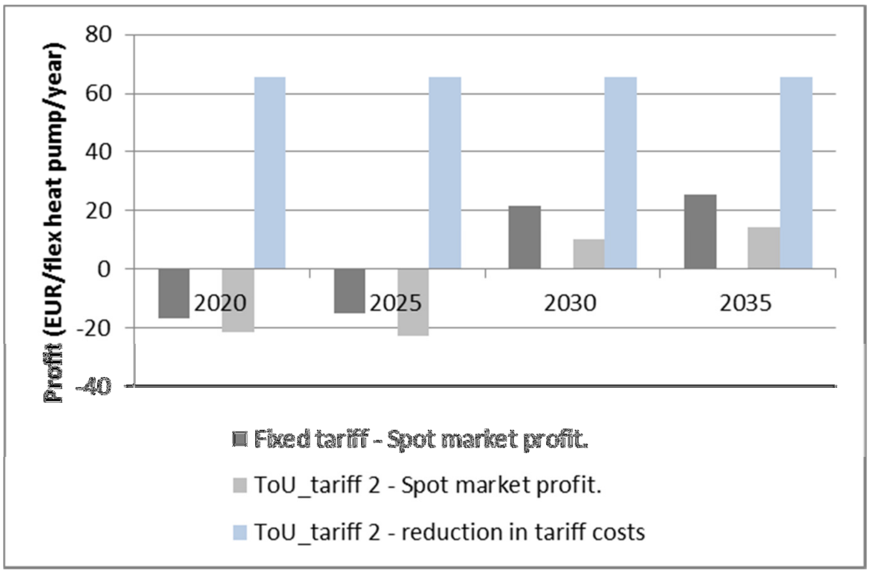


Figure 47. The profit from spot market (dark and light gray) and tariff optimization (blue) in the base scenario with fixed and ToU tariff, respectively. The total profit in the ToU tariff scenario is higher than fixed tariff scenario despite the reduction in spot market profit. The negative private economic profit of spot optimization in 2020 and 2025 is because Balmorel invest in flexibility from a system perspective.

In conclusion, the net private economic profit due to ToU tariff 2 is ~55 EUR/year = ~400 DKK/year per flexible heat pump in 2035:

- Net profit due to ToU tariff 2 = Increased revenue of ToU tariff 2 – decreased spot market profit = 490/7,45 EUR/flex heat pump/year – 11 EUR/flex heat pump/year = ~55 EUR/flex heat pump/year

Variable taxes

By allowing taxes to be variable with the same profile as ToU tariff 2, the private economic profit will increase proportional to ToU tariff 2 profit compared to fixed tariff. This is based on the assumption that the

ToU tax does not significantly change the demand profile of flexible heat pump compared to optimization towards both spot market and ToU tariff 2.

According to Figure 39 the fixed tax on electricity to heat pump is 412 DKK/MWh. Hence, the average ToU tax is the 412*148/244=250 DKK/MWh by applying the same profile as ToU tariff 2.

Private economic business case with ToU tariff and tax

The electricity cost in 2035 of an average non-flexible heat pump (with ~5,1 MWh/year according to Table 6) is calculated in four scenarios. The tariff and taxes are according to 2014 level (Figure 39):

- Non-flexible heat pump with fixed tariff and taxes.
    - Commercial power = ~71 EUR/MWh according to Figure 27
    - Fixed tariff = 244 DKK/MWh, fixed taxes = 412 DKK/MWh
- Flexible heat pump with fixed tariff and taxes
    - Commercial power = ~61 EUR/MWh Figure 27.
    - Fixed tariff = 244 DKK/MWh, fixed taxes = 412 DKK/MWh
- Flex heat pump with ToU tariff 2 and fixed tariffs
    - Commercial power ~61 EUR/MWh + ~11 EUR/year according to Figure 27 and Figure 47.
    - Average Flex tariff = 148 DKK/MWh, fixed taxes = 412 DKK/MWh
- Flex heat pump with ToU tariff 2 and variable taxes
    - Commercial power ~61 EUR/MWh + ~11 EUR/year according to Figure 27 and Figure 47.
    - Average Flex tariff = 148 DKK/MWh, variable taxes = 412*148/244=250 DKK/MWh

The electricity bill of an average non-flexible heat pump with fixed tariff and flexible heat pump in the three scenarios above is shown in Figure 48. The investment costs in flexibility are not included in the figure.

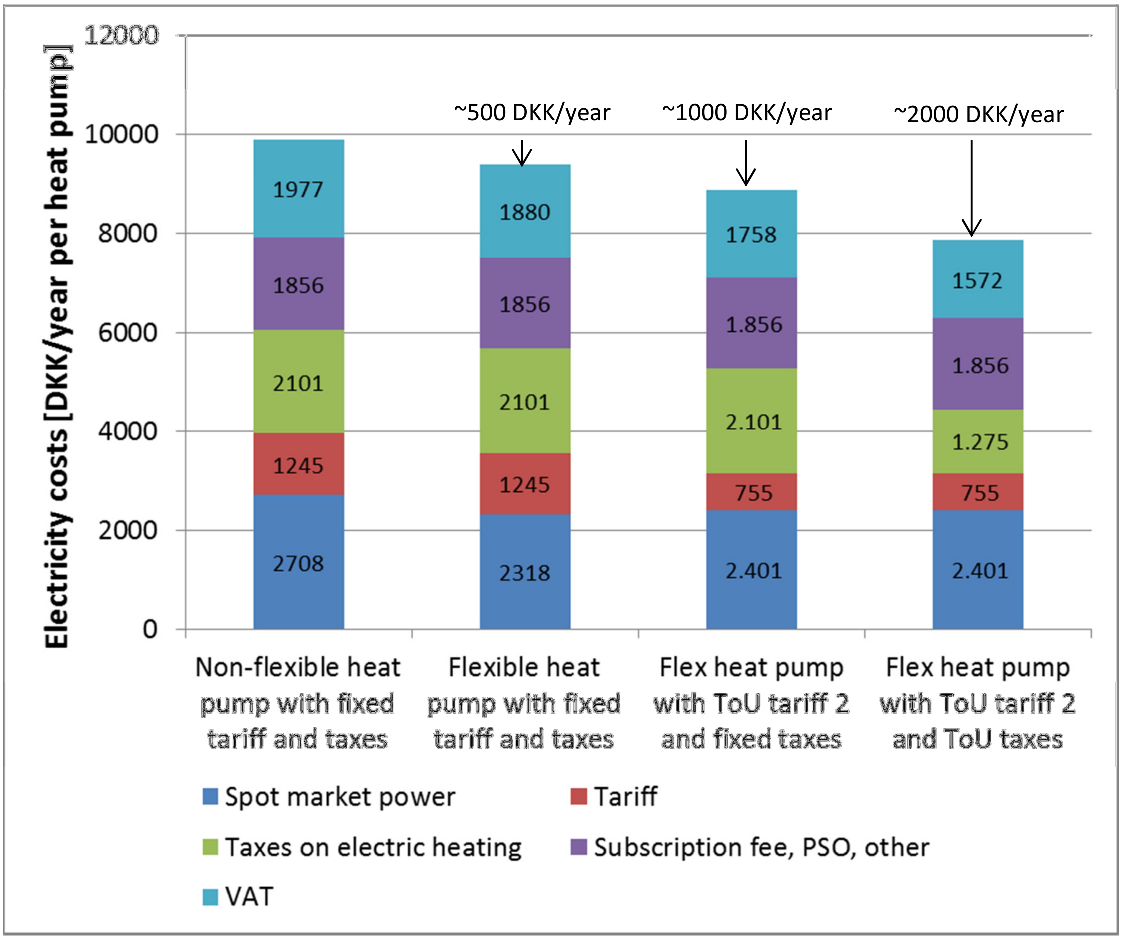


Figure 48. The electricity cost of flexible residential heat pumps (2035 spot market power savings according to Balmorel) with different tariffs and taxes compared to non-flexible heat pumps with fixed tariffs

3.2.3 SOCIOECONOMIC IMPACT OF VARIABLE TARIFFS AND TAX

Socioeconomic cost of ToU tax

Supposing all flexible heat pumps would optimize according to variable taxes (similar profile as ToU tariff 2), the reduction in tax and VAT revenue would be ~1000 DKK/heat pump * ~300.000 heat pumps = ~300 million DKK/year in 2035 according to Figure 48.

However, the reduction in total tariff revenue is much smaller if only the initial flexible heat pumps receive the tax reduction.

Socioeconomic cost of ToU tariff 2

1). The tariff revenue from residential heat pumps is smaller with the applied ToU tariff 2 compared to Non-flexible heat pumps with fixed tariff according to Table 11. The total reduction in revenue is ~37 mio DKK/year by 2035.

2). According to Figure 49 the system costs in Balmorel are increased with ToU tariffs 2 compared to only spot market optimization by ~23 mio DKK/year by 2035. However, the cost savings in the distribution grid due to variable tariffs are not included.

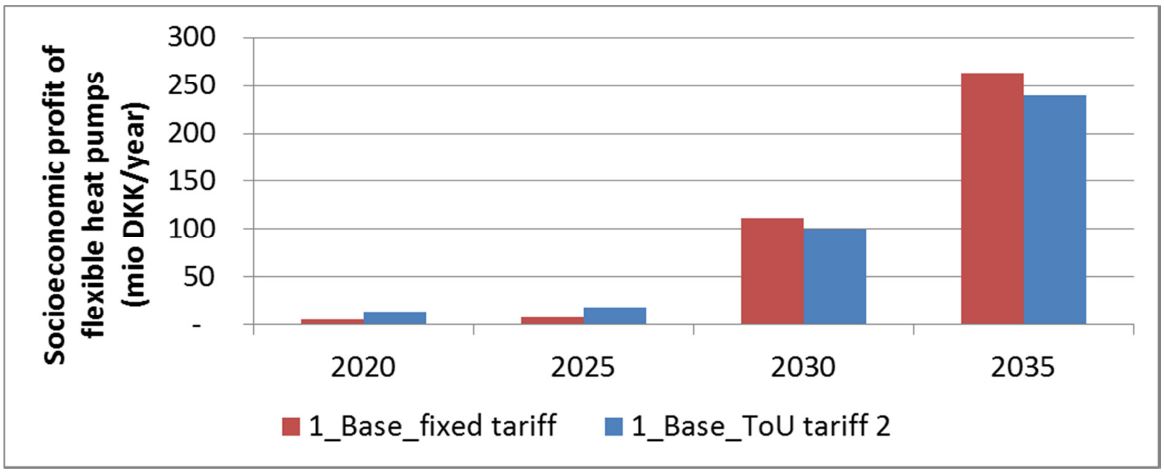


Figure 49. The system costs (excl. tariff revenue and distribution grid savings) of flexible heat pump with fixed and ToU tariffs, respectively.

In conclusion, the total socioeconomic cost of ToU tariff 2 is ~60 mio DKK/year by 2035

Socioeconomic revenue of variable tariffs

The socioeconomic revenue of variable tariffs will depend on the change in customer behavior (consumption profile), which then lead to e.g. reduced cost in grid investment. The methodology of assessing the value of reduced grid investment due to flexible heat pumps is described in the following chapter.

3.2.4 VALUE OF REDUCED GRID INVESTMENTS DUE TO FLEXIBLE HEAT PUMPS

The investments in grid capacity are affected by implementation of smart grid strategy as illustrated in Figure 50. The grid reinforcements are reduced due to better utilization of existing capacity by measurement (step 1) and by flexible consumption (step 2). Flexible heat pump's impact on reduced grid investments is part of step 2.

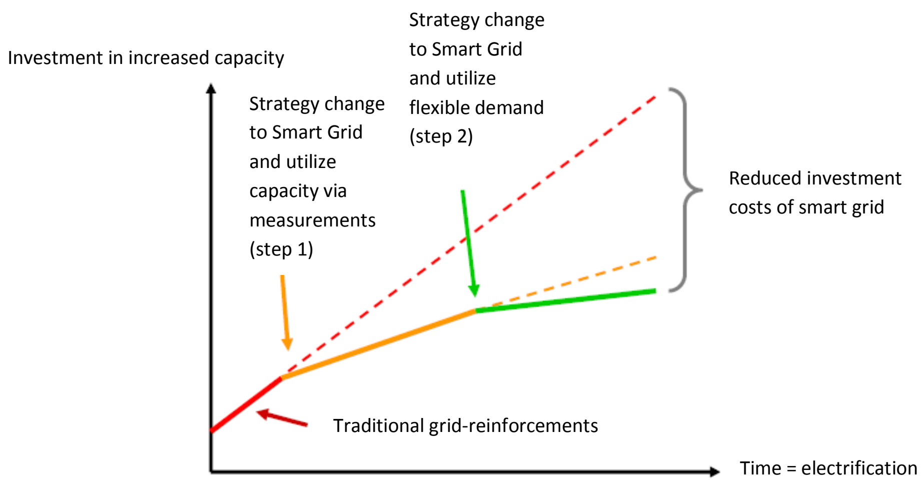


Figure 50. The investments in grid reinforcements are reduced due to better utilization of existing capacity by measurement (step 1) and by flexible consumption (step 2) [Energinet.dk et al 2012].

The capacity in distribution grids is restricted due to:

- Voltage quality (the voltage at the customer in the end of the radial)
- Bottlenecks:
  - Current, i.e. temperature in cables
  - Transformer max. load

When the capacity limit is reached investment in new grid is necessary. The change in demand profile of flexible heat pumps towards off-peak periods can influence how large share of heat pumps the existing grid capacity can accommodate. The change in demand profile can be caused by applying variable network tariffs and/or DSO services.

As illustrated in Figure 51 the capacity limit is increased with flexible heat pumps compared to non-flexible heat pumps:

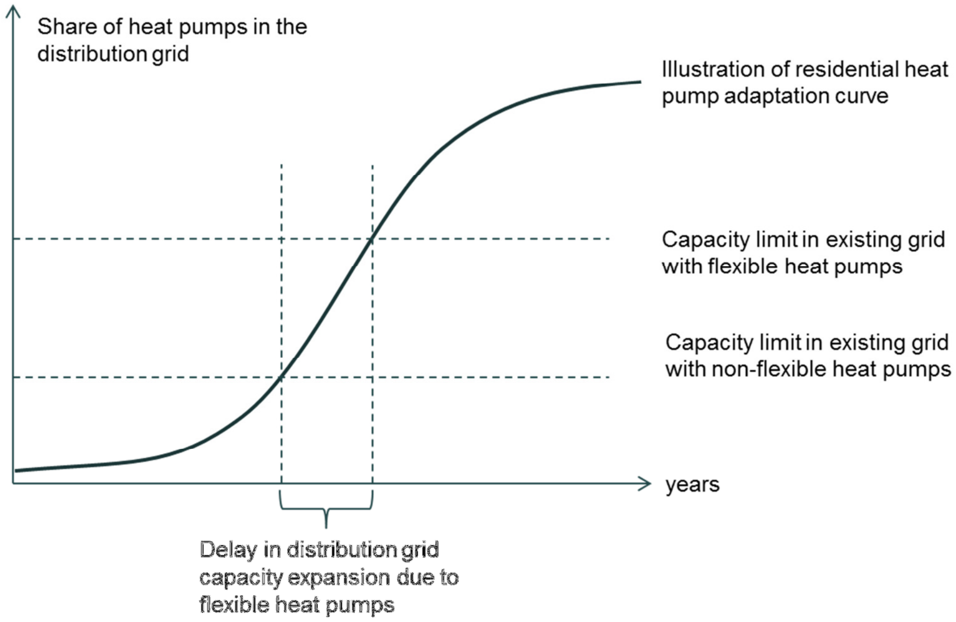


Figure 51. Illustration of the capacity limit in the existing distribution grid with flexible and non-flexible heat pumps, respectively. The delay in grid capacity expansion corresponds to an economic saving of the DSO.

The delay in grid capacity expansion corresponds to economic savings of the DSO due to:

- Net present value of investment is smaller if the investment is postponed (time-value-of-money)
- Postponing investment allow additional technology development which can lead to cheaper solutions
- Using existing assets longer. From an accounting point-of-view capacity expansion can lead to depreciation on remaining value of the existing grid

The potential DSO value of flexible heat pumps depends on the possible postponing of reaching the capacity limit:

- The local distribution grid typology will determine the capacity limit with non-flexible and flexible heat pumps, respectively. The degree of heat pump flexibility is important.
- The shape of the adaptation curve of residential heat pumps influence the time between the capacity limit with non-flexible and flexible heat pumps.

The impact of residential heat pump's 'Kickback effect' (see iPower WP 3.6) should also be taken into account when calculating the capacity limit in the existing grid. The kickback effect is caused by higher simultaneous power consumption in the period after many heat pumps have been shut off, either due to e.g. simultaneously price optimization or due to power failure.

Further work in iPower WP5.5 will focus on the value of DSO grid investments, where case studies are used to estimate the mentioned capacity limits of existing grids with different mix of residential heat pumps, EV and PV.

3.3 SUBCONCLUSION

In Denmark most customers at 0,4 kV grid experience fixed distribution grid tariff. This chapter has described possible tariff models and their advantages to impact consumption profile. In the near future the Local distribution grid will be changed to a Time-of-use tariff (ToU).

The impact of two different time-of-use tariffs on flexible heat pump consumption profile was investigated in Balmorel. The results show that optimization towards the variable tariffs lead to higher investment in flexible heat pumps compared to optimization towards spot market only.

The tariff cost reduction compared to fixed tariff of flexible heat pump with variable tariffs has been calculated. The results indicate that ToU tariff 1 leads to a smaller change in tariff of flexible heat pumps compared to ToU tariff 2. From a private economic business case perspective only ToU tariff 2 leads to a significant profit of flexible heat pumps. However, the ToU tariff 2 also gives rise to a reduction in tariff revenue of the DSO.

Further analyses are needed of the change in distribution grid reinvestments cost due to flexible heat pumps with different consumption profiles to assess the full socioeconomic value of variable tariffs.

The Business case of flexible heat pump impact on the distribution grid is summarized in the table below:

Demander of flexibility	DSO – reduce investment in distribution grid
Market requirement of participation	-Hourly read meter – mandatory in Denmark by 2020
Socioeconomic cost	-Reduced tariff costs with flexible heat pumps with ToU tariff 2 compared to non-flexible heat pumps with fixed tariff: ~40 mio DKK/year in 2035 (Table 11) -Reduced profit of flexible heat pump in spot market due to simultaneously optimization towards ToU tariffs 2: ~20 mio DKK/year in 2035 (Figure 49) -complicated tariffs lead to higher administrative costs than traditional fixed tariffs -Variable tariffs and/or price optimization could lead to kickback effect (peak load due to high simultaneous power consumption of residential heat pump)
Socioeconomic value	-Reduced grid cost due to delay of grid investments (not monetized in this analysis)

Private economic costs	-Reduced spot market profit of flexible heat pump due to simultaneously optimization towards ToU tariffs 2: ~11 EUR/flexible heat pump/year
Private economic profit potential	-Increased revenue of flexible heat pump optimised towards spot market and ToU tariff 2 compared to non-flexible heat pump with fixed tariff: ~490 DKK/year = ~66 EUR/year -The net profit of flexible heat pumps with ToU tariff 2 compared to non-flexible heat pumps with fixed tariff is ~55 EUR/year = ~400 DKK/year
Risks	-Variable tariffs with low profit potential for flexible heat pumps -Low impact of flexible consumption on distribution grid reinforcement costs
Drivers for Danish business opportunities	-Implementation of variable tariffs

Table 12. Business case of flexible heat pumps regarding variable tariffs.

4 FLEXIBLE HEAT PUMPS IN BALANCING AND ANCILLARY SERVICE MARKETS

The chapter focuses on existing balancing and ancillary service markets in Denmark and neighboring countries. The following chapter defines the balancing and ancillary service markets as:

- Balancing markets: Intraday market, Regulating power market
- Ancillary service markets: Reservation of primary, secondary and tertiary/manuel reserves

The demand for balancing is expected to increase in the future due to increased wind and solar penetration. Flexible heat pumps have the potential to participate in balancing and ancillary service markets. Due to technical requirements in the markets it is likely that residential heat pumps have to be aggregated to participate in ancillary service market.

The associated value for flexible heat pumps of the balancing is discussed in the following section

4.1 METHODOLOGY AND KEY ASSUMPTIONS

4.1.1 INTRODUCTION TO BALANCING AND ANCILLARY SERVICE MARKETS

The majority of the energy balancing between consumption and production is secured in the Day ahead market (Elspot). Due to difference between day ahead traded volumes and actual production and consumption additional balancing is required. The TSO is responsible for system balancing which require a number of ancillary services. In Denmark the TSO, Energinet.dk, is currently sourcing the majority of the ancillary service products via short term (days to weeks) markets and via long term (years) bilateral agreements. Further, compulsory systems services are provided by central power plants.

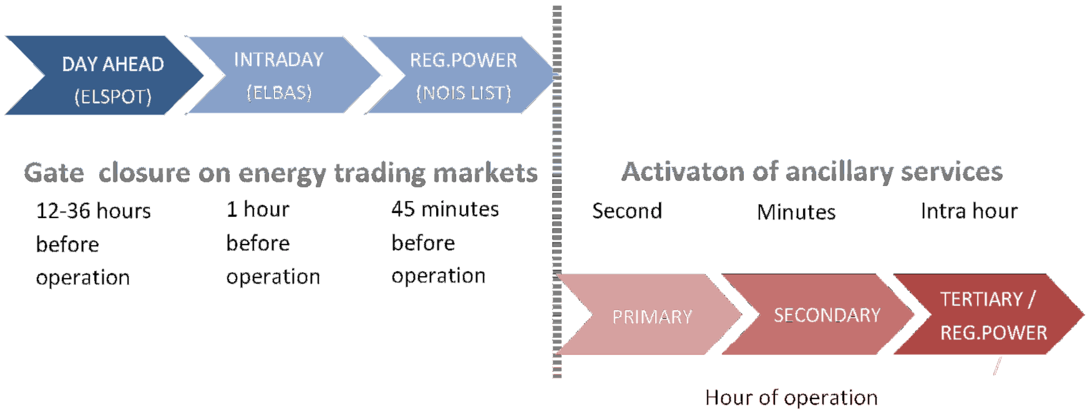


Figure 52. Illustration of energy balancing via different market places. The majority of the power production and consumption is traded (and balanced) Day ahead in the Elspot market. Energy can also be traded Intraday in the Elbas market up to one hour before the hour of operation. Subsequently, the ancillary services (primary, secondary or tertiary/regulating power) are activated to avoid unbalances in the hour of operation. (figure based on [DONG Energy 2013]).

In Denmark the intraday market (Elbas) has gate closure one hour before the operating hour. The market is used by commercial actors to voluntarily trade unbalances (up and down regulation) due to differences between day ahead traded volumes and updated forecasts of e.g. wind, solar and demand. Commercial actors in Denmark also trade Danish production and consumption units in other European intraday markets and with other national TSO's to generate additional profit. During recent years the intraday trading has increased and is expected to increase even further in the future due to more wind and solar production [Holmberg 2014].

In the operating hour the TSO uses the ancillary services to balance the grid. An overview of the Danish ancillary services terminology is shown in Table 13 [Energinet.dk 2013c]. Denmark is divided in two different synchronous areas, and different products exist in Denmark West (part of continental Europe) and in Denmark East (part of Scandinavia).

Function	Terminology		
	ENTSO-E	**Vestdanmark**	**Østdanmark**
Primary reserve	Frequency Containment Reserves (FCR)	Primær reserve	Frekvensstyret driftsfor-styrrelsesreserve (FDR)
			Frekvensstyret normal-driftsreserve (FNR)
Secondary reserve	Frequency Restoration Reserves (aFRR)	Load Frequency Control (LFC)	-
Tertiary reserve	Frequency Restoration Reserves (mFRR)	Manuel reserve	Manuel reserve
	Replacement Reserves (RR)	-	-

Table 13. An overview of the different ancillary service products in Denmark West and East [Energinet.dk 2013c].

The main TSO controlled balancing in terms of energy volume is secured via the Nordic Regulating power market (also called Balancing market) that is dimensioned to handle outages of the largest unit or transmission line in each system area. The required activations and value in the Regulating power marked is depending on the intraday market, because balancing is performed via both options.

The supply to the regulating power market is a combination of day ahead reservations via the Tertiary/Manuel reserve market and new bids provided before the Regulating power market gate closure 45 minutes before the operating hour. All bids (price/MWh) are collected in the NOIS List, and the national TSO control center can activate the required volume between all Nordic bids [Energinet.dk 2013b] with a delivery time of max 15 min. All activated bids are paid the same marginal price per MWh (transmission restrictions can lead to different prices between the system areas).

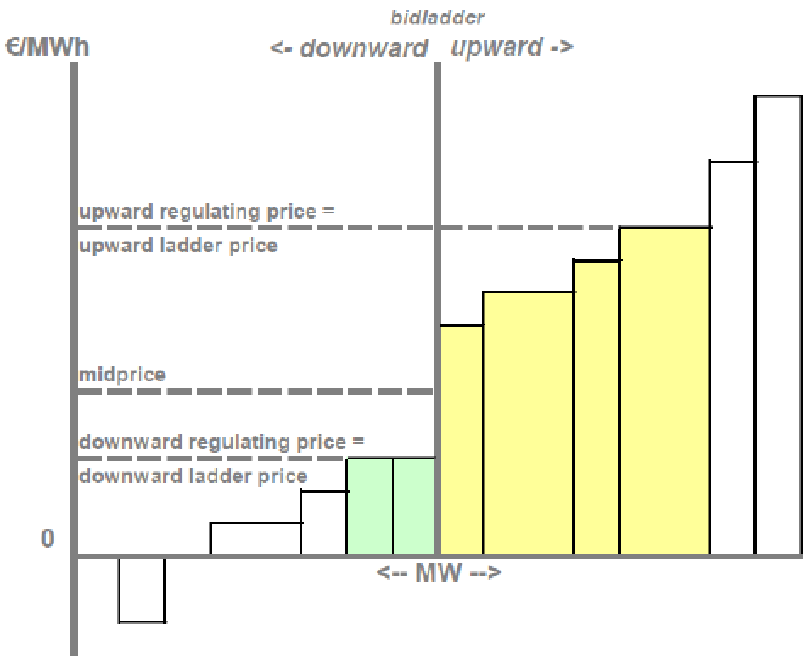


Figure 53. Providers of down regulating (reduce production or increase consumption) pay the marginal energy price per MWh to the TSO, providers of up regulating (increase production or decrease consumption) receives the marginal energy price per MWh [E-harbours electric 2012].

After the operation hour production and consumption unbalances are settled according to the Regulating power price and Spot price (consumption is only settled according to Regulating power price). This market design implicates that the actual value of unbalances is unknown in the operation hour, which does not allow demand to react to the cost of unbalances. The importance of Regulating power prices access in the operating hour is highlighted [VindEnergi Danmark 2012] as a main driver for participation of flexible consumption in the Regulating power market.

The short term power balance in the system is maintained via Primary and Secondary reserves. These products are paid only via reservation payments. The primary reserve is activated by frequency deviations according to a predefined response characteristic. The secondary reserve is an online regulation signal controlled by the TSO.

The activation principle of the different ancillary services in Denmark is illustrated in Figure 54:

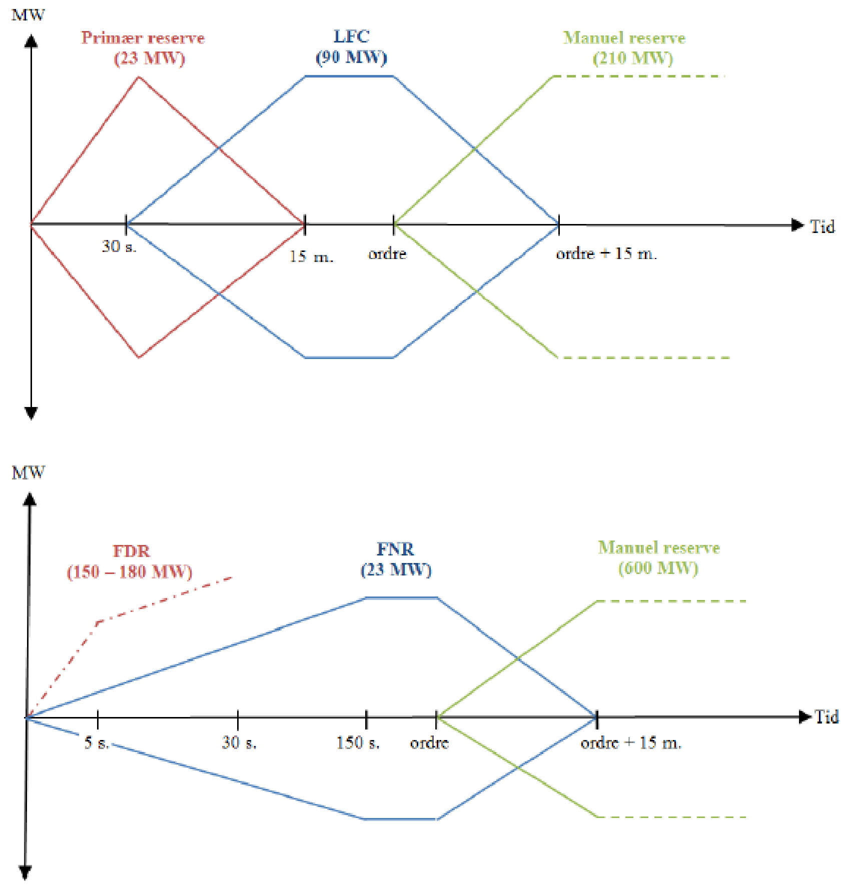


Figure 54. Ancillary services in Denmark West (top) and in Denmark East (below), cf. terminology in Table 13 [Energitilsynet 2013].

The TSO also request system support services ("systembærende egenskaber") [Energinet.dk 2013c] that today are provided mainly by online central power plants:

- Short-circuit effect
- Continuous voltage regulation (reactive power)
- Voltage support during errors
- Inertia
- Critical frequency reserve from central power station (deviations > + 150 mHz and <-150 mHz)

Finally, black start (no voltage in the grid) capability is also required by the TSO

4.1.2 ANCILLARY SERVICES CAPABILITY OF RESIDENTIAL HEAT PUMPS

Aggregation of heat pumps can be combined with other DER's to provide ancillary services as illustrated in Figure 55:

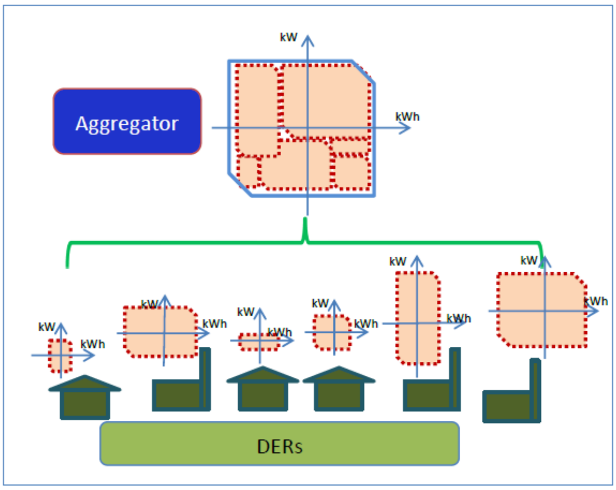


Figure 55. Illustration that show DER flexibility can be aggregated to products for TSO's and DSO's [iPower WP3.8 2013].

The ancillary service capabilities of residential heat pumps can be assessed by comparing the technical capability of the heat pumps with the technical requirement to provide the ancillary service product.

The technical capability of heat pump is determined by e.g.

- Size of unit
- Energy restrictions (heat storage size)
- Predictability / security of supply
- Regulation capability
    - Ramp rate
    - Allowed number of start and stop
    - Minimum start and stop time

Energy restrictions (heat storage size)

The heat storage size determines how long time residential heat pumps can be turn on or off. As explained in e.g. Chapter 2.2.4 heat pumps have a significant heat storage potential. The consumption can be delayed or moved forward within the customer heat comfort level (indoor air temperature).

Regulation capability

Heat pumps can be regulated according to power prices and to provide ancillary services. One suggested strategy is that the heat pump's power consumption can be regulated by controlling the temperature set-point. With higher temperature set-point more heat pumps will turn on and vice versa.

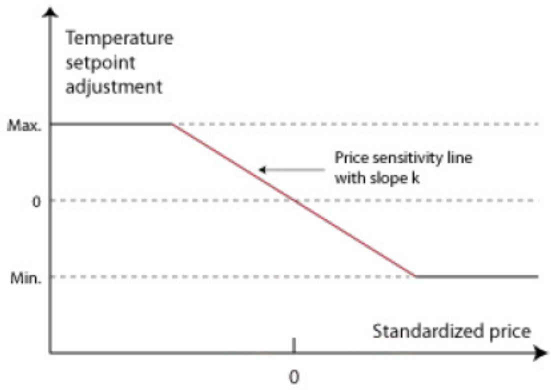


Figure 56. Control strategy of temperature setpoint adjusted according to standardized price [Madsen 2014].

Frequency control

The aggregated consumption from a large population of start-stop operated heat pumps can form a linear frequency response if the temperature set point is regulated according to the grid frequency [Rasmussen 2014]. The consumption (temperature set point) will be decreased during under-frequency and increased during over-frequency.

Heat pumps with frequency converters can individually provide a linear response according to the grid frequency.

Overall assessment of ancillary service capabilities

In general residential heat pumps will individually not meet the technical requirements to provide the ancillary service product. However, an aggregated portfolio of heat pumps is expected to have the technical capability to participate in ancillary service markets in the future given they are designed for demand response participation.

4.1.3 MARKET REQUIREMENT TODAY AND POSSIBLE FUTURE DEVELOPMENT

The ancillary service market regulation was originally made for ancillary services from large single units and not for provision of ancillary services from many small units. The market design has to be changed for aggregated residential heat pump to participate, which is gradually taken place in Denmark [Twenties 2013a].

The possibility of demand response including flexible heat pumps to participate in ancillary service markets depends on the technical requirements and the market prices. The future value of Danish ancillary service markets is difficult to estimate due to a number of uncertainties that is caused by changes in:

- market volume (MW or MWh) – influenced by integration of markets
  - Day ahead wind prognosis uncertainty
- technical requirements to participate in the market [Twenties 2013a], e.g.
  - Pay-as-bid vs. marginal price
  - minimum bid size
  - time between gate closure and delivery (predictability)
  - bid duration (security of supply)
  - activation time (ramp rate)
  - symmetric bids vs. separate up and down regulation bids
  - bundling of consumption and production
  - settlement according to predetermined plan or actual consumption/production [Biegel et al 2014]
  - data-communication requirement (meters, protocols, etc.)
- future suppliers in the markets (both national and cross-border supply)
  - transmission capacity (e.g. access of hydro generation regulation)
  - power plants
  - wind turbines
  - Demand response (including EV, large electric boilers, large heat pumps)
- compulsory requirements of services vs. market supply (mainly for system support services)

Integration of ancillary service markets between the synchronous areas in Denmark and neighboring countries has started and is expected to continue in the future [Energitilsynet 2013]. Market integration between Denmark East and Sweden regarding primary reserve ('FNR' and 'FDR') has taken place in 2012. In the future market integration between Denmark West and Germany regarding primary reserve is expected.

Further, secondary reserve in Denmark West will be provided via Skagerak 4 (100 MW reservation on the 700 MW extension of the transmission capacity to Norway) from 2015 and next five years. Market integration regarding secondary reserve with Germany is under investigation.

<u>Due to the large uncertainty the historical market prices of ancillary services in Denmark and neighboring countries are used to give indications of the value of each market product</u>.

The description of the ancillary service markets in Denmark today and possible future development is shown in ([Energinet.dk 2013c], [Energitilsynet 2013] and [Energinet.dk 2013d]).

Area	**Ancillary service**	**Danish market requirement today**	**Possible future development**
DK West	Primary reserve	Demand: +/- 25 MW (daily auctions). Reduced to +/- 15 MW after	Integration with the German market, first stage is to maintain technical

		commissioning of 'Skagerak 4' in 2015 Minimum bid size: non-symmetric +/- 0,3MW, Bid duration: 4 hours Only reservation payment	requirements in each market, i.e. Danish suppliers can participate in the German market (Minimum bid size: symmetric +/-1 MW, weekly bid durations, pay-as-bid). The market demand will be increased to 123 MW for Danish suppliers [Energitilsynet 2013].
	Secondary reserve	Demand:+/- 90MW(UCTE requirement) Bid duration: 1 month, symmetric bid Danish and German TSO's reduces activation of secondary reserve if unbalances are in opposite direction in the two areas Only reservation payment	Supply from 2015 and five years ahead via 'Skagerak 4' Investigation to integrate with German secondary reserve market (2.200-2.500 MW in 2013) [Energitilsynet 2013].
	Manuel reserves	Demand: Ad-hoc, depends on largest online unit. Max 600 MW up regulation Approximately 300 MW is supplied via 'Storebælt' when the power flow is from Denmark West to East 2013 average: 185 MW up regulation Activation time: 15 min	Increased Cross-border balancing Joint demand in Denmark West and East
DK East	Frekvensstyret normaldriftsreserve ('FNR')	Demand: +/- 253 MW (in 2012, joint demand in Denmark East and Sweden) Market integration with Sweden, payed-as-bid, symmetric bids Only reservation payment	
	Frekvensstyret driftsforstyrrelsesreserve ('FDR')	Demand: +/- 450 MW (in 2012, joint demand in Denmark East and Sweden) Market integration with Sweden,	

		payed-as-bid, symmetric bids Only reservation payment	
	Manuel reserves	Demand: Ad-hoc, depends on largest online unit. Max 600 MW up regulation Until 2015 delivery is almost exclusively by Kyndbyværket and Masnedøværket Activation time: 15 min	Increased Cross-border balancing Joint demand in Denmark West and East

Table 14. Ancillary service products in Denmark West and Denmark East today and possible future development.

<u>System support services</u>

The Danish TSO, Energinet.dk, expects that voltage regulation from central power plant can be provided by reactive components in the transmission grid in the future. This will allow the required number of online central power plants to be reduced to 0-1 units in D enmark West and 1-2 units in Denmark East.

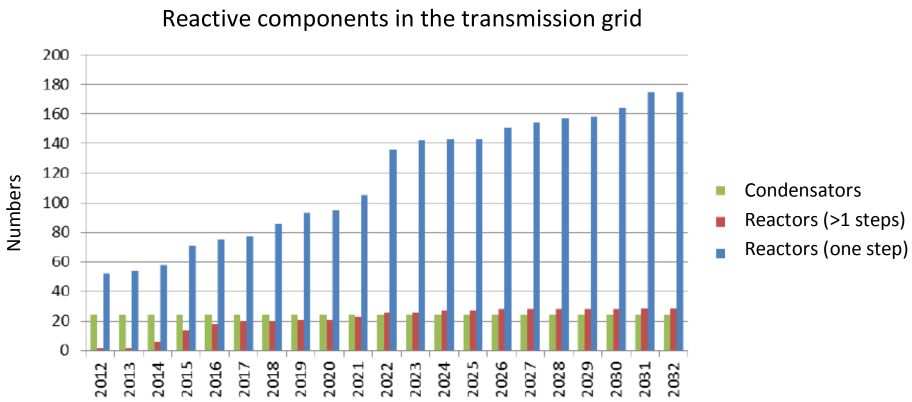


Figure 57. Reactive components in the transmission grid to provide voltage control [Energinet.dk 2013c].

Other system support services like inertia will also be provided by active components in the grid. Black start operation is expected to be secured via future DC connections supplemented with one emergency generator in both Denmark West and East [Energinet.dk 2013c].

4.2 RESULTS

4.2.1 VALUE OF ANCILLARY SERVICES FOR FLEXIBLE HEAT PUMPS

Cost of participation of demand response in ancillary service markets

The marginal cost of providing ancillary services from residential heat pumps is very small and could be considered to be zero. The cost of metering and data communication is a barrier for flexible demand to participate in ancillary service markets. Today expensive meters and a dedicated communication protocol are required from each unit to the TSO which is not realistic with residential heat pumps.

It is a condition in the valuation of residential heat pumps that standardized meters and internet based low cost communication is allowed for ancillary services purposes, which will make the cost regarding metering and data communication negligible for residential heat pumps [Biegel et al 2013].

The frequency control capability (adjusts load according to frequency measurement) of a heat pump requires additional software and a frequency meter, which have additional cost regarding an external box or upgraded heat pump functionality. The investment cost of a future commercial product with frequency control capability is expected to be in the range of 25-50 EUR [Rasmussen 2014].

Prices of ancillary services

The recent development of ancillary services prices is discussed in Appendix 7.4.

- Reservation payment in primary, secondary and manual reserve (Denmark West and Denmark East)
- Revenue from activation in Regulating power market

In general the Danish historical regulating power prices show that a significant share of the revenue is generated in short time periods with very high prices (extreme situations). This adds significant uncertainty to the possible future profit in the ancillary service markets, because the historical average prices are influenced by the peak prices.

Area	**Ancillary service**	**Historic reservation price** **(symmetric +/- 1MW)**	**Source**
DK West	Primary reserve	~100.000 DKK/MW/month (90 % upregulation, 10% down regulation)	Average German price 2012-2014
	Secondary reserve	~90.000 DKK/MW/month	Average Danish and German price 2012-2014

	Manual reserves	~25.000 DKK/MW/month	Long-term contract of Kundby and Masnedø [Energinet.dk 2013d].
DK East	Frekvensstyret normaldriftsreserve ('FNR')	~70.000 DKK/MW/month	Energinet.dk, average 2013-2014 price
	Frekvensstyret driftsforstyrrelsesreserve ('FDR')	~35.000 DKK/MW/month	Energinet.dk, average 2013-2014 price
	Manual reserves	~500 DKK/MW/month	Energinet.dk, average 2013

Table 15. Estimated prices of regulation reserve in Denmark West and East, cf. terminology in Table 13.

Primary and secondary reserve

Based on the average primary and secondary reserve prices (Table 15) the average revenue potential per flexible heat pump can be estimated. The following assumptions are made:

- The prices of ancillary services remain unchanged in the future, i.e. the participation of residential heat pumps does not significantly change the prices. This requires that not all residential heat pumps will provide e.g. frequency control, because the market volume is too small.
- The availability/reliability of the flexible heat pump in the ancillary service markets is assumed to be 50%. This should also take reduced spot market profit into account which can be experienced due to high ancillary service prices during peak hours (e.g. see Figure 98 in the appendix). Consequently, this corresponds to the average heat pump power is reduced from 1,2 kWh/h (Table 6) to 1,2*0,50 = 0,6 kWh/h.

The revenue from participation in primary and secondary reserve is:
70.000-100.000 DKK/MW/month during heat season ->
70-100 DKK/kW/month * 0,6 kWh/h * 6 month/year = ~250-360 DKK/year per flexible heat pump

Reservation payment of manual reserve is significantly less and participation would most likely restrict heat pumps to participate in more valuable primary and secondary reserve markets.

Regulating power market

The objective of flexible demand participation in the Regulating power market is to decrease the cost of electricity compared to only optimization towards the spot market. There are many possible strategies for flexible consumption to participate in the Regulating power market. The flexible consumption can provide bids for both up regulation (decrease consumption) and down regulation (increase consumption) in the Regulating power market. Optimization between the markets requires e.g. forecast of consumption, the consumption flexibility, expected unbalances and market prices.

In Figure 58 the theoretical flexible consumption profit is calculated as 1). Optimization towards spot market and 2). Optimization towards spot market and regulation power market. The optimization methodology is explained in Appendix 7.3.1 [Biegel et al 2013] and the calculated revenue is based on 2011 data.

The flexible consumption is simplified with e.g. equal distribution of load in all hours and without storage losses. Hence, the best case optimization potential is calculated, and actual restrictions due to e.g. load profile will reduce this potential.

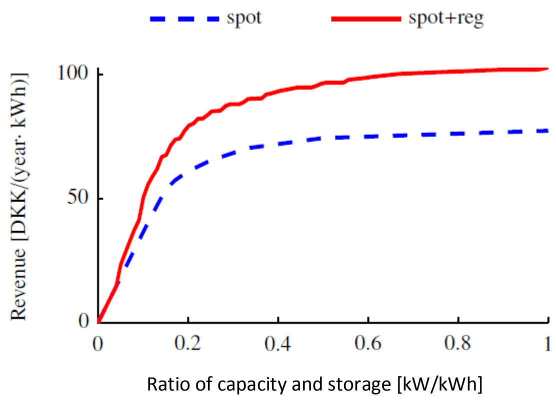


Figure 58. The theoretical profit per kWh storage when flexible consumption is optimized towards the spot market and when optimizing to both spot and regulating power market as function of the consumers power capacity [Biegel et al 2013].

The figure illustrates how the ratio between capacity and heat storage size of flexible consumption influence the revenue potential per MWh storage on spot market and spot market+regulation power market optimization, respectively.

The heat storage of residential heat pumps is ~30-60 kWh_heat (Figure 18) and the capacity is ~7 kW_heat (Figure 20). Thus, the ratio between heat capacity and heat storage is ~0,12-0,25 kW/kWh. <u>The increased profit of flexible residential heat pumps due to regulation power market participation is ~10-20% extra compared to only spot optimization</u> according to Figure 58.

The historical average difference in each hour between the spot price and the regulating power price (up and down regulation price, respectively) is approximately ~150 DKK/MWh from 2008-2013 (see Figure 111 in the Appendix). This indicates flexible consumption can increase the profit compared to only spot market participation. However, few peak prices contribute significantly to the average profit. Further, the flexible heat pump will not be able to obtain the price difference on the entire power consumption (i.e. not buy all energy in the Regulating power market), which will reduce the average profit potential per MWh.

Intraday market

According to the balance responsible party, NEAS, power producers can increase the power revenue by ~20-25% [Holmberg 2014] due to participation in intraday market compared to spot market participation only. Flexible consumers are also estimated to have similar benefit via lower power prices if participating in the intraday market [Holmberg 2014].

Estimated savings from Regulating power market and Intraday market

Based on the estimations above the potential increase in revenue additional to spot optimisation is estimated:

- Regulating power market: ~10-20% additional revenue
- Intraday market trading: ~20-25 % additional revenue

Hence, it is assumed that flexible heat pumps can increase spot market profits with approximately 30% via participation in Regulating power market and intraday market.

Given the spot market profit of flexible heat pump is ~440 DKK/year in Scenario 1 in 2035 (Table 9), the additional profit of participation in Regulating power market and intraday market is then ~130 DKK/year.

4.3 SUBCONCLUSION

The chapter has provided an overview of the Danish balancing and ancillary service markets. Estimates of the economic value have been provided based on historical prices of:

- Reservation payment in primary, secondary and tertiary reserve
- Additional profit in Regulating power market and Intraday market compared to spot market only

It is concluded that residential heat pumps have the required energy storage, predictability, controllability and marginal cost to provide ancillary service and balancing in the future. Thus, participation of flexible heat pump in balancing and ancillary service market can lead to socio economic value due to increased supply of potentially cheap resources. In the future with less conventional power plants online and a high share of renewables, demand response can be essential for intra-hour balancing.

Due to the design of ancillary service markets it is likely that aggregation of residential heat pump is necessary to participate. The possible ancillary services revenue of each residential heat pump will be determined by e.g. the Aggregator/BRP trading strategy between different markets.

The Business case of flexible heat pump in the balancing and ancillary service markets is summarized in the table below:

Demander of flexibility	-Commercial actors – Intraday trading -TSO – ancillary services for balancing of the grid
Market requirement of participation	-Ancillary services: Different requirement for primary, secondary and tertiary reserve -Aggregation of heat pumps needed (possibly with other demand or production)
Socioeconomic cost	-higher administration cost of ancillary services due to more suppliers
Socioeconomic value	-overall cheaper balancing and ancillary services due to higher supply
Private economic costs	-Control of heat pump and heat storage (similar to control towards Day-ahead market) -Frequency meter and additional control capability regarding primary regulation: 25-50 EUR per heat pump
Private economic profit potential	-Primary and secondary reserve: 70.000-100.000 DKK/MW/month during heat season -> 70-100 DKK/kW/month * 0,6 kWh/h * 6 month/year = ~250-360 DKK/year per flexible heat pump -Regulating power market and Intraday market: increased spot market profit with approximately 30% via participation in Regulating power market and intraday market: ~130 DKK/year.
Risks	-Changes in technical requirement for ancillary service market participation -Unknown market volume and prices of ancillary services in Denmark -Unknown market supply, especially other types of flexible demand during the winter period -Continued high cost of communication and meters for small DR-units
Drivers for Danish business opportunities	-Standardisation of ancillary service products between countries -Standardisation of heat pump control and communication [Stærmose 2013] -Proof-of-concept of aggregated delivery including residential heat pumps -Increased prices due to conventional suppliers (power plants) have fewer operating hours

Table 16. Business case of flexible heat pump in the balancing and ancillary service markets

5 FLEXIBLE HEAT PUMPS PARTICIPATION IN A CAPACITY MECHANISM

The objective of a capacity mechanism is to secure the sufficient capacity balance to reach the desired security of supply in the system. The capacity mechanism can maintain existing power capacity (otherwise decommissioned), attract new power capacity investment and create economic incentive for demand reductions/curtailment.

As shown in Chapter 0 non-flexible heat pumps create an additional peak power demand which require investment in new power capacity. Flexible residential heat pumps can reduce the requirement for peak power investments by switching the consumption to off-peak periods.

The required demand response of heat pumps can be activated via:

- Indirect control: Real time price signal (including dynamic tariffs)
- Direct control: Activation of System service contract/market for reliable peak power capacity

The following chapter deals with the contract/market between TSO and aggregator/BRP as a mean to secure sufficient capacity. The activation method of the customer can be either indirect or direct control.

The payers of the capacity mechanism could e.g. be TSO's on behalf of all consumers (uniform payment) or distributed to consumers based on actual contribution to the peak demand, e.g. via capacity based tariffs.

5.1 METHODOLOGY AND KEY ASSUMPTIONS

According to Figure 59 the requirement for new power capacity in EU will increase in the coming years due to decommissioning of old power plants is expected because of new emission requirements and technical lifetime limitations.

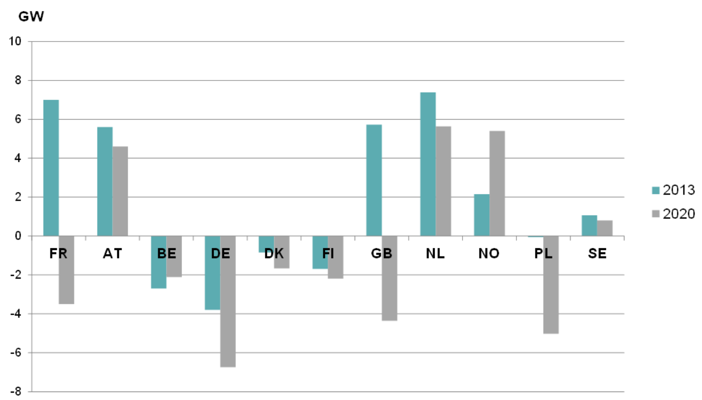


Figure 59. Capacity balance (GW) in selected European countries according to the national TSO's conservative scenario. In this scenario only new power plants until 2020, that the TSOs are certain will be built, are included. The capacity balance is calculated according to ENTSO-E's reliable power capacity margin. [ENTSO-E 2013].

5.1.1 INTRODUCTION TO CAPACITY MECHANISMS

There are several mechanisms to secure reliable power capacity, which is illustrated in Figure 60. The three main categories are:

- *Strategic reserve* – contract between TSO and power plant, where the power plant against payment is withdrawn from ordinary energy market and used as backup peak capacity. This is especially targeted to maintain existing power capacity that otherwise would have been decommissioned.
- *Capacity market* – auction based market together with the normal power market (the income from the normal power market influence the cost of capacity). The value of flexibility depends on supply and demand, both consumption and production can supply capacity reserve.
- *Capacity payment* – fixed payment on capacity (different technical requirements may lead to different payment categories). The price is set administratively and not by a market.

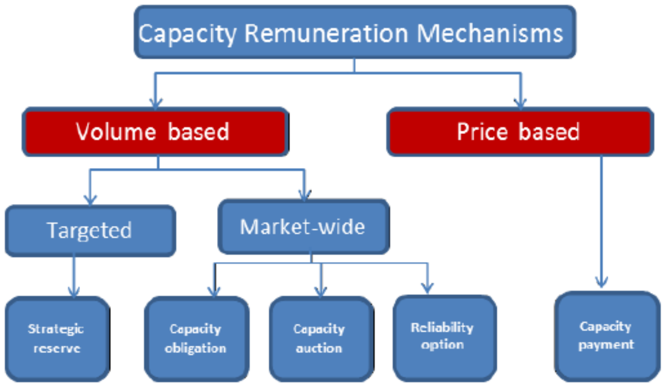


Figure 60. Different mechanism to secure sufficient reliable capacity [ACER 2013].

In Chapter 2 an energy-only market is assumed in the Balmorel simulations (similar to existing Danish market conditions) where capacity is secured via the power price. However, many countries struggle to attract new power capacity investments due to uncertainty of future power prices. Hence, capacity mechanisms appear to be needed to secure sufficient power capacity.

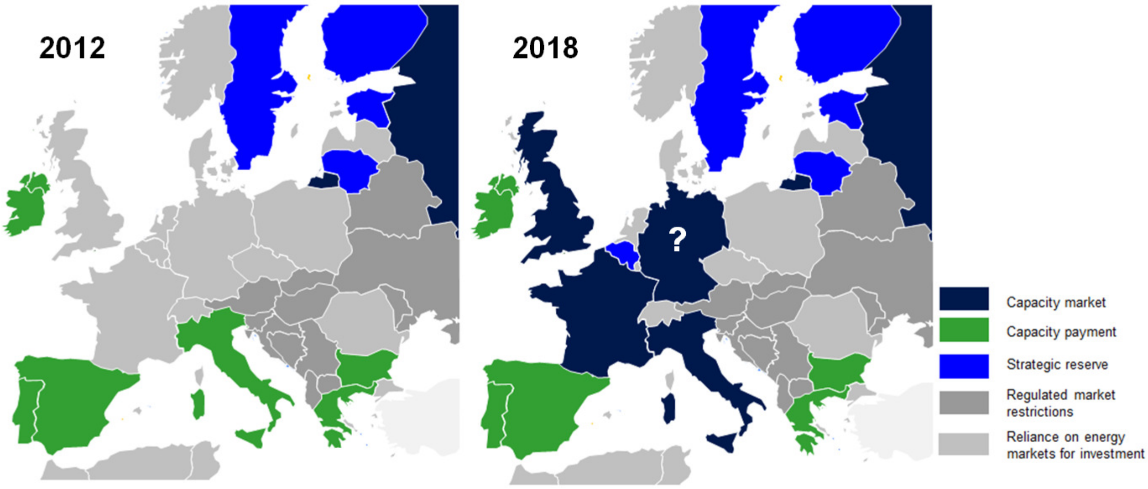


Figure 61. Development towards capacity mechanisms in Europe [IHS CERA 2013].

In theory flexible consumption can participate in all the different capacity mechanisms as reliable capacity. The reliable capacity is often sourced 3-4 years ahead [PJM] to allow time to build new power plants, implement energy efficiency improvements or flexible demand technology and contracts with customers.

In Sweden, all Strategic reserve capacity is expected to be supplied by consumption in 2020 (~750 MW) [Svenska Kraftnät 2011]. The tendering period is November to March and the gate closure is approximately ½ year before. The capacity reserve is activated if supply could not meet the demand in the Day-ahead market. The production reserves is activated at a fixed price (0,1 EUR above highest bid in the Day-ahead market). The consumption reserves can provide bids to the day-ahead market after given rules. The non-activated production and consumption reserve can provide bids to the Regulating Power market [Svenska Kraftnät 2011].

In UK capacity markets is planned to provide physical delivery in the winter 2018/19. The different stages in the UK capacity market operation are illustrated below:

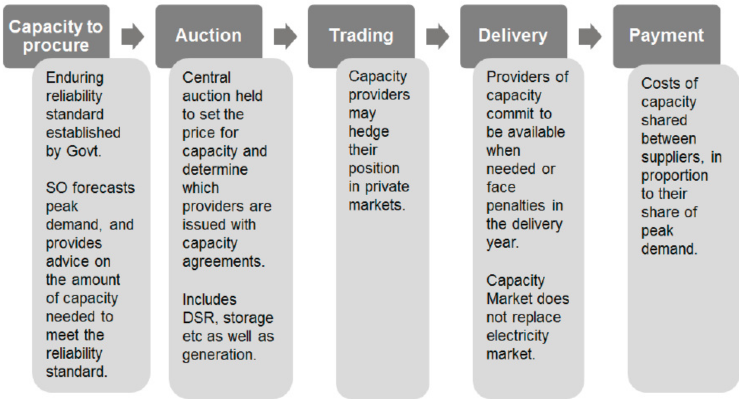


Figure 62. Stages of Capacity Market operation in UK [DECC 2013]

In the US capacity markets have been developed through several years to target peak load problems. Demand response has proved to provide a significant share of capacity in the markets [Danish Energy Association 2014a]. One example of demand response capacity program is described on PJM´s homepage (TSO in USA):

"(Demand response) Participants have the choice of a day-ahead option or a real-time option. In the day-ahead option, a CSP's (Curtailment Service Provider's) customers can offer – in advance of real-time operations – to reduce the amount of electricity they will draw from the PJM system. If the offers are accepted, they will receive payments based on the day-ahead prices for the reductions. In the real-time option, a CSP helps customers reduce their usage voluntarily during times of high prices and receive payments based on realtime prices for those reductions" according to PJM homepage [PJM]

5.2 RESULTS

5.2.1 PARTICIPATION OF FLEXIBLE HEAT PUMPS IN CAPACITY MECHANISM

The main challenge of demand response participation in capacity mechanism is to secure *availability* and to *validate the delivery of the service* [Energinet.dk 2012]. Thus, it is important to establish the 'baseline' to be able to validate and reimburse the change in consumption.

The non-flexible residential heat pumps will increase the peak power capacity requirement during periods with high heat demand. Figure 24 illustrates the conditions when activation of the consumption capacity reserve is required to secure balance between consumption and available power production.

In Figure 63 different baselines are illustrated:

- non-flexible heat pumps: the total volume that should be down regulated
- flexible heat pumps optimized towards spot market: the remaining volume that is down regulated due to the capacity mechanism

The capacity mechanism contract could specify both baselines. The capacity product has similar characteristics as "power-cut planned" described as DSO-service to avoid exceeding the grid capacity [iPower WP3.8 2013].

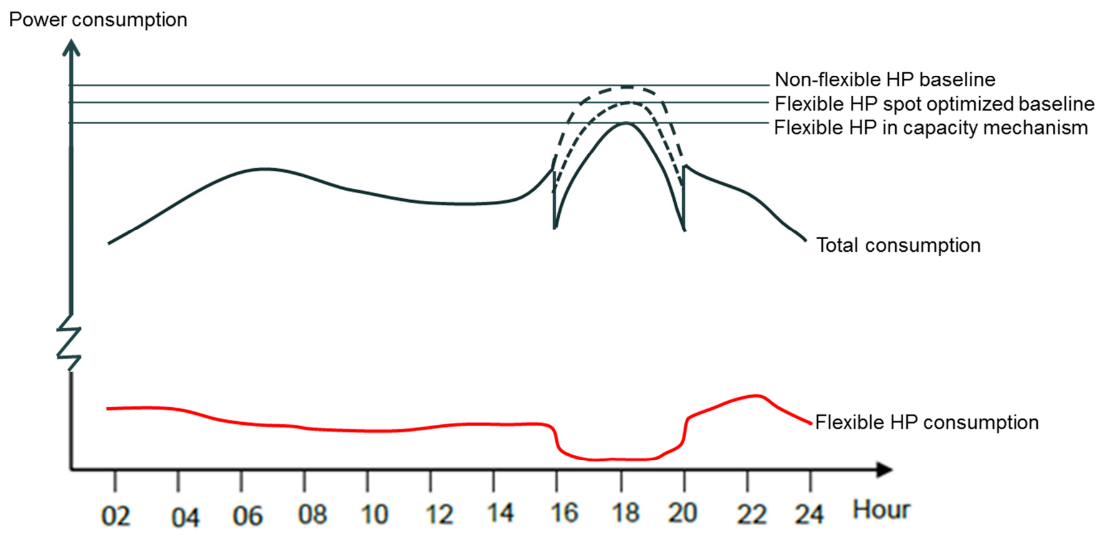


Figure 63. Illustration of the peak power consumption in scenarios with non-flexible heat pumps, flexible heat pumps optimized towards the spot market and flexible heat pumps after applying capacity mechanism (in hour 16-20).

It is a precondition that the heat pump has a heat storage that can allow the heat pump to switch of during the peak hours (preferably 3-4 hours). According to Figure 18 this amount of heat storage is available via heat storage in building constructions for all three heat capacity categories assuming an allowed indoor temperature variation of +/- 1,5 C. However, especially for houses with lower heat capacity it requires the full heat storage is utilized, i.e. the indoor temperature should be controlled to be maximal prior to the shutdown period to preserve the required heat comfort. This means the activation of consumption as capacity reserve should be announced as soon as possible to allow optimal demand profile.

A suggestion for flexible heat pump participation in the capacity mechanism is illustrated below:

1. **Months/years ahead.** The aggregated flexible heat pump is accepted as capacity reserve by the TSO. The bid include flexible volume (MW), maximum activation time (hours), reservation price (EUR/MW) and possibly activation price (EUR/MWh).
2. **Day(s) ahead.** The baseline prognosis of the flexible volume of heat pump power consumption is developed by BRP or TSO based on weather forecast and historical data.
3. **Day(s) ahead.** Based on the baseline prognosis the TSO inform the BRP/aggregator that the capacity reserve of flexible heat pumps has to be activated the coming day during a specified activation period.
4. **D-1.** The aggregator/BRP incorporates the capacity activation in the bid to the Day-ahead market. If the capacity reserve is not activated, the flexible heat pumps can provide bids for ancillary service or balancing markets.
5. **Day of operation.** The heat pumps reduce the power consumption via direct or indirect control in the activation period. The heat storage levels in the buildings are optimized to handle the period where the heat pump power consumption has to be decreased.

5.2.2 VALUE OF FLEXIBLE HEAT PUMP CAPACITY

The value of reliable capacity in the future is difficult to assess due to several reasons:

- The demand depends on e.g. degree of market integration, desired security of supply and development of prices in the normal energy markets.
- The supply price depends on the different sources that can provide reliable capacity.

Prices on capacity prices in Sweden 2012/13:

In the winter 2012/13 approximately 1500 MW was purchased at 130 million SEK. The average contract price was ~85.000 SEK/MW/year, corresponding to ~14.000 DKK/MW/month from November to March.

Prices on capacity assumed in Balmorel:

In Balmorel the value of reliable capacity is the annuity and fixed O&M cost of OCGT-plants:

41.200 EUR/MW/year = 307.000 DKK/MW/year = ~26.000 DKK/MW/month

The price per MW/month is very similar to reservation price of Manuel Reserve in Denmark East (see Table 15).

In the Balmorel simulations investment in peak power capacity is needed in Denmark in 2030 and 2035, which increases the investment in flexible heat pumps in the model (Figure 19). However, in real life a Danish capacity mechanism could be needed sooner, which would provide business opportunity for flexible heat pumps.

Private economic profit of flexible heat pumps participation in a capacity mechanism

The price of the capacity is assumed to be equal to the capacity price assumed in Balmorel, i.e. ~26.000 DKK/MW/month. However, it is assumed that the payment is only in the Winter period (November – March) where the peak power demand of heat pumps will occur (and the maximum peak power capacity is needed).

The following baselines according to Figure 63 are assumed:

- Non-flexible heat pump baseline: ~3 kW (Table 6).
- Spot market optimization baseline: ~50% moved due to spot optimisation

This means the yearly revenue of a flexible heat pump with average max power is:

Capacity revenue of flexible heat pump = ~3kW * ~50% * 26 DKK/kW/month * 5 month = ~190 DKK/year.

The establishment of capacity mechanism would decrease the power prices in an energy-only market, i.e. the spot and ancillary service markets. The design of the Capacity mechanisms, e.g. the defined activation price and contracted volume of capacity, would affect the level and frequency of peak prices in the spot market. This could diminish the electricity cost reduction of flexible heat pumps compared to non-flexible heat pumps found in the Balmorel simulation with an energy-only market.

Since the actual design of a capacity mechanism is unknown the potential reduction in power price is disregarded in this analysis.

Socioeconomic value of flexible heat pumps participation in a capacity mechanism.

The socioeconomic value is due to replacement of new peak power investments with flexible demand participation. The socioeconomic value is already included in the benefits of flexible heat pumps in the Day-ahead market.

5.3 SUBCONCLUSION

The chapter has described the potential need for capacity mechanisms in Europe in the future. The different capacity mechanisms found in Europe and USA are briefly described and examples of demand response participation are given. A suggestion for how activation of flexible heat pump as a capacity reserve can take place is also presented in this chapter.

The Business case of flexible heat pump participation in capacity mechanism is summarized in the table below:

Demander of flexibility	TSO (behalf of responsible for security of supply) – reduce future investment in peak power capacity
Market requirement of participation	-Unknown market conditions since capacity mechanism is not implemented in Denmark -Length of activation is important for required heat storage to participate -Notification of activation of capacity reserve is important to plan demand profile accordingly.
Socioeconomic cost	-Increased cost of baseline prognosis and validation of supply
Socioeconomic value	-Impact of flexible heat pumps in Balmorel is ~150 million DKK/year (profit included in Chapter 2.2.8 regarding energy-only market)
Private economic costs	-Same as control of flexible heat pump in Day-ahead market
Private economic profit potential	-Capacity revenue of flexible heat pump = ~3kW * ~50% * 26 DKK/kW/month * 5 month = ~190 DKK/year
Risks	- Longterm capacity mechanism is not implemented or decided in Denmark (Energinet.dk will purchase Stategic Reserve in Denmark East from 2016-2020) - Flexible heat pumps has to compete with other technologies to provide reliable capacity
Drivers for Danish business opportunities	- Danish or European ambition to establish capacity mechanisms. - Future demand of Capacity mechanism depends on the ability of an energy-only market to attract new power capacity or to maintain existing capacity. Thus, a driver for establishment of a capacity mechanism is low power prices.

Table 17. Business case of flexible heat pump participation in capacity mechanism

6 CONCLUSION - BUSINESS CASE FOR FLEXIBLE HEAT PUMPS

The objective of this analysis was to investigate the Business case for flexible residential heat pumps in Denmark from 2020-2035 from a private economic and socioeconomic perspective, respectively.

The business case for flexible heat pump can include value derived from one or more demand of flexibility. The private and socioeconomic value of flexibility from residential heat pump has been investigated within the following areas:

- Chapter 2. Flexible heat pumps in the day-ahead market
- Chapter 3. Flexible heat pumps impact on distribution grids

Chapter 4. Flexible heat pumps in balancing and ancillary service markets
Chapter 5. Flexible heat pumps participation in a capacity mechanism

The findings and contribution to the business case are summarized in the subconclusion in each chapter. The calculated numbers and assumptions used in this chapter can be found in the individual chapters.

6.1 SOCIOECONOMIC BUSINESS CASE

The contributions to the total socioeconomic value of flexible heat pumps in 2035 (Scenario 1) are shown in Figure 64. The socioeconomic value of reduced grid reinforcement and reduced balancing costs due to flexible heat pumps has not been analyzed; hence, values are only illustration of potential profit.

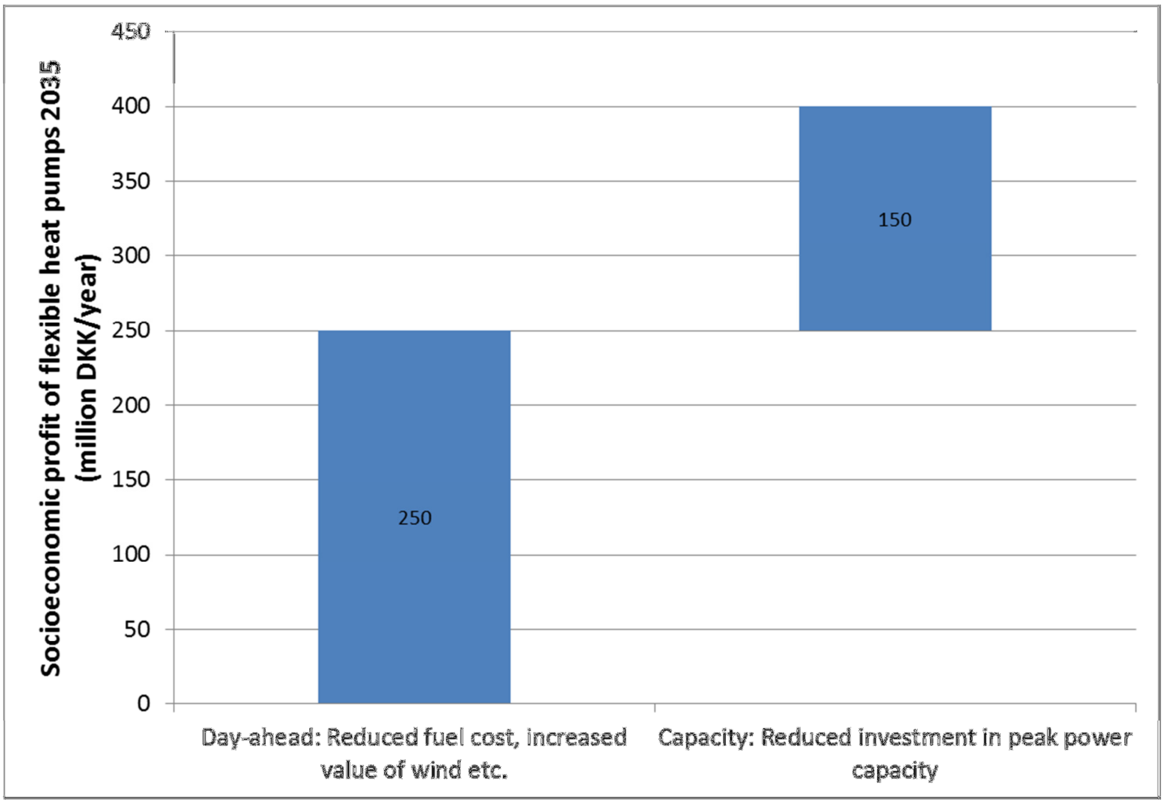


Figure 64. The contributions to the socioeconomic value of flexible heat pumps in Scenario 1.

	Estimate (mio DKK/year)	Reference
Day-ahead: Reduced fuel cost, increased value of wind etc.	250	Table 9
Capacity: Reduced investment in peak power capacity	150	Table 17

Table 18. References of socioeconomic value estimates of flexible heat pumps in Scenario 1.

The total socioeconomic value of flexible heat pumps is estimated at 400 million DKK/year in 2035 in Scenario 1. The main contributions to the socioeconomic value are:

- the reduction in fuel consumption cause by flexible heat pump move consumption to off-peak periods with lower power prices and higher wind production.
- the reduction in peak power capacity is also caused by flexible heat pumps ability to reduce the power consumption during periods with peak consumption and low wind production, which would otherwise increase the required peak power capacity.

The savings in grid reinforcement costs and savings in ancillary services will contribute to additional socioeconomic value of flexible heat pumps.

The business case is depending on the volume of flexibility, because the impact of flexible consumption on the energy system increases with higher power consumption from residential heat pumps. Thus, the business case is attractive in a long term perspective with increasing electrification of residential heating. However, short/medium term initiatives have to facilitate the transition of markets and regulations which are needed to improve the private economic business case.

6.2 PRIVATE ECONOMIC BUSINESS CASE

The private economic profit of flexible heat pumps is important to secure it is possible to activate flexibility via a market based approach, where commercial actors (Aggregators, BRP, wholesale traders) motivated by economic opportunities will develop solutions that will enable flexible consumption of residential heat pumps.

The contribution to the private economic profit of flexible heat pumps in 2035 (Scenario1) is shown in Figure 65. The revenue from 'Primary or secondary reserve' only apply to residential heat pumps with additional control capabilities, and is calculated under the assumption of 2014 prices.

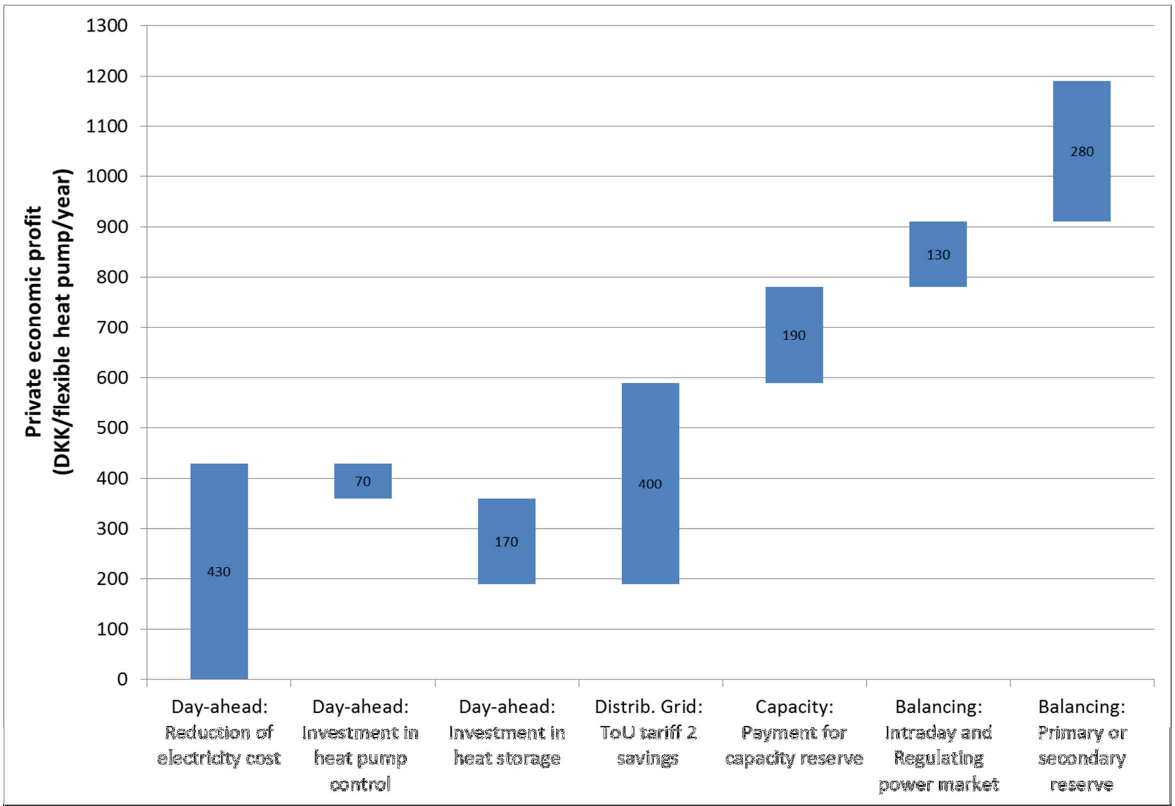


Figure 65. The contributions to the private economic profit of flexible heat pumps in Scenario 1.

	Estimate excl. VAT (DKK/year per flexible heat pump)	Reference
Day-ahead: Reduction of electricity cost	430	Table 9
Day-ahead: Investment in heat pump control	-70	Table 9
Day-ahead: Investment in heat storage	-170	Table 9
Distrib. Grid: ToU tariff 2 savings	400	Table 12
Capacity: Payment for capacity reserve	190	Table 17
Balancing: Intraday and Regulating power market	130	Table 16
Balancing: Primary or secondary reserve	280	Table 16

Table 19. References of private economic profit estimates of flexible heat pumps in Scenario 1.

The average profit including investment in flexibility is ~1200 DKK/year (ex. VAT) in 2035 according to Figure 65. As stated previously residential heat pumps with higher power consumption have a 'better' business case for flexible consumption (measured in absolute profit), because larger power consumption can be shifted between hours with different power prices. Further, contribution from capacity reserve and balancing also increases for larger heat pumps.

The electricity bill of non-flexible residential heat pumps is compared to flexible heat pumps with fixed tariff and ToU tariff 2, respectively. The investment costs in flexibility are not included in the figure.

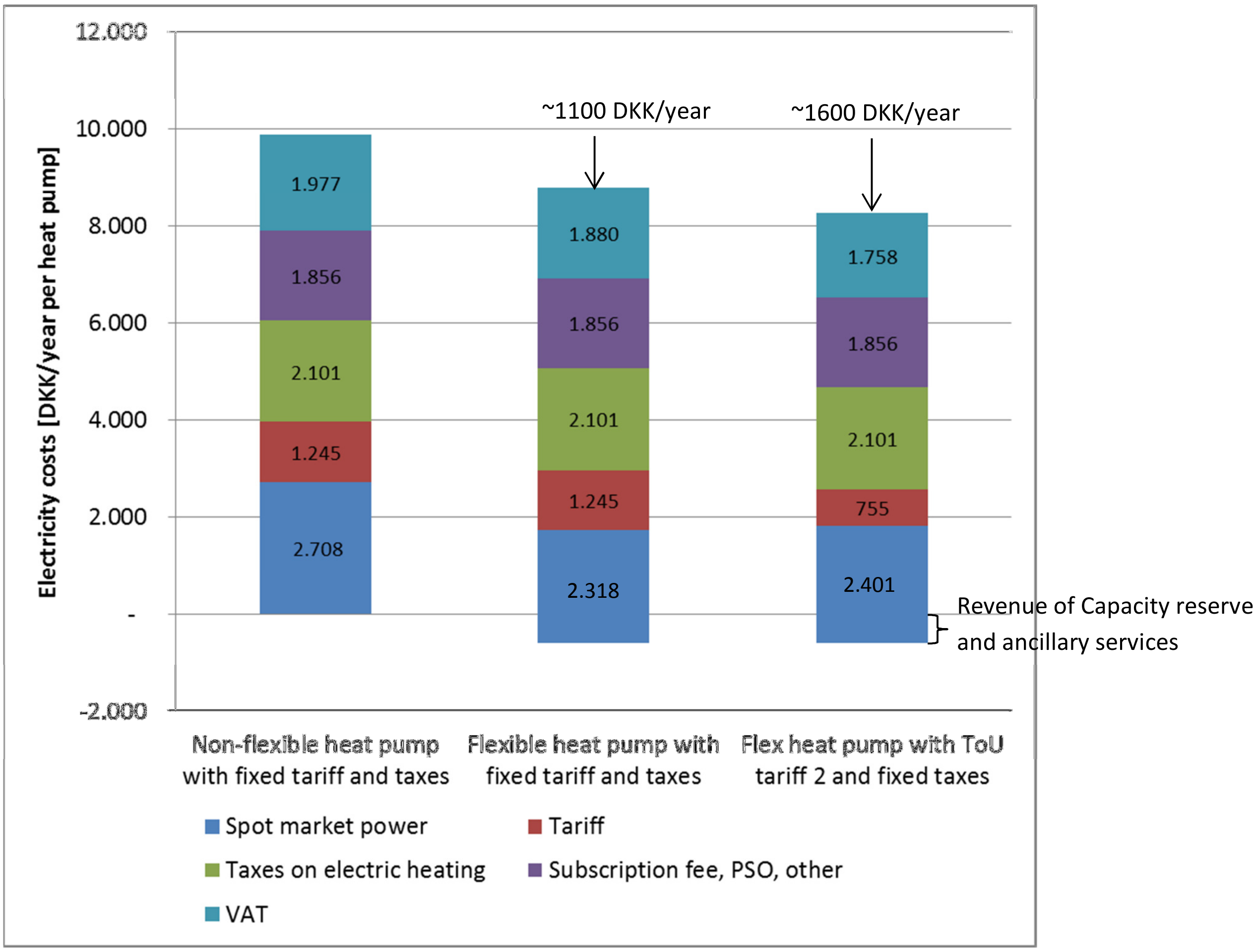


Figure 66. The electricity cost of flexible residential heat pumps (2035 spot market power savings according to Balmorel) with different tariffs compared to non-flexible heat pumps with fixed tariffs.

6.3 DISCUSSION

6.3.1 DEVELOPMENT OF PRIVATE ECONOMIC BUSINESS CASE

The short/medium term business case potential for flexible residential heat pumps is based on optimization towards the spot market. However, variable tariffs (and taxes) could be used to strengthen the short/medium term economic incentive to invest in flexible heat pumps. Variable tariff (and taxes) targeted flexible consumption would provide incentive to develop commercial solutions for residential flexibility.

The long term business case potential for flexible residential heat pumps would also include profits of capacity reserve and ancillary services for TSO and DSO. It is likely that a change in market design and a critical mass of flexible heat pumps has to be established to provide these market based products.

In Figure 67 the *possible* development of available market value (spot optimization, ancillary service for TSO and DSOs, and capacity mechanism) for flexible heat pumps is illustrated together with the total required payment per flexible heat pump. Customers and commercial actors (Aggregator/BRP/wholesale trader) expects a certain payment to engage in flexible consumption of heat pumps. Customers have individual preferences, adaptation speed and risk willingness which affects their actual required payment. Thus, required payment is expected to increase as the target customer is changing from early adapters to mainstream customers.

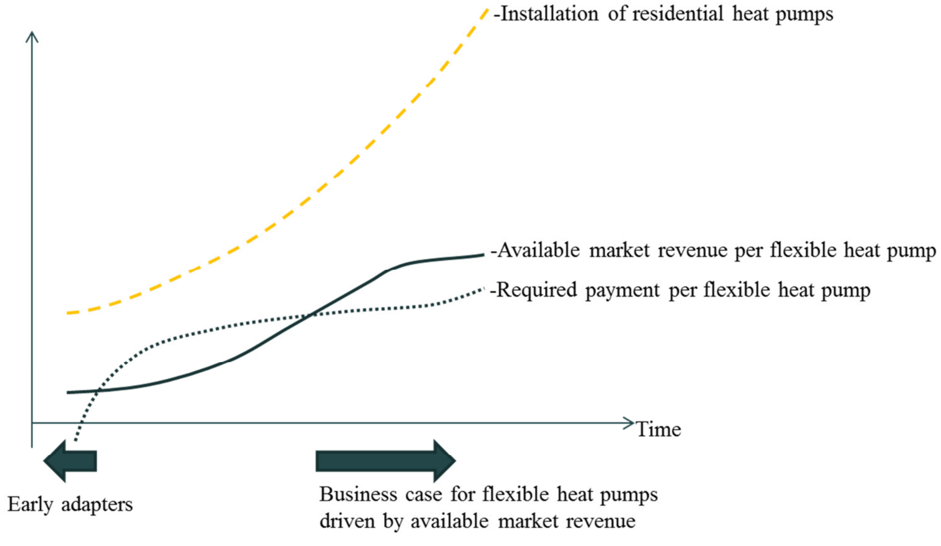


Figure 67. Illustration of *possible* development of available market revenue for flexible heat pumps. The increasing available market revenue is assumed to be a consequence of a continuous technology development and implementation of smart grid strategy. The increase in required payment is expected to allow more price-focus customers to engage in flexible consumption.

The illustration indicates that the available market revenue per flexible heat pump has to reach the required payment per flexible heat pump before the private economic flexibility business case can be driven sustainably by payment from markets.

A ToU tariffs (and taxes) targeted flexible consumption could be needed to drive the development of flexibility while the available market revenue for flexible heat pumps is lower. The advantages and challenges of special ToU tariffs targeted flexible heat pumps are discussed in Chapter 3.2.1.

The contribution of ToU tariff/tax revenue to the total available revenue per flexible heat pump is shown in Figure 68. It is illustrated (not demonstrated in reality) that ToU tariff/tax makes it possible to meet the customer's and commercial actor's required payment before sufficient market based revenue is available.

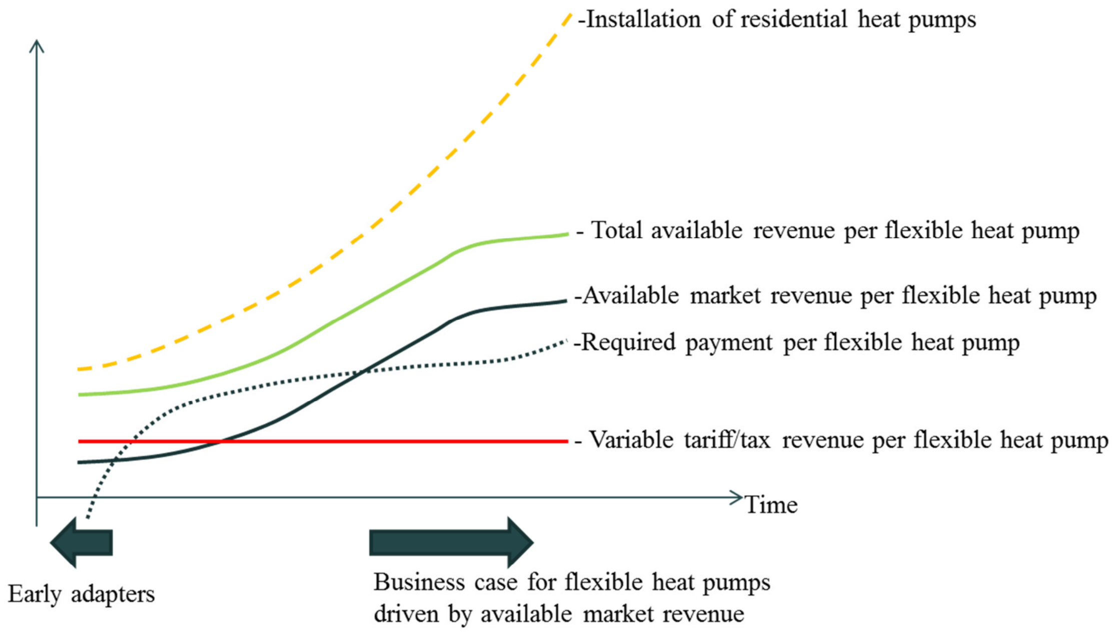


Figure 68. Illustration of contribution from variable tariff/taxes to the business case for flexible heat pumps, which makes the total available revenue per flexible heat pump surpass the target customer's expectations.

ToU tariffs/taxes could be replaced with other variable tariffs, e.g. dynamic tariffs designed for moving consumption towards renewable production.

6.3.2 FURTHER WORK

The list below show examples of areas that can be focused on in further work to improve the business case analysis and modelling of residential heat pumps.

Investigation of business opportunities

- More contributions to the socioeconomic value of flexible heat pumps could be investigated, e.g.:
  - The value of delaying grid reinforcements due to flexible heat pumps as explained in Chapter 3.2.4
  - The reduction in cost of ancillary services due to flexible heat pumps explained in Chapter 4.2.1
- The private economic business case could be expanded to include:
  - Examples of revenue of DSO products according to [iPower WP3.8 2013]
  - Optimization of flexible heat pumps towards both Day-ahead and Intraday/Regulating power market, cf. Chapter 4.2.1.
- Design of variable tariff and taxes to maximize socioeconomic value of flexible consumption and provide attractive DSO and private economic business case.
- Optimization of flexible heat pump together with remaining household consumption and production, e.g.:
  - Conventional oil or gas boiler (hybrid heat pump)
  - PV – increase own consumption of solar power production via flexible heat pump consumption and heat storage (in building structure or heat accumulator tank)
- Payment requirement for customer and commercial actors participation in domestic flexible demand schemes.
- The business concept of flexible residential heat pump could be developed together with energy efficiency products, since both areas can require control of heating and screening of household's energy saving (and flexibility) potential
- Focus on flexible heat pumps in buildings with higher heat demand – possibly with new radiators

Modeling of residential heat pump

- Heat capacities:
  - Validation of model calculated indoor air temperature change in different buildings (insulation and heat capacity) at cold air temperature (e.g. -12 C) if the heat pump is stopped.
- Heat transfer coefficient:
  - Compare old buildings with improved insulation to applied assumptions
  - Effect of wind chill factor on building heat loss
  - Improved heat loss modeling
- Heat pump dimensioning
  - Require minimum time to increase indoor air temperature (increased heat pump heat capacity)
- Heat storage optimization constraints:

   - Optimization horizon: Require flexible heat pumps provide average indoor air temperature = 21,5 C during shorter periods, e.g. during 24 or 48 hours
   - Allowed variation of indoor air temperature depending on electricity cost saving potential, i.e. no required average indoor air temperature.
   - Different heat comfort (i.e. allowed indoor temperature variation) in different part of the building.
   - Include reduction of heat comfort (required indoor temperature) during working hours and during the night. This lead to heat savings and heat costs savings compared to constant indoor temperature – which is part of the business case for installing digital thermostats and heat controlling.
- COP modeling of heat pumps
   - Model supply temperature as function of actual heat production instead of daily heat demand
   - Improve modeling of hot water demand on COP
   - Effect of wind chill factor on COP of air-to-water heat pump
   - Updated COP of future heat pumps
- Energy market modeling in Balmorel:
   - Influence of residential heat pumps in other countries on Danish socioeconomic business case
   - Simulate capacity market instead of energy-only market
   - Optimized according to grid maximum capacity (i.e. aggregated maximum capacity)
   - More variable power prices, less availability of transmission capacity

Technical proof-of-concept

- Aggregated control of many heat pumps as one.
- Controllability of on/off heat pumps compared to variable speed heat pumps
- User experiences of allowed variable indoor air temperature. Optimization of heat storage operation within customer's heat comfort boundaries.
- Forecast of heat demand in buildings. Technical demonstration could involve forecast of aggregated portfolio of residential heat pump
- Smart grid ready heat pump. The cost of flexible operation of heat pumps could be significantly reduced via "smart grid ready" heat pumps; i.e. standardization of communication protocols to minimize need of additional control equipment. Further, lack of accessible control and measurement signals in the heat pump make it difficult for 3rd parties commercial actors (aggregators of DER units) to operate the heat pump on behalf of the customer [Stærmose 2013].

7 APPENDIX

7.1 ADDITIONAL ASSUMPTIONS: DAY-AHEAD MARKET

7.1.1 KEY INPUT TO BALMOREL

The development of the CO2 price 2020-2035 is set to half of the average CO2 price in three scenarios from EU 2050 Roadmap [European Commission 2011]:

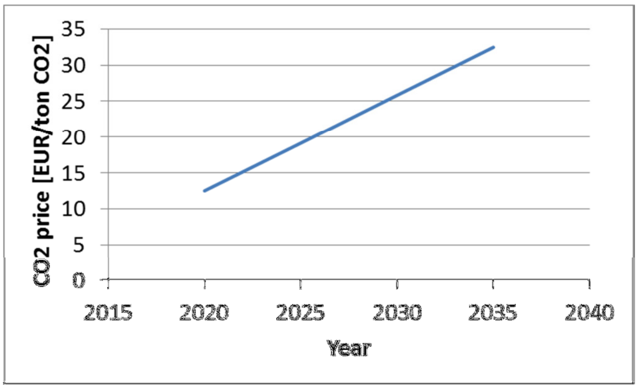


Figure 69. The applied CO2 price in all scenarios

Electric vehicles are included in all countries in Balmorel. The EV's charging profile during the week is shown in Figure 70. In Denmark 47.000 and 221.000 EV's are assumed installed in 2020 and 2030, respectively [Danish Energy Association 2013].

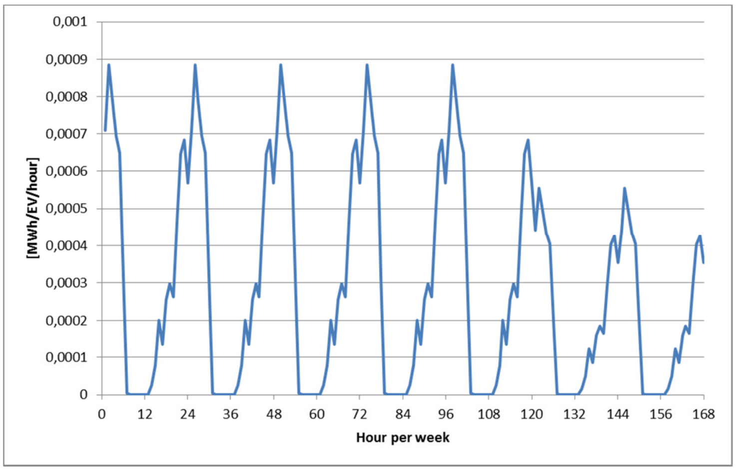


Figure 70. The applied EV hourly charging profile in all countries and all scenarios based EV population simulation.

7.1.2 INVESTMENT IN HEAT PUMP FLEXIBILITY

The methodology for investment in flexible heat pumps in Balmorel is:

1). The technology investments in all countries 2020-2035 are calculated without the Thermal Building Module. The investments from all countries (except Denmark) are loaded and therefore constant when the Thermal Building Module is active. Thus, only Danish technology investments are affected by flexible heat pumps.

The steps to find optimal investment in flexibility 2020-2035 in Denmark with the Thermal Building Module:

2). Balmorel with the Thermal Building Module is run without possibility of investment in flexible heat pumps. Hourly heat production of non-flexible heat pumps in each building category is saved in each year.

3). Balmorel with the Thermal Building Module is run with allowed investment in flexible heat pumps. The heat production of the residential heat pumps is determined based on the non-flexible heat production ("loaded" from step 2) and amount of optimized heat production of flexible heat pumps.

In each investment year Balmorel determines the optimal amount of new flexible heat pump in each building category, HP_T_{flex}. The optimization criterion is to minimize the total system costs.

The amount of flexible heat pumps influences the following equations and constraints in Balmorel:

a). The share of flexible heat pumps of all installed heat pumps in each building category Ω_{flex}

$$\boldsymbol{\Omega_{flex} = (\Sigma HP_{flex} + HP\_T_{flex})/HP_{installed}) \leq 1}$$

, where:

ΣHP_{flex} = Accumulated number of flexible heat pumps before investment year

HP_T_{flex} = Investment in flexible heat pumps in investment year

$HP_{installed}$ = Accumulated installed heat pumps in investment year

b). The heat pump heat production in each building category $Q_{HP,\ total}$ is then:

$$\boldsymbol{Q_{HP,\ total} = Q_{Flex\ heat\ pump} + Q_{Non\text{-}flex\ heat\ pumps} * (1 - \Omega_{flex})}$$

, where:

$Q_{Flex\ heat\ pump}$ = Heat production of flexible heat pump

$Q_{Non\text{-}flex\ heat\ pumps}$ = Heat production of non-flexible heat pump c). The indoor temperature in each building category T_{in} is calculated:

$$T_{in} = (\Sigma Q_{losses} + \Sigma Q_{source} + Q_{HP, total})) / (C * A)$$

, where:

ΣQ_{losses} = heat losses from building to surroundings

ΣQ_{source} = heat added in the building from persons, electronic appliances etc.

C = heat capacity in building category

A = heated area in building category

d). The investments in flexible heat pump also affect the allowed indoor temperature variation in each building category given by the actual minimum temperature $T_{in,min, act}$ and actual maximum temperature $T_{in,max, act}$. The indoor temperature variation is a measure of the heat storage; thus, the more flexible heat pump the higher variation in indoor temperature is allowed:

$$T_{in,min, act} \geq T_{fixed} + (T_{in,min,flex} - T_{fixed}) * \Omega_{flex}$$

$$T_{in,max, act} \leq T_{fixed} + (T_{in,max,flex} - T_{fixed}) * \Omega_{flex}$$

, where:

T_{fixed} is fixed indoor temperature of non-flexible heat pumps, e.g. 21,5 °C

$T_{in,min,flex}$ is allowed minimum indoor temperature in a building with flexible heat pump, e.g. 20 °C

$T_{in,max,flex}$ is allowed maximum indoor temperature in a building with flexible heat pump, e.g. 23 °C

7.1.3 HEAT DEMAND IN DIFFERENT BUILDING CATEGORIES

This subchapter explains which assumptions are used to divide the total heat demand of all individually heated buildings 2006-2035 into heat demand in the building categories used in the Balmorel simulations 2020-2035.

In Figure 71 the heat supply from heat pumps (according to the forecast by Energinet.dk [Energinet.dk 2013a]) is shown together with the total heat demand of individually heated buildings. The 2006 data is according to [Aalborg Universitet 2006]. The 2030 estimate is based on Danish Climate Commission forecast (including demolition and heat savings in existing buildings) by [Hedegaard 2013]. Others years are made with linear interpolations.

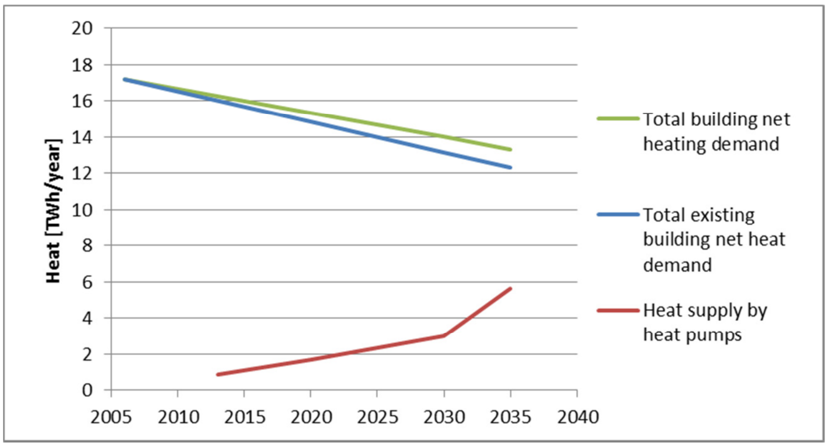


Figure 71. The heat supply of heat pumps and the total heat demand of individual heated buildings excluding new built (blue) and including new built (green).

The total heat demand of existing buildings 2020-2035 from Figure 71 is shown in the different building construction year categories in the figure below:

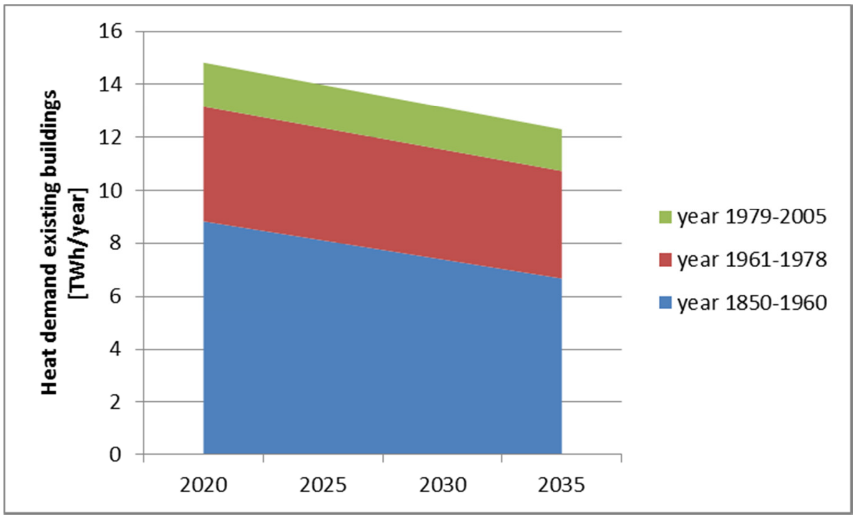


Figure 72. Breakdown of heat demand of individual heated buildings into three building categories (year group, excluding new-built).

The development in yearly heat consumption per building (in different building year categories) is shown Figure 73:

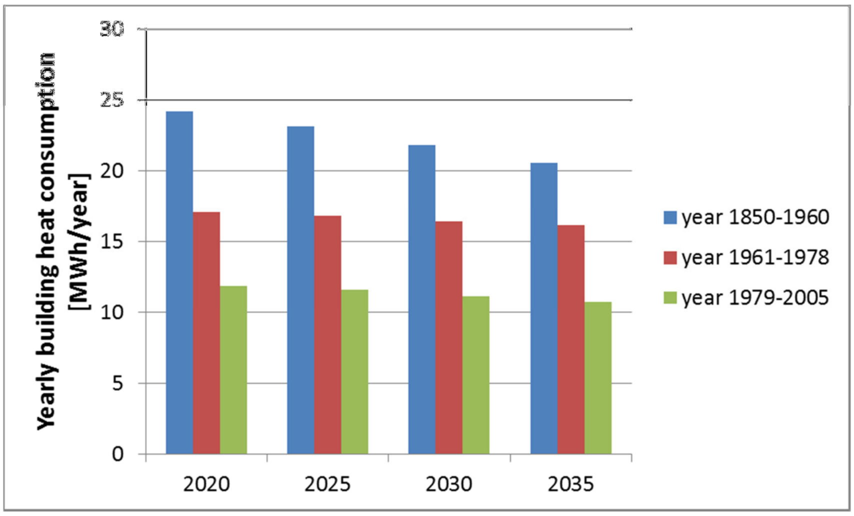


Figure 73. The yearly heat consumption per building from 2020-2035 in the different building year categories (different U-values).

The share of heat pumps in buildings after 1960 is assumed to be double as high as before 1960 (own estimate based on Catalyst [Catalyst 2013]). Thus, the share of heat pumps in each building category can be calculated 2020-2035 to make the sum of heat supply in each building category equal to the total heat supply of all heat pumps showed in Figure 71. The calculated shares are shown below:

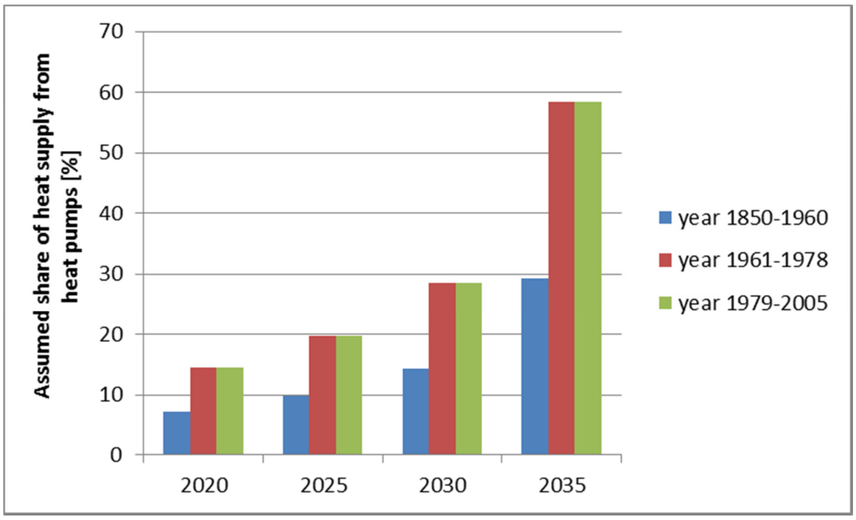


Figure 74. The assumed share of houses with heat pumps in the different building categories (assumptions based on [Catalyst 2013]).

An overview of the parameters for heat demand and heat pumps in the different categories is presented in Table 20:

Parameters describing buildings heat demand 2020-2035			Construction period		
Description	Unit	Average or total (1850-2005)	1850-1960	1961-1978	1979-2005
2006					
Net heat demand	TWh	17,2	10,83	4,59	1,75
Av. heat demand per area	kWh/m2	150	198	123	78
Heated floor area	mio m2	114	55	37	22
Hot water share		0,16	0,10	0,14	0,24
House size, av.	m2/house	155	142	151	171
Calculated number of houses		*763.115*	*384.466*	*247.150*	*131.499*
Calculated heat pump demand per house	*MWh_power/house/year*	*6,68*	*9,39*	*6,20*	*4,45*
2020					
Net heat demand	TWh	14,8	8,83	4,33	1,66
Av. heat demand per area	kWh/m2	133	174	116	72
Heated floor area	mio m2	111	51	37	23
Hot water share		0,18	0,12	0,15	0,26
House size, av.	m2/house	155	142	151	171
Calculated number of houses		*738.501*	*356.173*	*246.956*	*135.372*
Calculated heat pump demand per house	*MWh_power/house/year*	*6,07*	*8,26*	*5,85*	*4,09*
Assumed share with heat pump	pct.		7,3	14,6	14,6
Heated floor area, ajusted	mio m2	*12,5*	*3,7*	*5,5*	*3,4*
Heat pump power consumption	*TWh_power/year*	***0,51***	*0,21*	*0,21*	*0,08*
Calculated number of heat pumps		*81874*	*26.018*	*36.079*	*19.777*
2025					
Net heat demand	TWh	14,0	8,11	4,24	1,63
Av. heat demand per area	kWh/m2	129	169	115	71
Heated floor area	mio m2	108	48	37	23
Hot water share		0,19	0,13	0,16	0,27
House size, av.	m2/house	155	142	151	171
Calculated number of houses		*717.807*	*337.608*	*244.895*	*135.303*
Calculated heat pump demand per house	*MWh_power/house/year*	*5,93*	*8,01*	*5,77*	*4,01*
Assumed share with heat pump	pct.		9,9	19,8	19,8
Heated floor area, ajusted	mio m2	*16,6*	*4,8*	*7,3*	*4,6*
Heat pump power consumption	*TWh_power/year*	***0,66***	*0,27*	*0,28*	*0,11*
Calculated number of heat pumps		*108668*	*33.412*	*48.474*	*26.781*
2030					
Net heat demand	TWh	13,1	7,4	4,1	1,6
Av. heat demand per area	kWh/m2	122	157	111	68
Heated floor area	mio m2	108	47	37	24
Hot water share		0,19	0,13	0,16	0,28
House size, av.	m2/house	155	142	151	171
Calculated number of houses		*716.099*	*330.722*	*246.802*	*138.575*
Calculated heat pump demand per house	*MWh_power/house/year*	*5,63*	*7,46*	*5,60*	*3,84*
Assumed share with heat pump	pct.		14,3	28,6	28,6
Heated floor area, ajusted	mio m2	*24,2*	*6,7*	*10,7*	*6,8*
Heat pump power consumption	*TWh_power/year*	***0,90***	*0,35*	*0,40*	*0,15*
Calculated number of heat pumps		*157631*	*47.329*	*70.639*	*39.663*
2035					
Net heat demand	TWh	12,3	6,68	4,06	1,56
Av. heat demand per area	kWh/m2	116	149	109	65
Heated floor area	mio m2	106	45	37	24
Hot water share		0,20	0,14	0,16	0,28
House size, av.	m2/house	155	142	151	171
Calculated number of houses		*702.876*	*315.815*	*246.720*	*140.341*
Calculated heat pump demand per house	*MWh_power/house/year*	*5,42*	*7,05*	*5,48*	*3,71*
Assumed share with heat pump	pct.		29,2	58,4	58,4
Heated floor area, ajusted	mio m2	*48,9*	*13,1*	*21,8*	*14,0*
Heat pump power consumption	*TWh_power/year*	***1,75***	*0,65*	*0,79*	*0,30*
Calculated number of heat pumps		*318397*	*92.257*	*144.146*	*81.994*

Table 20. Parameters describing heat demand and heat pumps in the three construction periods in 2006, 2020, 2025, 2030 and 2035.

7.1.4 HEAT CAPACITY AND HEAT TRANSFER COEFFICENT

Illustration of the heat capacities and heat transfer coefficients are shown in Figure 6.

Heat capacity

The heat capacity of indoor air and furniture etc. in the building is $C_{i.a.}$ = 4 Wh/m2/°C.

Each building construction year category is divided into three *heat capacity* categories: C_{wall} = 60, 100, 140 Wh/m2/°C. The assumptions regarding share of building with different heat capacities are described in [Hedegaard 2013].

Houses with floor heating have C_{wall} = 100 Wh/m2/°C and additional heat capacity C_{Floor} = 67 Wh/m2/°C.

Validation:

The simplified heat capacities in different rooms as function of the floor area are illustrated in Table 21 [SBI]:

Category	**Indoor building construction description**	**Heat capacity C_{wall}**	
		W h/K m²	**kJ/K m²**
Very light	Light walls, floors and ceilings, e.g. boards, no heavy parts at all.	40	144
Middle light	Isolated heavy parts, e.g. concrete floor with wooden floor or lightweight concrete	80	288
Middle heavy	More heavy parts, e.g. concrete floor with floor tile, clincer concrete walls etc.	120	432
Extra heavy	Heavy walls, floors and ceilings in concrete, floor tile etc.	160	576

Table 21. The description of heat capacities in different building constructions [SBI].

Heat transfer coefficient

The buildings heat loss is calculated as the sum of ventilation loss and heat loss via the building structure (walls and floor)

The *heat transfer coefficient* of different buildings groups is calibrated to meet the space heating demand in 2020 and 2030. Linear interpolation is used to find the heat transfer coefficient in other years.

U-Values used in simulation	Unit	Average or total (1850-2005)	Construction period 1850-1960	1961-1978	1979-2005
2020					
Heat transfer coefficient for ventilation loss from indoor air to surroundings	W/m2 floor area/°C		0,34	0,32	0,29
RAD: Heat transfer coeff. for heat transfer from construction to outdoor air	W/m2 floor area/°C		1,57	0,98	0,53
FLO: Heat transfer coefficient for transmission loss from walls/ceiling to outdoor air	W/m2 floor area/°C				0,47
2025					
Heat transfer coefficient for ventilation loss from indoor air to surroundings	W/m2 floor area/°C		0,32	0,31	0,28
RAD: Heat transfer coeff. for heat transfer from construction to outdoor air	W/m2 floor area/°C		1,49	0,97	0,52
FLO: Heat transfer coefficient for transmission loss from walls/ceiling to outdoor air	W/m2 floor area/°C				0,45
2030					
Heat transfer coefficient for ventilation loss from indoor air to surroundings	W/m2 floor area/°C		0,31	0,30	0,28
RAD: Heat transfer coeff. for heat transfer from construction to outdoor air	W/m2 floor area/°C		1,41	0,95	0,50
FLO: Heat transfer coefficient for transmission loss from walls/ceiling to outdoor air	W/m2 floor area/°C				0,44
2035					
Heat transfer coefficient for ventilation loss from indoor air to surroundings	W/m2 floor area/°C		0,29	0,30	0,28
RAD: Heat transfer coeff. for heat transfer from construction to outdoor air	W/m2 floor area/°C		1,33	0,93	0,48
FLO: Heat transfer coefficient for transmission loss from walls/ceiling to outdoor air	W/m2 floor area/°C				0,43

Table 22. Three U-values per construction period for 2020, 2025, 2030 and 2035, respectively.

7.1.5 HEAT PUMP DIMENSIONING CRITERIA

The dimensioning criteria regarding the

a) *Total installed heat capacity.*
The heat capacity has to cover the buildings space heating demand and hot water demand at Tdesign = -12 °C outside temperature [iPower WP3.6 2014]. As it is seen in Figure 75 the possible heat effect is reduced at lower outdoor temperatures, whereas the heat demand increases. Due to different heat demands the heat capacity of the heat pump is depending on the building category (insulation level).

b) *The split between heat effect from the COP-heat pump and the (auxiliary) electric heater.*
The COP-heat pump without electric heater has to cover the heat demand at -7 °C [Pedersen 2014].

Thus, in the base scenario the heat effect split of 80% COP-heat pump and 20% electric heater (efficiency=0,99) is used. A sensitivity analysis with 65% COP-heat pump and 35% electric heater is also performed.
However, today the installed electric heater can often provide similar heat effect as the COP-heat pump (e.g. 8-10 kW in 2-3 step) and not just 20% of the total heat capacity. It is assumed that full use of the electric boiler in houses is highly uncorrelated; hence, the average electric boilers supply 20% of the heat demand at -12 °C and the COP-heat pump provide the remaining 80% of the heat demand at -12 °C.

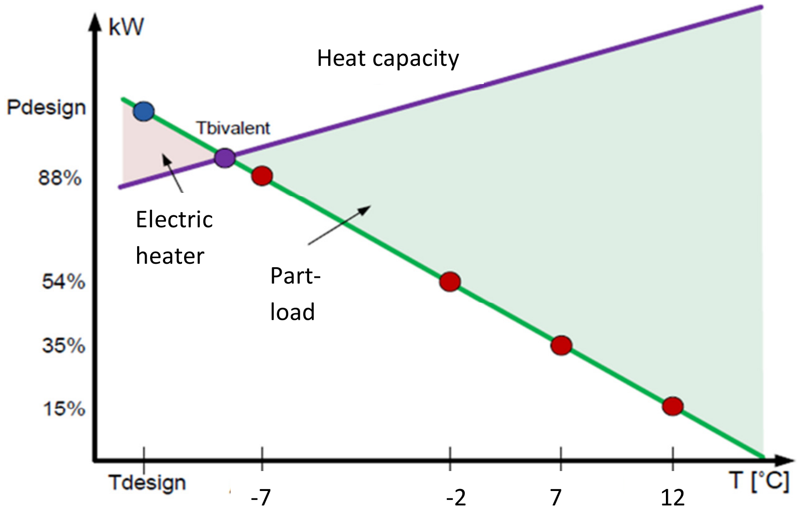


Figure 75. Dimensioning of heat pump and electric heater. The heat capacity is the maximum heat effect of heat pump and electric heater at Tdesign = -12C [Danish Energy Agency].

7.1.6 MODELING OF HEAT PUMP COP

The following modeling concerns the COP of the heat pump without electric boiler.

The heat pumps in all building categories have similar COP characteristic to reflect they represent an aggregated volume.

Development of Air-to-water and ground source heat pumps

The COP is a weighted average of the COP of air-to-water and ground source, respectively:

$$COP_{HP} = COP_{GS\ HP} * GSshare + COP_{A/W\ HP} * (1-GSshare)$$

The share of air-to-water and ground source heat pumps is shown in Figure 76.

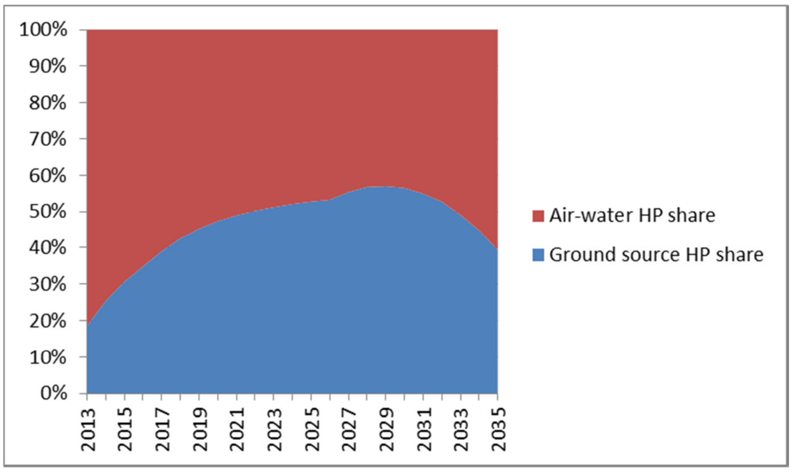


Figure 76. Share of air-to-water and ground source heat pumps in the simulation. Assumptions based on detailed information regarding heat pump development found in [Energinet.dk 2013a].

Influence of reservoir temperature and supply temperature

The heat pumps COP vary during the season according to several factors, two of the most dominant are the *reservoir temperature* and *supply temperature.* In general the COP depends on the temperature lift required, i.e. the COP decreases when the distance between the reservoir temperature and supply temperature increases. Thus, the COP is modelled as a function of the reservoir temperature (ground and air temperature, respectively) and supply temperature for both air-to-water and ground source heat pump.

- COP (Tsource,Tsupply)

Two data sheet are used to model the COP of an air-to-water and ground source heat pump, respectively. The parameters in an algebraic equation are fitted based on the COP values with different source temperature and supply temperatures in the data sheets. The model uses linear interpolation to estimate any COP value within 30C<Tsupply<55C and -20C<Tsource<20C:

COP (Tsource,Tsupply) = COP(Tsource,$\text{Tsupply}_{\text{constant}}$) + DeltaCOP(Tsource)*f(Tsupply) =>

COP (Tsource,Tsupply) = COP(Tsource,Tsupply=55C) + DeltaCOP(Tsource)*(55-Tsupply)/(55-35)

This function requires the following input:

- Tsource profiles, i.e. ground and air temperature profiles
- Tsupply profiles in houses with Radiator and Floor heating

In the following sections the data sheets, Tsource and Tsupply are explained.

The data sheet for ground source heat pump (Figure 77) and the equations used in the model (Figure 78):

Tekniske data for varmepumpe (Effekter og COP er opgivet i henhold til EN14511)										
		Queen 5			Queen 7			Queen 9		
Kold side Indg./ udg.	Varm side fremløb/ retur	Afgivet effekt	Tilført effekt	Effekt-faktor	Afgivet effekt	Tilført effekt	Effekt-faktor	Afgivet effekt	Tilført effekt	Effekt-faktor
°C	°C	kW	kW	COP	kW	kW	COP	kW	kW	COP
-5/-8	35/30	4,7	1,3	3,6	6,4	1,7	3,8	8,0	2,1	3,8
	45/40	4,6	1,5	3,0	6,1	1,9	3,1	7,6	2,4	3,2
	55/50	3,7	1,6	2,4	5,2	2,1	2,5	6,5	2,6	2,5
0/-3	35/30	5,2	1,2	4,3	7,3	1,7	4,3	9,1	2,1	4,3
	45/40	4,9	1,4	3,4	6,9	2,0	3,5	8,6	2,4	3,5
	55/50	4,7	1,8	2,6	6,6	2,4	2,7	8,2	3,0	2,8
5/2	35/30	6,4	1,4	4,6	8,8	1,8	4,9	11,1	2,3	4,8
	45/40	6,1	1,6	3,8	8,2	2,2	3,7	10,4	2,7	3,8
	55/50	5,7	2,0	2,9	7,8	2,6	3,0	9,7	3,2	3,0
10/7	35/30	7,5	1,5	5,0	10,4	2,0	5,2	13,0	2,4	5,3
	45/40	7,1	1,8	3,9	9,6	2,3	4,2	12,2	2,8	4,3
	55/50	6,6	2,1	3,1	9,1	2,8	3,2	11,4	3,4	3,3
Varmepumpe										
Kølemiddel		R407C/1,6kg			R407C/1,6kg			R407C/1,6kg		
Kompressor		Copeland scroll ZH15			Copeland scroll ZH21			Copeland scroll ZH26		
Kondensator/ fordamper		Pladeveksler			Pladeveksler			Pladeveksler		

Figure 77. The 'Queen 9' COP for different cold side temperature and supply temperature of 35C and 55C is used in the model [Nielsen 2014].

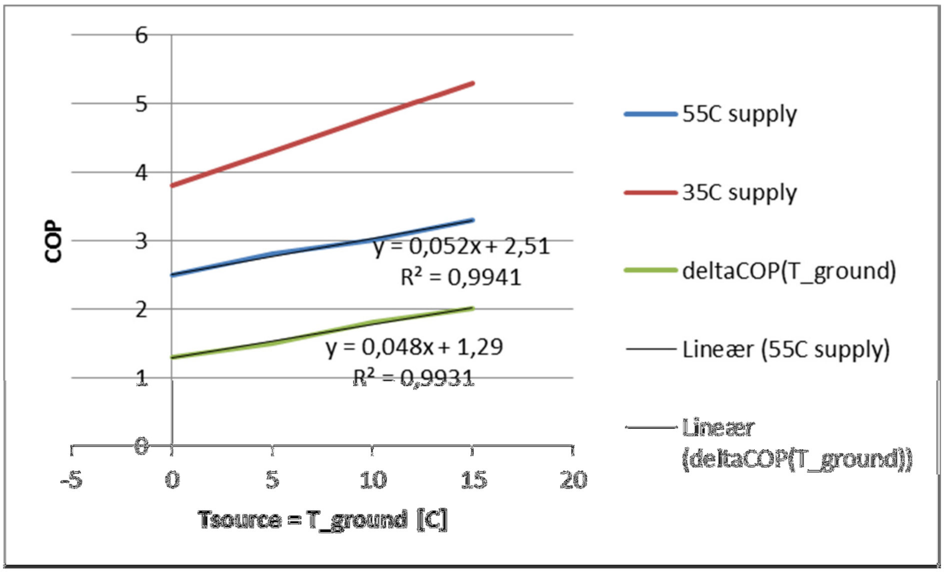


Figure 78. The COP with different supply temperatures (35C and 55C) as function of different ground temperatures. The temperature difference between cold side inlet temperature and ground temperature (T_ground) is assumed 5 °C [Heerup 2014].

<u>The data sheet for air-to-water heat pump</u> (Figure 79) and the equations used in the model (Figure 80):

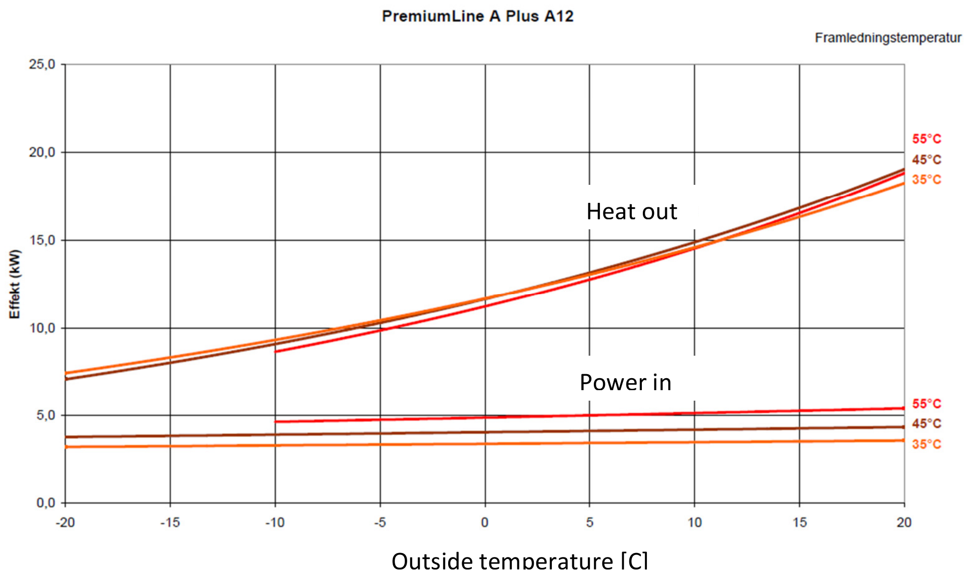


Figure 79. Data sheet of air-to-water heat pump with consumed power and supplied heat with different supply temperatures [Nielsen 2014].

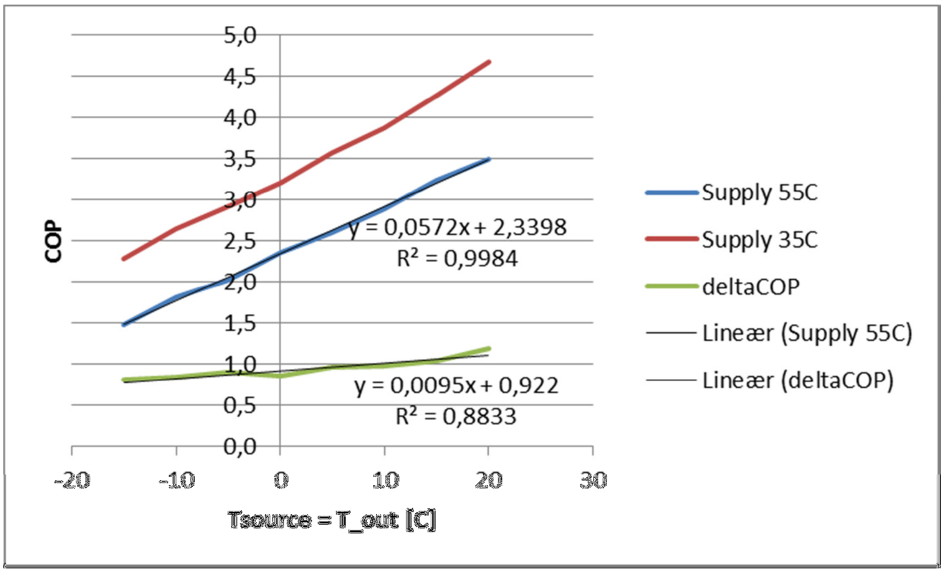


Figure 80. COP with different supply temperatures calculated based Figure 79.

<u>Tsource profiles, i.e. ground and air temperature profiles</u>

The source temperature is:

- Tout: The temperature profile for the air
- Tground: The ground is calculated as the <u>weekly average outdoor air temperature, minimum 0 C.</u>

The applied ground temperature based on the average weekly outdoor temperature is shown in Figure 81:

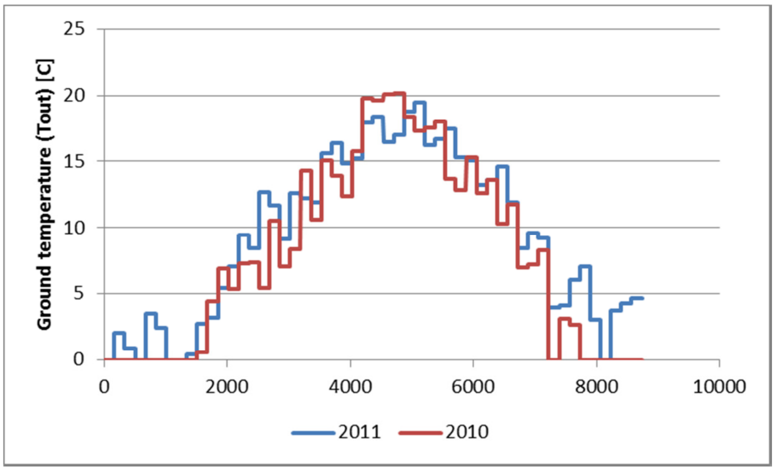


Figure 81. The ground temperature as the average air temperature in the week.

Data reference:

The correlation between the brine return temperature (≈ground temperature) and the outdoor air temperature is based on the measurements in [Danish Technological Institute 2012]:

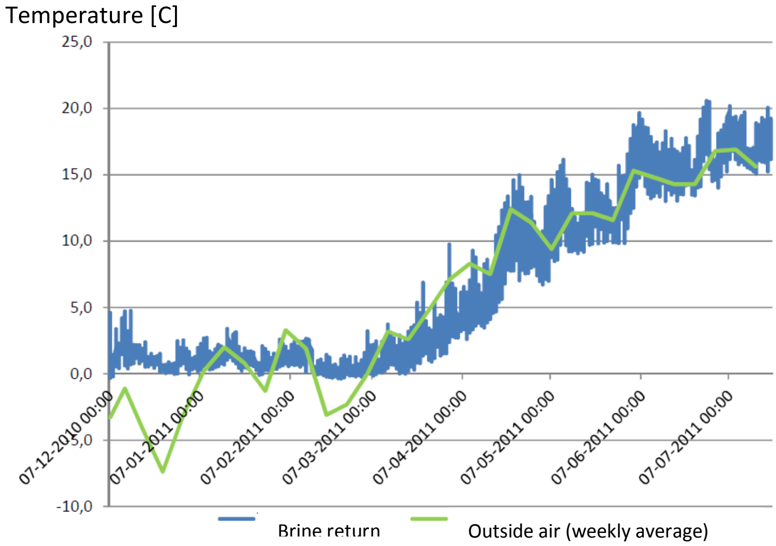


Figure 82. The measurement of weekly average air temperature and brine return temperature ≈ ground temperature [Danish Technological Institute 2012].

Tsupply profiles in houses with Radiator and Floor heating

When a high heat production is needed, the supply temperature has to be increased to transfer the heat (due to flow and heat transfer area restrictions) and vice versa.

The required supply temperature is calculated as function of the average daily (24 hours) outside temperature, $T_{out,DayAverage}$, which is a proportional with the buildings daily required heat demand. The COP is decreased when the supply temperature is increased.

T_{supply} ($Q_{heat\ pump\ production}$) and $Q_{heat\ pump\ production}$ ($T_{out,DayAverage}$)

=> T_{supply} ($T_{out,DayAverage}$)

For -20C< $T_{out,DayAverage}$ <20C the supply temperature for space heating and floor heating, respectively, is assumed to vary between:

- Radiator heating: 30C<Tsupply<55C

- Floor heating: 30C<Tsupply<42,5C

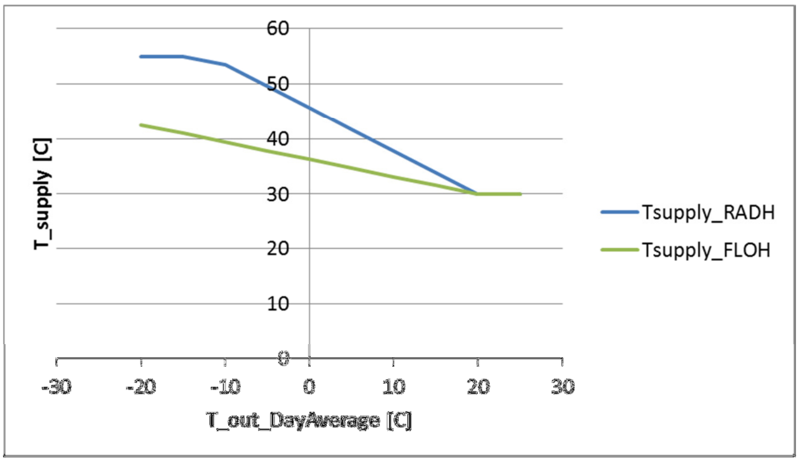


Figure 83. The supply temperature as function of the daily outdoor temperature for radiator and floor heating.

The daily average outside temperature, $T_{out,DayAverage}$, is shown for 2011 and 2010 profile in Figure 84:

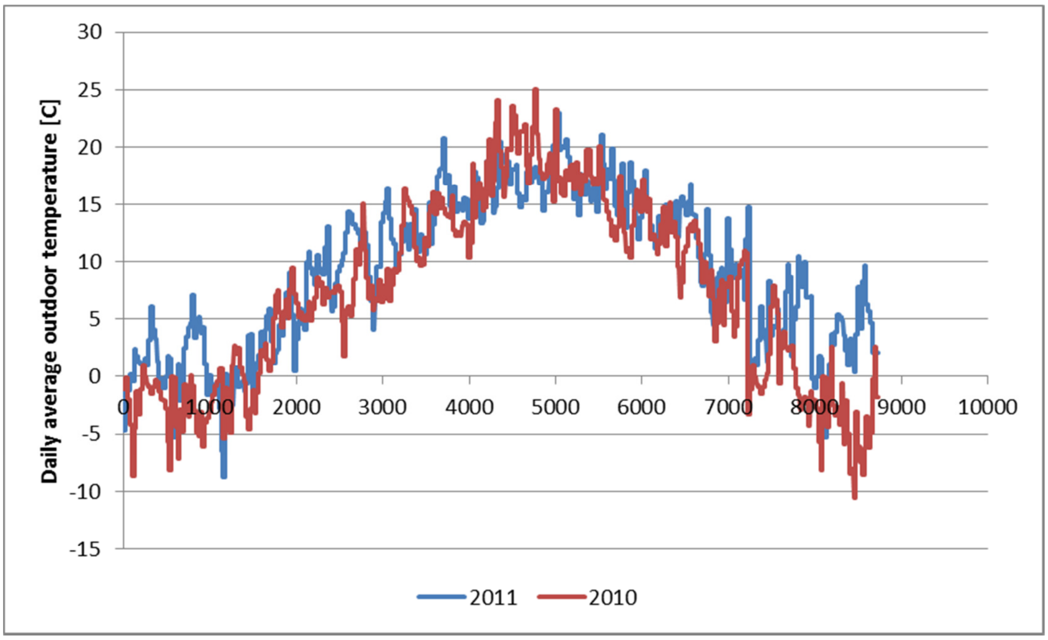


Figure 84. The daily average outdoor temperature for 2011 and 2010 profile (Denmark West).

Data reference:

The temperature is measured for a number of Danish heat pump installations and an example of the relationship between supply temperature and outdoor temperature in houses with radiator heating is shown in Figure 85 [Danish Technological Institute 2012]:

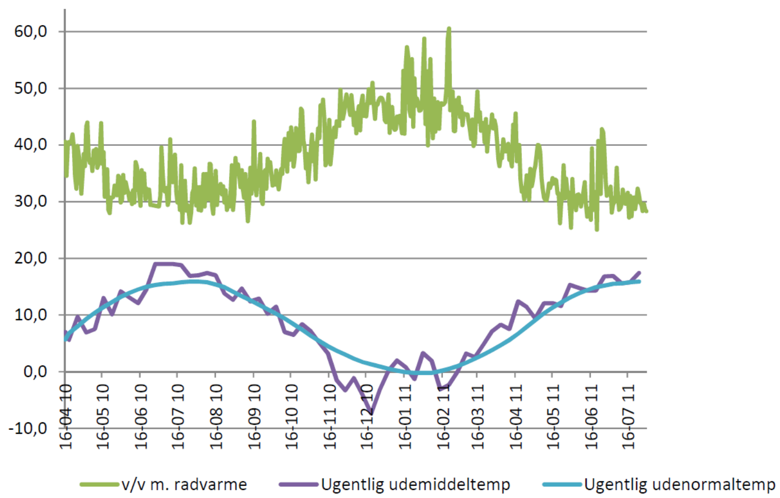


Figure 85. Supply temperature and outside temperature, measurement of 14 ground source heat pumps in houses with radiator heating [Danish Technological Institute 2012].

7.1.7 HOT WATER DEMAND PROFILE

The hot water consumption is implemented with a constant daily profile and daily heat demand in each building year group. The hot water demand profile is shown in Figure 86:

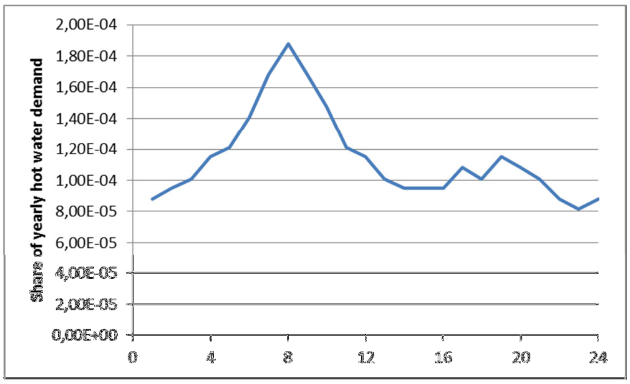


Figure 86. Profile of hot water demand

The hot water demand is calculated as:

Hot water demand (MWh/h per building year group) = Hot water demand profile (%/h) * Hot water share of total heat demand (% per building year group) * Total heat demand (MWh/year per building year group)

The hot water share of total heat demand is shown in Table 23 for different building year groups:

	Buidling year 1850-1960	Buidling year 1961-1978	Buidling year 1979-2005
Hot water share of total heat demand 2020-2035	~13%	~16%	~27%

Table 23. The hot water share of the total heat demand (incl. space heating) in different building year groups. The share is average from 2020-2035. [Hedegaard 2013]

The hot water demand is not optimized for flexible heat pumps.

7.2 ADDITIONAL RESULTS: DAY-AHEAD MARKET

7.2.1 HEAT PUMP COP

Based on the modeling of the COP as function of supply and source temperature (see Appendix 7.1.6) the COP in each simulation hour in Balmorel is shown for two different temperature profiles in 2035:

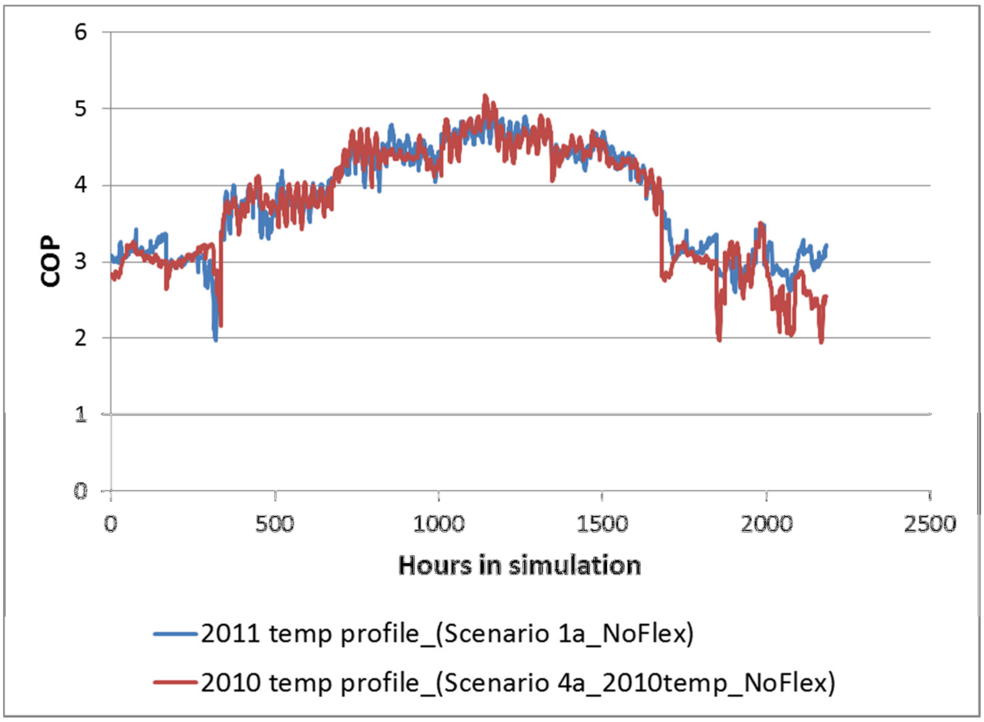


Figure 87. The calculated COP in each simulation hour in Balmorel in 2035 for two different outdoor temperature profiles.

The calculated COP for different outdoor temperature is shown in the figures below:

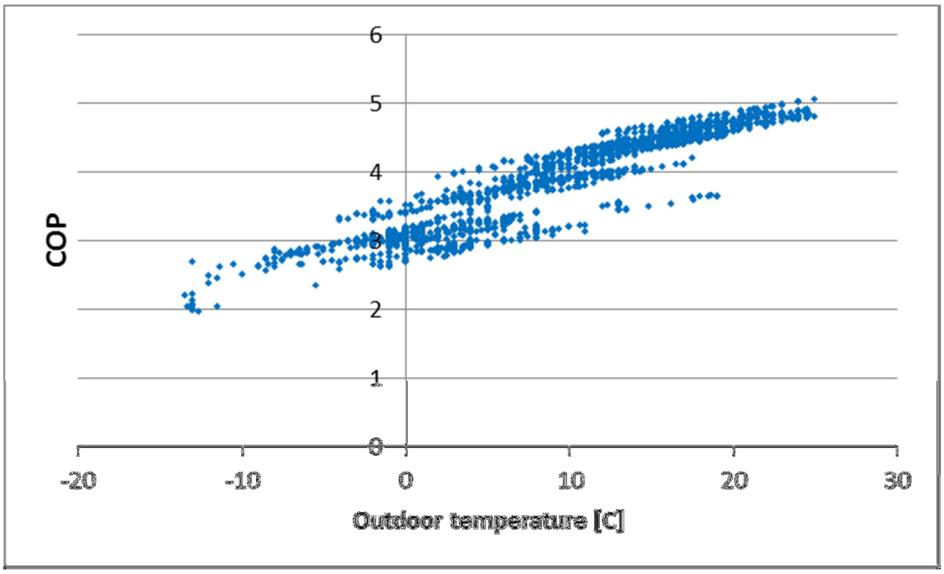


Figure 88. The COP for different outdoor temperature (2011 temp profile).

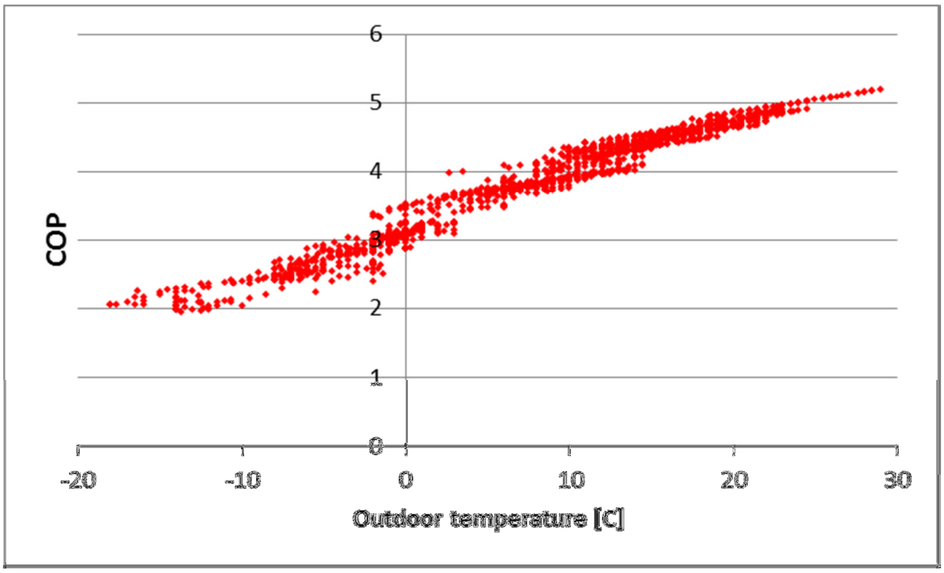


Figure 89. The COP for different outdoor temperature (2010 temp profile).

Development of COP 2020-2035

COP according to data-sheets

The COP (T_{supply}, T_{source}) is calculated according to data-fitting of air-to-water heat pump (Figure 80) and ground source heat pump (Figure 78). The weighted average COP is calculated according to share of the two different heat pumps presented in Figure 76.

Adjusting the COP

The COP data sheets are valid for 2011-2013 heat pumps. The applied COP is reduced with 5% compared to the data sheet to include the effect of older heat pumps and reduced efficiency due to start-stop and part-load operation.

The development in yearly consumption-weighted COP of all new heat pumps in Balmorel is assumed to be:

	Year 2020	Year 2025-2030	Year 2035
$COP_{adjusted}$	3/3 = 1	3,2/3 = 1,067	3,4/3 = 1,133

Table 24. Development in yearly consumption-weighted COP of all new heat pumps

The COP of heat pumps installed in the year 2020, 2025, 2030 and 2035, respectively, is calculated as:

$$COP(year) = COP\ (T_{supply}, T_{source}) * 0{,}95 * COP_{adjusted}$$

The calculated COP in Balmorel

The development in yearly average COP of all heat pumps (with different installation year) from 2020-2035 in Balmorel in two scenarios with different outdoor temperature profile is shown in Figure 90.

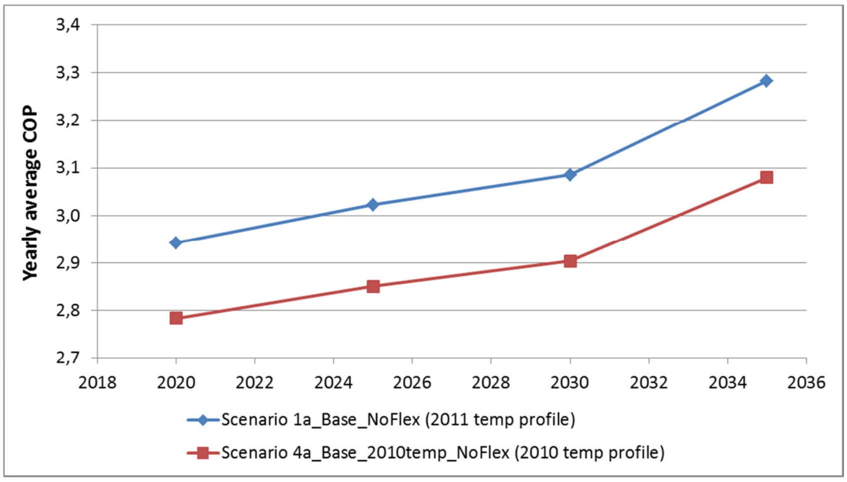


Figure 90. Yearly average COP of all residential heat pumps in scenarios with 2011 (blue) and 2010 (red) temperature profiles.

7.2.2 ILLUSTRATION OF HEAT PUMP OPTIMISATION

The power consumption, indoor temperature in building categories and the power price is shown below:

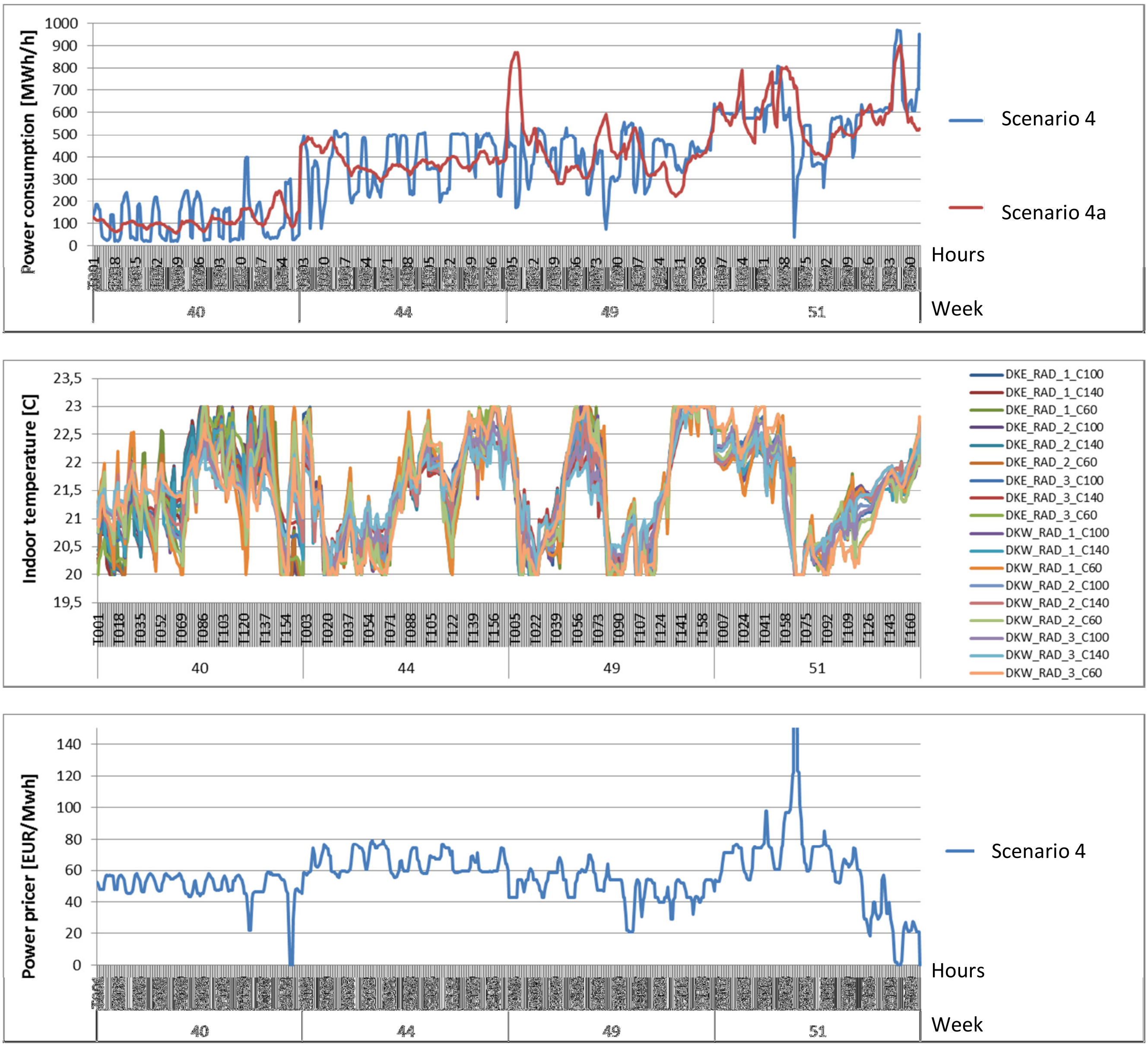


Figure 91. Result from Scenario 4 and 4a in 2035: Total residential heat power consumption (above), Indoor temperature in building categories (middle) and power price (below) during 4 simulation weeks.

The power consumption of the electric boiler is shown in Figure 92 for the non-flexible heat pumps:

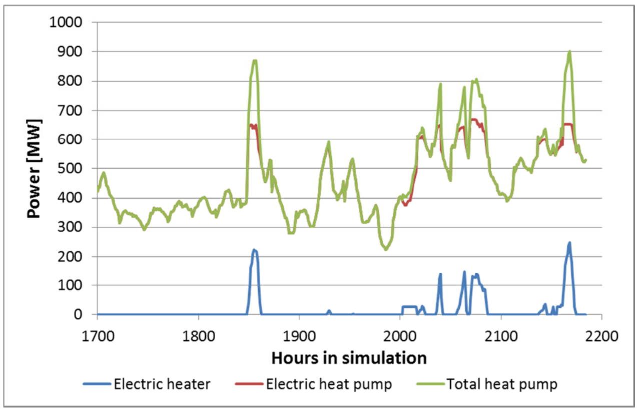


Figure 92. The electric heater part of the total power consumption of the heat pump (Scenario 4a).

The aggregated hourly power consumption of residential heat pumps for different outdoor air temperatures is shown in Figure 93. The data show the expected increase in power consumption when the outdoor temperature decreases. The variation in power consumption for similar outdoor temperature is due to different COP value (influence of ground temperature), power consumption of electric heater, hot water demand and heat contribution from persons etc.

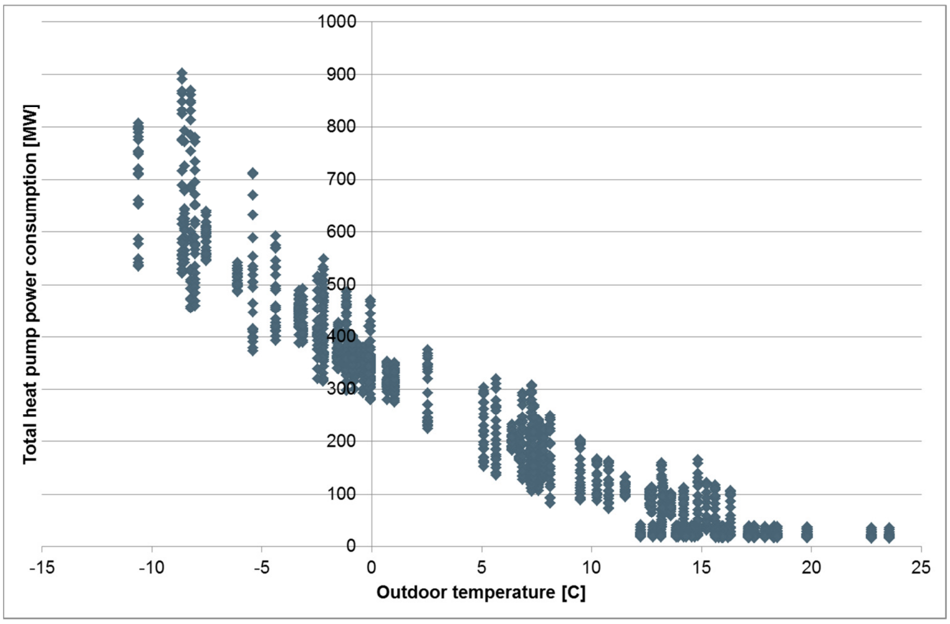


Figure 93. Simulated total power consumption of non-flexible residential heat pumps with 2010 temperature profile (Scenario 4a).

7.2.3 FLEXIBLE HEAT PUMP INVESTMENTS IN EACH BUILDING CATEGORY

The investment in flexible heat pumps in Scenario 1 from 2020-2035 in % of number of houses in each building category is shown Figure 91:

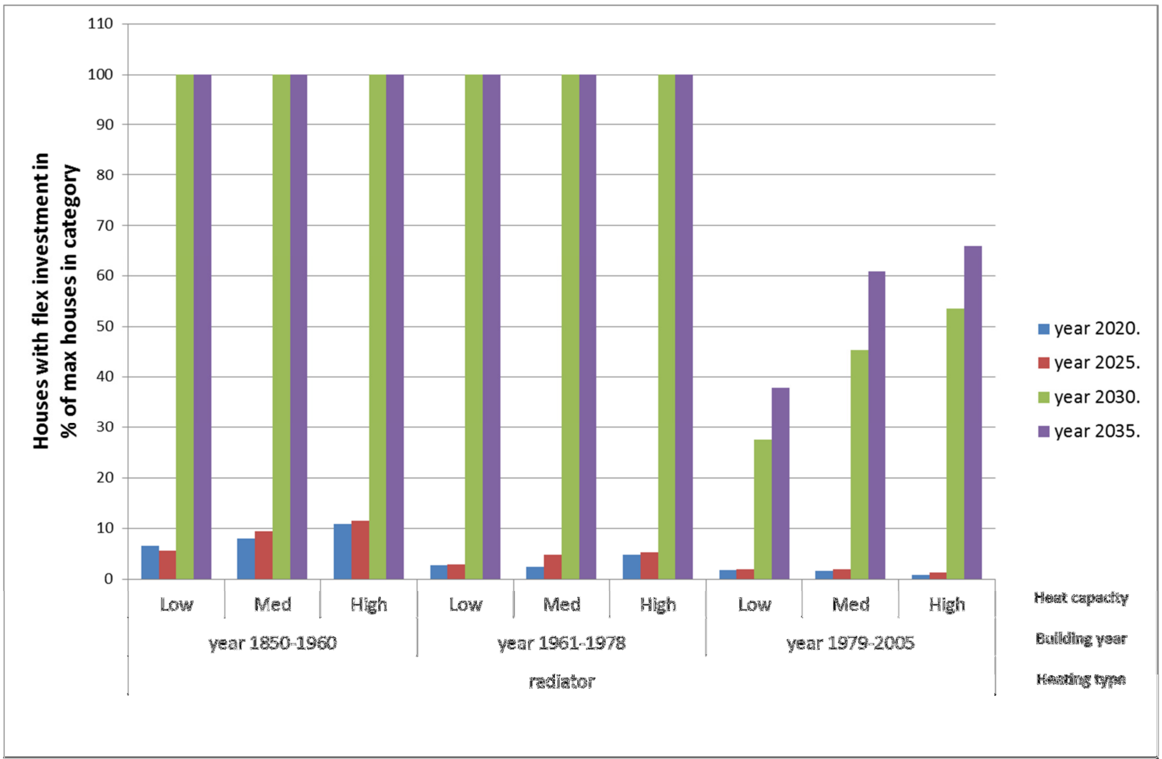


Figure 94. Investment in flexible heat pumps, Scenario 1 (base). The attractiveness of flexible heat pumps increases from 2020 to 2035. Houses with higher heat consumption has higher investments.

The similar results are shown for Scenario 3 with high Flexible investment costs in Figure 95:

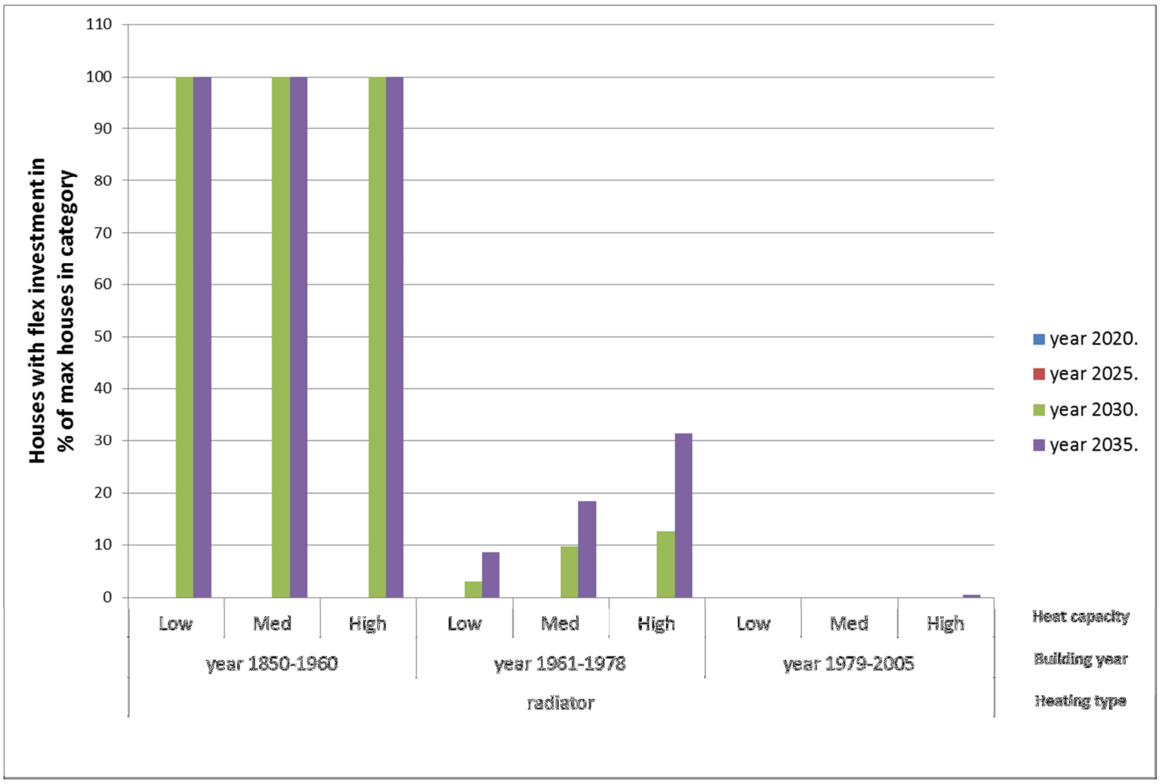


Figure 95. Investment in flexible heat pumps in Scenario 3 with high investment costs (double cost of flexibility).

7.3 ADDITIONAL ASSUMPTIONS: ANCILLARY SERVICES

7.3.1 OPTIMISATION OF FLEXIBLE CONSUMPTION TOWARDS REGULATING POWER MARKET

Optimisation methodology towards spot market and regulating power market [Biegel et al 2013]:

"In this work we utilize the following simple strategy. After gate closure at 1 p.m., the spot price realizations will be published. Based on these spot price realizations, we reoptimize the consumption of the portfolio. Following, for each hour of the day, we bid the difference between the purchased electricity and the volume gained from the reoptimization, if feasible, with a bidding price equal to the spot price. If activated, we will get a regulating power price equal to or better thanthe spot price (our bid). Hereby we still avoid trading balancing power with the TSO, but enable ourselves to get access to regulating power prices when they are favorable." Source: [Biegel et al 2013]

7.4 ADDITIONAL RESULTS: ANCILLARY SERVICES

7.4.1 PRICES OF ANCILLARY SERVICES

<u>Denmark West: Primary reserve</u>

Denmark West: The Danish prices are expected to convert the German prices due to market integration. A comparison of prices (Danish prices calculated with bid duration of 1 month) is shown in Figure 96 [Energitilsynet 2013]. The German prices are stabile whereas the Danish prices are fluctuating and in general declining.

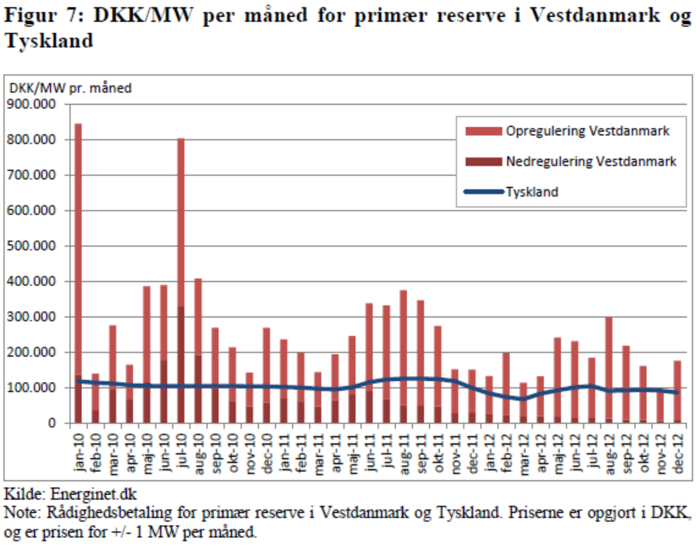


Figure 96. Primary reserve prices in Denmark West and Germany [Energitilsynet 2013].

The Danish prices for up regulation (under-frequency) and down regulation (over-frequency) are very different according to Figure 97, especially because electric boiler can provide down regulation reserves (increase power consumption) in all period without heat production. The price of up regulation (decrease power consumption) is still relative high and contributes to approximately 90% of the total Danish primary reserve price.

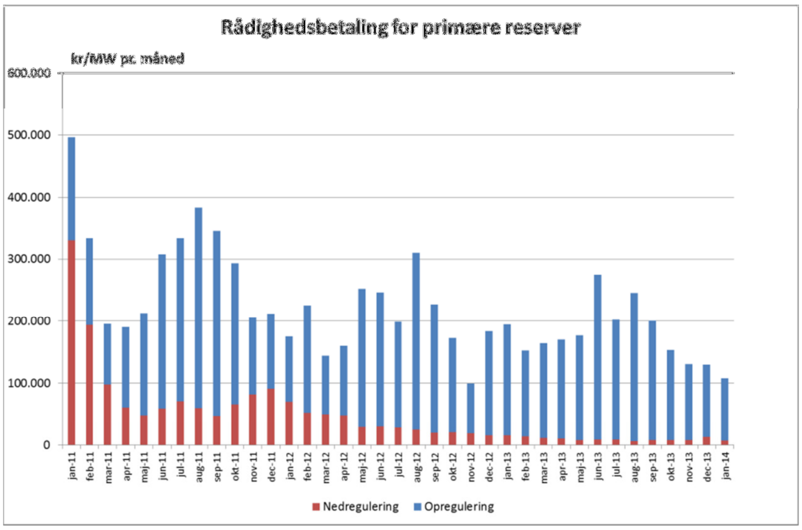


Figure 97. Availability payment of frequency control in Denmark West [Parbo 2014].

The average Danish primary regulation price (2 year period) is shown in Figure 98. The figure indicates a variation in prices between summer and winter and during day and night, which is important for flexible demand in general and especially heat pumps.

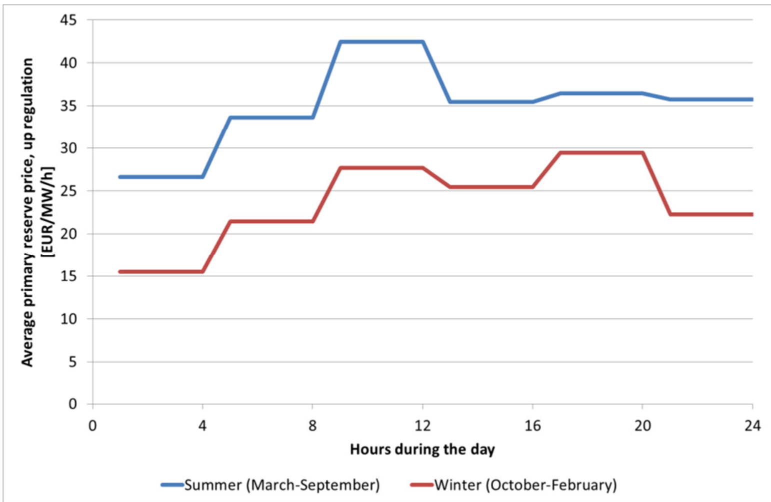


Figure 98. Average primary reserve prices 1 March 2012 – 28 February 2014 in winter and summer season [Energinet.dk].

To optimize the profit of flexible heat pumps both Elspot prices and ancillary service payment has to be included to calculate the optimal consumption pattern. As shown the primary reserve payment is highest during the day and lowest during the night. The power price follows the same pattern. Hence, cheaper power consumption leads to lower primary reserve payment and vice versa.

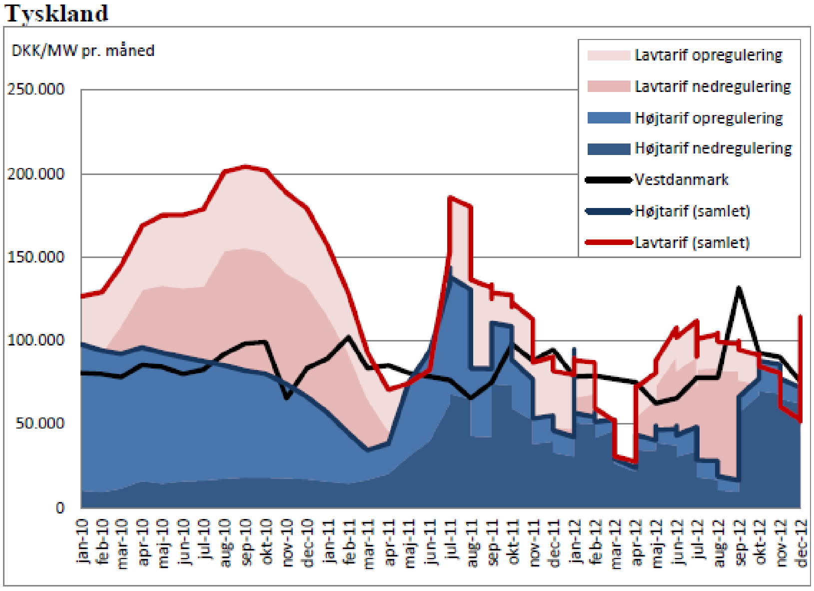
However, if the bid duration is longer (above 24 hours) the variation between day and night reserve prices will disappear.

The assumed primary reserve payment: ~100.000 DKK/MW/month (symmetric)

Denmark West: Secondary reserve

The secondary reserve price in Germany and Denmark West is shown below to be on similar level:

Figur 8: DKK/MW per måned for sekundær reserve i Vestdanmark og Tyskland



Kilde: Energinet.dk, www.regelleistung.net, SET's egne beregninger
Note: Rådighedsbetaling for sekundær reserve i Vestdanmark og Tyskland. Priserne er opgjort i DKK, og er prisen for +/- 1 MW per måned. Den tyske pris er opdelt i en højtarifperiode og en lavtarifperiode. *Højtarif (samlet)* er summen af op- og nedregulering i højtarifperioden, mens *lavtarif (samlet)* er summen af op- og nedregulering lavtarifperioden. Sidst i juni 2011 overgår tysk data fra at være opgjort pr. måned til at være opgjort pr. uge. Data efter juni 2011 er omregnet, således de er svarende til prisen for +/- 1 MW standard måned (30 dage). Enkelte uger strækker sig mellem to måneder, hvor ugens sidste dag afgør, hvilken måned ugen kommer til at tilhøre i beregningen. Der er ikke taget forbehold for afkortning af bud i de tyske priser.

Figure 99. The secondary reserve prices in Denmark West and Germany [Energitilsynet 2013].

The development of availability payment of secondary reserve in Denmark West is shown in Figure 100:

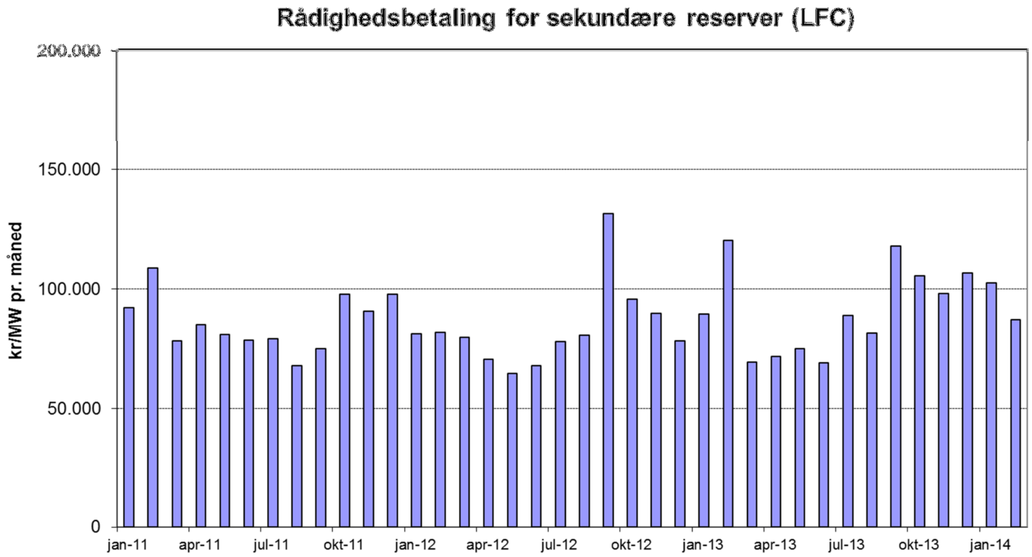


Figure 100. The development of availability payment of secondary reserve in Denmark West [Parbo 2014].

The assumed secondary reserve payment: ~90.000 DKK/MW/month (symmetric)

Denmark East: FNR

The development of availability payment of FNR in Denmark East is shown below:

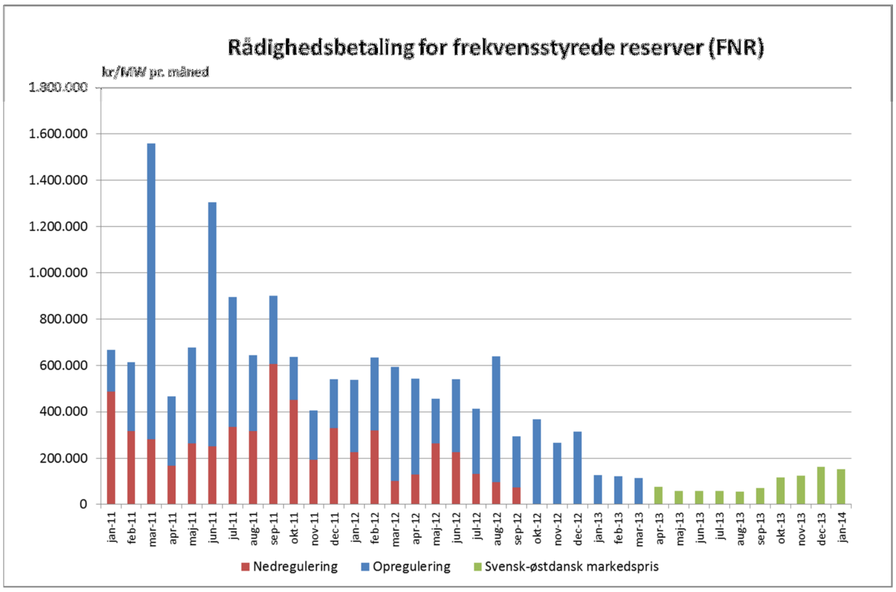


Figure 101. FNR prices in Denmark East [Parbo 2014].

The assumed FNR payment: ~100.000 DKK/MW/month (symmetric)

Denmark East: FDR

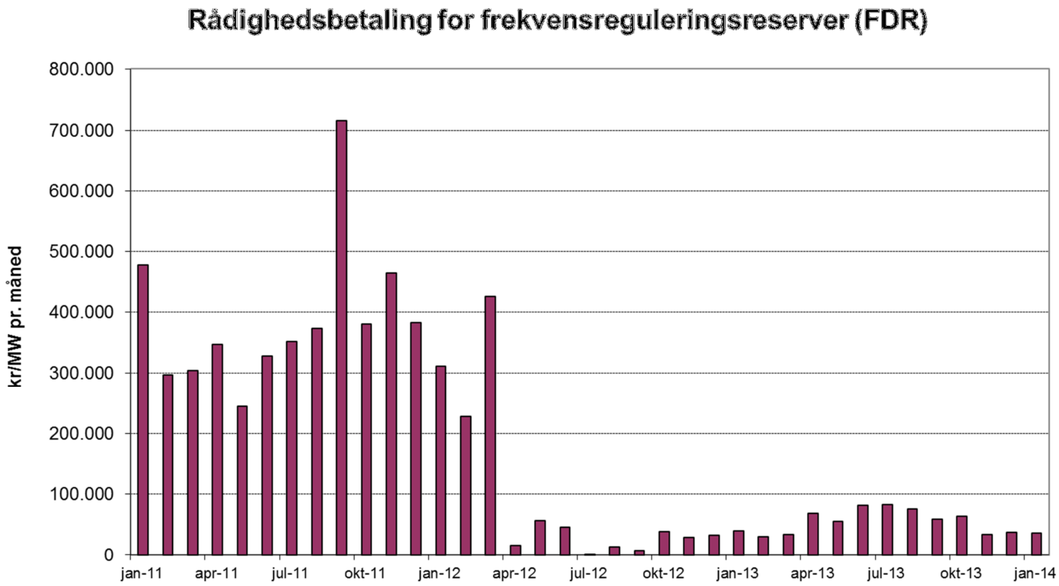


Figure 102. FDR prices in Denmark East [Parbo 2014].

The assumed FDR payment: ~35.000 DKK/MW/month (symmetric)

Denmark East: Manuel reserve

The manuel reservation in Denmark East (Sealand only) is approximately 213 million/year for 681 MW, corresponding to average availability payment of 26.000 DKK/MW per month [Energitilsynet 2013].

The manuel reserve contract in Denmark East (Sealand only) from 2016-2020 has an average availability payment of 22.600 DKK/MW per month [Energi-supply.dk].

The assumed Manuel reserve payment: ~25.000 DKK/MW/month (symmetric)

Denmark West: Manuel reserve

Availability payment of Manuel reserve

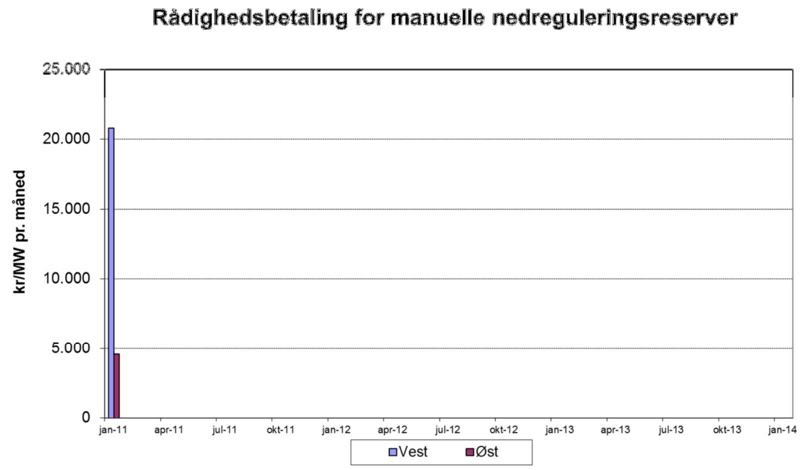


Figure 103. Down regulation reserves [Parbo 2014].

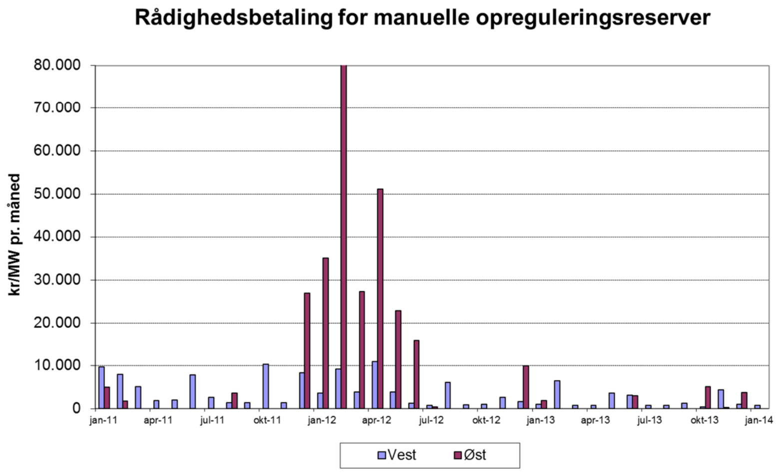


Figure 104. Upregulaiton reserves [Parbo 2014].

The development in manuel up regulation reservation (MW) and average payment per MW in Denmark West

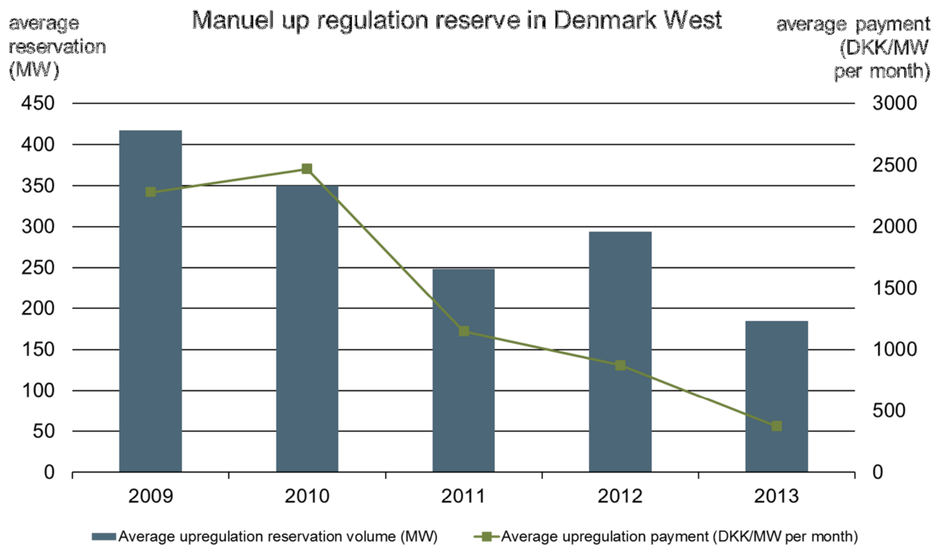


Figure 105. The manuel reserve reservation and average payment per MW.

The assumed Manuel reserve payment: ~500 DKK/MW/month (symmetric)

7.4.2 REGULATING POWER MARKET

The majority of the traded energy volume is on the Elspot market compared to the regulating power market.

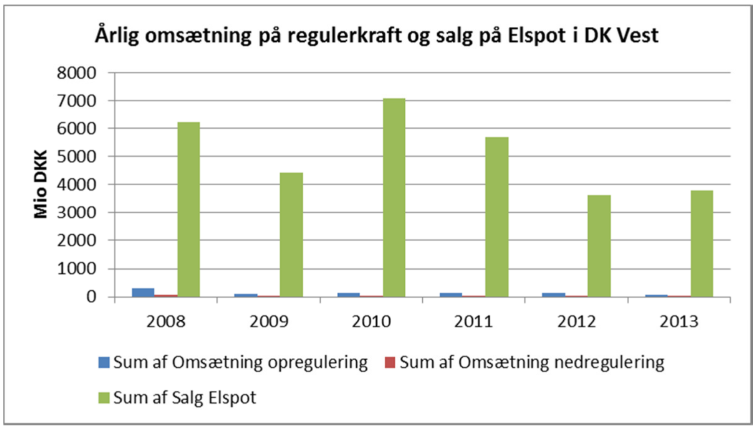


Figure 106. Yearly trade on Elspot and regulating power up and down, respectively.

The requirement for balancing (via Regulating power market and Intraday trading) increases with more wind power in the system. The yearly regulation power (up and down regulation) in Denmark West 2008-2013 is shown Figure 107. Despite larger wind power production the traded volumes of up and down regulation has been relatively constant from 2009-2013:

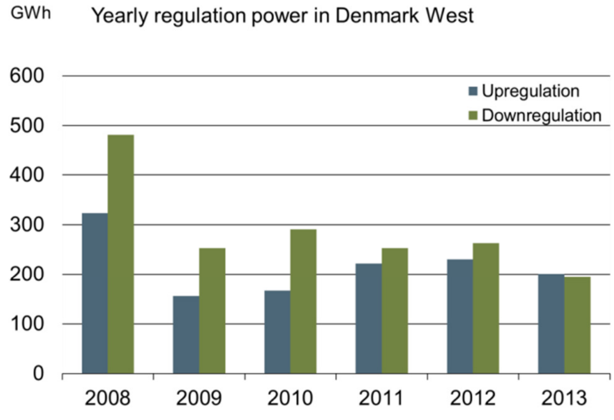


Figure 107. The yearly volume of energy in the Regulating power market.

The traded volume in 2012 in Intraday and regulating power market is shown below:

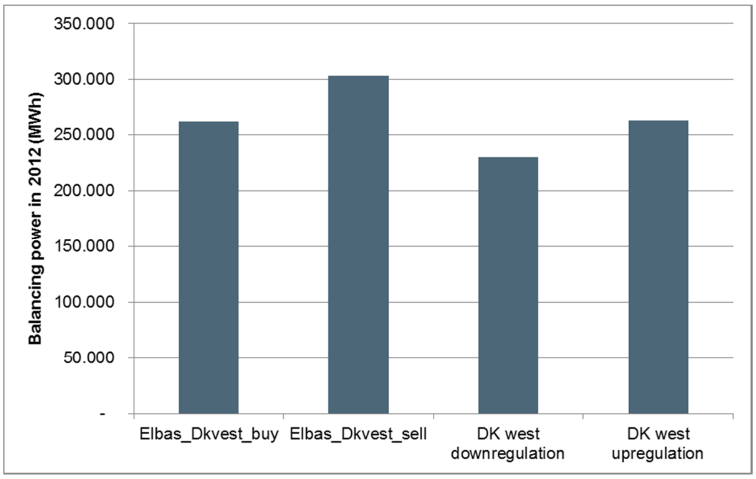


Figure 108. Balancing in 2012 in Intraday market (Elbas) and Regulating power market (up and down regulation) in Denmark West in 2012.

The duration curve of activation of up and down regulating power is shown below. In approximately 8760-2100-2500 = ~4200 hours there is no activation of regulating power

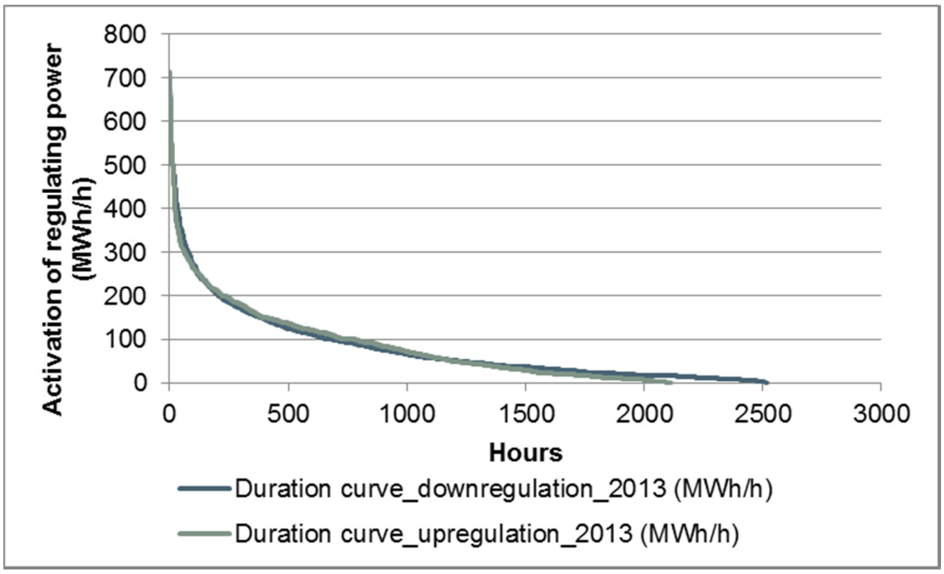


Figure 109. The activation of regulating power (duration curve).

Profit of Flexible consumption on regulating power market

The total profit on the regulating power market is estimated as:

- Profit upregulation [DKK]: (Up regulation price [DKK/MWh] - Elspot price [DKK/MWh]) * Volume of upregulation [MWh]
- Profit down regulation [DKK]: (Elspot price [DKK/MWh] - Down regulation price [DKK/MWh]) * Volume of down regulation [MWh]

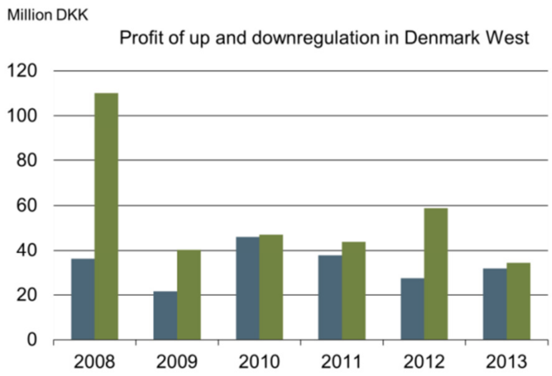


Figure 110. Yearly average profit of up and down regulation compared to spot market price [Energinet.dk].

The average price difference [DKK/MWh] between up and down regulation compared to the spot price in each hour is in average ~150 DKK/MWh from 2008-2013 (Figure 111). The median is ~60 DKK/MWh.

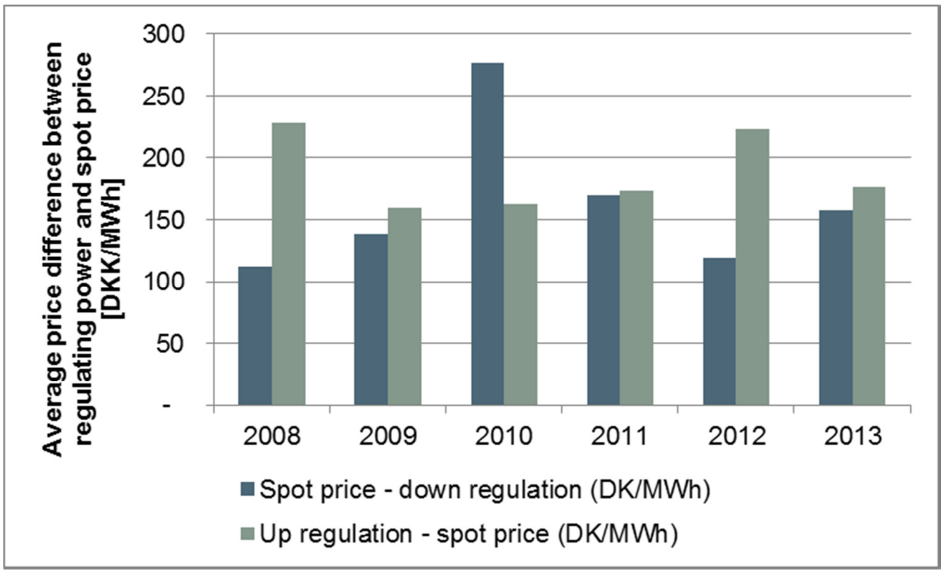


Figure 111. Average price difference between regulating power and spot price [Energinet.dk].

However, as seen in the duration curves in Figure 112 the variation in price spread between regulating power and spot price is very different per hour during the year 2013. This indicates a large part of the potential profit is found in few hours (100-200 hours). Increased supply during these hours could reduce the price significantly, which would also reduce the average price spread.

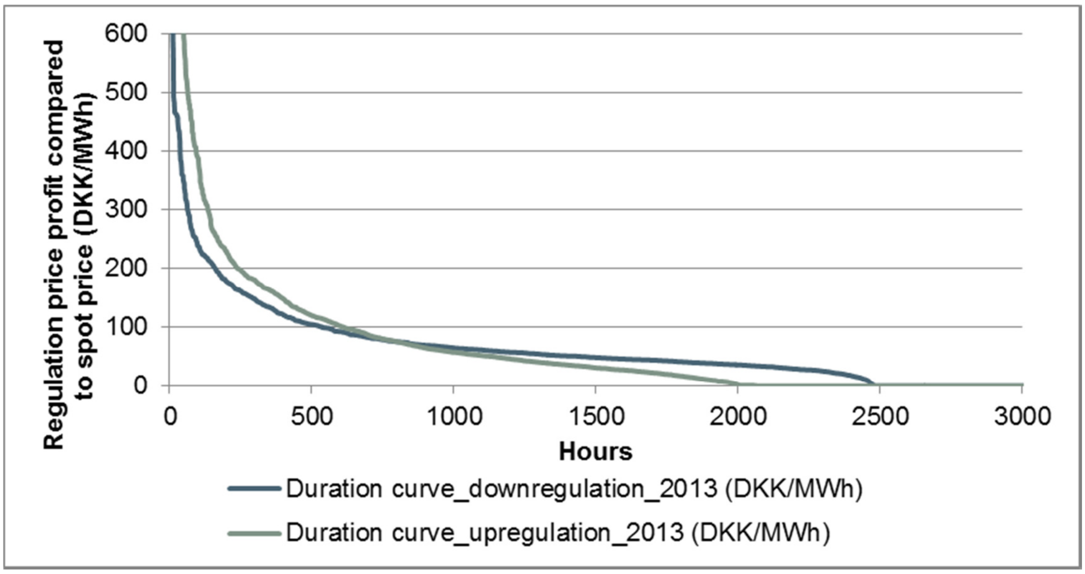


Figure 112. Duration curve in 2013 of profit in regulating power market compared to spot market [Energinet.dk].

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