TALLINN UNIVERSITY OF TECHNOLOGY
SCHOOL OF ENGINEERING
Department of Mechanical and Industrial Engineering

HEAT PUMPS INTERFACE CONCEPTUAL MODEL DEVELOPMENT FOR BALANCING MARKETS

SOOJUSPUMPADE LIIDESTAMISE KONTSEPTUAALSE MUDELI ARENDUS REGULEERIMISTURGUDELE

MASTER THESIS

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Tallinn 2023

(*On the reverse side of title page*)

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THESIS TASK

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Thesis topic:

(in English) HEAT PUMPS INTERFACE CONCEPTUAL MODEL DEVELOPMENT FOR BALANCING MARKETS

(in Estonian) SOOJUSPUMPADE LIIDESTAMISE KONTSEPTUAALSE MUDELI ARENDUS REGULEERIMISTURGUDELE

Thesis main objectives:

1. To study balancing markets and their requirements
2. To analyse heat pumps potential and suitability for balancing markets
3. To develop a heat pump interface conceptual model to balancing markets

Thesis tasks and time schedule:

No	Task description	Deadline
1.	Literature review and planning of thesis structure	15.02.2023
2.	Review of requirements and specification of objectives	15.03.2023
3.	Conceptual model development and analysis	15.04.2023
4.	Compilation of thesis	10.05.2023

Language: English **Deadline for submission of thesis:** 22 May 2023

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PREFACE

Master thesis topic "Heat pumps interface conceptual model development for balancing markets" was initiated from the author's discussions with his colleagues in Eesti Energia AS. Author expresses gratitude to all colleagues for the discussions and support on this topic. Special thanks to Marko Paavel, flexible energy services business development manager in Eesti Energia AS, who provided his knowledge and advice during the development of this work.

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This thesis aims to develop an interface conceptual model which would enable heat pumps to participate balancing markets. Market requirements and heat pumps' technical specifications are researched to develop a conceptual model to participate in balancing markets. A conceptual model together with balancing process description, cost and SWOT analyses are presented.

Keywords: Heat pumps, balancing markets, demand response, master thesis

LIST OF ABBREVIATIONS AND SYMBOLS

aFRR	Automatic Frequency Restoration Reserve
API	Application Programming Interface
BRP	Balance Responsible Party
BSP	Balancing Service Provider
DR	Demand Response
DSM	Demand Side Management
DSO	Distribution System Operator
ENTSO-E	European Network of Transmission System Operators
ERG	Energy Router Gateway
EU	European Union
FCR	Frequency Containment Reserve
FRR	Frequency Restoration Reserve
HVAC	Heating, Ventilation, and Air Conditioning
IEA	International Energy Agency
IoT	Internet of Things
LPWAN	Low Power Wide Area Network
LTE	Long-Term Evolution (Telecommunications)
mFRR	Manual Frequency Restoration Reserve
MPC	Model Predictive Control
NB-IoT	Narrowband Internet of Things
PV	Photovoltaic
RES	Renewable Energy Source
RR	Replacement Reserve
SCADA	Supervisory Control and Data Acquisition
SWOT	Strengths, Weaknesses, Opportunities, Threats
TSO	Transmission System Operator
VPP	Virtual Power Plant

1. INTRODUCTION

Electrical energy produced from renewable energy sources has increased significantly in recent decades. Due to the dependency on external and uncontrollable factors such as wind speed and sunlight intensity the electrical energy generated from renewable sources is constantly changing and hard to predict. This presents new challenges to power systems as electrical energy production and consumption need in balance all the time.

Traditionally the power system balance has been maintained with conventional power plants. Due to increasing fuel, environmental and equipment costs the conventional power plants are becoming more expensive to build and operate. Alternative is to adjust energy consumption to balance the system from the consumers' side. Demand response technologies enable consumers to adjust their consumption according to the electricity prices and provide balancing services to the power system.

High share of total electrical energy is consumed in buildings for heating and cooling. Heat pumps are recognized as key technology to increase energy efficiency and decarbonize heat production. Heat pump sector has experienced high growth in recent years and the growth is forecasted to continue. Due to high number of heat pumps already in operation, their strong projected growth, and consumption flexibility heat pumps show high potential for balancing services.

The main objective of this work is to develop heat pumps interface conceptual model which would enable heat pumps to provide balancing services. The first part gives a literature review on electricity markets, heat pumps and their demand response potential, and related research. In the second part specification of objectives is given and requirements for the conceptual model are presented. In the third part development and analysis of conceptual model is covered and heat pumps interface conceptual model is presented.

2. LITERATURE REVIEW

2.1 Electrical power system overview

Electrical power system is a network of generation, transmission and consumption units where electrical energy is generated, transmitted, and consumed simultaneously. Electrical energy is typically generated in thermal, hydro, nuclear, wind and solar power plants where energy from the source is converted into electrical energy. Electricity generated in power plants is transferred to consumers through transmission and distribution networks. [1]

Within a power system the energy generation and consumption need to be equal and in balance all the time. If power generation falls below the consumption the system frequency starts to decrease and deviate from the system nominal frequency. When generation exceeds consumption the system frequency starts to increase and exceed the system nominal frequency. Nominal frequency for power systems in Europe is 50 Hz. Some countries like the United States, Canada and Japan have nominal power system frequency of 60 Hz. [1]

Historically the power system balance has been achieved through continuously regulating the power output of generators. Mismatch in energy production and consumption is constantly compensated by controlling the output of power plants. For large disturbance events like network and generator failures the system needs to have reserves ready to be dispatched in case of faults. Developing new generation units and keeping the power plants in reserve has significant costs. Reserve capacity needs to be kept in reserve and cannot participate in regular electricity markets causing lost revenues for the operators. [2]

In the last decade the integration of renewable energy sources (RES) has grown rapidly in Europe. Electrical energy produced from solar panels and wind turbines doubled between 2012 and 2019 in Europe [3]. Integration of RES has helped countries to reduce their emissions, but it also has remarkable effects on the power system stability. Power output of RES is intermittent and largely affected by the changes in weather conditions [4]. This presents new challenges to the power system as the power output fluctuations from RES power plants need to be balanced.

New concepts like Demand Side Management (DSM) and demand response (DR) present opportunities for more intelligent and economical methods of ensuring power system stability. DSM refers to all that is done on the demand side of the system. DSM can significantly increase system security and lower the costs through energy efficiency, incentives to motivate off-peak consumption and DR of electrical loads. DR has potential to provide various balancing services and reduce the cost of maintaining the power system reserves. [5]

2.2 Electricity markets overview

Electricity market enables market participants to trade through bilateral agreements as well as on the electricity exchange. The purpose of the electricity exchange is to provide market participants short-term planned and standardized options to execute their transactions. Electricity market enables trading on a neutral platform where all participants have equal access and anonymity. As a result, electricity exchanges have lower transaction costs than bilateral trading and market information is more transparent. [6]

In Europe the development of electricity markets began in the early 1990s. First markets were introduced in England and Wales, followed by Scandinavia and central Europe countries. The largest operators in Europe are Nordpool in Scandinavia, EPEX Spot in Germany, France and Switzerland, APX in Netherlands and United Kingdom, OMEL in Spain and Portugal, POLPX in Poland, OPCOM in Romania. All European markets are using day-ahead and intraday auctions. [7]

Day-ahead market enables market participants to buy and sell energy for the next day. Day-ahead trading process starts by publishing available capacity on interconnectors. Then sellers and buyers submit their production and consumption bids for the next day. Submitted orders are matched with other orders in the pan-European market coupling process. Single price for every hour and bidding zone is set where the curves for selling and buying price intersect. [8]

Intraday market allows buyers and sellers to trade closer to the delivery hour to help secure balance between supply and demand. Being balanced is beneficial to market participants and power systems as this reduces the need for reserves and reduces balancing costs. Intraday market enables participants to take into account unforeseen changes and outages. Necessary action can be taken to reduce the potential imbalance for market participants and for the whole power system. With an increasing amount of renewable production, the need for intraday trading is increasing as it allows renewable energy producers to trade with a deficit or surplus of energy and keep their portfolio balanced. [9]

2.3 Balancing markets overview

Energy consumption and production are constantly changing in the power system. There are always changes and fluctuations in the system which cause imbalance. Market participants buy and sell energy based on their forecasts but actual amount of consumed and produced energy is always different from predicted volumes due to forecasting errors and outages. [10]

Transmission system operators (TSOs) regulate the system with balancing capacities in intra-hour balancing markets to maintain system balance. Based on the system state TSO can dispatch upward or downward regulation capacities. In case of up-regulation there is energy deficit in the system and TSO purchases additional energy from market participants. Up-regulation is done by increasing energy production or by decreasing energy consumption. In case of down-regulation there is surplus energy in the system and TSO sells excess energy to market participants. Down-regulation is done by decreasing energy production or by increasing energy consumption. [11]

Balancing reserves are offered to the balancing market by balancing service providers (BSPs) who bid balancing reserves to the market. BSP bids the available balancing reserve to market by specifying the amount, availability, and price of the balancing reserve. After Gate Closure Time all bids are arranged into the Common Merit Order List based on their bid prices. In case of system imbalance TSO can activate offered bids from the list. Balancing market sequence is presented on Figure 2.1. [11]

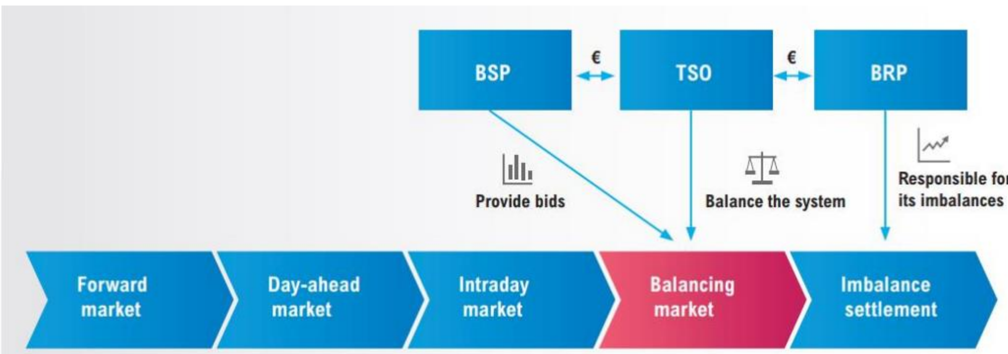


Figure 2.1 Balancing market sequence in electricity markets [12]

In Baltic countries balancing market price is calculated in marginal price principle. Same principle is used in many European balancing markets. In the event of up regulation TSO pays BSP for electrical energy supplied according to the highest price of the bid activated. In case of down regulation BSP pays TSO for electrical energy supplied according to the lowest price of the bid activated. Final settlement for the previous month is done together with overall imbalance settlement between TSOs, BSP and balance responsible parties (BRPs) in the beginning of next month. [11]

2.4 Balancing reserves overview

Balancing market reserve products are divided into four categories based on their activation speed, type, and duration. Reserve products are presented on Figure 2.2. European Network of Transmission System Operators (ENTSO-E) defines standard balancing reserve products as follows:

- Frequency Containment Reserve (FCR);
- automatic Frequency Restoration Reserve (aFRR);
- manual Frequency Restoration Reserve (mFRR);
- Replacement Reserve (RR). [13]

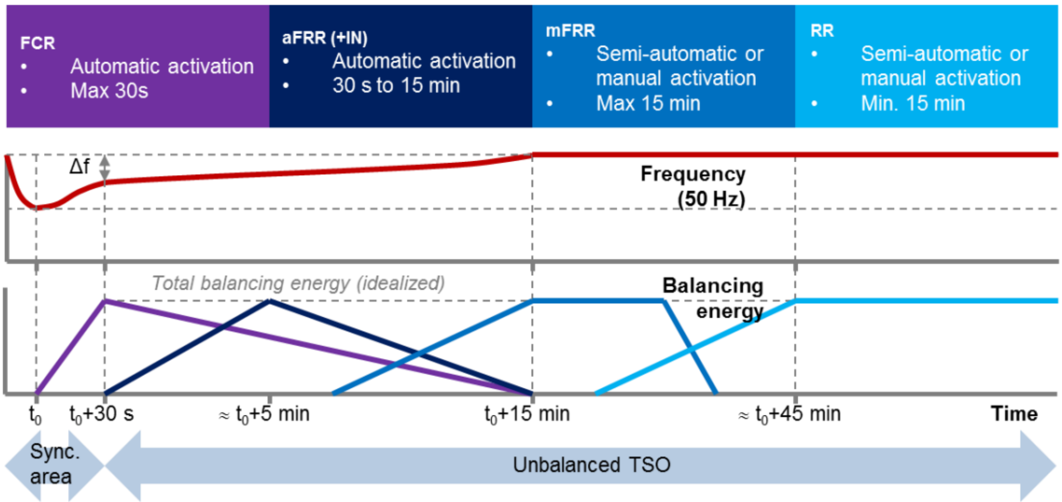


Figure 2.2 Balancing reserve products for frequency restoration [14]

2.4.1 Frequency Containment Reserve (FCR)

FCR is an automatic reserve with a purpose to contain the system frequency in the synchronous area by stabilizing active power fluctuations in the system. FCR is the fastest reserve which is automatically activated based on the local measurement of system frequency deviation. FCR needs to fully activate within 30 seconds from the occurrence of frequency deviation. FCR is the first reserve to be activated before aFRR and mFRR restore the system frequency and release the FCR capacity. To provide FCR a reserve providing unit needs to fulfill and prequalify for the technical requirements set by TSO. FCR technical requirements are given in Table 2.1 and FCR activation ideal characteristic is presented on Figure 2.3. [14]

Table 2.1 FCR technical requirements [14]

Parameter	**FCR technical requirement**
Deadband, mHz	±10
Full activation frequency deviation, mHz	±200
Direction	Upward or downward
Activation method	By decentralized frequency measurement
Activation time, s	≤15
Full activation time, s	≤30
Minimum bid size, MW	1

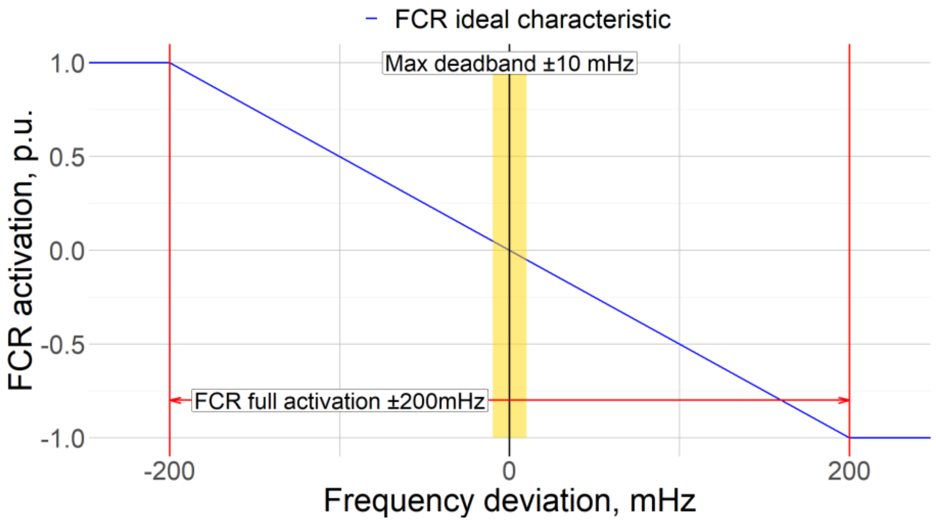


Figure 2.3 FCR activation ideal characteristic based on frequency deviation [14]

2.4.2 Automatic Frequency Restoration Reserve (aFRR)

aFRR is an automatically activated reserve with a purpose to replace FCR activations and mitigate imbalance on the interconnection lines. After FCR activation limits the frequency deviation the aFRR is activated to restore the frequency back to nominal value. aFRR activation shall start no later than 30 seconds after TSO sends the activation signal to BSP. Reserve capacity must be fully activated within 5 minutes. aFRR activation signals are automatically generated as Supervisory Control and Data Acquisition (SCADA) signals in the frequency controller and sent to BSP control system to activate the reserve providing unit. This ensures FCR is released and can be activated for disturbances which may occur in the system. aFRR technical requirements are given in Table 2.2 and aFRR minimum activation speed is presented on Figure 2.4. [14]

Table 2.2 aFRR technical requirements [14]

Parameter	aFRR technical requirement
Activation start time, s	≤30
Full activation time, s	≤300
Direction	Upward or downward
Activation method	Automatic
Minimum duration of delivery period, min	Not defined
Maximum duration of delivery period, min	15
Minimum bid size, MW	1

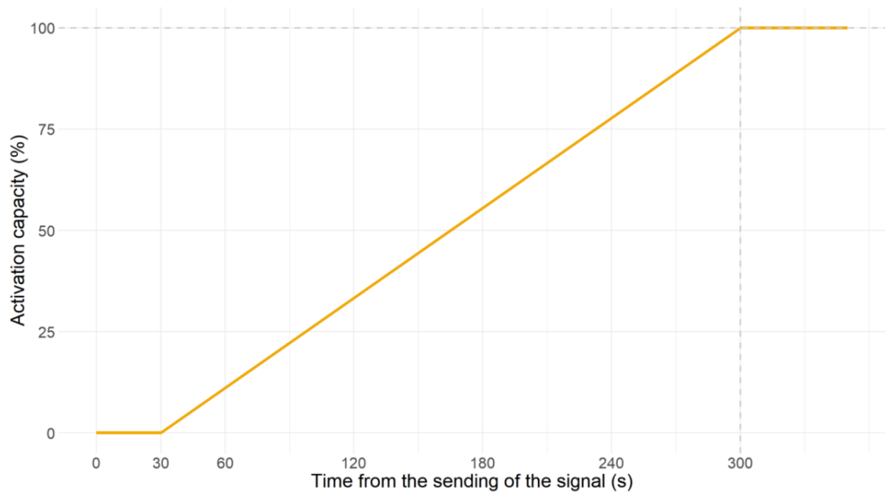


Figure 2.4 Minimum activation speed for aFRR [15]

2.4.3 Manual Frequency Restoration Reserve (mFRR)

mFRR is manually activated reserve used to release the previously activated aFRR capacity or to provide additional frequency restoration power. It is used for longer lasting deviations that cannot be resolved by upstream balancing services such as FCR and aFRR. mFRR activation must start within 7 minutes and shall be fully activated after 12,5 minutes the signal is sent by TSO to BSP. The activation of manual reserve includes human operator involvement who identifies the need for balancing power and sends out activation messages to BSP. In Europe electronic messages are mostly used for communication of orders. Phone or e-mail messaging can be used as backup communication methods. mFRR technical requirements are given in Table 2.3 and mFRR minimum activation speed is presented on Figure 2.5. [14]

Table 2.3 mFRR technical requirements [14]

Parameter	mFRR technical requirement
Full activation time, min	12,5
Direction	Upward or downward
Activation method	Manual
Minimum duration of delivery period, min	5
Maximum duration of delivery period, min	Scheduled activation: 20 Direct activation: 35
Minimum bid size, MW	1

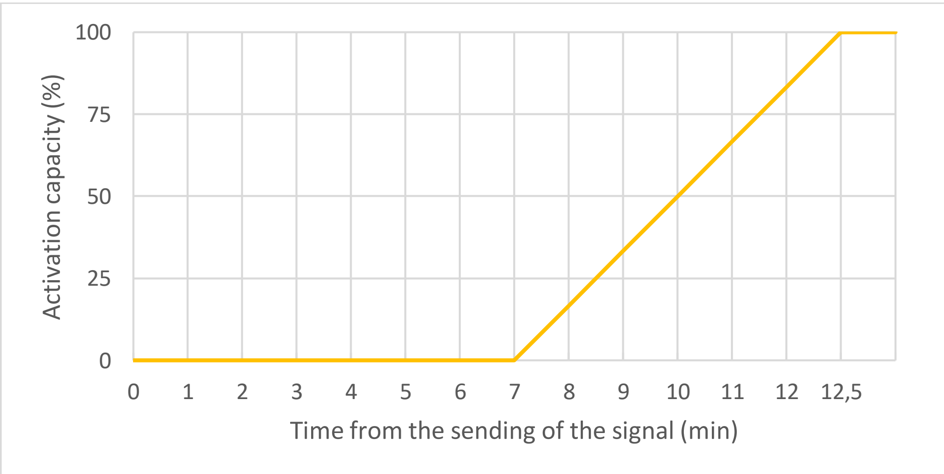


Figure 2.5 Minimum activation speed for mFRR [16]

2.4.4 Replacement Reserve (RR)

RR is a manually activated reserve intended to replace and release frequency restoration reserves (FRR). RR activation must be fully activated not later than 30 minutes from the moment activation signal is sent by TSO [17]. Baltic TSOs do not foresee to implement reserve replacement process and procure RR as a standard balancing product [14]. Similarly, RR is not used in Nordic power system covering Norway, Sweden, Finland, and eastern part of Denmark [18]. Therefore, RR is not covered in detail in this thesis.

2.5 Harmonization of balancing reserves

In 2017 European Union (EU) Commission Regulation 2017/2195 entered into force. The regulation lays down a guideline on electricity balancing and establishes harmonized principles for the activation, procurement and settlement of balancing reserves including FCR, aFRR, mFRR and RR. The Regulation applies to all TSOs, distribution system operators (DSOs), responsible third parties, transmission systems and interconnection in the EU. [19]

Main objectives of the Regulation 2017/2195 are following:

- ensure transparent, effective, market-based competition in balancing markets;
- increase efficiency of balancing and balancing markets;
- integrate and promote the possibility of exchanging balancing services;
- facilitate the participation of demand response and ensure fair playing field with other balancing services;
- support the participation of RES and achievement of EU targets for the penetration of renewable energy [19].

ENTSO-E has started implementation projects to establish common rules and requirements for all TSOs. Main targets for the implementation projects are to design, implement and operate common platforms for different reserves, enhance efficiency and integrate balancing markets in cooperation with TSOs in EU. As balancing reserves FCR, aFRR, mFRR, RR are different by their nature and technical requirements it is necessary to have a separate platform and implementation project for each reserve. [13]

FCR Cooperation aims to develop and integrate FCR reserve markets within the TSOs participation in the project. The project currently involves eleven TSOs from eight countries who procure their FCR in the common market. Participating countries are

Austria, Belgium, Switzerland, Germany, Western Denmark, France, the Netherlands and Slovenia. The Czech Republic is expected to join the cooperation in March 2023. FCR Cooperation map is shown on Figure 2.6. [20]

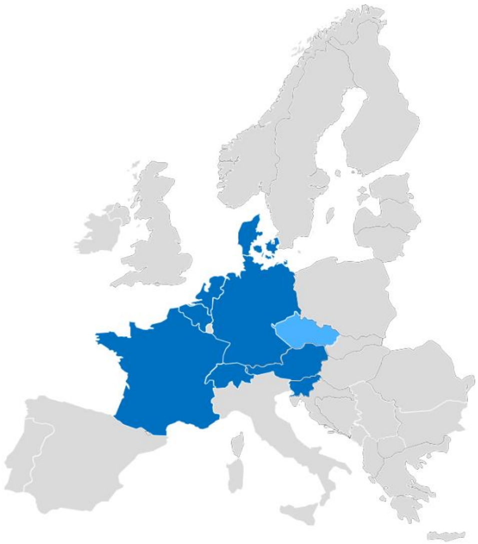


Figure 2.6 FCR Cooperation map [20]

PICASSO is a **P**latform for the **I**nternational **C**oordination of **A**utomated **F**requency **R**estoration and **S**table **S**ystem **O**peration. The aim of the implementation project is to design, implement and operate a common aFRR platform where participating TSOs can procure the aFRR. PICASSO implementation project members and observers as of April 2021 are shown on Figure 2.7. Baltic states are planning to join PICASSO in 2024. [21, 22]

30 TSOs + ENTSO-E (Observer)		
PICASSO Members (26 TSOs)		PICASSO Observers (4 TSOs + ENTSO-E)
Austria	Hungary	Latvia
Belgium	Italy	Lithuania
Croatia	The Netherlands	Estonia
Czech Republic	Norway	North Macedonia
Denmark	Poland	ENTSO-E
Finland	Portugal	
France	Romania	
Germany	Slovak Republic	
	Slovenia	
Sweden	Spain	
Bulgaria	Greece	
Switzerland	Luxembourg	

Figure 2.7 PICASSO members and observers [21]

MARI is **M**anually **A**ctivated **R**eserves **I**nitiative with a purpose to design, implement and operate a harmonized mFRR platform where transparent procurement of mFRR can take place. A common platform is developed in cooperation with all participating TSOs. MARI platform will boost competition and will enable larger participation of renewables and demand response in balancing markets. MARI implementation project members and observers as of October 2022 are shown on Figure 2.8. [23]

33 TSOs + ENTSO-E (Observer)			
MARI Members (29 TSOs)			MARI Observers (4 TSOs + ENTSO-E)
Austria	Greece	Spain	Serbia
Belgium	Italy	Sweden	Ireland
Croatia	Latvia	Switzerland	Northern Ireland
Czech Republic	Lithuania	Luxembourg	North Macedonia
Denmark	Norway	Bulgaria	ENTSO-E
Estonia	Netherlands		
Finland	Portugal		
France	Poland		
Hungary	Romania		
Germany (50hertz, amprion, TenneT, TRANSNETBW)	Slovak Republic		
	Slovenia		

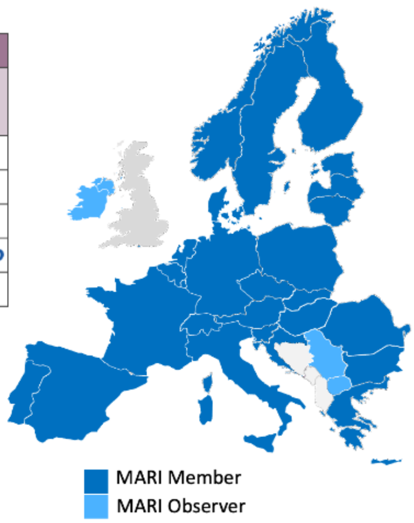


Figure 2.8 MARI members and observers [24]

2.6 Demand response for balancing markets

Electricity generation from RES has grown rapidly in recent decades. Figure 2.9 and Figure 2.10 illustrate the growth on solar photo-voltaic (PV) and wind energy production globally. Solar PV power production increased more than 30 times from 2010 to 2021 [25] and wind power generation increased more than five times from 2010 to 2021 [26]. Due to the intermittency and forecasting errors of power generation from RES the power systems need increased capacity of balancing reserves [27]. Historically power system balancing has been done on generation side with conventional thermal or hydropower plants which regulate power output according to the balancing need in the system. However, management of consumption and DR concepts have potential to provide balancing services and reduce the need for conventional power plants [28].

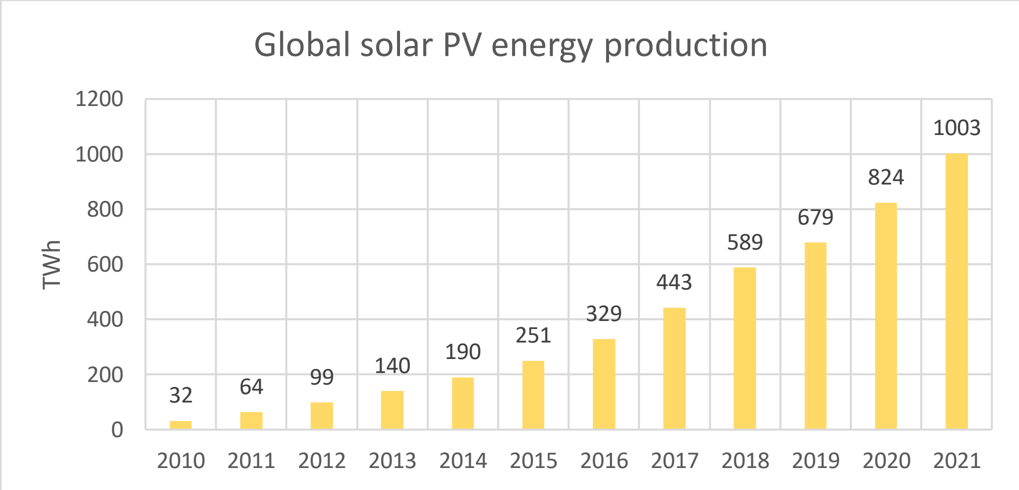


Figure 2.9 Global solar PV energy production [25]

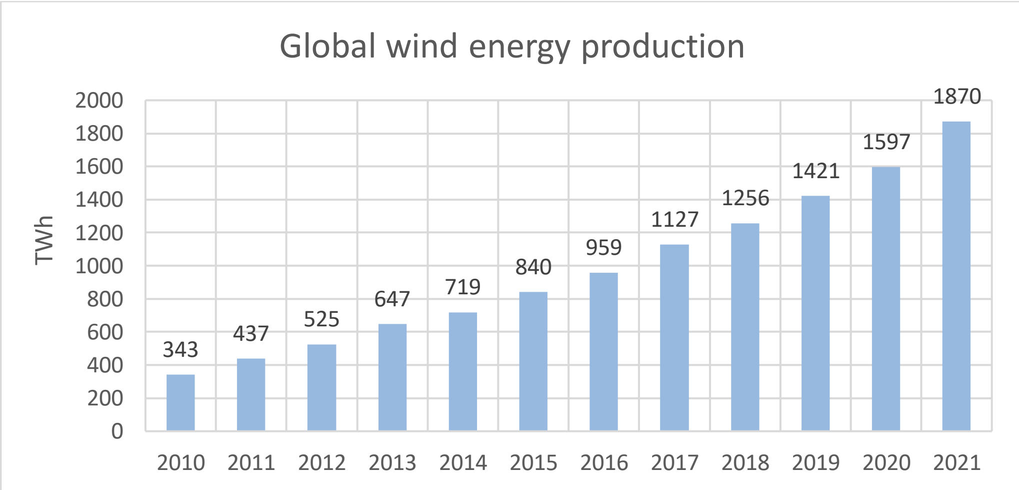


Figure 2.10 Global wind energy production [26]

DR is defined as a change in the usage of electrical energy by end customers from their typical consumption patterns in response to electricity price changes over time. DR can be used to reduce the need for additional power distribution and generation facilities. DR enables consumers to adapt their energy usage according to the system imbalance and avoid investments to expensive storage solutions and fast-responding power plants. As a result, the system maintenance costs are decreased, and end-customers benefit from lower expenses on electrical energy. [29]

In balancing markets DR can be used to ensure the system balance. Customer consumption flexibility is traded in balancing markets and customers are paid for providing balancing services. It is complicated for a single customer to participate in balancing market due to technical limitations, knowledge, and minimum capacity requirements. Due to this the business model usually contains a demand aggregator who aggregates high number of assets and customers to larger portfolio. Demand aggregator can be an independent party who provides flexibility to TSOs. Demand aggregator can also provide balancing services to BRP and help BRPs to balance their portfolio. Demand aggregator itself can also be BRP if it has the balancing responsibility. [30]

Virtual Power Plant (VPP) can be used by aggregator to include various demand-side loads, storage and generation assets to one aggregated portfolio. VPP enables an aggregator to monitor and control of high number of assets efficiently and offer the aggregated flexibility to balancing markets. [31]

World Energy Outlook 2017 estimates the global DR potential to be almost 4000 TWh per year which accounts around 15% of total energy demand [32]. However, this is a theoretical potential which still needs to be unlocked and deployed. International Energy Agency (IEA) Net Zero Scenario has a milestone of 500 GW of demand response to be brought to market. This corresponds to ten times increase from the deployment levels in 2020 [33]. While progress has been made during recent years much more resources and efforts are needed to bring more technologies and sectors to balancing markets.

2.7 Heat pumps for demand response

Buildings sector has significant energy consumption and carbon footprint. Operation of buildings accounted for 30% of global energy consumption and 27% of total energy sector emissions in 2021. According to IEA Net Zero Scenario the energy consumption in buildings needs to decrease by 25% and emissions from buildings need to be reduced by more than 50% by 2030. Additionally, fossil fuels consumption must be lowered by 40%. IEA has set several key activities which need to be followed to achieve the target set by the Net Zero Scenario. Critical activities set by IEA are following:

- improved efficiency of building envelopes;
- more efficient and clean technologies like heat pumps and district heating;
- increased flexibility of consumption [34].

In buildings the main function of heat pumps is to provide heating or cooling to the rooms. Heat pumps are key element in buildings heating, ventilation, and air conditioning (HVAC) systems. Heat pumps are widely recognized as important technology for decarbonization and increased energy efficiency. Due to their efficient use of electrical energy heat pumps provide great potential to support the increasing deployment of RES. In 2021 there were 190 million heat pumps in operation in buildings, and record sales were recorded in markets in Europe, United States and China. Heat pumps accounted for 10% of global heating need in 2021. This is below the target set by Net Zero Scenario and faster deployment of heat pump technology is still needed. As presented on Figure 2.11 by 2030 at least 600 million heat pumps need to be installed to cover at least 20% of global heating needs. [35]

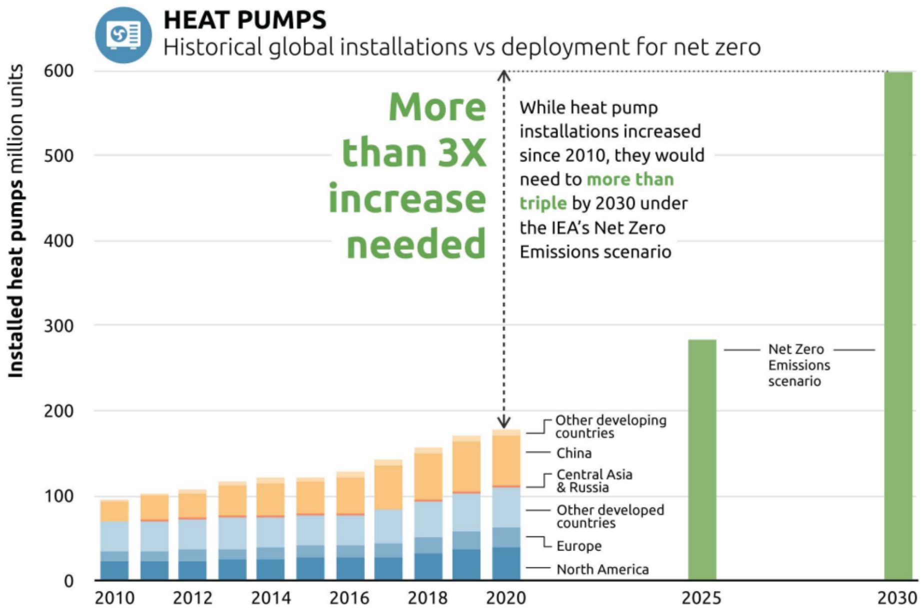


Figure 2.11 Heat pump historical global installations and deployment for Net Zero Scenario [36]

Together with increasing deployment levels of heat pumps their potential as source of flexibility needs to be exploited. Due the high share in annual total energy consumption heat pumps represent high potential if made available for DR. While the control of smart appliances has been studied the strongest the focus has been on the heating and cooling loads as they are a major part of building's energy use. To provide DR it is crucial to have inertia in the system which allows to decouple heat production and usage. Inertia can be provided due to building's built-in thermal mass which acts as a storage medium and enabler of flexibility. [37]

Heat pumps represent various implementation options for DSM strategies. These DSM technologies can be classified as energy efficiency, energy storage systems and demand response programs. Energy efficiency covers the areas related to optimal equipment design and control technologies, natural refrigerants. Energy storage technologies refer to thermal energy storage and thermally activated buildings. Demand response technologies are aimed at three main purposes including balancing services, RES integration and energy costs reductions for end users. These main purposes are further described in Table 2.4. [38]

Table 2.4 Demand Side Management (DSM) technologies in HVAC sector [38]

Category	Technology
Energy efficiency	Natural refrigerants Optimal design Not-in-kind technologies Optimal control strategies
Storage	Cold Thermal Energy Storage Thermal Energy Storage Thermally Activated Buildings Phase Change Materia
Demand Response	Balancing services Renewable Energy Sources integration Cost reduction

Comprehensive amount of research is available on the DSM strategies related to optimizing heat pumps' load against day-ahead electricity markets and time-of-use tariffs. Peak-shaving and valley-filling which refer to load-shifting methods are also widely researched. Providing balancing services with heat pumps is less researched and needs further research. Increasing share of intermittent RES in the system creates more need for balancing services in the system. At the same time operational and maintenance costs for conventional power plants are increasing because of growing prices of fuel, carbon permits, human and capital resources. Power systems need more consumers in the balancing markets and heat pumps provide great potential to bring million of new consumers to markets.

2.7.1 Heat pumps overview

First heat pump system was developed by Peter von Rittinger between 1855 – 1857. Rittinger recognized heat pump principle while conducting experiments on using water vapour latent heat for the evaporation of salt brine. As a result, Rittinger developed a first practical application of the heat pump principle which was used to produce salt from concentrated brine in the Ebensee salt factory in Austria. In 1948 American inventor Robert C. Webber built the first closed-loop heat pump while experimenting with deep freezer. Webber discovered that outlet pipes of the cooling system were producing excess heat. He started using the excess heat from cooling system to heat the building. By further experimenting with the system Webber buried copper tubes filled with freon in the ground to harvest the heat from the ground. This marks the birth of first closed-loop heat pump. [39]

Heat pump works based on a reversed Carnot thermodynamic cycle. Heat pump moves heat from low-temperature source to high-temperature source consuming the drive energy. Most common low-temperature heat sources are outdoor air, water reservoirs, and ground. However, many other potential sources are available depending on the location and nature of the installation. Drive energy is consumed to run the cycle and generate the output thermal energy. Drive energy sources are mostly electrical or mechanical. Principal diagram for heat pump is presented on Figure 2.12. [40]

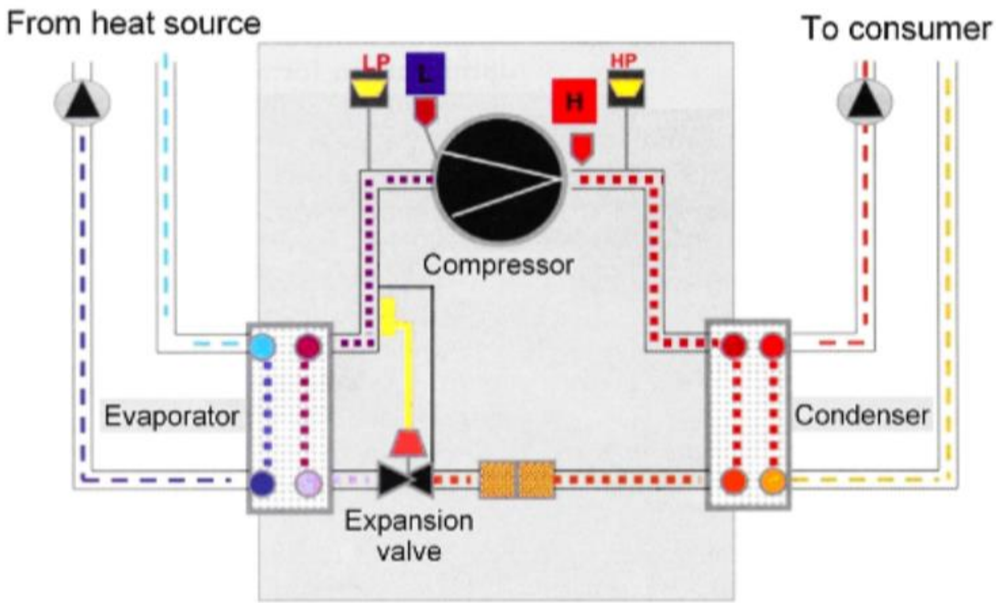


Figure 2.12 Principal diagram of heat pump [40]

The basic heat pump cycle consists of four stages. In case of cooling the process is reversed so it will extract heat from the conditioned area. Basic heat pump cycle is presented on Figure 2.13. Main steps of the heat pump cycle are:

- evaporation where the working fluid is evaporated in the evaporator by absorbing heat from a low-temperature source such as the outdoor air, ground, or water;
- compression where vaporized refrigerant is then compressed by a compressor to increase its pressure and temperature, this process requires mechanical work and increases the temperature of the refrigerant;
- condensation where high-pressure, high-temperature refrigerant is condensed back into a liquid by releasing heat to a high-temperature sink such as indoor air or water;

- expansion where high-pressure liquid refrigerant is expanded through an expansion valve or a throttling device to a low-pressure and low-temperature liquid state [41].

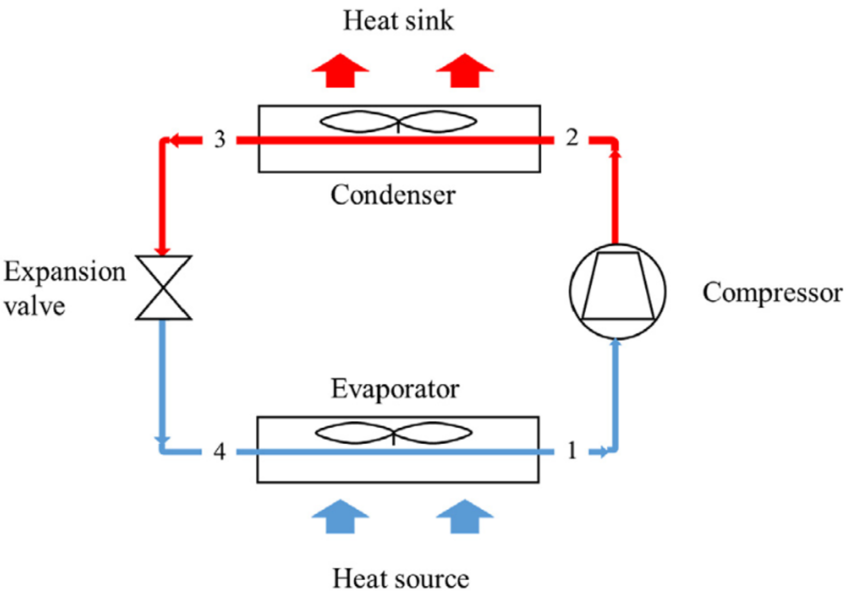


Figure 2.13 Heat pump cycle [42]

2.7.2 Classification of heat pumps

Heat pumps are classified based on cooling methods of the condenser and evaporator. The condenser can be either air- or water-cooled and evaporator can be used to remove heat from air or liquid. Different heat pumps are similar as they facilitate the transfer of heat between different mediums. Based on the different mediums used for heat transfer the heat pumps are divided as following:

- air-to-air heat pump;
- air-to-liquid heat pump;
- liquid-to-air heat pump;
- liquid-to-liquid heat pump [41].

Here the first part of the classification describes the source of the heat for the system when operating in heating mode. Air-source heat pump transfers heat from air into the medium that is heated. Similarly, liquid-source heat pump transfers heat from liquid to the medium that is being heated when operating in heating mode. The second part of the classification describes the medium that is being treated by the system. In air-to-air and liquid-to-air heat pumps the air is being treated as the indoor medium where heat is transferred to. In air-to-liquid and liquid-to-liquid heat pumps the liquid is being treated as indoor medium. [41]

In addition to the types listed above a separate stand-alone classification is a geothermal heat pump which uses earth as a source or sink of heat. During cold periods the heat is transferred from the ground to refrigerant and used for heating purposes. During warm periods the ground acts as a sink and heat from conditioned space is transferred to earth through refrigerant. Geothermal heat pumps can be further classified as open-loop, closed-loop, and direct burial systems. [41]

2.7.3 Heat pumps flexibility

Heat pumps can provide flexibility because they are able to efficiently use building's infrastructure for thermal storage. Thermal mass of the building acts as a storage medium for heating or cooling while allowing to shift heat pump's electrical energy consumption without affecting user comfort negatively. Additional buffers like hot water tanks may be used to further increase flexibility and extend building's capability for thermal energy storage. More thermal mass and storage capability results in higher potential for flexibility because heat or cold produced by heat pump can be stored for longer periods. Building's thermal mass includes interior walls, ceilings, floors, and also furniture and equipment installed in the building. Figure 2.14 describes the flexibility profiles of different internal mass resources. [43]

Another source of flexibility is end-user tolerance for room temperature. If end-users are willing and able to tolerate change in temperature setpoints the building's flexibility can be increased resulting higher financial benefits for customers for their tolerance. As the tolerance depends on the age group, economic status, personal preferences, climate, and other factors it is quite difficult to evaluate the flexibility from tolerance. However, it should be considered as a potential source of flexibility. [43]

Heat pumps flexibility can be utilized on balancing markets. The capability and readiness to increase or decrease electrical load can be traded to balancing markets to receive fees from TSOs. Heat pumps are best suitable for slower balancing services such as mFRR and aFRR because heat pumps can react to changes in setpoints in the matter of minutes. Linear or stepwise FCR service which is activated based on frequency deviation in the gird is generally too fast for heat pumps. [44]

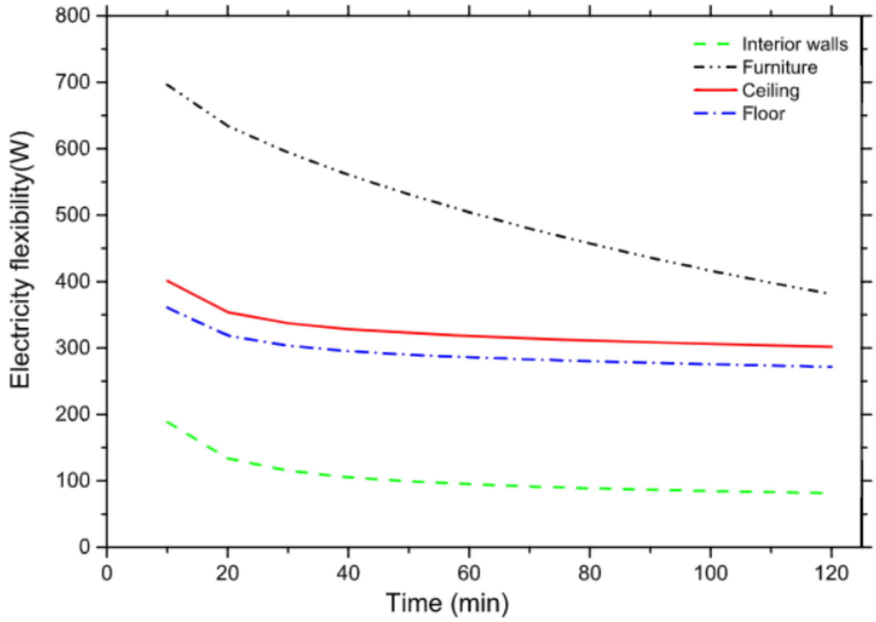


Figure 2.14 Electricity flexibility profiles of different internal mass resources [43]

2.7.4 Related work

Various studies have been conducted in the field of DR with heat pumps. Considerable proportion of studies focus on the optimization of heat pump electricity consumption based on the electricity market prices as it has the highest potential to reduce costs for customer and shift the peak-loads from power system perspective. Methods for calculating buildings flexibility are also widely researched and many potential methods are proposed. Balancing services and heat pump interfaces to balancing markets are less researched and need further investigation. While theoretical frameworks have been presented in various articles the practical applications are not widely researched. This section covers the related research work for heat pump DR services.

In [45] the performance of heat pumps with Carnot batteries for providing FCR, aFRR and mFRR services is researched. Study shows that heat pumps with Carnot batteries show potential to deliver all three balancing reserves. Article [46] suggests that heat pump electrical loads are fast enough to provide slower balancing services such as aFRR and mFRR. The article presents an assessment chain for flexibility service provision shown on Figure 2.15.

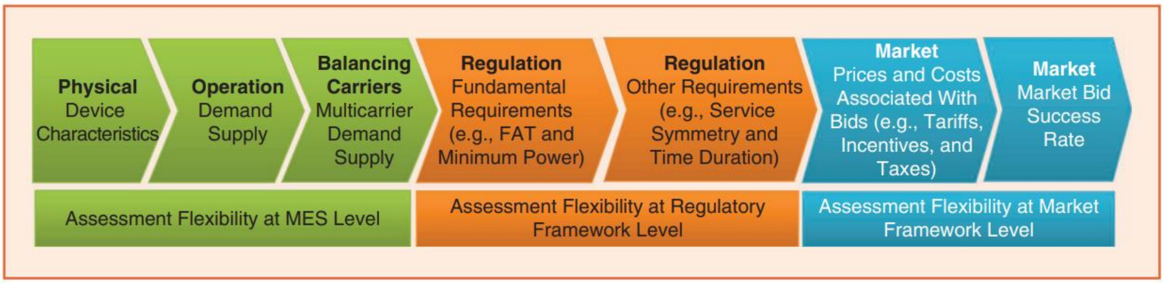


Figure 2.15 An assessment chain for flexibility service provision [46]

Authors of [47] present a dynamic demand response controller which changes the temperature set point of the thermostat based on the electricity price. In situation where electricity price is higher than the threshold price the thermostat setting is lowered, and electricity consumption is decreased. HVAC model is developed with EnergyPlus simulation program based on the size of the house, HVAC type, and geographical location. A coefficient of temperature is developed and used to convert the electricity price to the temperature for the thermostat. As a result, electricity consumption on coldest month is reduced by about 12% and on the hottest month by about 21%. Electricity costs for the coldest and hottest months are curtailed by 29% and 31% respectively.

Article [48] describes important metrics for describing heat pump flexibility. Authors describe the amount of flexibility depends on the heat pump capacity and operational level. For simplification purpose it is assumed that heat pumps modulate between On and Off states. However, it is acknowledged that modern heat pumps are inverter-driven and can be more finely adjusted in real situations. Article presents calculation methods for maximum available upward and downward flexibility.

Authors of [48] further highlight the potential negative side effects of DR with heat pumps. After upward regulation and decreasing power consumption the heat pumps require extra power to re-establish the desired temperature. This may lead to network congestion issues if significant amount of heat pumps are synchronized to the service. Downward regulation and power consumption increase may lead to overheating and uncomfortable temperatures for the end-user.

In [49] authors investigate the potential of Narrowband Internet of Things (NB-IoT) for DR. NB-IoT is a low-power and dense-area coverage cellular technology designed to enable new IoT devices and services to be connected. Due to NB-IoT low power consumption, deep coverage, reliability, and high device intensity it is considered as a good candidate for DR applications. A complete end-to-end NB-IoT solution for controlling a smart plug is designed and implemented in the article. It is observed that connected devices can be controlled and monitored with maximum latency of 8 seconds in the deep-indoor environment and 2 seconds in outdoor environment. As a conclusion authors believe NB-IoT can provide complete solution for DR management system. Network architecture of the developed system is presented on Figure 2.16.

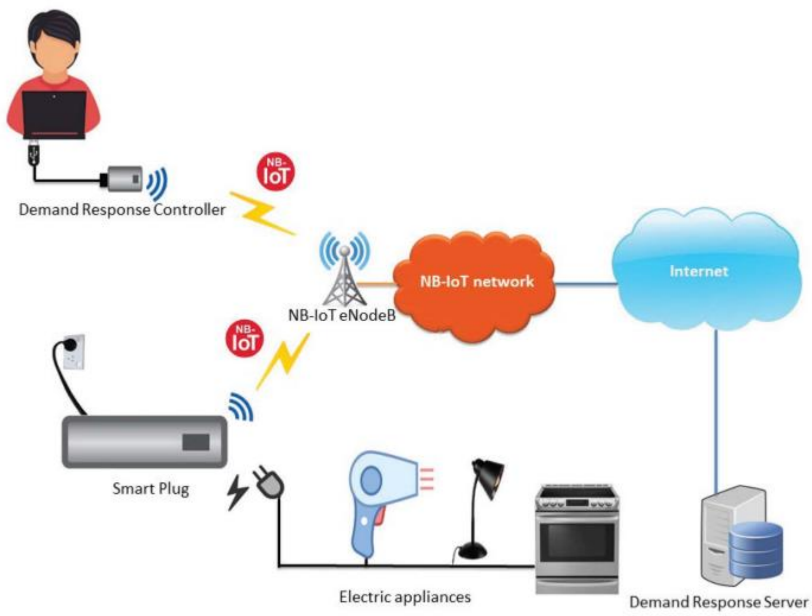


Figure 2.16 NB-IoT network architecture [49]

Article [50] covers the cloud-based architecture developed for controlling the dispatchable resources of users. Most of the computation is moved to cloud level to allow calculations and optimization through Model Predictive Control (MPC) framework. Local data is gathered from smart meter, local controllers, sensors, and power meters to Energy Router Gateway (ERG) using Modbus protocol. ERG is also capable of communicating with other industrial protocols like CAN-BUS, Profibus and home automation standards such as Wi-Fi, KNX, LoRaWAN, Zigbee, Z-Wave. ERG communicates with cloud using open-source message-oriented middleware RabbitMQ which supports MQTT and AMQP protocols. JSON data format is used for payload. Architecture shown on Figure 2.17 can communicate real-time data in every 500 ms.

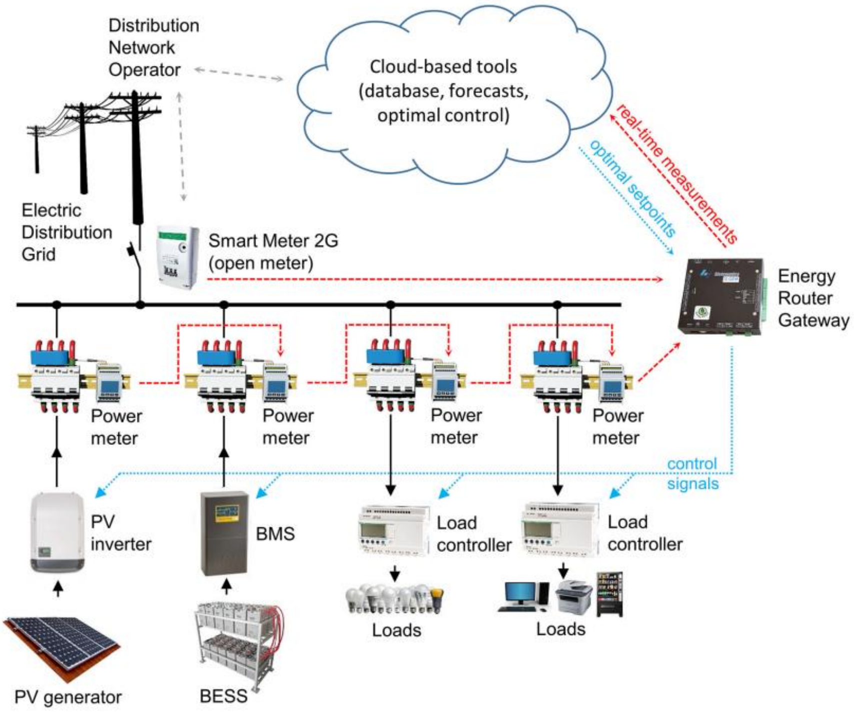


Figure 2.17 Model Predictive Control system architecture [50]

2.7.5 Market overview

There are several companies which offer DR solutions for heat pumps. However, these solutions are still in early stages and offered only in few countries. Service providers have developed software platforms and devices through which customers can join DR services with heat pumps. While exact technical details of these solutions are not publicly available, a brief overview of these companies and their solutions is provided.

Kapacity.io is Finnish based company offering energy optimisation and DR services for buildings. Their two main services are smart heat pump control and CO2 intensity control. Customers can sign up for a smart heat pump control service and save up to 15% in electricity distribution costs with night-time control and peak load management. Additionally, customer's building is connected to balancing market for grid supporting services. Kapacity.io is using application programming interface (API) to connect heat pumps for DR services. According to Kapacity.io the smart control through API can easily save 15% in electricity costs to customer without an effect on the indoor climate. Solution is currently available only in Finnish market and for NIBE, Thermia, Gebwell, Bosch heat pumps. Kapacity.io principle API connection to building management system is shown on Figure 2.18.

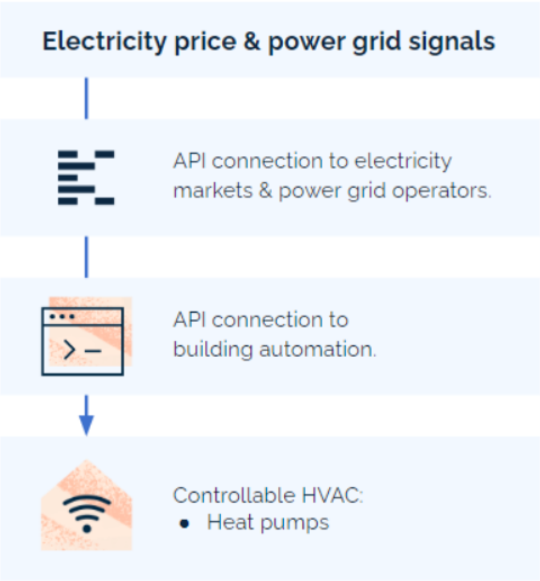


Figure 2.18 Kapacity.io API connection to building management system [51]

Voltalis is a company founded in France in 2006 offering smart thermostats for electrical radiators. „Bluepod" thermostats are offered free of charge and installed to customer premises by Voltalis. As a result, customer can track energy consumption and control radiators remotely, but they do not get additional financial benefit. According to Voltalis customers can save up to 15% on energy costs. Voltalis aggregates all consumers to offer balancing services to TSO. Voltalis has extended their solutions providing DR services also for heat pumps and they are currently operating in France, United Kingdom, Finland, Belgium, and Slovenia.

Tiko Energy is Swiss company providing DR services through their software and hardware solutions. Tiko solutions include Room Temperature Programming, Tiko Sun for solar PV optimization, Tiko Power to control and monitor heat pumps, boilers and night storage systems, Tiko Peak Shaving to manage electric car charging and optimize consumption. Customers can monitor and control their consumption. Additionally, customers can earn revenues from ancillary services as their equipment is connected to Tiko VPP. Tiko's main market is Switzerland where they have substantial number of heating equipment connected.

2.7.6 Demand response challenges

Implementation of DR for heat pumps can provide benefits for end-users, market participants and power systems. DR technologies are recognized as key elements to support the integration of RES to power systems, reduce investment costs to conventional power plants, create additional revenues for the equipment owners. While DR methods have numerous advantages there are also technological, economic, and political challenges which need to be addressed.

DR is defined as a change in consumer typical consumption pattern. Energy is consumed earlier or later than initially planned and through this action flexibility is achieved. Changing heat pump's typical consumption pattern creates potential threats to power grid. If a high number of heat pumps become synchronized with similar consumption patterns it may lead to congestion issues in the power grid. In scenario where consumption of aggregated heat pumps is decreased for balancing service the heat pumps will require additional power to re-establish normal conditions after providing the service. This could lead to increased simultaneous power consumption which can create congestion issues in distribution networks. [48]

Participating in balancing markets requires forecasting of flexibility as BSP needs to submit bids for up and down regulation before Gate Closure Time. Heat pump power consumption is affected by numerous variables like indoor and outdoor temperatures, building's insulation, and heat pump technical parameters. All those variables need to be considered when flexibility of heat pumps is forecasted. Due to relatively small nominal power heat pumps need to be aggregated by demand aggregator which significantly increases the complexity of the prediction. [52]

Another challenge is the potential revenues and end-customer motivation for participating in DR programs. As residential heat pump nominal electrical power is usually in the range of 2-3 kW the possible revenues from balancing markets are low and may not motivate end-users to participate in the DR programs. Estimated annual revenues from German ancillary markets in 2020 for 1 kW heat pump were 30-55 € from FCR market and 10-50 € from aFRR market. Better incentives are needed to attract more customers to join DR services. [53]

Additionally, the equipment and installation costs for DR technologies for heat pumps is high and expected returns may not be sufficient to cover the costs in reasonable time [53]. Developing equipment and software for heat pump DR needs significant investments which need to be covered by returns to make the business cases viable. Aggregators and developers need be confident that future revenues from the markets are sufficient to cover the investments to innovative technologies. Companies need to develop standardized and scalable solutions which would support the growth of DR of heat pumps.

Current market regulations need further development and transparency to enable more widespread DR implementation. One of the main objective of EU Regulation 2017/2195 is to increase transparency and efficiency of balancing markets [19]. Requirements for market participants need to ensure all market participants are treated equally. Barriers for entering balancing markets need to be removed to enable more participants to join the market. Current regulations set minimum bid size of 1 MW to participate in ancillary markets, but this amount of flexibility is not easily achievable with residential heat pumps.

3. SPECIFICATION OF OBJECTIVES

The purpose of this work is to develop a conceptual solution for connecting heat pumps to balancing markets. Based on the literature review the necessary functionalities and requirements are presented in this chapter. Four main functionalities are described as a core of the conceptual model. Without these functionalities, it would not be possible for heat pumps to participate in balancing markets. Final solution must be able to perform a set of activities and meet the requirements of harmonized balancing reserves. Required functionalities are presented in Table 3.1. Requirements for measurement accuracy and data refresh rate are shown in Table 3.2.

Table 3.1 Required functionalities for the final solution

Functionality	Purpose
Automatic measurement of heat pump active power	Measure active power for flexibility provision and settlement with TSO and customer
Automatic reading of heat pump data	Read heat pump status data for available flexibility and customer comfort limitations
Send automatic activation commands to heat pump	Change heat pump temperature setpoints and operation modes to increase or decrease power consumption
Automatic communication with aggregator server	Communicate power measurements, heat pump status data and activation between heat pump and aggregator

Table 3.2 Measurement accuracy and data refresh requirements

Parameter	FCR	aFRR	mFRR
Measurement inaccuracy, %	≤2		
Data refresh rate, s	≤10		

In addition to technical requirements the cost of the solution must be considered. As described in 2.7.6 the average revenue for heat pump with nominal electrical power of 1 kW is estimated to be €30-55 and €10-50 from FCR and aFRR markets, respectively. Based on this the annual revenue for heat pump with 1 kW electrical power is estimated to be €30 annually in this work. Cost target is calculated based on a heat pump with 3 kW nominal electrical power. Payback period is set to three years meaning the investment into the solution should be returned by the end of third year. Cost target is calculated based on payback time formula 3.1.

$$T = \frac{C_{Inv}}{C_{CF}} \qquad (3.1)$$

Where T – payback time, years

C_{Inv} – initial investment, €

C_{CF} – annual cashflow from investment, €

Table 3.3 Cost target

Criteria	Value
Annual revenue 1 kWel heat pump, €	30
Heat pump electrical power, kW_{el}	3
Payback period, years	3
Cost target, €	270

4. CONCEPTUAL MODEL DEVELOPMENT

This chapter focuses on the development of heat pumps interface conceptual model for balancing markets. According to the specification of objectives each required functionality and potential solutions are analysed. These solutions are compared based on their technical capabilities and price to find the most suitable methods for necessary functionalities. A conceptual model for heat pumps interface to balancing markets is proposed.

4.1 Automatic active power measurement

To provide balancing services with heat pumps it is necessary to measure the active power consumption. Aggregator needs this information to calculate the consumption of aggregated portfolio in real time. Harmonised principles for Baltic LFC reserve prequalification [54] specify that inaccuracy of measurement shall not exceed 2%. This can be achieved by direct measurement with a meter of 1.0 class (B class) or indirect with measurement transformer and meter of class 0.5 (C class) each. Time-stamped metering data of each technical entity must be available for 10 s interval. In this section different measurement and communication methods are reviewed to find the most suitable method for active power measurement. Requirements for the active power measurement solution are summarized Table 4.1.

Table 4.1 Requirements for active power measurement

Parameter	Requirement
Measurement error, %	≤2
Measurement interval, s	≤10
Data exchange interval, s	≤10
Meter accuracy class for direct measurement	1.0 or better
Meter and transformer accuracy class for indirect measurement	0.5 or better

Aggregator must have real-time information about the active power consumption of the aggregated portfolio. Selected measurement technology must be able to communicate measurement data with low latency. Harmonized requirements specify that aggregator needs to provide active power measurement to TSO in 10 s intervals. Additionally, aggregator must be capable of providing time-stamped measurement data with 10 seconds interval for each technical entity. As aggregator needs to process and summarize all measurement data before sending it to TSO the latency with between each meter and aggregator needs to be not more than few seconds. Therefore, the maximum allowed latency limit for measurement data communication between the meter and aggregator is set to 1 s.

Various communication methods are available for metering devices. Commercial energy meters mostly use Power Line Communication where data is transmitted over the same conductors as power. Small fraction of commercial meters exchange metering data via mobile networks. Power Line Communication is well suited for commercial energy metering but not for real-time power metering as measurements are taken for each imbalance settlement period and sent to central system once a day. Today imbalance settlement period in Baltic states is 60 min and implementation of 15 min imbalance settlement period will start from 2025. Therefore, commercial energy meters and their communication methods are not suitable for real-time active power measurements. [55, 56]

Communication via mobile network is widely used by smart meters for bi-directional data-exchange. Cellular networks provide a wide-coverage, low-latency, cost-effective and scalable method to communicate with energy meters. Several aspects need to be considered when choosing a suitable wireless telecommunication technology. Older generation 2.5G and 3G networks are being phased out in many countries and using these networks is not a future-proof solution. 4G is well suited for media streaming but not designed for high number of devices exchanging small amounts of data. Technologies like NB-IoT, Long-Time Evolution (LTE) Cat 1 and LTE Cat M1 are designed specifically for Internet of Things (IoT) and have high security, low-latency, high-coverage. Parameters for NB-IoT, LTE Cat 1 and LTE Cat M1 are presented in Table 4.2. Based on the benefits and suitability the metering equipment must have a capability to communicate using NB-IoT, LTE Cat 1 or LTE Cat M1 technology. [57, 58]

Table 4.2 Parameters for LTE Cat 1, LTE Cat M1, NB-IoT [59]

Criteria	LTE Cat 1	LTE Cat M1	NB-IoT
System Bandwidth	20 MHz	1.4 MHz	200 KHz
Peak Data Rate (UL/DL)	10 Mbps/5 Mbps	300 kbps/375 kbps	17 kbps/30k bps
Coverage/penetration	Same as GSM	Approx. 2-3 x GSM	Approx. 4 x GSM
Latency	Milliseconds, effectively real time	80ms to 4s	1s to 10s
Battery life	<5 years	>10 years	>10 years
End-point Density	Urban and rural	Urban and rural	Rural and light urban Tendency for available bandwidth per session to drop in high-density applications
Mobility (not applicable to smart meters, but referenced)	Seamless, full handover	Some limitations, but reasonable mobility	Limited, changing cells without handover
Voice (not applicable to smart meters, but referenced)	Full voice	Restricted voice for simple use-cases such as alarms	No voice, data only
Application	High bandwidth, real-time/low-latency, highly mobile	Limited data stream, suitable for telemetry with SW upgrade	Message centric, constraints on SW upgrade

Direct measurement refers to the method where the measurement is taken explicitly of the measured entity. Current and voltage are measured directly from the lines and no additional equipment such as current or voltage transformers are used. A power meter designed for direct measurements has input and output terminals where the incoming and outgoing power cables are connected, respectively. Benefits of direct metering are high accuracy, low costs, and no need for additional current or voltage transformers. Connection diagram of three-phase direct meter is presented on Figure 4.1.

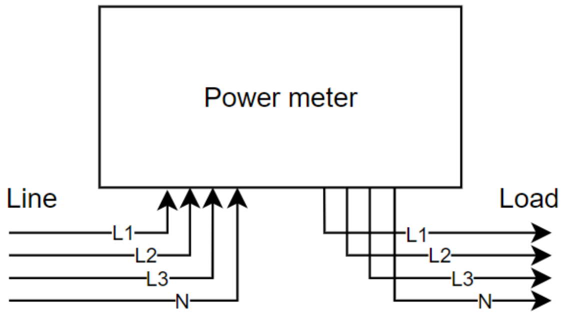


Figure 4.1 Connection diagram for direct meter

Indirect measurement is a method where measurement is not done directly on the line under examination. Typically, current transformers are used for indirect measurement of current. Indirect current measurement is based on sensing the magnetic field generated by a current carrying conductor. Current transformers are installed on the lines, and they provide a proportional measurement value which is provided to measurement instrument. For indirect current measurement split core current transformers can be installed without disconnecting the lines. This is the main advantage of using indirect current measurement for heat pump applications. A typical wiring diagram for low-voltage three-phase power meter with current transformers is presented on Figure 4.2.

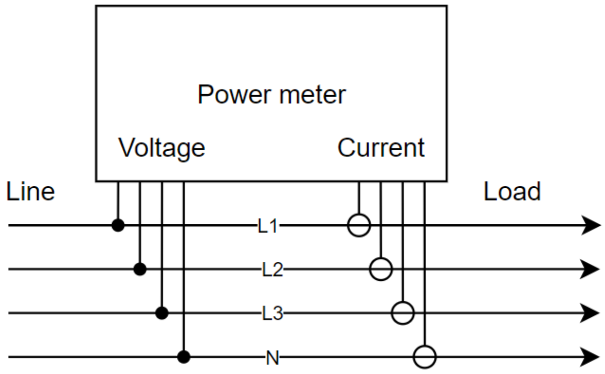


Figure 4.2 Connection diagram for power meter with current transformers

Consumption modelling provides another potential solution for power consumption data. Heat pump's electrical power consumption can be modelled based on its technical parameters, outdoor temperature and building heating demand. Using heat capacity and relevant electricity consumption curves from manufacturer's data sheet, outdoor temperature, and building heating demand data the electrical consumption of heat pump can be modelled and calculated [60]. Main advantage of consumption modelling is the possibility to eliminate electrical power meter. However, it must be considered that creating a precise consumption model for each user is technically complex and modelled consumption data is strongly affected by modelling and measuring errors. Basic principle of consumption modelling is presented on Figure 4.3.

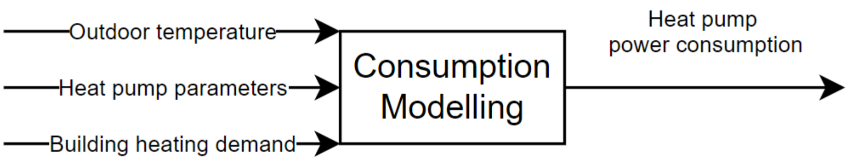


Figure 4.3 Consumption modelling

To select the best method for active power measurements three main criteria are considered. First, the solution must fulfil requirements set by harmonized prequalification requirements [60] and measurement inaccuracy shall not exceed 2%. Second, the measurement method must have a low cost. Third, it must be easy to install to allow fast and convenient connection to heat pumps. Both direct and indirect power meters can fulfil required accuracy classes of 1.0 or 0.5, respectively. Direct and indirect meter price are approximately in the same range. Based on author's discussion with electrical engineer and electrician the indirect meters are the easiest to install. Current transformers can be simply installed on the conductors and voltage input can be taken from panel or equipment terminals. Direct meters need to be installed between the source and consumer and disconnection of supply lines is required. Evaluation criteria and their importance, scores for every method are presented in Table 4.3.

Table 4.3 Criteria and scores for measurement methods

Criteria	Score weight	Direct measurement	Indirect measurement	Consumption modelling
Accuracy	3	3	3	1
Price	2	3	3	1
Easy to install	1	1	2	3
Total weighted score		16	**17**	8

Based on Table 4.3 indirect measurement is the most suitable for active power measurement. It offers sufficient accuracy and is widely used for different applications. The most fitting technologies for metering data communication are Low Power Wide Area Networks (LPWANs) such as NB-IoT, LTE Cat 1 and LTE Cat M1. These provide low-latency and cost-effective solution to exchange data between power meter and server. LPWAN compatible power meters are still in the early implementation stage and not widely available. Price for commercially available power meters is in the range of €100 to €240 [61, 62]. An alternative solution would be to integrate a Modbus power meter with LPWAN gateway to exchange measurement data over cellular network. This could decrease the cost of measurement system but needs separate development work.

4.2 Automatic reading of heat pump data

Data from heat pumps provides valuable information to aggregator. Using temperature settings and values, heating curve information, operation mode, and other data from heat pump the aggregator can calculate and forecast the available flexibility which can be offered to balancing market. Without this data the aggregator is unable to understand the status of whole portfolio and successfully trade the flexibility for balancing services. Reading and monitoring data from heat pumps enables to follow customer settings and ensure that customer comfort and critical temperature conditions are not interfered.

To choose a suitable method for reading the data from heat pumps the available interface options need to be analysed. In this section data from various manufacturers is reviewed and analysed to find the most suitable method for reading the data from heat pumps. Four air-to-water heat pumps from different manufacturers are selected and their interface options are shown in Table 4.4. Detailed information for selected heat pumps can be found in APPENDICES.

Table 4.4 Interface options for heat pumps [63, 64, 65, 66]

Manufacturer	**Heat pump model**	**Analog outputs**	**Digital outputs**	**Modbus**	**API**
Samsung	EHS	No	No	Yes[1]	Yes[2]
Panasonic	T-CAP	No	No	Yes[1]	Yes[2]
Daikin	Altherma 3	No	Yes[1]	Yes[1]	Yes[2]
NIBE	S2125	No	Yes[1]	Yes	Yes[2]

Notes: 1) requires additional control module; 2) requires heat pump Wi-Fi adapter

Data in Table 4.4 shows that heat pumps have almost no capability to communicate over analog or digital outputs. Available outputs cover only certain signals (e.g. external On and Off switching) and do not provide full functionality required. Daikin and NIBE heat pumps would require additional control module to exchange digital signals. As presented in Table 4.6 price for NIBE SMO 20 control module is €750 and price for Daikin RTD 10 module is €320. Therefore, reading data over analog and digital outputs is not a preferred method as it would result excessive costs and it is not scalable to different manufacturers.

Modbus shows better suitability for reading data from heat pump. Heat pump manufacturers provide a comprehensive list of parameters with read and write possibilities. Temperature setpoints, room and supply temperatures, operation modes and other values can be read over Modbus communication. An example of data available for reading through Samsung CL-MC03 module is shown in Table 4.5. Using Modbus protocol data like On/Off status, operation mode, set temperature, room temperature can be read from heat pump. Therefore, Modbus communication has all the functionality needed. However, three heat pumps presented in Table 4.4 require additional control modules to communicate over Modbus. As shown in Table 4.6 control modules for Samsung, Panasonic, Daikin, NIBE heat pumps cost from €320 to €750.

Table 4.5 Data available for reading through Samsung CL-MC03 module [67]

Indoor Unit Addresses				Length (Byte)	Name	Value	Notes	Read/ Write
IDU 00	IDU 01	....	IDU 63					
40001	40021	....	41261	2	IDU ON/OFF STATUS	0	OFF	R
						1	ON	R
40002	40022	....	41262	2	IDU OPERATION MODE	0	AUTO	R
						1	COOLING	R
						2	DRY (DEHUMIDIFICATION)	R
						3	FAN	R
						4	HEAT	R
						11	AUTO COOL	R
						12	AUTO DRY	R
						13	AUTO FAN	R
						14	AUTO HEAT	R
40005	40025	....	41265	2	SET TEMPERATURE		SET TEMP = Data/10	R
40006	40026	....	41266	2	ROOM TEMPERATURE		ROOM TEMP = Data/10	R
40009	40029	....	41269	2	IDU FAN SPEED CONTROL	0	AUTOMATIC	R
						1	LOW	R
						2	MIDDLE	R
						3	HIGH	R
						4	TURBO	R
40010	40030	....	41270	2	IDU DECO PANEL LOUVER SWING	0	SWING OFF	R
						1	SWING ON : UPPER & LOWER LOUVER	R
						2	SWING ON : RIGHT & LEFT LOUVER	R
						3	SWING ON : UPPER&LOWER/RIGHT&LEFT LOUVER	R
40011	40031	....	41271	2	Supply Air(Discharge) Temperature (Duct unit only)		SET TEMP = Data/10	R
40012	40032	....	41272	2	States of Supply Air(Discharge) Temperature Control	0	DISABLE	R
						1	ENABLE	R
40013	40033	....	41273	2	Set Temp. of Cooling Supply Air (Duct unit only)		SET TEMP = Data/10	R
40014	40034	....	41274	2	Set Temp. of Heating Supply Air (Duct unit only)		SET TEMP = Data/10	R

Table 4.6 Control module prices for Modbus communication [68, 69, 70, 71]

Manufacturer	Heat pump model	Control module	Price, €
Samsung	EHS	CL-MC03	420
Panasonic	T-CAP	PA-AW2-MBS-1	480
Daikin	Altherma 3	RTD 10	320
NIBE	S2125	SMO 20	750

Application programming interface (API) is a set of rules that enables different software applications to communicate with each other. API acts as a middle layer that processes data transfer between different systems and lets companies open their application data and functionality to third-part developers and partners [72]. API provides a simple and scalable solution for data reading. Heat pump manufacturers provide a standard API documentation which can be used to establish an API connection to server as shown on Figure 4.4. All heat pumps listed in Table 4.4 are accessible through API. Parameters like equipment status, operation mode, heating and cooling setpoints, indoor and outdoor temperatures can be read with API [73]. A list of parameters which can be requested through Daikin API is presented on Figure 4.5.

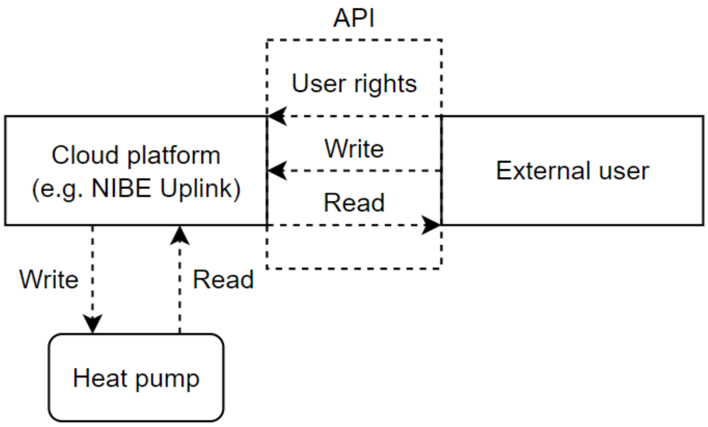


Figure 4.4 Basic principle of heat pump API

3.1.2 Device State

Returns the state parameters of a device.

- RETURN
- GET https://dkncloudna.com/api/v1/open/{{INSTALLTION_ID}}/{{MAC}}
- BODY: none
- EXAMPLE:
- GET https://dkncloudna.com/api/v1/open/5cd51f1684c09013f6765d9c/AA:BB:CC:DD:EE:0D
- RESPONSE:

```
{
  "mode": <number>,
  "power": <boolean>,
  "setpoint": <number>,
  "temperature": <number>,
  "speed": <number>,
  "isConnected": <boolean>,
  "error": <number>,
  "errorStr": <string>,
  "warning": <number>,
  "warningStr": <string>
}
```

- ***mode***: device's current operation mode.
- ***power***: *true* if on; *false* if off.
- ***setpoint***: setpoint for the current operation mode.
- ***temperature***: room temperature.
- ***speed***: fan speed.
- ***isConnected***: if device is online or not (connected to the cloud).
- ***error***: AC unit's error code. **If there's no error, this field will not be returned.**
- ***errorStr***: ASCII representation of the error. **If there's no error, this field will not be returned.**
- ***warning***: AC unit's warning code. **If there's no warning, this field will not be returned.**
- ***warningStr***: ASCII representation of the warning. **If there's no warning, this field will not be returned.**

Figure 4.5 Device state request from Daikin Open API [74]

A separate Wi-Fi adapter is needed to connect heat pump to internet and enable API connection. Heat pumps shown in Table 4.4 have API readiness but they require additional Wi-Fi adater which is offered by heat pump manufacturers or third-party vendors. Exception is NIBE S2125 which has built-in internet connectivity. After installing Wi-Fi adapter a heat pump can be connected to external devices like smartphones, and API connection to heat pump cloud platform can be established. Prices for Wi-Fi adapters are presented in Table 4.7.

Table 4.7 Prices of WiFi adapters for API communication [75, 76, 77, 78]

Manufacturer	Heat pump model	Wi-Fi adapter	Price, €
Samsung	EHS	MIM-H04EN	150
Panasonic	T-CAP	CZ-TAW1B	190
Daikin	Altherma 3	DKN Cloud Adapter	190
NIBE	S2125	Integrated to heat pump	-

As described in this section there are three potential communication methods for getting data and feedback from heat pumps. Communication could take place over analog or digital outputs, Modbus, or API. Based on the comparison and analysis it was found that analog and digital outputs do not offer the full functionality needed. Modbus and API are both technically suitable and have the capability to provide necessary data to aggregator. However, Modbus control modules have two to three times higher price than Wi-Fi adapters needed for API communication. Additionally, many users already have Wi-Fi adapter installed for remote control and extra investment would not be needed. As of 2022 Samsung SmartThings app has over 62 million users globally [79]. Therefore, the API communication shows the highest potential for being suitable to automatically read data from heat pump.

4.3 Sending automatic activation commands to heat pump

To participate in balancing markets and provide balancing services it is necessary to have the capability to control the power consumption of heat pumps. Demand aggregator adds all connected heat pumps to one large portfolio. Based on the available flexibility to increase or decrease the power consumption the aggregator can offer the flexibility to balancing markets. After successful bid the aggregator is responsible to deliver the amount of power offered to and ordered by TSO. This requires aggregator to have a method to send activation signal to each available heat pump to deliver the upward or downward regulation to TSO.

Available interface options for heat pumps need to be analysed to find a suitable method for sending the activation signals. Data from different manufacturers is examined and analysed to find the best method for sending the activation signals to heat pumps. Methods for sending the activation signals to heat pumps presented in Table 4.8 are analysed in this section.

Table 4.8 Interface options for heat pumps [63, 64, 65, 66]

Manufacturer	Heat pump model	Digital input	Modbus	API
Samsung	EHS	Yes[1]	Yes[1]	Yes[2]
Panasonic	T-CAP	Yes	Yes[1]	Yes[2]
Daikin	Altherma 3	Yes	Yes[1]	Yes[2]
NIBE	S2125	Yes[1]	Yes	Yes

Notes: 1) requires additional control module; 2) requires heat pump Wi-Fi adapter

As presented in Table 4.8 the selected heat pumps have three different interfaces available for receiving the activation signals. With digital inputs the activation signals can be sent to digital inputs located on the equipment. For this method the heat pump's digital inputs need to be wired to a controlled external source, e.g. a relay. By opening or closing the relay contact the heat pump mode can be controlled. All selected heat pumps are Smart Grid Ready meaning they can be controlled based on the Smart Grid principles and through Smart Grid contacts. Smart Grid Ready is a standard functionality which allows heat pump to be controlled by two external inputs. Main purpose of the Smart Grid Ready is to allow external control of heat pump consumption based on the electricity price. Smart Grid Ready functionality is described in . Using Smart Grid contacts would require development of relay control device with communication capability. Samsung and NIBE heat pumps would also need additional control modules.

Table 4.9. Using Smart Grid contacts would require development of relay control device with communication capability. Samsung and NIBE heat pumps would also need additional control modules.

Table 4.9 Smart Grid Ready functionality [80]

Contact A	Contact B	Behaviour of the heat pump	Balancing service
Open	Open	Normal operation	-
Open	Close	Switch-on recommendation, cheap electricity	-
Close	Open	Reduced operation command, expensive electricity	For upward regulation
Close	Close	Switch-on command, cheap electricity	For downward regulation

Activation signals can be also sent to heat pump using Modbus communication which allows to send commands to change operation mode or switch equipment like compressors, fans, or circulation pumps [81]. Control data which can be written to Samsung heat pump through CL-MC03 is shown in Table 4.10. Samsung, Panasonic, Daikin and NIBE provide a wide range of functionalities through Modbus, and Modbus is technically feasible for upward and downward regulation commands. However, as covered in Section 2 and presented in Table 4.8 Samsung, Panasonic and Daikin heat pumps require additional control module to communicate over Modbus. Prices for the control modules are higher than the target cost of the final solution. Therefore, Modbus communication for sending activation commands is not a suitable method due to high equipment cost.

Table 4.10 Data available for writing through Samsung CL-MC03 module [67]

Indoor Unit Addresses				Length (Byte)	Name	Value	Notes	Read/ Write
IDU 00	IDU 01	....	IDU 63					
40001	40021	....	41261	2	IDU ON/OFF & MODE		Data 1	W
						0	OFF	W
						1	ON	W
				2			Data 2	
						0	AUTO	W
						1	COOLING	W
						2	DRY (DEHUMIDIFICATION)	W
						3	FAN	W
						4	HEAT	W
						11	AUTO COOL	W
						12	AUTO DRY	W
						13	AUTO FAN	W
						14	AUTO HEAT	W
40005	40025	....	41265	2	SET TEMPERATURE		SET TEMP = Data/10	W
40009	40029	....	41269	2	IDU FAN SPEED CONTROL		Data 1	W
						0	AUTOMATIC	W
						1	LOW	W
						2	MIDDLE	W
						3	HIGH	W
						4	TURBO	W
				2	IDU DECO PANEL LOUVER SWING		Data2	
						0	SWING OFF	W
						1	SWING ON : UPPER & LOWER LOUVER	W
						2	SWING ON : RIGHT & LEFT LOUVER	W
						3	SWING ON : UPPER&LOWER /RIGHT&LEFT LOUVER	W
40011	40031	....	41271	2	Supply Air(Discharge) Temperature (Duct unit only)		SET TEMP = Data/10	W
40012	40032	....	41272	2	States of Supply Air(Discharge) Temperature Control	0	DISABLE	W
						1	ENABLE	W
40013	40033	....	41273	2	Set Temp. of Cooling Supply Air (Duct unit only)		SET TEMP = Data/10	W
40014	40034	....	41274	2	Set Temp. of Heating Supply Air (Duct unit only)		SET TEMP = Data/10	W

All heat pumps presented in Table 4.8 have API readiness. Through heat pumps manufacturer or third-party cloud platforms the commands to change operation modes can be sent. End-user would need to allow aggregator to access the heat pump and control certain parameters. By using specific username and password the API connection is established with heat pump and operation mode or temperature setpoints can be adjusted by aggregator. List of command requests for Daikin heat pump are shown on Figure 4.6. As described in Section 2 an additional Wi-Fi adapter is needed to enable API communication. Prices for Wi-Fi adapters are presented in Table 4.7. As Wi-Fi adapter prices are lower than prices for Modbus control modules the Wi-Fi adapter and API connection would be the most cost-efficient method. Also, API has better scalability as many users already have heat pumps connected to Wi-Fi network and API access can be easily extended to new users.

3.2.1 Device – State

Turn on/off the AC.

- REQUEST:
- PUT https://dkncloudna.com/api/v1/open/{{INSTALLTION_ID}}/{{MAC}}/state
- BODY: (JSON). Properties:
    - ***value***: (Boolean) true for on; false for off
- EXAMPLE:
- PUT https://dkcloudna.com/api/v1/open/5cd51f1684c09013f6765d9c/AA:BB:CC:DD:EE:0D/state

3.2.2 Device – Setpoint

Specify the AC's setpoint for the current operation mode.

- REQUEST:
- PUT https://dkncloudna.com/api/v1/open/{{INSTALLTION_ID}}/{{MAC}}/setpoint
- BODY: (JSON). Properties:
    - ***value***: (Number) value of the setpoint.
- EXAMPLE:
- PUT https://dkncloudna.com/api/v1/open/5cd51f1684c09013f6765d9c/AA:BB:CC:DD:EE:0D/setpoint

3.2.3 Device – Mode

Change the AC's operation mode.

- REQUEST:
- PUT https://dkncloudna.com/api/v1/open/{{INSTALLTION_ID}}/{{MAC}}/mode
- BODY: (JSON). Properties:
    - ***value***: (Number) value representing a valid mode.
- EXAMPLE:
- PUT https://dkncloudna.com/api/v1/open/5cd51f1684c09013f6765d9c/AA:BB:CC:DD:EE:0D/mode

In case the value is not valid, the request will return the following error:

- Response code: 400
- Body:

```
{
  "_id": "modeNotSupported",
  "msg": "The thermostat doesn't support the specified mode."
```

Figure 4.6 Command requests to heat pump through Daikin Open API [74]

4.4 Automatic communication with aggregator server

To effectively monitor, aggregate and offer flexibility to balancing markets the aggregator must have a central server or platform. This can be a specifically developed by aggregator itself or purchased from third-party software providers. VPP platforms are commonly used to aggregate assets virtually and bid upward or downward capacities to balancing markets. Regardless of the solution used by aggregator the communication with each device in aggregated portfolio needs to be set up.

As described in Section 4.1 the active power measurements are exchanged over LPWANs which provide wide-coverage, low-latency, and cost-effective method for gathering metering data from large amount on networks. According to Table 4.2 LTE Cat 1 and LTE Cat M1 show the highest suitability as these technologies have lower latency, higher bandwidth, and data rates than NB-IoT. LTE Cat M1 has two to three times better coverage than LTE Cat 1 and is suitable for rural areas. LTE Cat 1 has lower latency and higher data rate compared to LTE Cat M1 and is capable of real-time communication. With both technologies data from power meter is gathered for every heat pump over cellular network and sent to aggregator server.

Reading data from heat pumps and sending activation commands is described in Sections 4.2 and 4.3. Based on the comparison between available interfaces the API is the most suitable method both for reading data from heat pumps and sending activation commands. With API each heat pump is connected to manufacturer or third-party cloud platform using Wi-Fi adapter and customer internet connection. Once the heat pump is connected to cloud platform the customer can authorize aggregator for access. Aggregator can request data from heat pump and send commands to turn heat pump On or Off, change setpoints or operation mode.

4.5 Conceptual model

Previous sections cover the development of heat pump interface conceptual model to balancing markets. Required functionalities such as automatic active power measurement, reading of data from heat pump and sending activation commands to heat pumps, communication with aggregator server were analysed. Based on the analysis the suitable methods and technologies were proposed. It was found that indirect metering and LTE Cat 1 / LTE Cat M1 is the most suitable method for active power measurement and communication. API proved to be the best method to automatically read data and send activation commands to heat pump. Table 4.11 presents required functionalities and proposed solutions for these. Principle diagram for the conceptual model is shown on Figure 4.7.

Table 4.11 Proposed solutions

Functionality	**Solution**
Automatic measurement of heat pump active power	Indirect measurement with LTE Cat 1 or LTE Cat M1 communication
Automatic reading of heat pump data	API connection through manufacturer or third-party cloud server
Send automatic activation commands to heat pump	API connection through manufacturer or third-party cloud server
Automatic communication with aggregator server	LTE CAT 1 / LTE CAT M1 for power metering data, API for status data and commands

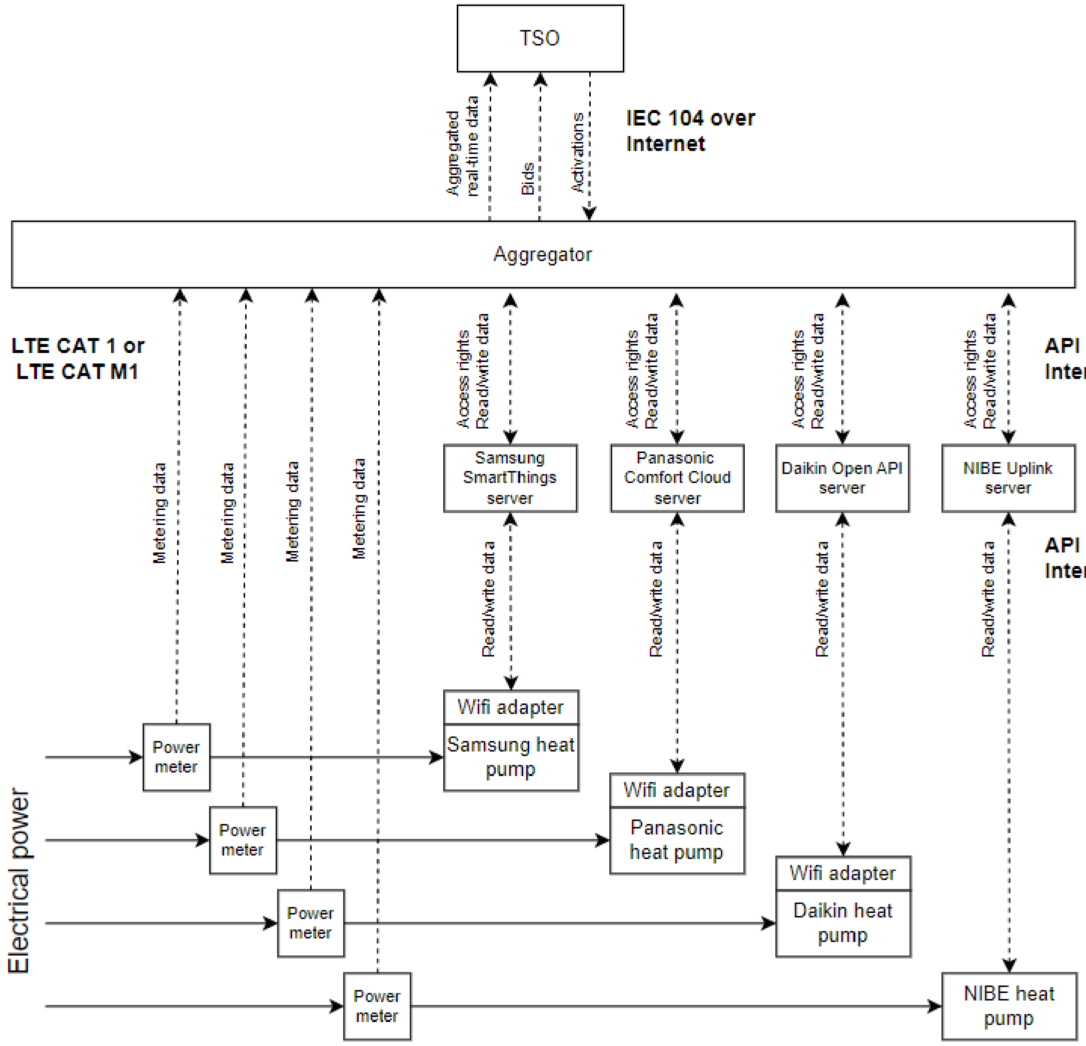


Figure 4.7 Principle diagram of the conceptual model

4.6 Balancing service process with heat pumps

To offer balancing services the aggregator must provide bids for upward and downward regulation to TSO. Aggregator needs to forecast the available flexibility from heat pumps using real-time and historical data, weather forecast and other variables. Bids must include the hour to which the bid is meant, direction of bid (upward or downward), available amount of power and price for the bid. TSO arranges all bids from service providers to Common Merit Order List based on the price of the bid. TSO activates balancing reserves starting from the lowest bid for up-regulation and starting from highest bid for down-regulation.

Balancing service process with heat pumps is presented on Figure 4.8. After submitting bids to TSO, the aggregator takes a responsibility to deliver the offered amount of power if activation order is sent by TSO. Once the aggregator receives an activation order from TSO the aggregator gathers the latest status of the aggregated portfolio. This includes real-time power consumption and status data of a whole portfolio. Then readiness of each heat pump is checked. Some of the units may not be available due to reasons such as maintenance, connection issues, user preferences and other. After receiving status data, the aggregator activates the units that are ready for activation. Real-time power and feedback are monitored continuously to ensure the delivery matches the TSO order. If needed, then aggregator can activate further assets which have not been activated previously. After the end of delivery, the heat pumps are returned to their normal operation mode and consumption. As a last step the settlement is done between aggregator, TSO, and end-customer.

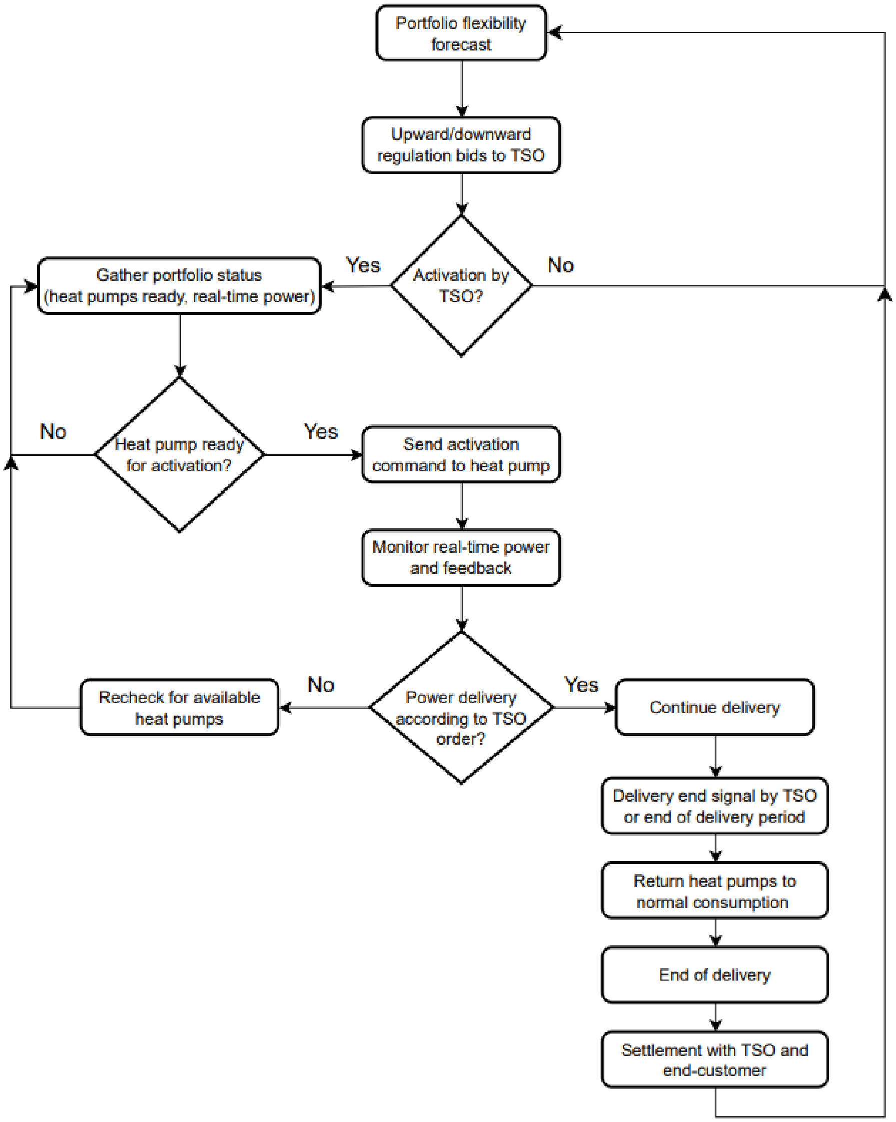


Figure 4.8 Balancing service process with heat pumps

4.7 Cost analysis

The initial cost target of €270 for the final solution was presented in Table 3.3 based on the estimated revenues, heat pump electrical power and expected payback period. Purpose of the cost target is to ensure the prices of different technologies are considered during the development of the conceptual model and most cost-effective technologies are selected. As residential heat pumps' electrical power consumption is relatively low it is important to develop low-price and scalable solution. This ensures that initial investment can be earned back in reasonable period and service providers would have financial incentive to develop solutions which enable heat pumps to participate in balancing markets.

In Section 4.2 the prices for metering equipment, Modbus control modules, and Wi-Fi adapters were provided. For better understanding of costs, it is also important to consider additional costs related IT developments and communication setup. These costs are divided between the total target portfolio of aggregator as these are initial investments which enable the aggregator to scale the solution from the first heat pumps to thousands of heat pumps. In this work it is assumed that aggregator has a target to connect and aggregate 10 000 heat pumps which would result a portfolio around 20 to 30 MW. There are approximately 200 000 heat pumps installed in Estonia [82] which shows that portfolio of 10 000 would be a realistic target already in a small country such as Estonia. Extending the service to potential markets in Europe would result much larger potential portfolio.

Cost calculations of the conceptual solution are presented in tables 4.12, 4.13, 4.14 and 4.15. Total cost includes equipment, installation, subscription, and data-exchange setup. Equipment costs are based on the distributors' prices [62, 75]. For installation it is estimated that both energy meter and Wi-Fi adaptor installation takes approximately one hour with electrician hour price of €30 [83]. LTE network subscription fee for 36 months is based on mobile service provider monthly fee of €1,2 [84]. API connection and energy metering data-exchange setup costs are based on work estimation by developers and standard hourly price for server development works [85]. It must be highlighted that development costs are divided with total target portfolio of 10 000 heat pumps. Once the data-exchange has been built and set up then adding new devices does not require new development work and adding devices is mostly related API setup with each device.

Table 4.12 Equipment and installation costs

Equipment and installation	Unit cost, €	Quantity, pcs	Total cost, €
Power meter	100	1	100
Power meter installation	30	1	30
Wi-Fi adapter	175	1	150
Wi-Fi adapter installation	30	1	30
LTE network monthly fee	1,2	36	31,2
			341,2

Table 4.13 Communication setup costs

Communication setup	Unit price, €/h	Quantity, h	Total cost, €
API connection setup	89	60	5340
Metering data-exchange setup	89	80	7120
			12 460

Table 4.14 Communication setup cost per unit

Communication setup per unit	Setup cost, €	Quantity, pcs	Setup cost, €
Communication setup	12 460	10 000	1,2

Table 4.15 Total costs per unit

Total costs per unit	Total cost, €
Equipment and installation	341,2
Setup costs	1,2
	342,4

Table 4.16 Target and calculated cost difference

Item	Unit cost, €
Target cost	270
Calculated cost	342,4
Difference	**72,4**

Cost analysis of the developed model shows that target cost is not achieved with current solution. Calculated cost for developed model with selected components is €72,4 higher than the target. Table 4.12 shows that equipment and installation costs account for 90% of the total costs. Therefore, further research is needed to decrease these costs and find more cost-effective devices and technologies. Additionally, heat pumps with existing Wi-Fi connection should be preferred in the first phase as it would eliminate the need to install a new Wi-Fi adapter for heat pump. Table 4.13 and

Table 4.14 illustrate that initial setup and development costs account for only a small fraction of final cost for every unit. This suggests that scalable software solutions should be preferred due to their low unit costs. It also supports the selection of API for data reading and writing as setting up a new API for each additional heat pump is simple and low-cost process.

4.8 SWOT analysis

SWOT is an acronym used to describe the **S**trengths, **W**eaknesses, **O**pportunities, and **T**hreats that are strategic factors for a company, a product, or any other entity. SWOT analysis allows company to assess external and internal factors to develop strategic planning for a company or a specific product. Analysis is conducted by gathering information about the related strengths, weaknesses, opportunities, and threats. This information is then organized into a SWOT table and into four quadrants each dedicated to one element of SWOT. SWOT analysis for the conceptual model developed in this work is presented in Table 4.17. [86]

Table 4.17 SWOT analysis

Strengths	**Weaknesses**
• Scalable to different heat pump manufacturers • Generates revenues for customers • Supports power system balance • Use of existing and proven technologies • Components available on the market	• Still in conceptual phase and needs further development • Needs cost reduction • Scalability to other heat pump manufacturers not analysed
Opportunities	**Threats**
• Increasing need for balancing services • High growth of heat pump sales and installations • Harmonization of markets • Expansion to different markets • Target to reduce CO2 emissions • Target to reduce grid investments	• Competing solutions on the market • Competing with other balancing reserves in the balancing market • Low balancing market prices • Customer unwillingness to enable access • Dependency on external cloud platforms • Cyber threats • Regulation changes

According to SWOT analysis the main strengths are the scalability to different heat pumps analysed in this work and the possibility to generate revenues for customers. Weaknesses are mainly related to the fact it is still a conceptual model which needs further development and unit cost reduction. Additionally, the scalability to other heat pump manufacturers not included in this work needs further analysis. Developed conceptual model has several opportunities related to wide-spread growth of RES and overall development of balancing markets. Most important opportunities are the increasing need for balancing capacity which grows total market capacity and enables more reserve providing units to markets. Similarly, increased heat pump sales create favourable market environment to connect more heat pumps to balancing markets. Main threats are the competing solutions from other players on the market and competition in the balancing markets. Dependency on external heat pump cloud platforms and threats regarding cyber-attacks must be also considered.

SUMMARY

The main objectives of the master's thesis were to research the balancing markets, analyse heat pumps potential for balancing services and develop an interface conceptual model which would enable heat pumps to participate in balancing markets.

The first part of the work gives an overview of the electric power system and electricity markets. Balancing markets and balancing reserves are described and harmonization of balancing reserves in Europe is reviewed. Heat pumps as a potential source of flexibility are presented and their demand response potential is investigated. Related research work in the field is covered. Additionally, a short market overview of existing solutions is provided, and demand response challenges are presented.

The second part of the thesis focuses on the development of heat pumps interface conceptual model for balancing markets. Based on the harmonized requirements for balancing reserves the objectives for conceptual model are described and required functionalities are specified. Conceptual model development process is described in detail and developed conceptual model is presented. The conceptual model proposes a solution where active power measurement data is exchanged over LTE network and heat pump data is exchanged over API.

The last part of the thesis describes balancing service process with heat pumps. A cost analysis for the conceptual model is presented together with comparison with cost target which shows that further research and development is needed to reduce the price of the interface solution. Additionally, a SWOT analysis for the conceptual model is done. According to SWOT analysis the market presents great opportunities such as increasing needs for balancing services and harmonization of balancing reserves over European market. However, potential threats like competing services and cyber threats need to be considered.

Developed interface conceptual model enables aggregator to monitor the power consumption and send activation commands to high number of aggregated heat pumps. Heat pumps have a significant potential to offer flexibility to balancing markets but today this potential remains locked. This work serves a foundation for further development and implementation to specific cases to unlock the full potential of heat pumps' flexibility for balancing markets.

KOKKUVÕTE

Käesoleva töö eesmärgiks on uurida reguleerimisturge ja nõudeid nendel osalemiseks, analüüsida soojuspumpade potentsiaali reguleerimisturgude jaoks ning töötada välja kontseptuaalne mudel, mis võimaldaks soojuspumpadel osaleda reguleerimisturgudel.

Töö esimene osa annab ülevaate elektrisüsteemidest ja elektriturgudest. Tutvustatakse reguleerimisturge ja nende harmoniseerimist Euroopas. Kirjeldatakse soojuspumpasid ja nende potentsiaali reguleerimisturgudel osalemisel. Antakse ülevaade valdkonnas tehtud uurimustöödest ning tutvustatakse lühidalt turul olevaid teenusepakkujaid ja lahendusi.

Töö teises osas määratakse nõuded ja lähteülesanne arendatavale mudelile arvestades harmoniseeritud reguleerimisturgude nõudeid. Vastavalt lähteülesandele kirjeldatakse kontseptuaalse mudeli arendust ja selle käigus tehtud tööd. Uurimus- ja arendustöö tulemusel esitletakse LTE andmesidel ja API liidestusel põhinevat kontseptuaalset mudelit, mis võimaldab soojuspumpadel osaleda reguleerimisturgudel.

Töö viimases osas kirjeldatakse reguleerimisteenuse protsessi soojuspumpadega. Tehakse kuluanalüüs arendatud kontsepuaalsele mudelile, mille tulemused näitavad, et liidestuse mudel vajab edasist arendamist kulude vähendamiseks. Lisaks viiakse läbi SWOT analüüs, mis tuvastab, et reguleerimisturud pakuvad mitmeid võimalusi tänu kasvavatele reguleerimismahtudele ja üleeuroopalisele harmoniseerimisele. Samuti tuuakse välja võimalikud riskid, mis on seotud konkureerivate lahenduste ja küberturvalisusega.

Arendatud kontseptuaalne mudel võimaldab agregaatoril monitoorida agregeeritud portfelli võimsust reaalaja lähedaselt ning saata automaatseid aktiveerimissignaale suurele hulgale soojuspumpadele. Soojuspumpadel on märkimisväärne potentsiaal pakkumaks paindlikkust reguleerimisturgudele, kuid see potentsiaal on täna kasutamata. Käesoleva töö pakub kontseptuaalse lahenduse ning põhimõtted teema edasiseks arenduseks, et realiseerida soojuspumpade potentsiaali reguleerimisturgudel.

LIST OF REFERENCES

[1] S. W. Blume, "Electric Power System Basics for the Nonelectrical Professional, 2nd Ed," New Jersey, John Wiley & Sons, Inc., 2017, pp. 3-8.

[2] E. H. Allen and M. D. Ilic, "Reserve markets for power systems reliability," *IEEE Transactions on Power Systems,* vol. 15, no. 1, pp. 228 - 233, February 2000.

[3] F. Schöniger and U. B. Morawetz, "What comes down must go up: Why fluctuating renewable energy does not necessarily increase electricity spot price variance in Europe," *Energy Economics,* vol. 111, 2022.

[4] M. &. C. G. &. C. A. &. S. A. &. D. A. Mureddu, "Green Power Grids: How Energy from Renewable Sources Affects Networks and Markets," *Plos One,* 2015.

[5] P. Palensky and D. Dietrich, "Demand Side Management: Demand Response, Intelligent Energy Systems, and Smart Loads," *IEEE Transactions on Industrial Informatics ,* vol. 7, pp. 381-288, 2011.

[6] Elering AS, "Electricity market," [Online]. Available: https://elering.ee/en/electricity-market#tab1. [Accessed 15 03 2023].

[7] K. Mayer and S. Trück, "Electricity markets around the world," *Journal of Commodity Markets,* vol. 9, pp. 77-100, 2018.

[8] E. Lundin and T. P. Tangerås, "Cournot competition in wholesale electricity markets: The Nordic power exchange, Nord Pool," *International Journal of Industrial Organization,* vol. 68, no. 102536, 2020.

[9] Nord Pool, "Intraday market," 2023. [Online]. Available: https://www.nordpoolgroup.com/en/the-power-market/Intraday-market/. [Accessed 15 03 2023].

[10] E. Rivero, J. Barquin and L. Rouco, "European balancing markets," in *8th International Conference on the European Energy Market (EEM)*, Zagreb, 2011.

[11] Elering, Elektrituru käsiraamat, Tallinn: Elering, 2022.

[12] EMTSO-E, "ELECTRICITY BALANCING IN EUROPE," ENTSO-E, Brussels, 2018.

[13] ENTSO-E, "Electricity Balancing," ENTSO-E, 2023. [Online]. Available: https://www.entsoe.eu/network_codes/eb/. [Accessed 18 03 2023].

[14] AST, Elering, Litgrid, "Baltic Load-Frequency Control block concept document," Elering, Tallinn, 2020.

[15] Elering AS, "The prequalification process and technical requirements of Automatic Frequency Restoration Reserves (aFRR) Service," 22 07 2022. [Online]. Available: https://elering.ee/sites/default/files/2022-07/aFRR%20service_prequalification%20process%20and%20technical%20requirements_20220722_0.pdf. [Accessed 18 03 2023].

[16] Elering AS, "The prequalification process and technical requirements of Manual Frequency Restoration Reserves (mFRR) Service," 22 07 2022. [Online]. Available: https://elering.ee/sites/default/files/2022-07/mFRR%20service_prequalification%20process%20and%20technical%20requirements_20220722.pdf. [Accessed 18 03 2023].

[17] ENTSO-E, "The proposal of all Transmission System Operators performing the reserve replacement process for the implementation framework for the exchange of balancing energy from Replacement Reserves," 18 06 2018. [Online]. Available: https://eepublicdownloads.entsoe.eu/clean-documents/nc-tasks/EBGL/EBGL_A19.1_181129_RR%20Implementation_framework_approved.pdf. [Accessed 18 03 2023].

[18] Fingrid, "Reserves and balancing power," Fingrid, 2023. [Online]. Available: https://www.fingrid.fi/en/electricity-market/reserves_and_balancing/#reserve-products. [Accessed 18 03 2023].

[19] European Union, "COMMISSION REGULATION (EU) 2017/2195," *Official Journal of the European Union,* pp. 6-53, 2017.

[20] ENTSO-E, "Frequency Containment Reserves (FCR)," 2023. [Online]. Available: https://www.entsoe.eu/network_codes/eb/fcr/. [Accessed 18 March 2023].

[21] ENTSO-E, "PICASSO," 2023. [Online]. Available: https://www.entsoe.eu/network_codes/eb/picasso/. [Accessed 18 March 2023].

[22] AST, E. and L. , "Baltic Balancing Roadmap," Elering, 2022.

[23] ENTSO-E, "Manually Activated Reserves Initiative," ENTSO-E, 2023. [Online]. Available: https://www.entsoe.eu/network_codes/eb/mari/. [Accessed 20 03 2023].

[24] ENTSO-E, "Manually Activated Reserves Initiative," 2023. [Online]. Available: https://www.entsoe.eu/network_codes/eb/mari/. [Accessed 29 04 2023].

[25] International Energy Agency, "Solar PV," International Energy Agency, 2022. [Online]. Available: https://www.iea.org/reports/solar-pv. [Accessed 20 03 2023].

[26] International Energy Agency, "Wind Electricity," 2022. [Online]. Available: https://www.iea.org/reports/wind-electricity. [Accessed 20 03 2023].

[27] L. Hirth and I. Ziegenhagen, "Balancing power and variable renewables: Three links," *Renewable and Sustainable Energy Reviews,* vol. 50, pp. 1035-1051, 2015.

[28] S. Impram, S. V. Nese and B. Oral, "Challenges of renewable energy penetration on power system flexibility: A survey," *Energy Strategy Reviews,* vol. 31, no. 100539, 2020.

[29] H. Algarvio and F. Lopes, "Bilateral Contracting and Price-Based Demand Response in Multi-Agent Electricity Markets: A Study on Time-of-Use Tariffs," *Energies,* vol. 16, no. 645, pp. 1-17, 2023.

[30] M. Barbero, C. Corchero, L. C. Casals, L. Igualada and F.-J. Heredia, "Critical evaluation of European balancing markets to enable the participation of Demand Aggregators," *Applied Energy,* vol. 264, no. 114707, 2020.

[31] M. B. R. E. S. A. P. E. B. J. K. Z. B. B. Ł.-G. C. B. H. M. F. D'Ettorre, "Exploiting demand-side flexibility: State-of-the-art, open issues and social perspective," *Renewable and Sustainable Energy Reviews,* vol. 165, 2022.

[32] Internation Energy Agency, "World Energy Outlook 2017," Internation Energy Agency, Paris, 2017.

[33] International Energy Agency, "Demand Response," International Energy Agency, 09 2022. [Online]. Available: https://www.iea.org/reports/demand-response. [Accessed 20 03 2023].

[34] International Energy Agency, "Buildings," 09 2022. [Online]. Available: https://www.iea.org/reports/buildings. [Accessed 25 03 2023].

[35] International Energy Agency, "Heat Pumps," 09 2022. [Online]. Available: https://www.iea.org/reports/heat-pumps. [Accessed 25 03 2023].

[36] M. Jeffery, R. Wilson, J. Emmrich, C. Jones, H. Fekete, N. Höhne, D. Ramalope and A. Kachi, "Decarbonising buildings: Achieving zero carbon heating and cooling.," *Climate Action Tracker,* pp. 11-12, March 2022.

[37] T. Q. Péan, J. Salom and R. Costa-Castelló, "Review of control strategies for improving the energy flexibility," *Journal of Process Control,* vol. 74, pp. 35-49, 2019.

[38] A. Arteconi and F. Polonara, "Assessing the Demand Side Management Potential and the Energy Flexibility of Heat Pumps in Buildings," *Energies,* vol. 11, no. 7, pp. 1-19, 2018.

[39] B. B. Sanner, "Ground Source Heat Pumps - history, development, current status, and future prospects," in *12th IEA Heat Pump Conference*, Giessen, 2017.

[40] I. Sarbu and C. Sebarchievici, "General review of ground-source heat pump systems for heating and cooling of buildings," *Energy and Buildings,* pp. 441-454, 2014.

[41] E. Silberstein, Heat Pumps, 2nd Edition, Boston: Cengage Learning, 2015.

[42] A. A. Chan Oussa Suong, "Evaluation of a single stage heat pump performance by figure of merit (FOM)," *Energy Reports,* vol. 6, pp. 2735-2742, 2020.

[43] Z. C. P. X. W. L. H. S. Z. Y. G. L. C. H. Yongbao Chen, "Quantification of electricity flexibility in demand response: Office building case study," *Energy,* vol. 188, 2019.

[44] I. A. S. H. P. Manner, "Domestic heat pumps as a source of primary frequency control reserve," in *17th International Conference on the European Energy Market (EEM)*, Stockholm, 2020.

[45] J. D. Craecker, "Performance analysis of heat pumps in Carnot battery systems for grid balancing services," 06 2022. [Online]. Available: https://libstore.ugent.be/fulltxt/RUG01/003/063/271/RUG01-003063271_2022_0001_AC.pdf. [Accessed 20 04 2023].

[46] R. Belhomme, "Bottom-Up Flexibility in Multi-Energy Systems: Real-World Experiences From Europe," *IEEE Power and Energy Magazine,* vol. 19, no. 4, pp. 74-85, 2021.

[47] J. H. Yoon, R. Baldick and A. Novoselac, "Dynamic Demand Response Controller Based on Real-Time Retail Price for Residential Buildings," *IEEE Transactions on Smart Grid,* vol. 5, no. 1, pp. 121-129, 2014.

[48] N. G. P. M. Lingxi Zhang, "Building-to-grid flexibility: Modelling and assessment metrics for residential demand response from heat pump aggregations," *Applied Energy,* vol. 233–234, pp. 709-723, 2019.

[49] F. M. J. F. A. K. Sultania, "Real-Time Demand Response Using NB-IoT," *IEEE Internet of Things Journal,* vol. 7, no. 12, pp. 11863 - 11872, 2020.

[50] G. G. M. L. S. S. Bruno, "A Demand Response Implementation in Tertiary Buildings Through Model Predictive Control," *IEEE Transactions on Industry Applications,* vol. 55, no. 6, pp. 7052-7061, 2019.

[51] Kapacity.io, "Heat pump optimization at DB Schenker's logistics terminal," 04 05 2023. [Online]. Available: https://kapacity.io/2023/05/04/heat-pump-optimization-at-db-schenkers-logistics-terminal/. [Accessed 08 05 2023].

[52] L. I. S. W. v. S. W. Posma J, "Provision of Ancillary Services from an Aggregated Portfolio of Residential Heat Pumps on the Dutch Frequency Containment Reserve Market," *Applied Sciences,* vol. 9, no. 3, 2019.

[53] J. S. D. B. R. S. T. E. M. P. M. K. M. Z. O. Terreros, "Electricity market options for heat pumps in rural district heating networks in Austria," *Energy,* vol. 196, 2020.

[54] A. L. Elering AS, "Harmonised principles for Baltic LFC reserve," 31 03 2022. [Online]. Available: https://www.ast.lv/sites/default/files/editor/Harmonised_principles_for_Baltic_LFC_reserve_prequalification.pdf. [Accessed 10 04 2023].

[55] E. OÜ, "Remote reading," 2023. [Online]. Available: https://www.elektrilevi.ee/en/abiinfo/naidud-ja-kauglugemine. [Accessed 20 04 2023].

[56] E. AS, "15 minute ISP," 2023. [Online]. Available: https://elering.ee/en/15-minute-isp. [Accessed 20 04 2023].

[57] J. -E. C. H. F. Y. -H. S. S. -Y. Wang, "Performance Comparisons of NB-IoT, LTE Cat-M1, Sigfox, and LoRa Moving at High Speeds in the Air," in *IEEE Symposium on Computers and Communications (ISCC)*, Rennes, 2020.

[58] M. R. N. M. A. M. I. N. A. Hidayati, "Techno-Economic Analysis of Narrowband IoT (NB-IoT) Deployment for Smart Metering," in *Asia Pacific Conference on Research in Industrial and Systems Engineering (APCoRISE)*, Depok, 2019.

[59] N. E. Services, "Next Gen Cellular and Smart Metering," 10 02 2022. [Online]. Available: https://networkedenergy.com/en/blog/next-gen-cellular-and-smart-metering. [Accessed 20 04 2023].

[60] P. M. Alejandro Navarro-Espinosa, "Probabilistic modeling and assessment of the impact of electric heat pumps on low voltage distribution networks," *Applied Energy,* vol. 127, pp. 249-266, 2014.

[61] S. Sklep, "SOLARMAN DTSD422-D3 energy meter," 2023. [Online]. Available: https://sofar-sklep.pl/en_US/p/SOLARMAN-DTSD422-D3-energy-meter/122. [Accessed 22 04 2023].

[62] GlobalSources, "Acrel ADW300," 2023. [Online]. Available: https://www.globalsources.com/DIN-rail/energy-meter-1186747956p.htm. [Accessed 30 04 2023].

[63] Samsung, "Air to Water Heat Pump Installation Manual," [Online]. Available: https://hemeltron.ee/kasutusjuhendid/category/123-samsung-ehs-r32?download=622:samsung-ehs-mono-r32-gen6-5-kw-installation-manual. [Accessed 22 04 2023].

[64] Panasonic, "Planning and installation manual," 2018. [Online]. Available: https://www.panasonicproclub.com/uploads/BE/catalogues/A2W_2018_DesignManual.pdf. [Accessed 22 04 2023].

[65] Daikin, "Installation manual," 2017. [Online]. Available: https://www.daikin.eu/content/dam/document-library/installation-manuals/heat/air-to-water-heat-pump-low-temperature/EHVH-DV,DVG_4PEN499571-1B_2017_12_Installation%20manual_English.pdf. [Accessed 22 04 2023].

[66] NIBE, "Air/water heat pump NIBE S2125 Intaller Manual," 2021. [Online]. Available: https://www.nibe.eu/assets/documents/30143/431990-1.pdf. [Accessed 22 04 2023].

[67] Samsung, "Modbus Interface Module Instruction Manual," 10 2016. [Online]. Available: https://s3.amazonaws.com/samsung-files/Tech_Files/Controls/Central+Control/Installation+Manuals/CL-MC03+C_Modbus/Modbus_InterfaceModule_Installation+Manual+_11092016.pdf. [Accessed 29 04 2023].

[68] Rfwel, "Samsung CL-MC0364C Modbus Adapter," 2023. [Online]. Available: https://shop.rfwel.com/samsung-cl-mc0364c-modbus-adapter/. [Accessed 20 04 2023].

[69] IvoryEgg, "Panasonic Air to Water (Aquarea H) to Modbus RTU Interface," 2023. [Online]. Available: https://www.ivoryegg.co.uk/shop/products/ibmbspan001a000-modbus-rtu-panasonic-air-to-water-units-aquarea-h-generation-series. [Accessed 20 04 2023].

[70] OpenAir, "Daikin Air Conditioning RTD-10," 2023. [Online]. Available: https://www.orionairsales.co.uk/daikin-air-conditioning-rtd-10uk-fb2-enhanced-interface-real-time-control-system-for-unit-connection-control-remote-on--off-status-and-temp-5869-p.asp. [Accessed 20 04 2023].

[71] WarmtepompOptimaal, "NIBE SMO 20," 2023. [Online]. Available: https://www.warmtepompen-webshop.nl/product/504943/067224-regeling-nibe-smo-20. [Accessed 22 04 2023].

[72] IBM, "What is an API?," 2023. [Online]. Available: https://www.ibm.com/topics/api. [Accessed 13 04 2023].

[73] Daikin, "Daikin ONE Open API," 2023. [Online]. Available: https://www.daikinone.com/openapi/documentation/index.html. [Accessed 15 04 2023].

[74] Daikin, "API Integration Manual For Daikin DKN Cloud Wi-Fi Adaptor," 2019. [Online]. Available: https://backend.daikincomfort.com/docs/default-source/product-documents/residential/manuals/othermanual/im-dknapi.pdf. [Accessed 29 04 2023].

[75] Midsummer, "Samsung EHS WIFI Controller Kit MIM-H04EN," 2023. [Online]. Available: https://midsummerwholesale.co.uk/buy/samsung-heat-pumps/samsung-ehs-wifi-controller-kit-mim-h04en. [Accessed 29 04 2023].

[76] ShopClima, "PANASONIC CZ-TAW1B," 2023. [Online]. Available: https://www.shopclima.it/en/panasonic-cz-taw1-aquarea-smart-cloud-for-remote-control-and-wi-fi-maintenance-or-via-wire-lan.html. [Accessed 29 04 2023].

[77] H. &. Cool, "DKN Cloud Wi-Fi Adapter," 2023. [Online]. Available: https://www.heatandcool.com/dkn-cloud-wi-fi-adapter-p1p2.html. [Accessed 29 04 2023].

[78] Prokliima, "NIBE S2125," 2023. [Online]. Available: https://prokliima.ee/tooted/ohk-vesi-soojuspumbad/nibe-f2120-s2125/nibe-s2125-12/. [Accessed 29 04 2023].

[79] Samsung, "SmartThings," 05 07 2022. [Online]. Available: https://community.smartthings.com/t/exclusive-what-the-new-smartthings-update-for-60-million-users-brings/244468. [Accessed 29 04 2023].

[80] Daikin, "Installation and operating instructions," 2021. [Online]. Available: https://www.daikin.eu/content/dam/document-library/installation-manuals/heat/domestic-hot-water-heat-pump/ekhhp-a2v3/EKHHP-A2V3_Installation%20and%20operation%20manual_0081423499_10_English.pdf. [Accessed 22 04 2023].

[81] Daikin, "Control systems," [Online]. Available: https://www.daikin.eu/content/dam/document-library/catalogues/ctrl/RTD_ECPEN14-308_Catalogues_English.pdf. [Accessed 23 04 2023].

[82] "Eesti Soojuspumba Liit," 2021. [Online]. Available: https://www.egt.ee/media/451/download. [Accessed 30 04 2023].

[83] E. OÜ, "HINNAKIRI," 2023. [Online]. Available: https://elektrikud.eu/hinnakiri/. [Accessed 30 04 2023].

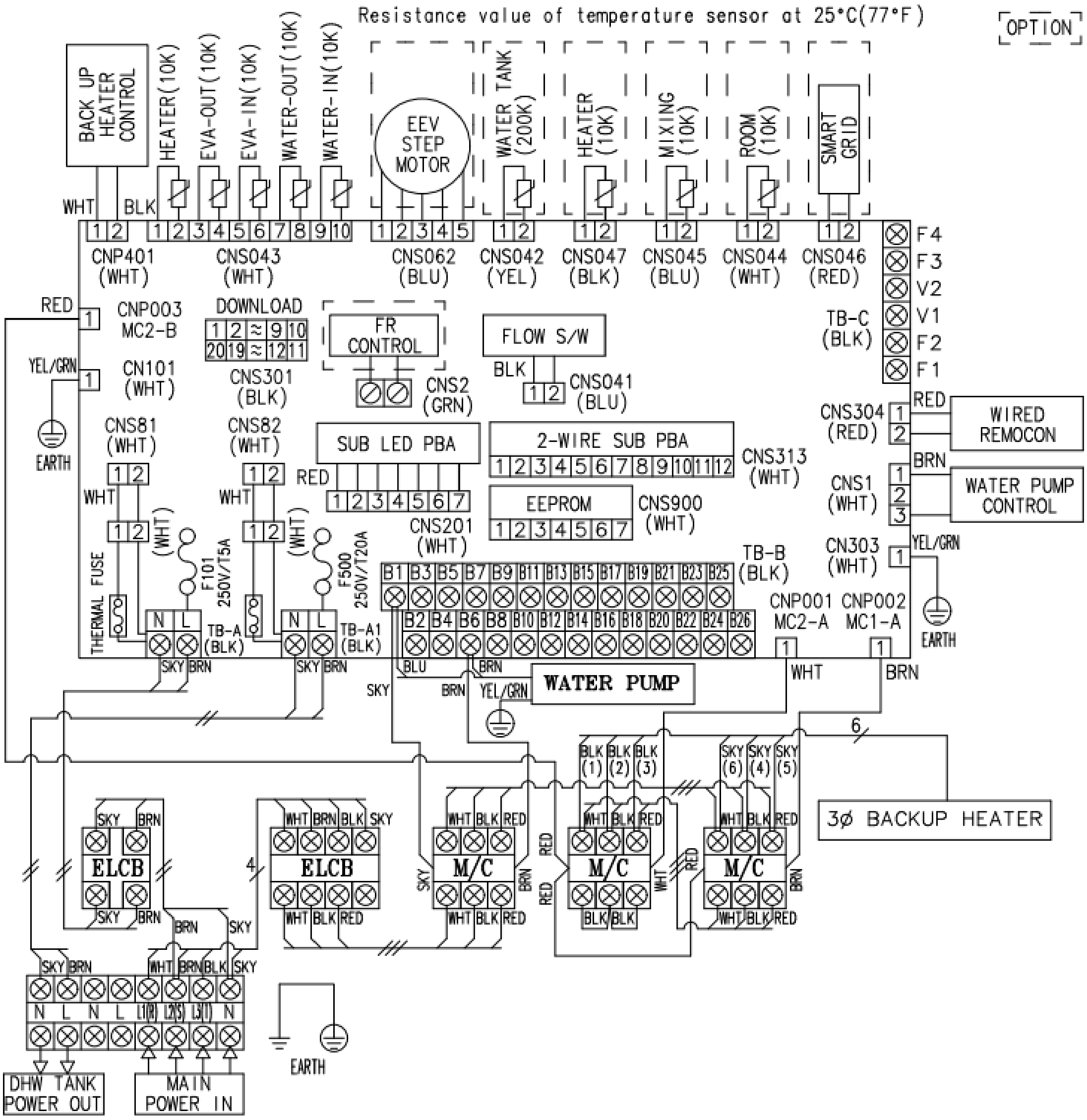
[84] T. AS, 2023. [Online]. Available: https://www.telia.ee/ari/mobiil/m2m-ja-iot-teenused/m2m/. [Accessed 30 04 2023].

[85] IThooldus, "TEENUSTE HINNAKIRI," 2023. [Online]. Available: https://www.ithooldus.ee/it-hooldusteenuste-hinnakiri. [Accessed 30 04 2023].

[86] J. D. H. Thomas L. Wheelen, Strategic Management and Business Policy: Toward Global Sustainability (13th ed.), London: Pearson, 2012.

APPENDICES

Appendix 1 Samsung EHS Split wiring diagram

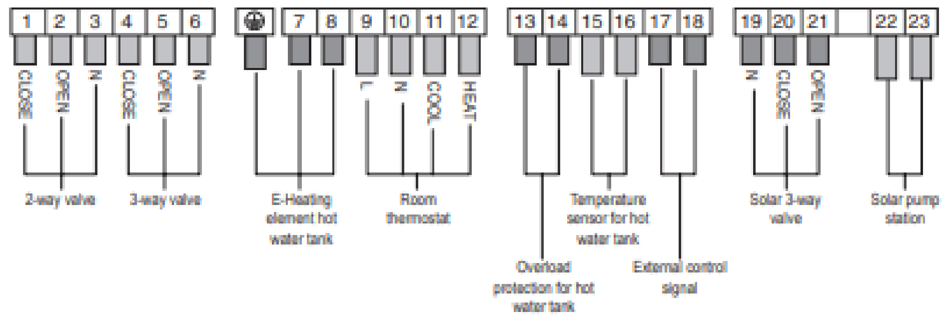


Appendix 2 Panasonic T-CAP external interfaces (F and G Gen. Models)

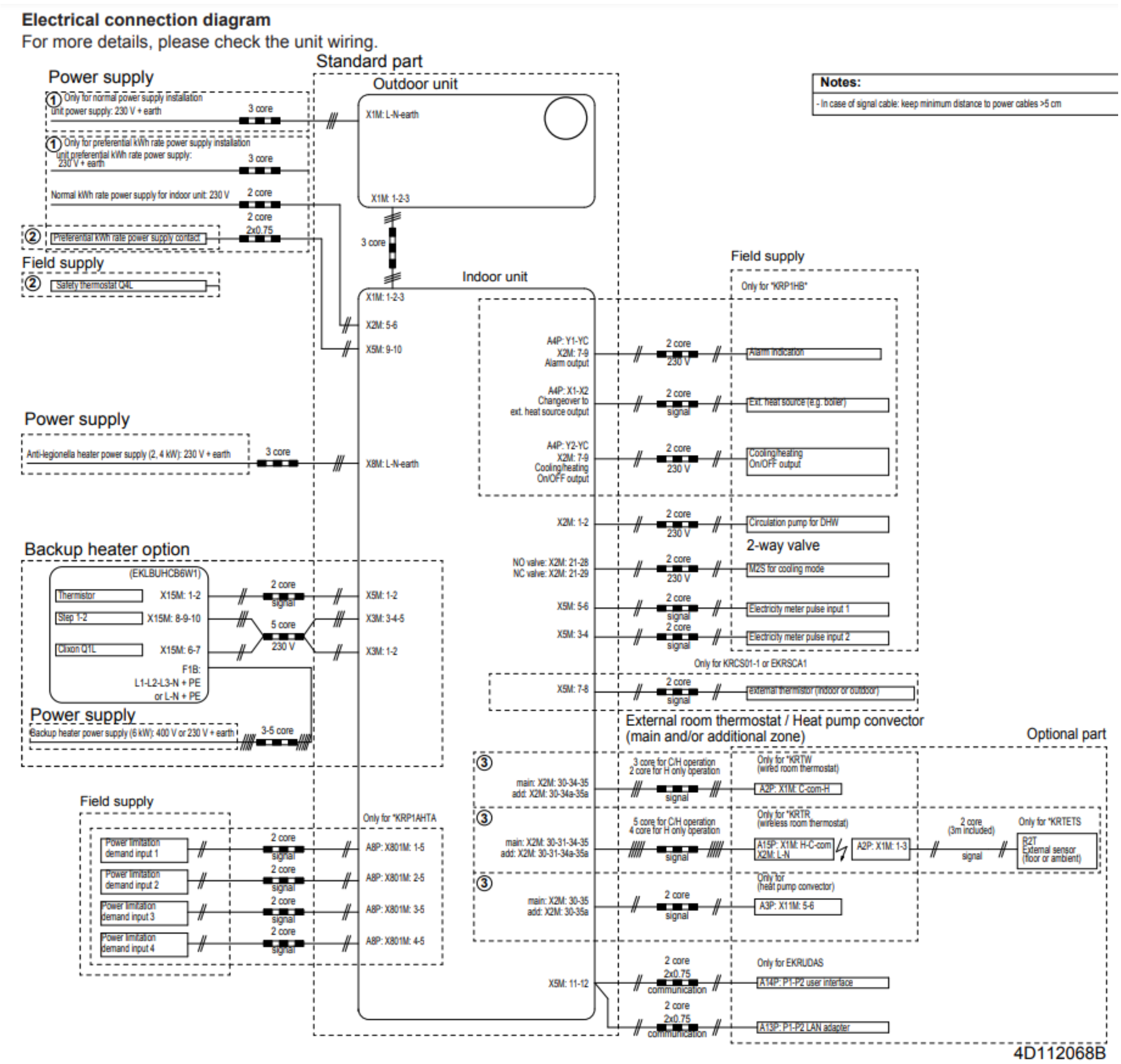
The overview of external interfaces is valid for the following models:

Split systems		Compact systems	
HT	WH-SHF09F3E5 + WH-UH09FE5	HT	WH-MHF09G3E5'
	WH-SHF12F6E5 + WH-UH12FE5		WH-MHF12G6E5
	WH-SHF09F3E8 + WH-UH09FE8		WH-MHF09G3E8
	WH-SHF12F9E8 + WH-UH12FE8		WH-MHF12G9E8

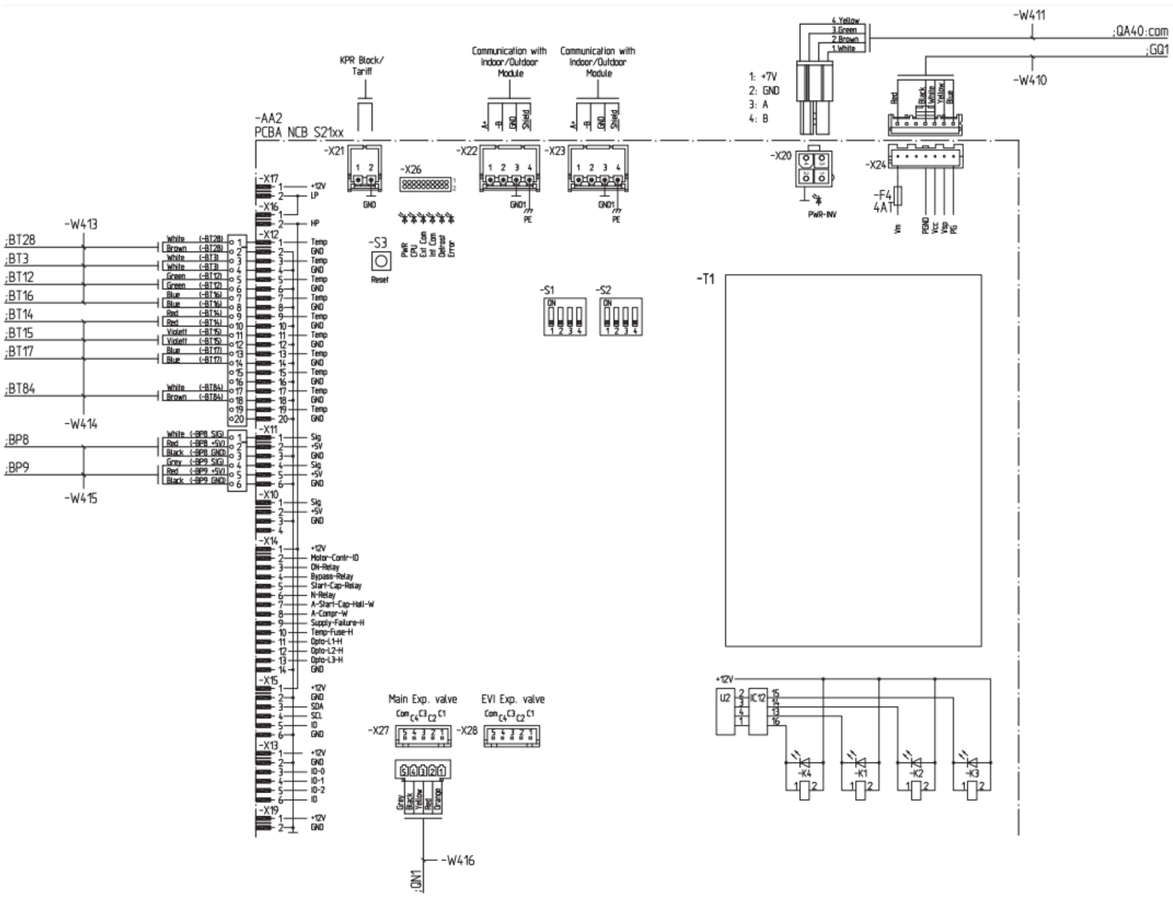
Overview of the External Interfaces



Terminals	Connection	Function	Condition	Cable cross section
1 to 3	2-way valve	Output for actuation of the 2-way valve (e.g. for floor heating, cooling)		3 × min. 0.5 mm²
4 to 6	3-way valve	Output for actuation of the 3-way valve (e.g. for heating, domestic hot water tank)		3 × min. 0.5 mm²
Earth to 8	E-Heating element hot water tank	Output for on/off switch of the E-heating element hot water tank	The maximum power output of the E-heating element hot water tank should be maximum 3 kW.	3 × min. 1.5 mm²
9 to 12	Room thermostat	Input for room thermostat signals		4, or 3 × min. 0.5 mm²
13 to 14	Overload protection for domestic hot water tank	Input for overload protection of the domestic hot water tank	The terminals 13/14 must be used if overload protection is not used for the hot water tank.	2 × min. 0.5 mm²
15 to 16	Temperature sensor of the hot water tank	Input for temperature sensor of the domestic hot water tank		2 × min. 0.5 mm²
17 to 18	Ext. control signal	Input for the external control signal	These two terminals are bridged at the time of dispatch. Connection: 1-pin (min. 3 mm contact distance)	2 × min. 0.5 mm²
19 to 21	Solar 3-way valve	Output for actuation of the solar 3-way valve		3 × min. 0.5 mm²
22 to 23	Solar pump station	Input of the ON signal of solar pump 2 (230 V AC)	Use additional PCB CZ-NS1P, CZ-NS2P or CZ-NS3P.	2 × min. 0.5 mm²


Electrical connection diagram
For more details, please check the unit wiring.
Standard part
Power supply
Only for normal power supply installation
Unit power supply: 230 V + earth
3 core
Only for preferential kWh rate power supply installation
unit preferential kWh rate power supply: 230 V + earth
3 core
Normal kWh rate power supply for indoor unit: 230 V
2 core
2 core 2x0.75
Preferential kWh rate power supply contact
Field supply
Safety thermostat Q4L
Outdoor unit
X1M: L-N-earth
X1M: 1-2-3
3 core
Indoor unit
X1M: 1-2-3
X2M: 5-6
X5M: 9-10
Power supply
Anti-legionella heater power supply (2, 4 kW): 230 V + earth
3 core
X8M: L-N-earth
Backup heater option
(EKLBUHCB6W1)
Thermistor
X15M: 1-2
Step 1-2
X15M: 8-9-10
Clixon Q1L
X15M: 6-7
F1B: L1-L2-L3-N + PE or L-N + PE
2 core signal
5 core 230 V
X5M: 1-2
X3M: 3-4-5
X3M: 1-2
Power supply
Backup heater power supply (6 kW): 400 V or 230 V + earth
3-5 core
Field supply
Only for *KRP1AHTA
Power limitation demand input 1
Power limitation demand input 2
Power limitation demand input 3
Power limitation demand input 4
2 core signal
A8P: X801M: 1-5
A8P: X801M: 2-5
A8P: X801M: 3-5
A8P: X801M: 4-5
Notes:
- In case of signal cable: keep minimum distance to power cables >5 cm
Field supply
Only for *KRP1HB*
A4P: Y1-YC X2M: 7-9 Alarm output
2 core 230 V
Alarm indication
A4P: X1-X2 Changeover to ext. heat source output
2 core signal
Ext. heat source (e.g. boiler)
A4P: Y2-YC X2M: 7-9 Cooling/heating On/OFF output
2 core 230 V
Cooling/heating On/OFF output
X2M: 1-2
2 core 230 V
Circulation pump for DHW
2-way valve
NO valve: X2M: 21-28
NC valve: X2M: 21-29
2 core 230 V
M2S for cooling mode
X5M: 5-6
2 core signal
Electricity meter pulse input 1
X5M: 3-4
2 core signal
Electricity meter pulse input 2
Only for KRCS01-1 or EKRSCA1
X5M: 7-8
2 core signal
external thermistor (indoor or outdoor)
External room thermostat / Heat pump convector (main and/or additional zone)
Optional part
main: X2M: 30-34-35
add: X2M: 30-34a-35a
3 core for C/H operation
2 core for H only operation
signal
Only for *KRTW (wired room thermostat)
A2P: X1M: C-com-H
main: X2M: 30-31-34-35
add: X2M: 30-31-34a-35a
5 core for C/H operation
4 core for H only operation
signal
Only for *KRTR (wireless room thermostat)
A15P: X1M: H-C-com
X2M: L-N
A2P: X1M: 1-3
2 core (3m included)
signal
Only for *KRTETS
R2T External sensor (floor or ambient)
main: X2M: 30-35
add: X2M: 30-35a
2 core signal
Only for (heat pump convector)
A3P: X11M: 5-6
X5M: 11-12
2 core 2x0.75 communication
Only for EKRUDAS
A14P: P1-P2 user interface
2 core 2x0.75 communication
A13P: P1-P2 LAN adapter
4D112068B

Appendix 4 NIBE S2125 wiring diagram



Appendix 5 Samsung EHS Split specifications (AE040, AE060, AE090 models)

Model Name	Indoor Unit				AE090JNYDEH/EU	AE090JNYDEH/EU	AE090JNYDEH/EU
Model Name	Outdoor Unit				AE040JXEDEH/EU	AE060JXEDEH/EU	AE090JXEDEH/EU
System	Mode			-	Heat Pump (A2W)	Heat Pump (A2W)	Heat Pump (A2W)
System	Performance (A7/W35) *1	Nominal Capacity	Heating (Min/Std/Max)	kW	1.667 / 4.40 / 4.00	1.667 / 6.00 / 6.00	2.394 / 9.00 / 9.00
				Btu/h	5,700 / 15,000 / 15,000	5,700 / 20,500 / 20,500	8,200 / 30,700 / 30,700
			Cooling (Min/Std/Max)	kW	1.625 / 5.00 / 5.00	1.625 / 6.50 / 6.50	1.818 / 8.00 / 8.00
				Btu/h	5,500 / 17,100 / 17,100	5,500 / 22,200 / 22,200	6,200 / 27,300 / 27,300
		Power Input (Nominal)	Heating (Min/Std/Max)	kW	0.348 / 0.86 / 0.86	0.348 / 1.25 / 1.25	0.535 / 2.01 / 2.01
			Cooling (Min/Std/Max)	kW	0.438 / 1.26 / 1.26	0.438 / 1.75 / 1.75	0.50 / 2.20 / 2.20
		Current Input (Nominal)	Heating (Min/Std/Max)	A	1.6 / 4.1 / 4.1	1.6 / 5.7 / 5.7	2.5 / 9.2 / 9.2
			Cooling (Min/Std/Max)	A	2.0 / 5.7 / 5.7	2.0 / 8.0 / 8.0	2.3 / 10.1 / 10.1
		COP (Nominal Heating)			5.10	4.80	4.48
		EER (Nominal Cooling)			3.97	3.71	3.64
		SCOP(35℃)			4.44	4.43	4.45
		ESEER			5.37	5.35	4.79
	Performance (A2/W35) *2	Capacity	Heating	W	3,400	4,600	7,700
		COP			3.52	3.31	3.38
	Performance (A-7/W35) *3	Capacity	Heating	W	3,750	5,100	7,600
		COP			2.62	2.49	2.45
	Field Wiring	MCA		A	20	20	22
		MFA		A	25	25	27.5
	Water Connections	Water Flow Rate (Heating / Cooling)		LPM	13/15	17/20	26/25
		Water Pressure (Max)		bar	3	3	3
		Water Pipe	Inlet	Φ, inch	BSPP male 1 1/4"	BSPP male 1 1/4"	BSPP male 1 1/4"
			Outlet	Φ, inch	BSPP male 1 1/4"	BSPP male 1 1/4"	BSPP male 1 1/4"
		Leaving Water Temperature	Heating	°C	25~55	25~55	25~55
			Cooling	°C	5~25	5~25	5~25
	Refrigerant Connections	Liquid Pipe		Φ, mm	6.35	6.35	6.35
				Φ, inch	1/4"	1/4"	1/4"
		Gas Pipe		Φ, mm	15.88	15.88	15.88
				Φ, inch	5/8"	5/8"	5/8"
		Installation Limitation	Max. Length	m	30	30	50
			Max. Height	m	20	20	30
		Chargeless Length		m	15	15	15
	Operating Temp. Range	Heating (A2W) *4		℃	-25~35	-25~35	-25~35
		Cooling (A2W)		℃	10~46	10~46	10~46
		DHW (A2W) *5		℃	-25~43	-25~43	-25~43

Appendix 6 Panasonic T-CAP specifications (F Gen. Models)

Split systems with hydro-module / HT series / F Generation

HT series			Single phase (230 V / 50 Hz), heating only		Three-phase (400 V / 50 Hz), heating only	
Hydro-module			**WH-SHF09F3E5**	**WH-SHF12F6E5**	**WH-SHF09F3E8**	**WH-SHF12F9E8**
Outdoor unit			**WH-UH09FE5**	**WH-UH12FE5**	**WH-UH09FE8**	**WH-UH12FE8**
Set (hydro-module + outdoor unit)			**KIT-WHF09F3E5**	**KIT-WHF12F6E5**	**KIT-WHF09F3E8**	**KIT-WHF12F9E8**
Model			**B6**	**B6**	**B6**	**B6**
Heating capacity at +7 °C (A7/W35)		kW	9.00	12.00	9.00	12.00
COP at +7 °C (A7/W35)			4.64	4.46	4.64	4.46
Heating capacity at +2 °C (A2/W35)		kW	9.00	12.00	9.00	12.00
COP at +2 °C (A2/W35)			3.45	3.26	3.45	3.26
Heating capacity at -7 °C (A–7/W35)		kW	9.00	12.00	9.00	12.00
COP at -7 °C (A–7/W35)			2.74	2.52	2.74	2.52
Heating capacity at +7 °C (A7/W65)		kW	9.00	12.00	9.00	12.00
COP at +7 °C (A7/W65)			2.27	2.22	2.27	2.22
Heating capacity at +2 °C (A2/W65)		kW	9.00	10.30	9.00	10.30
COP at +2 °C (A2/W65)			1.89	1.84	1.89	1.84
Heating capacity at -7 °C (A–7/W65)		kW	8.90	9.60	8.90	9.60
COP at -7 °C (A–7/W65)			1.63	1.62	1.63	1.62
Energy efficiency class[1] at 35 / 55 °C			A++ / A++	A++ / A++	A++ * / A++	A++ * / A++
Hydro-module						
Sound pressure level		dB(A)	33	33	33	33
Dimensions	H x L x W	mm	892 x 502 x 353	892 x 502 x 353	892 x 502 x 353	892 x 502 x 353
Weight		kg	46	47	47	48
Water-side connection		mm	28	28	28	28
High efficiency pump	Rotation speed stages		7	7	7	7
	Power consumption (min./ max.)	W	38 / 100	40 / 106	38 / 100	40 / 106
Water flow rate (A7/W35)		l/min	25.8	34.4	25.8	34.4
Power of E-heating element		kW	3	6	3	9
Power consumption		kW	1.94	2.69	1.94	2.69
Operating and start up current		A	9.3	12.9	3.0	4.2
Max. power consumption on network connection 1 / 2		A	28.5 / 13.0	29.0 / 26.0	14.5 / 13.0	10.8 / 13.0
Recommended fuse for network connection 1 / 2		A	30 / 30	30 / 30	30 / 16	30 / 16
Recommended cable cross section for network connection 1 / 2		mm²	3 x 4.0 or 6.0 / 3 x 4.0	3 x 4.0 or 6.0 / 3 x 4.0	5 x 1.5 / 3 x 1.5	5 x 1.5 / 5 x 1.5
Outdoor unit						
Sound pressure level		dB(A)	51	52	51	52
Dimensions	H x L x W	mm	1,340 x 900 x 320	1,340 x 900 x 320	1,340 x 900 x 320	1,340 x 900 x 320
Weight		kg	104	104	110	110
Line diameter	Fluid line	mm (inches)	9.52 (3/8)	9.52 (3/8)	9.52 (3/8)	9.52 (3/8)
	Gas line	mm (inches)	15.88 (5/8)	15.88 (5/8)	15.88 (5/8)	15.88 (5/8)
Pre-filled refrigerant (R407C) / CO_2-equivalent		kg / t CO_2-Equ.	2.90 / 5.145	2.90 / 5.145	2.90 / 5.145	2.90 / 5.145
Connection distance		m	3 – 30	3 – 30	3 – 30	3 – 30
Nominal connection distance		m	7	7	7	7
Pre-filled connection distance		m	10	10	10	10
Additional coolant fill-up quantity (R407C)		g/m	70	70	70	70
Max. height difference IU/OU		m	20	20	20	20
Operating range	Outside temperature	°C	-20 to 35	-20 to 35	-20 to 35	-20 to 35
	Water outlet temperature	°C	25 to 60	25 to 60	25 to 60	25 to 60

Appendix 7 Daikin Altherma 3 specifications (04S, 08S models)

Efficiency data				EHVX + ERGA	04S18D3V(G)/ D6V(G) + 04DV	04S23D3V(G)/ D6V(G) + 04DV	08S18D6V(G)/ D9W(G) + 06DV	08S23D6V(G)/ D9W(G) + 06DV	08S18D6V(G)/ D9W(G) + 08DV	08S23D6V(G)/ D9W(G) + 08DV
Heating capacity	Nom.			kW	4.30 (1) / 4.60 (2)		6.00 (1) / 5.90 (2)		7.50 (1) / 7.80 (2)	
Power input	Heating	Nom.		kW	0,850 (1) / 1.26 (2)		1.24 (1) / 1.69 (2)		1.63 (1) / 2.23 (2)	
Cooling capacity	Nom.			kW	5.56 (1) / 4.37 (2)		5.96 (1) / 4.87 (2)		6.25 (1) / 5.35 (2)	
Power input	Cooling	Nom.		kW	0,940 (1) / 1.14 (2)		1.06 (1) / 1.33 (2)		1.16 (1) / 1.51 (2)	
COP					5.10 (1) / 3.65 (2)		4.85 (1) / 3.50 (2)		4.60 (1) / 3.50 (2)	
EER					5.94 (1) / 3.84 (2)		5.61 (1) / 3.67 (2)		5.40 (1) / 3.54 (2)	
Space heating	Average climate water outlet 55°C	General	SCOP		3.26				3.32	
			η_s (Seasonal space heating efficiency)	%	127				130	
			Seasonal space heating eff. class		A++					
	Average climate water outlet 35°C	General	SCOP		4.48		4.47		4.56	
			η_s (Seasonal space heating efficiency)	%	176				179	
			Seasonal space heating eff. class		A+++(3)					
Domestic hot water heating	General	Declared load profile			L	XL	L	XL	L	XL
	Average climate	η_{wh} (water heating efficiency)		%	127	134	125	133	125	133
		Water heating energy efficiency class			A+ (3)					

Indoor Unit				EHVX	04S18D3V(G)/D6V(G)	04S23D3V(G)/D6V(G)	08S18D6V(G)/D9W(G)	08S23D6V(G)/D9W(G)	08S18D6V(G)/D9W(G)	08S23D6V(G)/D9W(G)
Casing	Colour				White + Black					
	Material				Resin / Sheet metal					
Dimensions	Unit	HeightxWidthxDepth		mm	1,650x595x625	1,850x595x625	1,650x595x625	1,850x595x625	1,650x595x625	1,850x595x625
Weight	Unit			kg	131	139	131	139	131	139
Tank	Water volume			l	180	230	180	230	180	230
	Maximum water temperature			°C	70					
	Maximum water pressure			bar	10					
	Corrosion protection				Pickling					
Operation range	Heating	Ambient	Min.~Max.	°C	5~30					
		Water side	Min.~Max.	°C	15 ~65					
	Cooling	Ambient	Min.~Max.	°CDB	5~35					
		Water side	Min.~Max.	°C	5~22					
	Domestic hot water	Ambient	Min.~Max.	°CDB	5~35					
		Water side	Max.	°C	70					
Sound power level	Nom.			dBA	42					
Sound pressure level	Nom.			dBA	28					

Outdoor Unit			ERGA	04DV	06DV	08DV
Dimensions	Unit	HeightxWidthxDepth	mm	740x884x388		
Weight	Unit		kg	58.5		
Compressor	Quantity			1		
	Type			Hermetically sealed swing compressor		
Operation range	Cooling	Min.~Max.	°CDB	10~43		
	Domestic hot water	Min.~Max.	°CDB	-25~35		
Refrigerant	Type			R-32		
	GWP			675.0		
	Charge		kg	1.50		
	Charge		TCO2Eq	1.01		
	Control			Expansion valve		
Sound power level	Heating	Nom.	dBA	58	60	62
	Cooling	Nom.	dBA	61	62	
Sound pressure level	Heating	Nom.	dBA	44	47	49
	Cooling	Nom.	dBA	48	49	50
Power supply	Name/Phase/Frequency/Voltage		Hz/V	V3/1N~/50/230		
Current	Recommended fuses		A	25		

(1) Cooling Ta 35°C - LWE 18°C (DT = 5°C); heating Ta DB/WB 7°C/6°C - LWC 35°C (DT = 5°C) (2) Cooling Ta 35°C - LWE 7°C (DT = 5°C); heating Ta DB/WB 7°C/6°C - LWC 45°C (DT = 5°C)
(3) According to EU n°81 1/2013 label lay-out 2019, on a scale from G to A+++.

Appendix 8 NIBE S2125 specifications (8, 12 models)

S2125		*8*	*12*	*8*	*12*
Voltage		*1 x 230 V*	*1 x 230 V*	*3 x 400 V*	*3 x 400 V*
Output data according to EN 14 511, partial load[1]					
Heating	-7 / 35 °C	4.72 / 1.72 / 2.82	7.23 / 2.73 / 2.65	4.72 / 1.72 / 2.82	7.23 / 2.73 / 2.65
Capacity / power input / COP (kW/kW/-) at nominal flow	2 / 35 °C	3.20 / 0.72 / 4.44	3.67 / 0.85 / 4.33	3.20 / 0.72 / 4.44	3.67 / 0.85 / 4.33
	2 / 45 °C	2.95 / 0.87 / 3.39	3.46 / 1.02 / 3.40	2.95 / 0.87 / 3.39	3.46 / 1.02 / 3.40
Outd. temp: / Supply temp.	7 / 35 °C	3.15 / 0.69 / 5.18	3.67 / 0.70 / 5.21	3.15 / 0.69 / 5.18	3.67 / 0.70 / 5.21
	7 / 45 °C	2.97 / 0.76 / 3.90	3.35 / 0.85 / 3.91	2.97 / 0.76 / 3.90	3.35 / 0.85 / 3.91
Cooling	35 / 7 °C	6.69 / 2.41 / 2.77	6.69 / 2.41 / 2.77	6.69 / 2.41 / 2.77	6.69 / 2.41 / 2.77
Capacity / power input / EER (kW/kW/-) at maximum flow Outd. temp: / Supply temp.	35 / 18 °C	8.68 / 2.60 / 3.34	8.68 / 2.60 / 3.34	8.68 / 2.60 / 3.34	8.68 / 2.60 / 3.34
SCOP according to EN 14825					
Nominal heat output ($P_{designh}$) average climate 35 °C / 55 °C (Europe)	kW	5.33 / 5.30	6.80 / 7.60	5.33 / 5.30	6.80 / 7.60
Nominal heat output ($P_{designh}$) cold climate 35 °C / 55 °C	kW	5.40 / 5.20	8.40 / 8.40	5.40 / 5.20	8.40 / 8.40
Nominal heat output ($P_{designh}$) warm climate 35 °C / 55 °C	kW	5.50 / 5.20	7.00 / 7.45	5.50 / 5.20	7.00 / 7.45
SCOP average climate, 35 °C / 55 °C (Europe)		5.00 / 3.70	5.00 / 3.80	5.00 / 3.70	5.00 / 3.80
SCOP cold climate, 35 °C / 55 °C		4.10 / 3.20	4.20 / 3.40	4.10 / 3.20	4.20 / 3.40
SCOP warm climate, 35 °C / 55 °C		6.30 / 4.50	6.30 / 4.60	6.30 / 4.50	6.30 / 4.60
Energy rating, average climate[2]					
The product's room heating efficiency class 35 C / 55 C[3]		A+++ / A++	A+++ / A+++	A+++ / A++	A+++ / A+++
The system's room heating efficiency class 35 C / 55 C[4]		A+++ / A+++			
Electrical data					
Rated voltage		230 V – 50 Hz	230 V – 50 Hz	400 V 3N – 50 Hz	400 V 3N – 50 Hz
Max. power, fan	W	30	50	30	50
Fuse	A_{rms}	16	20	10	10
Enclosure class		IP24			
Refrigerant circuit					
Type of refrigerant		R290			
GWP refrigerant		3			
Volume	kg	0.8			
Type of compressor		Rotary compressor			
CO_2-equivalent (The cooling circuit is hermetically sealed.)	t	0.0024			
Airflow					
Max airflow	m^3/h	2,400	2,950	2,400	2,950
Working area					
Min./max. air temperature, heating	°C	-25 / 38			
Min./max. air temperature, cooling	°C	15 / 43			
Heating medium circuit					
Max system pressure heating medium	MPa	0.45 (4.5)			
Cut-off pressure, heating medium	MPa	0.25 (2.5)			
Recommended flow interval, heating operation	l/s	0.08 – 0.32	0.12 – 0.48	0.08 – 0.32	0.12 – 0.48
Min. design flow, defrosting (100% pump speed)	l/s	0.32			
Min./max. HM temp, continuous operation	°C	26 / 75			
Connection heating medium S2125		G1" external thread			
Connection heating medium flex pipe		G1" external thread			
Min. recommended pipe dimension (system)	DN (mm)	25 (28)			
Dimensions and weight					
Width	mm	1,130			

S2125		*8*	*12*	*8*	*12*
Voltage		*1 x 230 V*	*1 x 230 V*	*3 x 400 V*	*3 x 400 V*
Depth	mm	820			
Height	mm	1,070			
Net weight (excluding packaging)	kg	163	163	179	179
Miscellaneous					
Substances according to Directive (EG) no. 1907/2006, article 33 (Reach)		Lead in brass components			
Part no.		064 220	064 218	064 219	064 217

1 Power statements including defrosting according to EN 14511 at heating medium supply corresponding to DT=5 K at 7 / 45.

2 The reported efficiency of the package also takes the controller into account. If an external supplementary boiler or solar heating is added to the package, the overall efficiency of the package should be recalculated.

3 Scale for the product's room heating efficiency class A++ to G. Control module model SMO S

4 Scale for the system's room heating efficiency class A+++ to G. Control module model SMO S