Pekka Manner

OPPORTUNITIES OF HOUSEHOLDS TO CONTRIBUTE TO PRIMARY FREQUENCY REGULATION IN POWER SYSTEMS—PROOF OF CONCEPTS

ACTA UNIVERSITATIS LAPPEENRANTAENSIS 1128

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OPPORTUNITIES OF HOUSEHOLDS TO CONTRIBUTE TO PRIMARY FREQUENCY REGULATION IN POWER SYSTEMS—PROOF OF CONCEPTS

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Abstract

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Our energy systems are undergoing a tremendous change. The increasing amount of inverter-connected production and consumption-side assets challenges the frequency stability in power systems. New solutions for balancing have been sought, and the focus has been shifting toward consumption side. The research conducted within this doctoral dissertation focuses on the capabilities of households to contribute to frequency stability. The main objective is to evaluate how the most electricity-consuming residential appliances could be harnessed to primary frequency regulation markets. The electric appliances considered here include electric space heating, heat pumps, electric water heating devices, and electric vehicle chargers.

The dissertation is based on four articles, published in scientific journals and conferences, each focusing on the aforementioned appliances. The particular focus in the research and all the articles is on concepts that are implementable in real life. The underlying idea was to present and evaluate concepts that are techno-economically viable and scalable. Hence, the research was conducted by verifying the technical functioning of the presented concept by real-life proof of concept tests and economical simulations uncovering the underlying business potential.

The results show that there are indeed concepts that can provide the required capacity with a latency complying with the tight requirements of the primary frequency regulation markets. The results showed that there are concepts for direct electric space and electric water heating that enable capacity provision for frequency containment reserves (FCR). However, the provision of such capacity from heat pumps was found to be challenging. The research also verified that EV chargers can provide fast frequency reserve (FFR) capacity. The economic simulations suggested that the concepts have also significant business potential.

Keywords: demand response, primary frequency regulation, direct electric space heating, heat pump, electric water heating, electric vehicle charging, flexibility

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Pekka Manner
March 2024
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Publications

List of publications

This dissertation is based on the following peer-reviewed papers. The rights have been granted by the publishers to include the papers in the dissertation.

I. Manner, P., J. Salmelin, S. Honkapuro, I. Alaperä, and S. Annala (2020), “A novel method to utilize direct electrical space heating for explicit demand response purposes –proof of concept,” published in the proceedings of *IEEE PES Innovative Smart Grid Technologies Europe (ISGT-Europe)*, pp. 86–90.

II. Manner, P., I. Alaperä, and S. Honkapuro (2020), “Domestic heat pumps as a source of primary frequency control reserve,” published in the proceedings of *17th International Conference on the European Energy Market (EEM)*, pp. 1–5.

III. Manner, P. and S. Honkapuro (2022), “Electric Water Heaters Contributing to the Primary Frequency Regulation Markets—Finnish Case,” published in the proceedings of *18th International Conference on the European Energy Market (EEM)*, pp. 1–5.

IV. Manner, P., V. Tikka, S. Honkapuro, K. Tikkanen, and J. Aghaei (2024), “Electric vehicle charging as a source of Nordic fast frequency reserve—proof of concept,” *IET Generation, Transmission & Distribution*, 18, pp. 1223–1234, DOI: https://doi.org/10.1049/gtd2.13042.

Author’s contribution

Pekka Manner is the principal author and investigator in all the publications.

In **Publications I**–**III**, the author created the research plans and wrote the articles. The author also conducted the technical analyses and economic simulations.

In **Publication IV,** the author created the research plan and wrote the vast majority of the article. Ville Tikka, Dr., helped with the research plan and designed the empirical test setup with Kyösti Tikkanen, M.Sc., who also conducted the laboratory experiments.

Nomenclature

Latin alphabet

C	cost	–
f	frequency	Hz
r	discount rate	–
T	temperature	C°
t	time	s
E	energy	Wh
P	power	W

Subscripts

bid	bid capacity
dr	demand response
frr	fast frequency reserve
FullAct	full activation
MinDur	minimum support duration
t	time

Abbreviations

aFRR	automatic frequency restoration reserve
API	application programming interface
BESS	battery energy storage system
DR	demand response
ENTSO-E	European Network of Transmission System Operators for Electricity
EV	electric vehicle
EWH	electric water heater
FCR	frequency containment reserve
FCR-D	frequency containment reserve for disturbances
FCR-N	frequency containment reserve for normal operation
FFR	fast frequency reserve
FMI	Finnish Meteorological Institute
LCOE	levelized cost of electricity
mFRR	manual frequency restoration reserve
PHEV	plug-in hybrid vehicle
PoC	proof of concept
RoCoF	rate of change of frequency
SLY	Sähkölaitosyhdistys
TES	thermal energy storage
V2G	vehicle to grid

1 Introduction

The ongoing climate change is challenging the way we use and produce energy in our societies. The energy sector plays a critical role in the fight against global warming. For example, in Finland, the proportion of renewable electricity production has been increasing rapidly, and old fossil-based production is quickly phasing out as a result of ambitious goals set not only through regulation but also by many customers demanding greener energy. In Finland, the share of nonfossil production has already reached 53% of the total production in 2021, as presented in Figure 1 (Statistics Finland, 2022a).

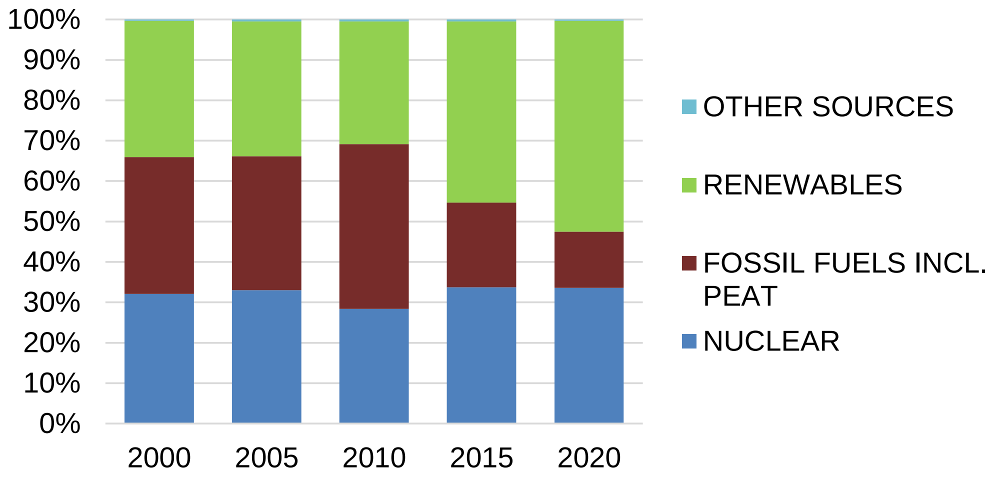

Figure 1 Electricity production in Finland (Statistics Finland, 2022a)

In general, the challenges of energy systems are threefold: they are related to affordability, sustainability, and reliability (Figure 2). The system must be as affordable as possible to enable economic growth, but it should also be highly reliable to keep the energy flowing seamlessly as society is more and more dependent on electricity. Environmental sustainability is also becoming increasingly more important as, for example, the awareness of climate change is increasing.

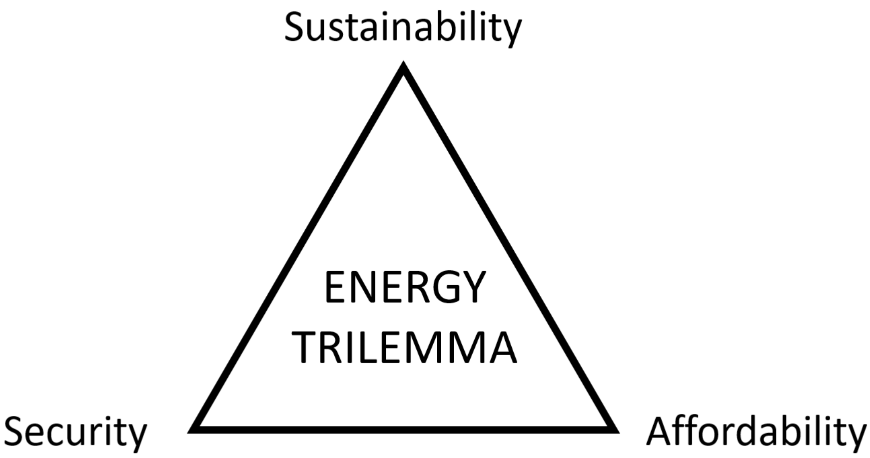

Figure 2 Energy trilemma

Today, green production is also often cheaper than the old fossil-based electricity as a result of the technological development, which has reduced the levelized cost of energy (LCOE) for renewables (Figure 3) (International Energy Association, 2022a). In addition, the ambitious regulation together with emission allowance pricing in Europe has increased the costs of fossil-based production.

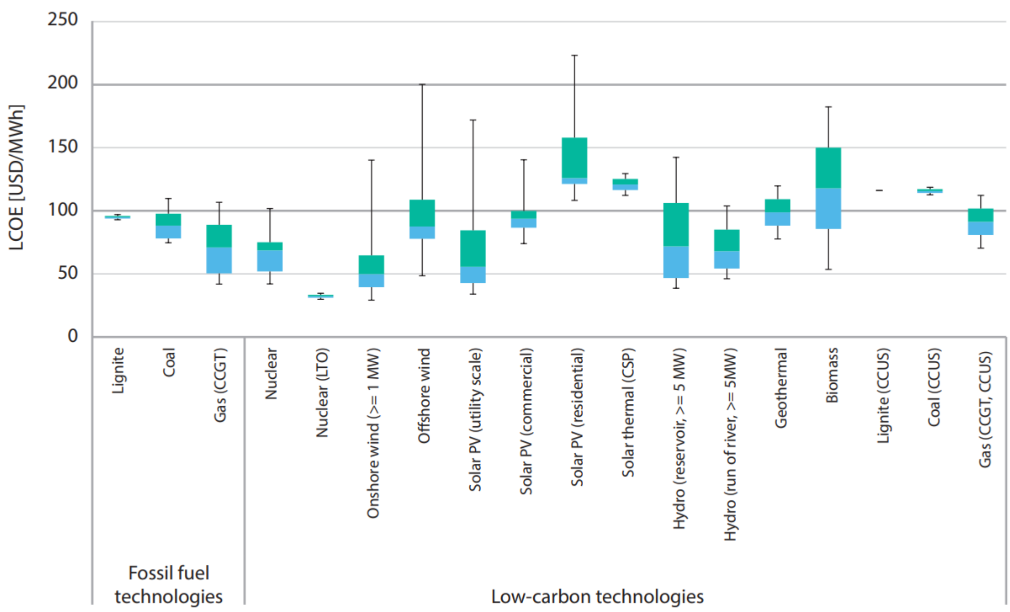

Figure 3 LCOE of different forms of electricity production (International Energy Association, 2022a)

In recent years, the rate of change related to the production mix has been relatively high, but now also the geopolitical situation has accelerated the change to an unprecedented speed. The flow of gas and oil from Russia has decreased drastically and even stopped completely in some countries, like in Finland. These factors force society to build more local self-sufficient green production. It seems that renewables once seen as challenging to be adopted have now become the key element for solving at least two of the above-mentioned challenges related to energy systems. A high share of renewables or nonfossil production is not only good for the climate, but they have also become an economically competitive source of energy. However, they also pose a challenge for the system due to their intermittent nature. The sun does not shine and the wind does not blow all the time. This means that there have to be other sources of energy to cover the times when there is a limited amount of renewable power in the system. The challenge is related to energy, but there is also another challenge not so obvious for many: the momentary frequency stability of the grid. The frequency of the grid is determined by the balance of production and consumption. If the production decreases, or the consumption increases suddenly, the frequency starts to decrease. However, the change happens at a certain rate, which is determined by the amount of inertia in the grid. Further, the inertia is determined by the rotating mass directly (electrically) connected to the system. The more inertia there is, the slower the deviations develop as seen in Figure 4, where the rate of change of frequency (RoCoF) is greater in low-inertia situations.

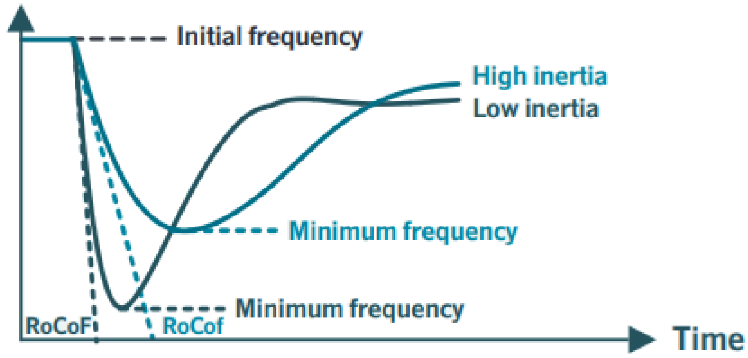

Figure 4 Effect of inertia on frequency dips during faults (Fingrid, 2023)

Traditionally, conventional production has been organized with fewer but larger generation units that operate with sizeable synchronous generators. These generators work, as the name says, in synchronism with the grid frequency. When the grid frequency drops or increases from the nominal value, the rotating mass of the generators naturally resists this change and thus provides inertia for the system. The renewable production units, by contrast, are smaller in per-unit size but larger in volume. These small generators are connected to the power grid with power electronics that isolate the inertia of the rotating generator from entering the grid. As these smaller renewable production units take space from the old conventional production, the amount of inertia in the system decreases (Fingrid, 2020).

To make things worse, the challenge is not only related to production. The pressure for energy efficiency and better controllability for processes is also pushing the rotating units of the consumption side to be equipped with power electronics, again isolating the inertia from entering the grid.

Hydropower has traditionally been the production type that provides most of the frequency regulating capacity in Finland. However, not all the needed capacity can be acquired from the versatilely controllable hydroturbines, especially when the need for regulating capacity is increasing for the aforementioned reasons. This unwanted development related to the amount of inertia and the traditional regulating capacity have turned the focus on demand-side assets. In Finland, the industry sector has already been participating in the frequency regulation business for years. Energy-consuming industrial processes, such as greenhouse lighting systems, can be turned off momentarily to support the frequency. The residential sector is also a large energy-consuming segment in Finland, especially in wintertime when the buildings must be heated. As a large share of the Finnish residential buildings are electrically heated, they also provide a significant opportunity to be used in primary frequency regulation markets. The advantage of residential demand response (DR) is that it can provide capacity from assets that already exist, making their costs significantly lower compared with traditional power plant investments.

The economic challenge related to residential DR is mainly associated with the implementation of connectivity to the assets while the operational costs are usually negligible. As these assets are usually small in power but large in volume, it is essential to find light and scalable ways to control them.

This doctoral dissertation presents new technical concepts that address the aforementioned problem and focuses especially on concepts that are implementable in practice with a positive business case. The methods used in this research focus on proof of concepts, demonstrating their functionality and evaluating their business potential. The results show that the developed concepts are indeed working in real life, meeting the tight prequalification requirements of the primary frequency markets. The simulations show that there is considerable business potential, and in some cases, the whole market volume could be covered by the solutions provided in this work.

1.1 Research questions

- **Main question**: Can the major electric loads in Finnish households contribute to the primary frequency regulation in a technically and economically feasible way?

- Is it possible to establish any techno-economically proven concepts to control the major electric loads of Finnish households within primary frequency regulation?
- Can aggregated domestic electric vehicle (EV) charging provide Fast Frequency Reserve (FFR) capacity?

1.2 Scope of the research

The objective of this research was to investigate the opportunities of Finnish households to contribute to the primary frequency regulation markets as aggregated entities. The main focus was to find and investigate actually implementable concepts from technical and economic points of view, focusing on electricity-based heating systems, which consume the most electricity in Finnish households (Figure 5) (Statistics Finland, 2022b).

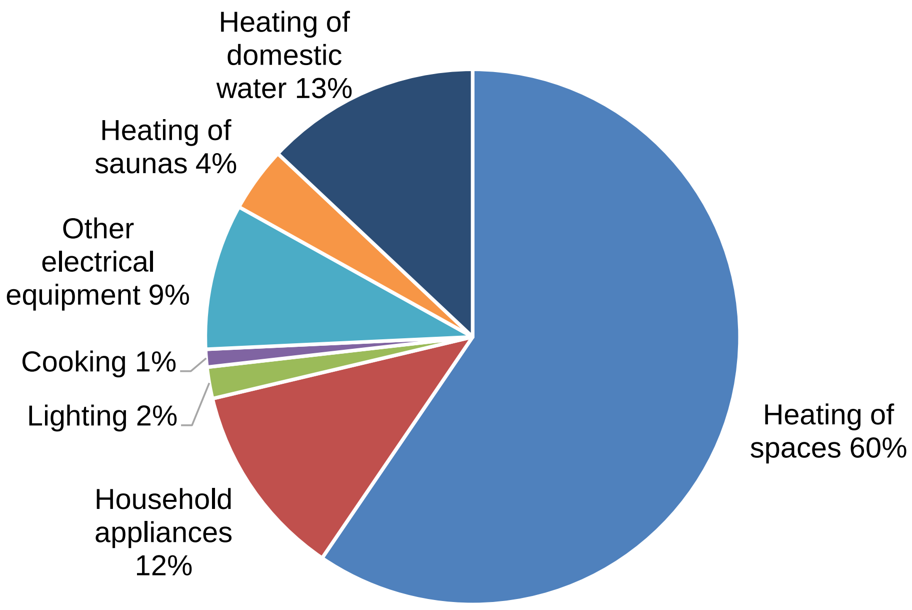

Figure 5 Energy consumption of households in Finland in 2021 (Statistics Finland, 2022b)

In this work, we also cover EV charging as it will be a major electricity consumer in the future as EVs are becoming increasingly popular in the near future. Everyday appliances like washing machines and dishwashers were left out from the scope as they were considered to be significantly smaller in terms of consumption and because of the practicality issues related to the possible remote DR control of those appliances. For example, the usage of a dishwasher and a washing machine is usually time-critical and might also cause some other discomfort to the users, like noise at night.

The idea was to evaluate how these energy-intensive domestic assets could be harnessed to primary frequency regulation and to find out if the developed control concepts could meet the tight prequalification requirements incorporated within the reserve markets. The main challenges in these requirements are related to the activation time and availability. The objective was also to determine the possible limitations and boundary conditions related to the concepts from technical and practical points of views. However, the possible effects on user experience or comfort were mainly outside the scope of the study as the concepts or control methods were chosen so that they should not significantly disturb the users.

The main research method was empirical testing with real-life proof of concept (PoC) pilots. Different kinds of PoC tests were performed in real-life environments. Tests were made, for example, in two electrically heated homes and with commercially available real EVs and heat pumps that were already in their intended use. Economic simulations were also made with real historical reserve market data to evaluate the real economic potential of the concepts, should they have been implemented in recent years.

1.3 Scientific contribution

Lately, residential DR has been intensively researched in the literature (as discussed later in Chapter 3). However, the previous research usually focuses on theoretical models, which are almost in any case very challenging to implement or otherwise impractical in real life. Furthermore, there are some studies including simulations that show a great economic potential of DR concepts; however, no indication is given of how these concepts could be actually implemented in real life. This dissertation, by contrast, concentrates solely on concepts that are implementable or demonstrated in real life. Hence, also the research methods mainly focus on empirical testing and demonstrations.

In short, the scientific contributions of this dissertation are as follows:

- Evaluating the feasibility of new concepts to harness domestic loads for primary frequency regulation purposes.
- Proving that it is possible to use domestic space and water heating in the Nordic FCR markets and the EV charging capacity for the Nordic FFR market as aggregated capacity-providing units.
- Evaluating the technical compliance of the above-mentioned concepts with the prequalification requirements and identifying their limitations on contributing to the aforementioned primary frequency regulation markets. This is done by conducting empirical proof of concept tests in a real environment (testing space

heating DR in houses with residents living their normal everyday life and testing EV charging DR with real commercially available chargers and EVs).
- Evaluating the business and market potential of the new concepts by running economic simulations with real-life load and market data.

1.4 Structure of the doctoral dissertation

This doctoral dissertation concentrates on residential flexibility. The first chapter gives motivational background information related to the research area and an overview of the research focus, including research questions, scope, and contributions. The second chapter delves deeper into specific background information about the focus of the dissertation giving the reader basic knowledge about demand response and primary frequency markets. The third chapter presents the current state of the research, including the identified research gaps.

The next four chapters address the actual research topics. The fourth chapter focuses on the research of electricity-based space heating, while the fifth chapter covers heat-pump-based heating. The sixth chapter is about electric water heating DR, and the seventh chapter presents the research made on EV charging. The last two chapters discuss and conclude the research, with impacts, limitations, and future research considerations.

2 Primary frequency regulation and demand response

TSOs around the world are obligated to keep transmission systems operational. One of the challenges they face is the need to maintain the frequency stability. Consequently, production and consumption must match at all times to keep the frequency within acceptable predefined limits. To ensure the frequency stability, different mechanisms have been implemented to tackle balance issues with different time constants. TSOs have acquired reserve capacity either by using their own reserve capacity-providing assets or by setting up specific reserve capacity markets to outsource the capacity provision. The challenge is universal, and solutions for frequency stability must be in place all around the world.

2.1 Primary frequency regulation

The first group of reserve capacity to react to sudden changes in the frequency is called primary frequency regulation. Reserve types in this group mainly supply capacity, while the purpose of the secondary and tertiary markets is to respond to longer-term changes in the production and consumption balance. The secondary and tertiary markets free the primary regulation capacity to be utilized again, as they offset the operating area of the primary frequency regulation to meet the altered power level in the system. Within primary frequency regulation there are usually markets operating under different principles and for different purposes based on the reaction speed (activation time) and the magnitude of frequency deviation. The existence of these markets is, of course, dependent on the local regulation and grid properties. In the Nordic countries the frequency regulation is organized as follows (Figure 6).

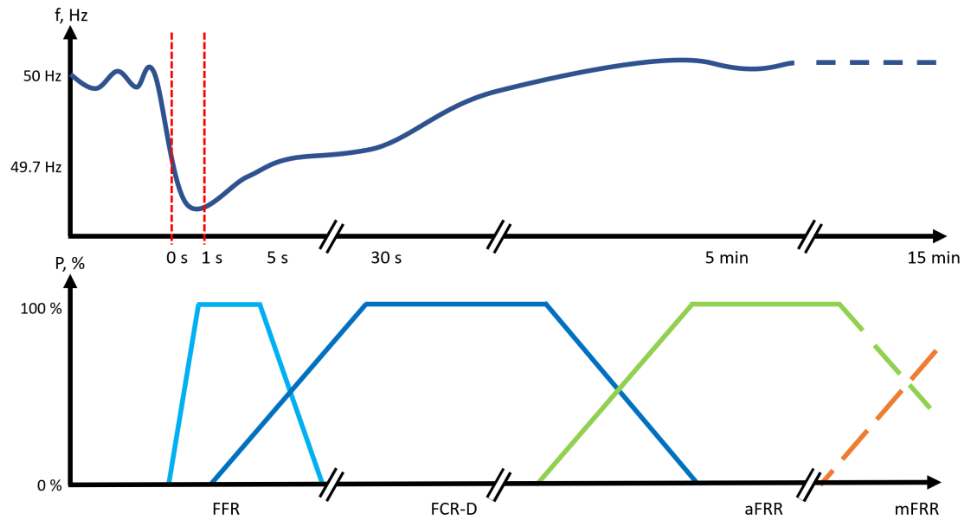

Figure 6: Frequency regulation products and their activation order, Entso-E (2022)

The Nordic countries have three different kinds of primary frequency regulation reserve capacity markets. Traditionally, a frequency containment reserve (FCR) is maintained for normal operation and for disturbances (Fingrid, 2023b). The frequency containment reserve for normal operation is called FCR-N, and it is, as the name says, operational all the time reacting to even small deviations above or below the system frequency of 50 Hz. When the frequency exceeds the boundaries of normal operation (FCR-N), the frequency containment for disturbances (FCR-D) is activated (Figure 7). The required reaction time of the FCR-D is shorter than that of the FCR-N as its aim is to quickly bring the frequency back to the normal level.

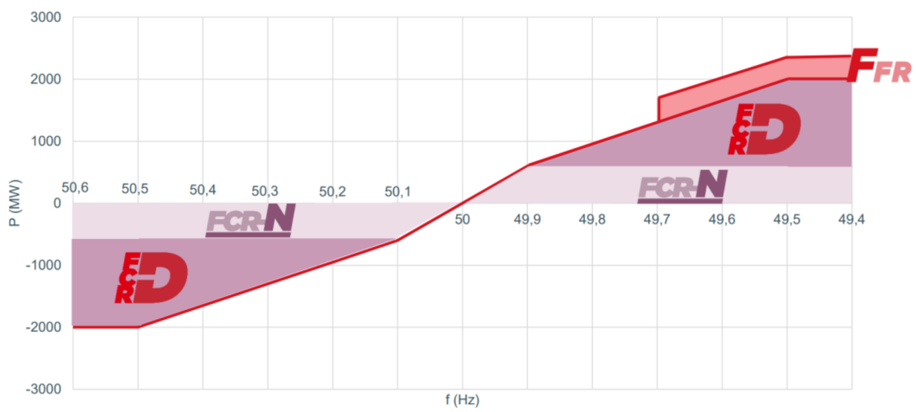

Figure 7 Role of the FFR and FCR markets in frequency control (Fingrid, 2023c)

The most challenging aspect of the requirements is usually the activation time requirement. For example, in FCR-D, 50% of the capacity should be provided in 5 s, which significantly limits the asset base that can provide this capacity (Table 1). Another challenge for the FCR capacity provision is the linearity requirement. The magnitude of supplied capacity has to follow the frequency deviation at least stepwise linearly.

Table 1 Requirements for the FCR markets in Finland (Fingrid, 2023b)

	Minimum size	**Full activation time**	**Other**
FCR-N	0.1 MW	in 3 min after a frequency step change of ± 0.1 Hz	Dead band max ±0.01 Hz
FCR-D (up)	1 MW	5 s / 50%, 30 s / 100%, after a frequency step from 49.9 Hz to 49.5 Hz	
FCR-D (down)	1 MW	5 s / 50%, 30 s / 100%, after a frequency step from 50.1 Hz to 50.5 Hz	

The newest primary frequency regulation reserve market is called Fast Frequency Reserve (FFR). It was introduced in 2020 to tackle the challenge related to the diminishing inertia. The idea of the FFR is to react extremely fast to sudden drops in the grid frequency. Such drops are often caused by abnormal disruptions in large power plants or transmission lines when a sizeable amount of capacity disappears from the system. The Nordic TSOs agreed to use common specifications for the FFR, defined by the European Network of Transmission System Operators for Electricity (ENTSO-E). The specifications state three optional activation times for the capacity, which depend on the chosen activation threshold (Table 2).

Table 2 Activation time and duration requirements for the FFR market (Statnett, 2021)

Frequency level, Hz	**Activation time, s**	**Activation duration, short, s**	**Activation duration, long, s**
49.7	1.3	5	30
49.6	1.0	5	30
49.5	0.7	5	30

Because the activations are relatively rare events and the disruption is more severe compared with the situation with the other market (FCR) activations, the deactivation must happen in a controlled way. There are two alternatives for the activation duration (Figure 8). Short activation capacity should decay with a predefined MW/s rate, whereas in long activation, the capacity can be released as wanted, even all at once. The prequalification can be carried out for single assets or as a type test for aggregated identical loads under 0.1 MW. The technical specifications also set limits on overdelivery and recovery. The requirement seems to be made for assets that could be recovered after activation so that they can be used again just after the first activation. The most obvious asset for this purpose is grid-connected batteries.

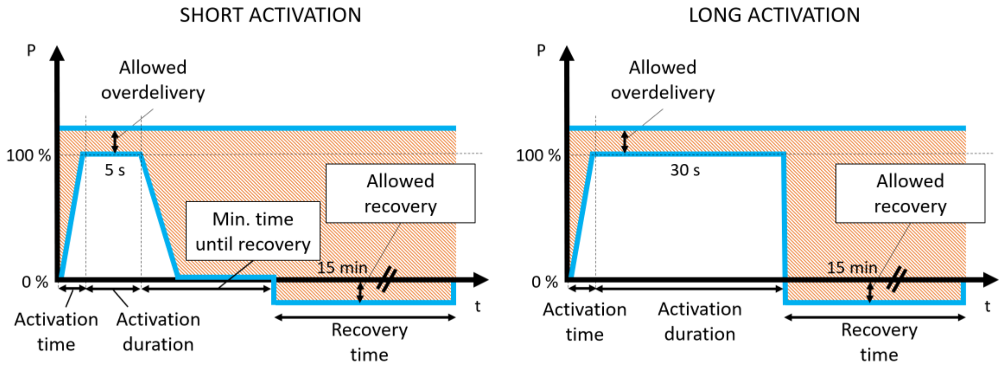

Figure 8 Short and long FFR activation (Statnett, 2021)

As the market is changing all the time, so are the requirements. There is a pan-Nordic process going on to change the prequalification requirements for primary frequency regulation. The main focus in the change process is the introduction of dynamic stability criteria. In practice, this means that the capacity-providing unit or aggregate proposed to the markets is also tested, for example, against harmful resonances that might start to oscillate with the disturbance, impairing the grid stability. However, the main principles of the different primary frequency markets remain the same; the greater the frequency deviation is, the greater and faster is the reserve activation

Currently, hydro power provides the majority of the regulation capacity needed, but because of its limited growth potential, the increasing need for regulating capacity, and tightening regulation, the focus has started to shift toward demand-side sources. There is already a significant amount of demand-side capacity provided to the Finnish power markets (Figure 9).

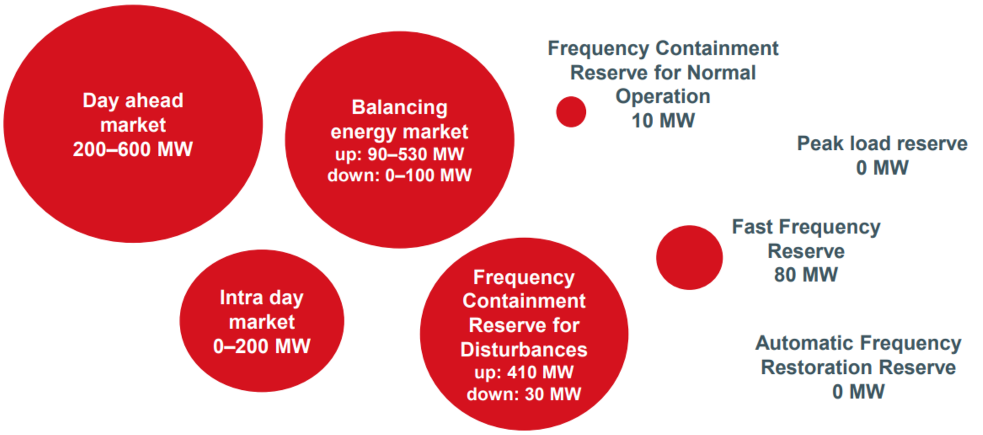

Figure 9 Demand-side participation in the Finnish markets, as of 1th February, 2022 (Fingrid, 2023c)

2.2 Demand response

Demand response (DR) has been a topic of active discussion over the last decade. By definition, it is a capacity or energy support from assets that normally consume energy (International Energy Association, 2022b). The assets vary from small loads, such as domestic space or water heaters, to industrial-scale ovens, for example, steel furnaces. DR is a versatile topic, and there are many ways to categorize it. One very common way to categorize DR is to divide it into two different groups based on the beneficiary. In the price-based DR, the end customer controls the adjustable load based on a dynamic retail or distribution tariff to reduce the energy costs. This category where the end customer is directly receiving the full benefit of the DR activity is called implicit DR. In the incentive-based DR, or in the explicit demand response, there is another party that is controlling the loads and benefiting directly from the DR activity. The other party then rewards the customer for being able to carry out DR activations (Figure 10).

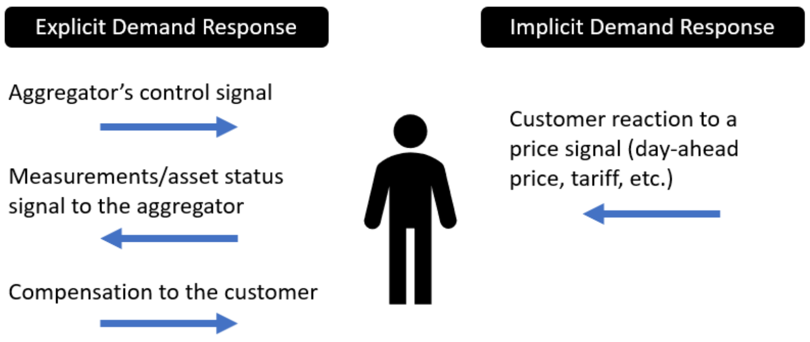

Figure 10 Implicit and explicit DR

Another way to categorize DR is to divide it based on the use cases. DR can be used for many purposes and by many stakeholders. Energy arbitrage (price optimization for the energy used) is maybe the best known and most often used target for the DR capacity, but it can also be used for network congestion management, behind the meter peak shaving, frequency regulation, and so on. The most common use cases are presented in Figure 11.

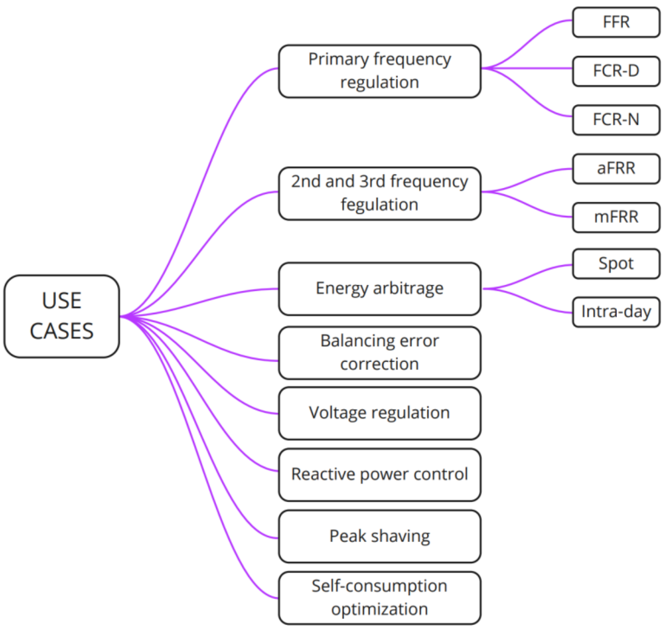

Figure 11 Typical use cases for DR

All these target cases for DR capacity have different kinds of requirements and properties. For example, the network congestion management usually requires stable power reductions to specific congested areas that last usually more than an hour, while the disturbance reserves in the frequency management usually require high power reductions that may last for seconds or minutes. Common parameters for flexible capacity requirements are illustrated in Figure 12.

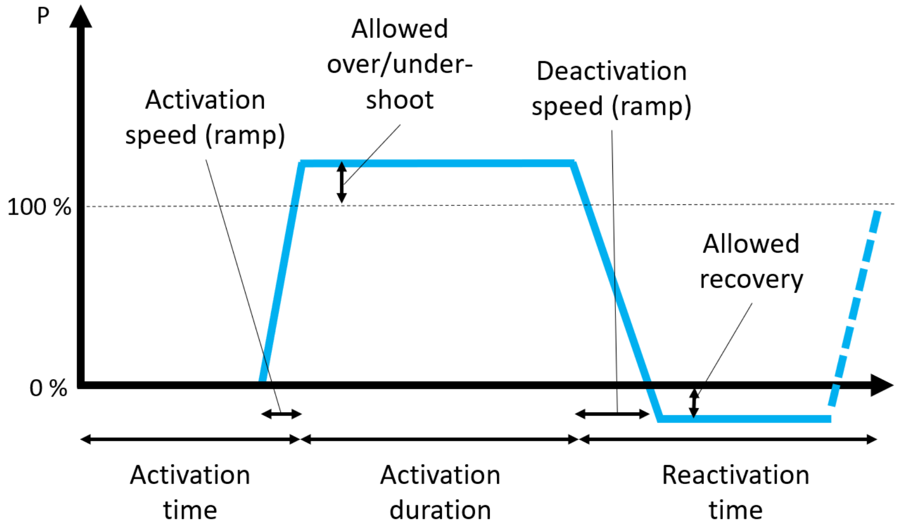

Figure 12 Common parameters for flexible capacity requirements

Furthermore, the use cases include also other factors that affect the suitability of an asset to perform in the specific use case. These are, for example, the number of activations, the relation between energy and capacity provision, and requirements for the verification of the activations, like measurement accuracy and frequency. Moreover, some cases may need local or remote logic for the DR activations.

The sources of DR capacity have different properties. For example, batteries are well suitable for providing capacity fast, while they are not particularly good for storing energy (as there are better/cheaper alternatives for this, such as (pumped) hydropower). Furthermore, there are usually costs related to using the DR capacity. These can be, for example, losses occurring when charging or discharging a battery, production lost in an industrial process, or reduced user comfort when lowering the temperature of an electrically heated house. Of course, the intention is to utilize the excess flexibility in the assets or processes so that it does not cause any cost or harm to the original purpose, but sometimes when the incentive is high enough (compared with the costs), it also makes sense to intentionally take risks or pay costs to gain additional revenues. Naturally, all the stakeholders need to agree upon the operational limits and risk levels.

Evaluation of the value or profitability of each use case is challenging, and the results vary based on market, season, country, regulation, network congestions, and so on—the list is long. Forecasting the profitability of these markets or use cases is thus challenging, and companies that are active in these markets have usually a dedicated team forecasting the future price levels. One rough way to evaluate the value is to look at the historical values. For the frequency regulation reserve markets, Fingrid publishes historical price information in their "open data portal" (Fingrid, 2023d). Figure 13 presents the historical non-volume-weighted hourly price information (years 2016–2022) of the Finnish primary regulation market.

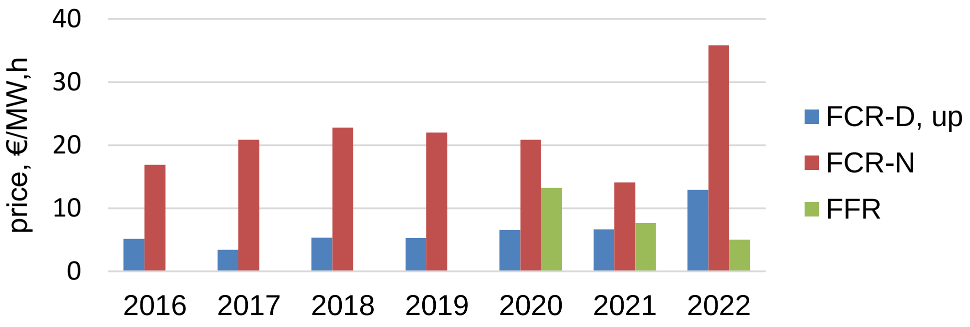

Figure 13 Fingrid's price statistics for the FFR and FCR markets (Fingrid, 2023d)

Hydropower has traditionally been dominating as a source of frequency regulation capacity. However, today, there are increasing amounts of DR capacity offered to the markets. For example, greenhouses occupy nearly the whole FCR-D market (at least during the hours when the greenhouses have the lights on). Greenhouses are also a good example of how the markets are dependent on each other. As the day-ahead prices have increased rapidly because of the recent energy crisis, many of the greenhouses have been forced to temporarily close down, which meant that they were also out of the FCR-D market (which probably partly explains the higher prices in the FCR-D in 2022).

2.2.1 **Potential residential DR sources in Finland**

Residential DR has a long history in Finland. The most common DR scheme is probably the night tariff system, still existing in Finland. The night tariff system was originally developed to shift some of the loads from the more congested daytime hours to night when the generation side and the network has more capacity available. Utilities across Finland agreed to use a standard way to implement (or at least recommend) the control of the energy-consuming household appliances. Usually, the loads connected to the night tariff control are the most energy-consuming appliances.

The same loads are also useful in the modern demand response. The modern demand response can be said to have emerged in Finland in the early 2010s when the first home automation or energy optimization services were launched. These systems usually steered the old electric space heating devices to schedule the heating to take place at the cheapest priced hours to generate savings for the homeowner (implicit demand response). Later, in the late 2010s, also the first explicit demand response services were launched. These services were designed to control the same energy-consuming domestic assets against primary frequency regulation markets.

As the heating-related systems are already identified as useful sources of DR capacity, it is essential to understand their DR potential. In cold climate countries, like Finland, the heating usually accounts for a large proportion of the total annual energy consumption. In Finland, the heating of buildings accounts for 27% of the total national energy consumption (Figure 14) (Statistics Finland, 2023).

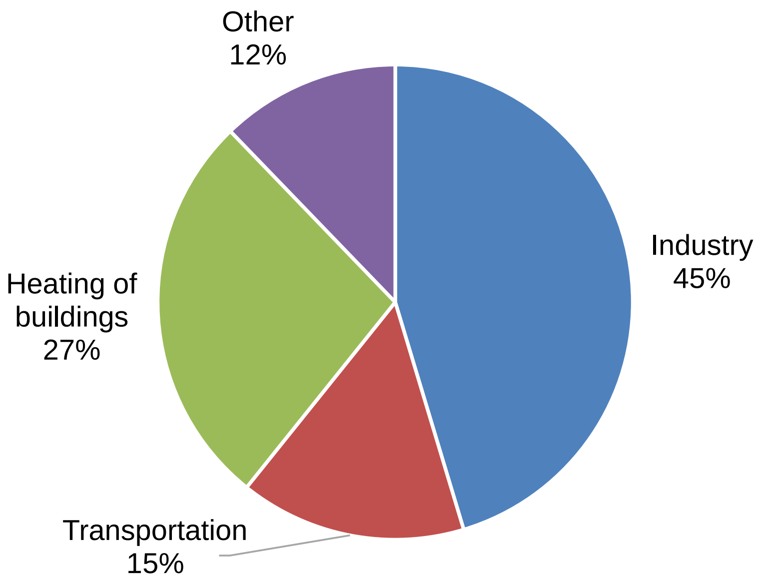

Figure 14 Energy usage by sectors in Finland, 2021 (Statistics Finland, 2023)

Of course, not all this energy is electricity as district heating is the most popular type of heating in densely populated areas. Yet, as Finland is quite a sparsely populated country, a significant proportion of homes are in areas where district heating is not available. In these cases, local heating solutions take care of the heating. These systems use mostly electricity as the primary source of energy. The other option is to use systems that burn fuel (mainly oil or wood products) to generate the required heat. However, because of the recent geopolitical development, especially the oil-based heating systems are becoming obsolete and replaced by heat-pump-based systems. Figure 15 shows the distribution of different primary heating sources of residential heating in Finland in 2021 (Statistics Finland, 2022c).

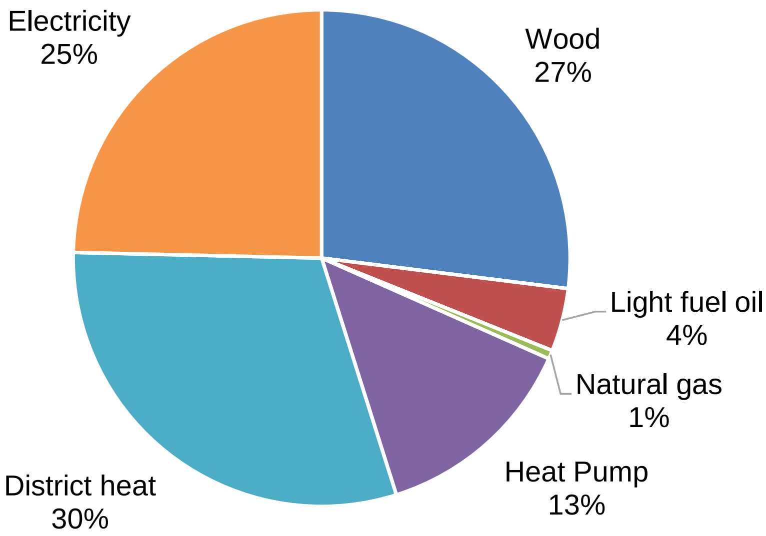

Figure 15 Fuels used for residential space heating in Finland (Statistics Finland, 2022c)

The direct electricity and heat-pump-based heating systems can be considered potential ones in DR applications. As seen in Figure 15, these loads provide a massive opportunity for TSOs to meet their needs for frequency regulation. To put those amounts into perspective, the space and water heating capacity can reach over 5 000 MW (Järventausta et al., 2015) during the coldest days of the year, while the maximum procured primary frequency capacity was 513 MW (FCR-D) in 2021 (Fingrid, 2023d). However, there is, naturally, very little heating capacity available for DR outside the heating season. It should also be noted that the actual activations of FFR and FCR-D are occasional and consume a fraction of the allocated capacity.

Furthermore, the table does not include the electricity used by EVs, which are replacing traditional internal combustion engine powered vehicles at a rapid pace. The number of sold EVs and PHEVs (Plug-in Electric Vehicles) has been roughly doubling globally each year according to the International Energy Association (2023). The same pace can be observed in the Finnish statistics, illustrated in Figure 16 (Traficom, 2022), making the EV capacity a significant potential source of domestic DR capacity.

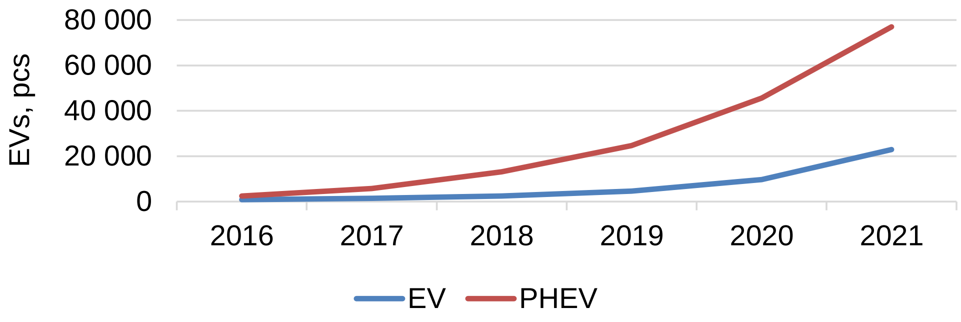

Figure 16 Number of EVs and PHEVs in Finland (Traficom, 2022)

To conclude, it can be stated that these loads (direct electric heating, domestic water heating, heat pump heating, and EV charging) are the most important domestic loads to be considered as sources for primary frequency regulation.

3 State of the art

3.1 Demand response of direct electric space heating

Demand response of space heating has been of interest for a long time. For example, in (Mubbashir et al., 2014), the authors studied the optimal DR of electric heating with partial storage taking into account the hourly electricity prices. In (Dong et al., 2023), the authors proposed an algorithm for thermostatically controlled loads that balance the grid loading in order to relieve the stress on the grid, taking also the living comfort into account. This is a highly relevant topic in areas with a considerable amount of electric heating or where the electrification of heating is proceeding rapidly. In order to evaluate the flexibility potential, the authors of (Haakana et al., 2023) developed a method where they use multiple data sets, including consumption, building, and grid data. A more holistic approach was taken in (Rinaldi et al., 2022), where the authors also considered the interplay of different kinds of flexibilities (implicit DR, energy efficiency, and infrastructure investments, among others). In (Nyholm et al., 2016), the DR potential of electrically heated single-family dwellings in Sweden was evaluated.

There are only a few studies on the DR of direct electric heating that focus on primary frequency regulation, for example (Herre et al., 2018), where energy arbitrage and optimization of ancillary service provision were considered, and (Rautiainen et al., 2009), where the authors proposed a concept where the power of the heating would automatically follow the grid frequency. Furthermore, according to the author’s best knowledge, there are no successful real-life demonstrations or proposals of how to harness the electric heating load for primary regulation in practice with a low-cost solution enabling economic scalability.

3.2 Heat pump demand response

The DR of heat pumps is a more common research topic compared with pure direct electric space heating. For example, in (Vivian et al., 2020), (Marini et al., 2019), and (Le et al., 2020), the effects of day-ahead scheduling of heat pump heating on distribution grid peak loading together with thermal energy storages were investigated. In (Kelly et al., 2021), the authors evaluated the ability of heat pumps to react to short-term increase or decrease load signals in the UK with the help of building models. Thermal Energy Storages (TESs) are often included in studies as they increase the flexibility in the heating system. This increased flexibility can be used for price optimization or to run the heat pumps more efficiently, as stated in (Meng et al., 2021). In (Müller et al., 2019), the authors not only present a method of how to disaggregate the heat pump consumption from the overall household consumption but also demonstrate how the heat pump DR activations can be predicted with a 7% absolute accuracy.

One of the few studies that focus on frequency regulation markets is presented in (Bünning et al., 2022), where the authors demonstrated the correct functioning of their heat pump control algorithm in real life.

However, the majority of the research has mainly focused on implicit demand response with known or easily forecastable activations. Furthermore, the empirical research on heat pumps has been done with retrofit or hardware-requiring solutions. There is a clear need to conduct research on DR with domestic, commercially available heat pumps that are controlled through manufacturers' cloud solutions.

3.3 Demand response of electric water heaters

Electric water heaters (EWHs) have also been an extensively researched topic, because in many countries, they usually have the ability to store the energy they use as heat. The ability to store energy enables flexibility for various use cases. Most of the research focuses on optimal scheduling or forecasting of EWH loads for DR purposes. For example, in (Marnell et al., 2020), the theoretical DR capabilities of a pool of 10,000 EWHs for providing capacity with different durations was studied. In (Kapsalis et al., 2018), the authors studied how EWHs could be used under dynamic pricing schemes and how the EWH control optimization should take into account comfort and costs. Like in many other studies, in (Shen et al., 2021), methods to forecast EWH flexibility were proposed.

Besides the recent research on direct electric heating DR, electric loads have been controlled to balance the loading in practice for decades. Many cold climate countries have or have had tariff control schemes where a control signal is sent to homes to control the energy consumption of a heating accumulator or a domestic hot water tank. The signal controls relays and contactors (located in the fuse board of the house), which, again, control the power supply of the aforementioned loads.

In Finland, the tariff control system was mainly implemented in the 1970s and 1980s when the power markets were not yet liberalized. These systems are efficient as such for slow and infrequent load shifting, such as regular night vs. daytime control, but cannot be used for fast-reacting markets, such as primary frequency regulation, because of the need for fast reaction times (which the existing tariff systems cannot provide). Furthermore, these systems are gradually reaching the end of their usable lifetime. Today, the tariff control readiness is often included in the smart meter functionalities. However, the price difference between the night and day tariffs is diminishing, leading to a reduced adoption rate of the tariff control in new buildings.

However, there is very little research on primary frequency regulation, especially where the primary frequency provision capabilities would be demonstrated in real life. Instead, many studies have been conducted using models or simulations. For example, in (Lakshmanan et al., 2021), the ramp-up and down behavior of a total of 1,000 modeled electric water heaters in Norway was evaluated. The ramp-up and down rates are essential information, for instance, for primary frequency regulation reserves, which require fast reaction. In (Paull et al., 2010), the authors created a model for EWHs where the availability of capacity provision can be estimated by analyzing the water usage profile of the households. In (Motalleb et al., 2016), the authors proposed a market model for EWH capacity to contribute to contingency reserves (only up-regulation), while in (Molina-Garcia et al., 2011), the authors presented evidence that EWHs could contribute to primary frequency regulation (up and down regulation) with a local control setup including local frequency measurements. In (Clift et al., 2023), a model where cost savings can be achieved by optimizing the energy price and provisioning of ancillary services with EWHs was proposed. An evaluation of the market potential of the contribution of EWHs to primary frequency regulation markets was presented in (Kjajeh, et al., 2022). Despite the extensive number of studies on the contribution of EWHs to primary frequency regulation markets, the literature lacks information on concepts that are demonstrated in real life.

3.4 Demand response of EV charging

EVs are known to be a versatile source of flexible capacity. Basically, they can be considered batteries on wheels and can be used for practically anything that a normal battery energy storage system (BESS) can do. Of course, they might be on the move and thus not available for DR purposes. Clearly the most popular topic with the DR of EV charging is, as with the other assets addressed in this dissertation, price optimization (Shahkamrani et al., 2021; Su et al., 2020). One popular target for the acquired DR capacity is also the network congestion management (Yang et al., 2021; Asrari et al., 2020). The aforementioned papers focus mainly on the DR of unipolar EV charging. There are also many studies on the same use cases with bidirectional charging (V2G) (Li et al., 2020; Crozier et al., 2020). As with BESS applications, many studies have been conducted with the primary frequency regulation in mind. The focus there has been on droop control, where the charging power follows the grid frequency and/or the rate of change of grid frequency (Teng et al., 2017; Magdy et al., 2021; Mu et al., 2013; Marinelli et al., 2021). However, because the inertia in our power systems is decreasing, faster regulation services are needed. In (Soares et al., 2018), it was demonstrated how EVs could provide this kind of capacity, but they used an artificial setup representing a bidirectional EV. Hence, there is a clear need for more empirical research on fast-reacting DR capacity on assets that are either already commercially available or at least closer to real-life applications.

3.5 Summary of the state of the art

The literature review shows that the demand response of domestic assets is indeed an interesting topic that deserves more research. Most of the research has focused on network congestion management, which is understandable as many countries struggle with network limitations in the era of renewables penetrating our system and the ever-increasing electrification of, for example, heating. Different kinds of pricing mechanisms are developed, and some even implemented (Tensio, 2022) to motivate customers to shift their consumption from peak consumption hours to low consumption hours. Further, pricing is also a research topic of high interest, because it is, naturally, maybe the most motivating way for energy users to react to the needs of our energy systems.

While the heat pumps are trickier to control because of their internal operation principle, there is very little information of them as a source of primary frequency regulation. The major concern related to them is the reaction time required in, for example, FCR markets. Although there is some research on heat pumps in primary frequency regulation, the literature lacks information about DR carried out with standard commercially available household-size heat pumps controlled via a cloud solution.

Despite the extensive research on the demand response of domestic assets, the literature review shows a gap in practical, empirically demonstrated concepts that enable the most electricity-consuming household assets to take part in primary frequency regulation. The only exception to this is the DR of EV charging. Currently, there are even some commercial implementations available (Virta, 2019), but the solutions do not cover the market that is most demanding from the perspective of latency, the FFR market, where the activation must happen in 1.3 s at the maximum. To sum up, the research gaps can be listed as follows:

- Previous research has mainly covered other use cases than primary frequency regulation markets
- The existing literature lacks real-life empirical evidence on DR functionality and is mostly theoretical.
- The existing solutions require high upfront investments, thereby posing challenges to the business potential of the concepts.

4 Direct electric space heating loads (Publication I)

The objective of the study in Publication I, in general, was to investigate the technical and economic potential of direct electric space heating solutions in the primary frequency regulation markets, as direct electric heating is one of the common heating methods in Finland. Space heating accounts for 27% of the total energy consumption in Finland, of which 25% is based on electricity. Hence, around 7% of the total energy consumption of Finland is due to electric heating.

A more specific objective was to identify the technical opportunities and limitations of the direct electric and heat pump heating potential of DR in the primary frequency regulation. One of the most challenging requirements of the primary frequency regulation markets is the reaction time from the frequency deviation to the supplied capacity. For example, in the FCR-D market, 50% of the capacity must be provided in only 5 s, and the rest in 30 s with the current prequalification specifications. Other evaluated technical aspects were the suitability of the load pattern for DR and the effect of various DR activations on the indoor temperature and other possible side effects affecting the comfort of living.

Furthermore, the idea was to find methods to practically harness the capacity of the heating systems. Lastly, rough economic analyses were conducted to evaluate the indicative monetary value of the controllable heating capacity.

4.1 Direct electric space heating

As the direct electric space heating accounts for a significant proportion of electricity consumption in Finland, it was a natural choice to be included in the evaluation of the DR potential in this study. In the study, the direct electric heating is considered to contain wall panel heaters, underfloor heaters, ceiling heaters, and electric central heaters that use resistive heating elements for heat production.

To be able to control the heating, either the settings of the thermostats or the supply of the heating devices must be accessed in one way or another. An obvious way is to use novel heating devices with inbuilt internet connectivity or smart thermostats connected to heating devices. This is usually a costly operation especially if the existing system has still some operational lifetime left, as these smart home systems can easily cost over €1000 per site. Hence, a cost-efficient retrofit solution must be developed to acquire several megawatts of capacity.

In order to evaluate the suitability of direct electric space heating to be used as a source of primary frequency regulation, a technical proof of concept pilot was carried out. The pilot study was conducted in wintertime to investigate whether the temperature reduction has a significant impact on the indoor temperatures in cold winter days.

4.2 Concept, research method, and assumptions

A good and practical approach is to use an existing setup or wiring that might exist on site. A common setup for houses or apartments heated with direct electric heating is to have a home-away functionality installed for the heating devices. Often, the manufacturers of wall-mounted panel heaters or thermostats controlling the heating devices have included a temperature reduction feature in their devices. The feature allows the set temperature to be dropped by a certain number of degrees. In advanced models, the magnitude of the temperature drop can be adjusted, whereas in standard models it is usually set around 5°C. Nevertheless, the assumption was that this feature can serve as a method to temporarily reduce the electric power of the heating and thus enable DR of electric space heating. Usually, this feature is enabled by feeding power to a separate connector in the heating device or the thermostat. One such setup is illustrated in Figure 17.

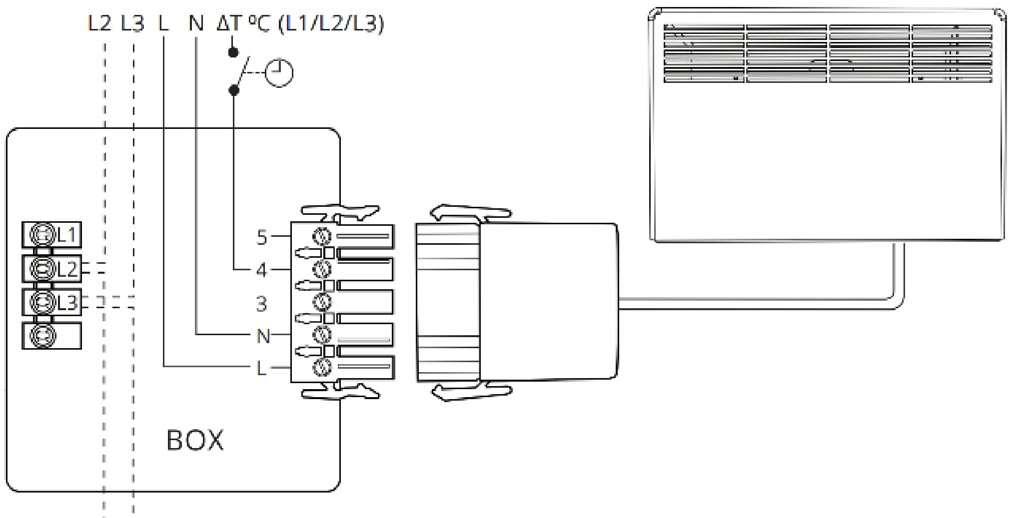

Figure 17 Implementation of the temperature reduction function in Ensto’s wall heater (Ensto, 2021)

Usually, power is fed to the temperature reduction connector by a separate home-away switch accessible to the residents of an apartment or a house. Because of the nature of primary frequency regulation, the residents cannot perform the activations by themselves, for example, triggered by messages sent to them, but rather, the DR must be automated. This can be done by installing a simple device that can feed a signal to the temperature reduction connector based on smart algorithms in the aggregator’s cloud solution (Figure 18).

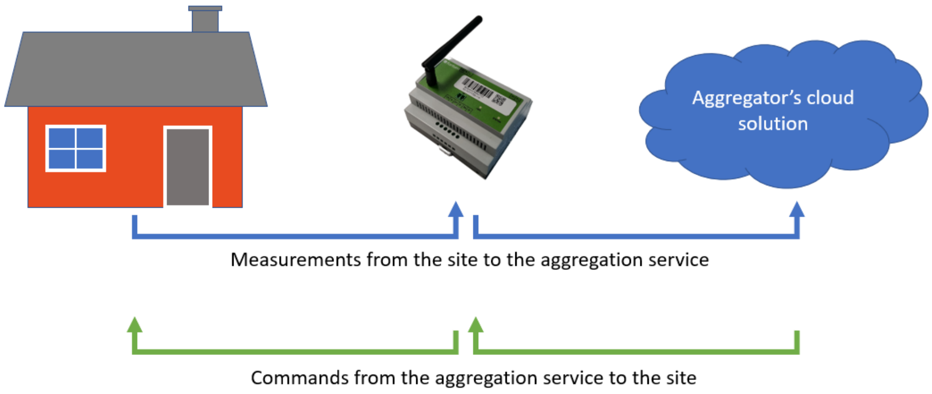

Figure 18 Communication from and to the DR asset (Publication 1) © 2020 IEEE

Another issue related to the concept is to evaluate if the DR control has a significant (negative) impact on the residents' comfort of living. To evaluate the possible harmful effects on the indoor temperature, extreme tests must be performed. The tests should reveal the worst possible effects of a DR activation in worst possible conditions. Hence, wintertime was chosen for the proof of concept tests.

In order to also qualify as an economically feasible concept, it should produce more value than costs. As it can be concluded that the per-unit income from primary frequency markets is marginal, the cost side of the concept must be minimal. This means that the control unit should be as affordable as possible. Furthermore, the installation should be as quick as possible to keep the installation time and costs minimal. In fact, installation is actually the most important factor affecting the costs in countries where the labor costs are high.

4.3 Results

To investigate whether the home-away functionality could be used for DR purposes, a small-scale proof of concept pilot was carried out. The intention was not to get statistically verified results but rather to get some indication of the functioning of the concept. The pilot consisted of two different homes with a home-away functionality implemented to the electric heating system. The homes were also equipped with indoor temperature monitoring units that logged the temperatures during the tests. A small device, specially designed to be used in scalable DR concepts (shown in Figure 18), was used to control the home-away functionality. Several tests were conducted with different activation durations to investigate the effect on the indoor temperature and electricity consumption. The residents of the homes were also asked if they noticed any changes in the comfort of living during the tests.

Firstly, the technical setup seemed to work fine; the device was able to relay DR commands within the required time, and the home-away feature was successfully activated remotely. Secondly, the indoor temperatures seemed to stay at reasonable levels even in cold winter days with outdoor temperatures below −20°C and a three-hour-long activation of temperature reduction. An example of the effect on the indoor temperature can be seen in Figure 19. The figure shows the effect of the activation of temperature reduction on the indoor temperature in a cold (appr. -20°C) winter day. It should be noted that according to Fingrid's statistics, this long activation never happens in practice when the acquired DR capacity is offered to primary frequency regulation markets (Fingrid, 2022).

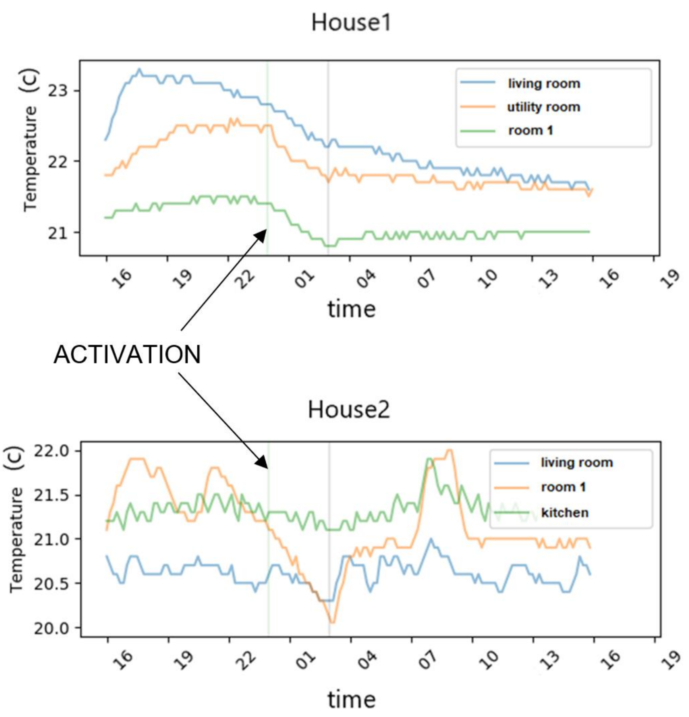

Figure 19 Effect of activation on indoor temperature (Publication 1) © 2020 IEEE

The activations also temporarily reduced the consumption of electricity. However, when turning the heating back to normal, a payback effect was observed (Figure 20). This payback effect is due to a simultaneous power increase in all of the controlled heaters as they try to reach the normal set temperature level. From the perspective of DR, this is unwanted phenomenon, which require mitigating actions from the aggregator. One way to smoothen the payback spike is to add a random delay to the activations of individual sites.

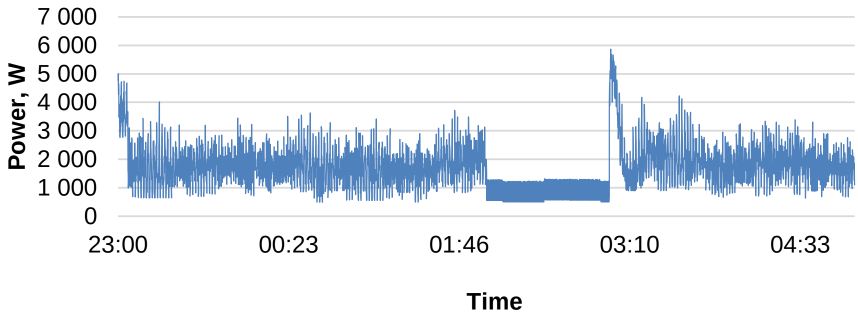

Figure 20 Effect of activation on power consumption (Publication 1) © 2020 IEEE

The other objective was to determine the relation of outdoor temperature to the amount of power reduction during an activation. As expected, the reduction in electric power was higher when the weather was colder as the heating need was higher. The dependence of the outdoor temperature on power reduction (harnessed DR capacity) can be seen in Figure 21. As there were people living in the house during the tests, they might have caused some of the power readings to differ significantly (even to the negative side) from the average. These deviations can most likely be explained by opening a window or a door during a test.

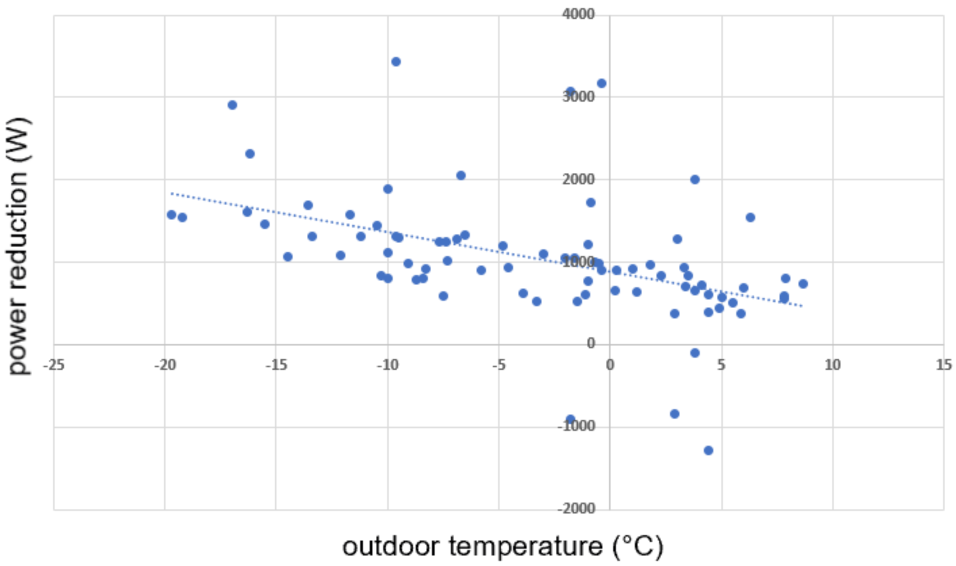

Figure 21 Magnitude of power reductions in different outdoor temperatures (Publication 1) © 2020 IEEE

The objective was also to evaluate the economic potential of the concept. An economic simulation shows that the per unit potential is considerable (Table 3) compared with the (negligible) costs. The economic simulation was carried out for night and whole-day DR operations by multiplying the average monthly FCR prices by the corresponding average monthly consumption of a single site with the following assumptions taken into account:

- The average yearly consumption is 10 MWh per site, distributed across the year by the heating indices published by the Finnish Meteorological Institute (FMI).
- 85% of the heating loads can be used for DR.

Table 3 Unit income (€/a) from the concept in nighttime and whole-day control with 2020 FCR prices (Publication 1) © 2020 IEEE

	Annual per-unit income (€/a)			
	night control (22:00-07:00)		***whole-day control (24h)***	
	FCR-N value	***FCR-D value***	***FCR-N value***	***FCR-D value***
TOTAL	42.56	7.09	126.81	22.81

If it is assumed that the initial costs (the control device and its installation) of the concept are €200, the concept would have had a payback time of two years.

4.4 Discussion and conclusions

As direct electric heating is a common method to heat homes in cold climate countries like Finland, it also provides a potential source of capacity to be used in energy markets. Electric heating DR has a long tradition in Finland as the night tariff system has been shifting heating loads between day- and nighttime. Similarly, the manufacturers of thermostats and heating devices have included an option to reduce the heating loads, for example, when people are not at home. This home-away functionality can now be employed for more delicate DR purposes like the primary frequency regulation markets.

It remained unclear how many home-away-enabled sites there are in Finland, but the same concept can be implemented with the existing night tariff control setup if the heating loads were also switched to obey the DR control signal connected to the night tariff control relay. The same applies to new cloud-connected thermostats and heating devices. By providing API connections to the manufacturers' cloud solutions, these "smart" thermostats could also be included in the DR control. Nevertheless, the research suggests that there is a clear business potential with the proposed concept using the home-away functionality. The empirical test results also suggested that DR capacity can be provided within the tight latency requirements without jeopardizing the comfortable indoor temperature levels, thus answering the following research question:

- Is it possible to establish any techno-economically proven concepts to control the major electric loads of Finnish households within primary frequency regulation?

However, as the proof of concept tests consisted of only two buildings, the real FCR provision could not be demonstrated in practice in this research. Hence, there is a need to conduct more empirical research with a reasonable number of pilot sites to statistically verify the FCR capabilities in practice.

4.5 Impact assessment

As noted in the first section, electric heating accounts for 7% of the total energy consumption in Finland. The installed domestic heating capacity reaches over 5000 MW, which is roughly a third of the total peak consumption of Finland (15 000 MW) (Järventausta et al. , 2015). This is a significant amount of flexible capacity, which could also be used in the primary frequency regulation markets. In the current literature, it is estimated that 3200 MW of the heating capacity is controllable through the existing night tariff system (Järventausta et al., 2015). Even if 10% of this capacity was harnessed to the FCR, it would cover the whole market need at the moment.

5 Heat pump loads (Publication II)

The other major contributor to space heating in Finland is the heat pump heating. The objective in Publication II was to evaluate if heat pumps could be used as a primary frequency regulation capacity. In this study, we considered only heat pumps that heat water on the secondary side, meaning that air-to-air heat pumps were excluded. The reason for excluding air-to-air heat pumps was that they are not well documented in the building statistics and are almost always controlled with a local infrared controller, which limits the possibilities to be controlled by externals.

Contrary to the resistive heating methods, heat pumps produce heat with a more complicated process, where a dedicated electronic controller is used to run the refrigeration process with multiple phases. The existence of a multiphase process makes also the consumption of a heat pump to vary depending on the phase of the process. The varying consumption means that the DR capacity is not always available, making also the DR operations more complex. Further, in some of the refrigeration phases, the process cannot be interrupted regularly without excess wear and tear to the heat pump components. Usually, the precoded internal protection mechanisms in heat pumps prevent the user from carrying out these possibly harmful actions.

The focus of the study was to evaluate if the heat pumps can be used for primary frequency regulation, despite the aforementioned limitations. The main issue to be observed is whether the heat pumps can react fast enough in a DR activation to meet the tight requirements of primary frequency regulation. In practice, the evaluated target markets were the FCR-N and the FCR-D as the FFR market requires reaction times faster than 1.3 s, which is naturally too short a time for a centrally controlled capacity. The other evaluated aspect was the economic potential of the concept in Finland.

5.1 Concept, research method, and assumptions

To find an economically scalable way to control the heat pumps, it was assumed that the best way to control a heat pump is to use cloud solutions employing API interfaces. Some heat pumps also have physical connectors dedicated to DR activities, but as they require an installation of control devices to signal the activation needs, they were not considered a viable option.

To evaluate the latency aspect, a small set of tests were conducted. The original idea was to control the heat pumps with a cloud-to-cloud setup, but due to the lack of resources, the tests were done manually through the heat pump manufacturer's (Nibe) cloud interface. Nibe was chosen as the system provider because it has one of the largest installed customer bases in Finland. As it was expected that heat pumps are slower to respond to any power-reducing control signal, alternative ways to achieve the power reduction were tested. The tests were conducted on the offset of the heating curve and in the hot tap water production mode. In Nibe's heat pump there are three different modes for hot tap water production: “eco,” “normal,” and “luxury.” In the “eco” mode, the hot tap water production has lower temperature thresholds for recharging the hot tap water tank, and the “luxury” mode has corresponding lower tolerances for too cold water. After finding the best way to affect the power consumption of the heat pump, several tests were conducted to be able to evaluate the response time.

5.2 Results

It was found that the fastest way to control the power consumption is to adjust the hot tap water production mode. Adjusting the mode to “luxury” produced the fastest response. The reason for this lies in the way in which the heat pumps operate. Heat pumps calculate the heating need or deficit to decide when to start heating the heating media, in other words, when to start the compressor. When controlling the heating curve, this “deficit” starts to grow, but as there are significant time constants in the heating water circulation and the building itself, the change in the heating need is fairly modest (red area in Figure 22). This means that it may take a long time for the heat pump’s internal logic to ask for more heat, especially if the heat pump has recently charged itself with heat. The heat pump manufacturer Nibe calls this heating deficit parameter “degree minutes” in their control logic.

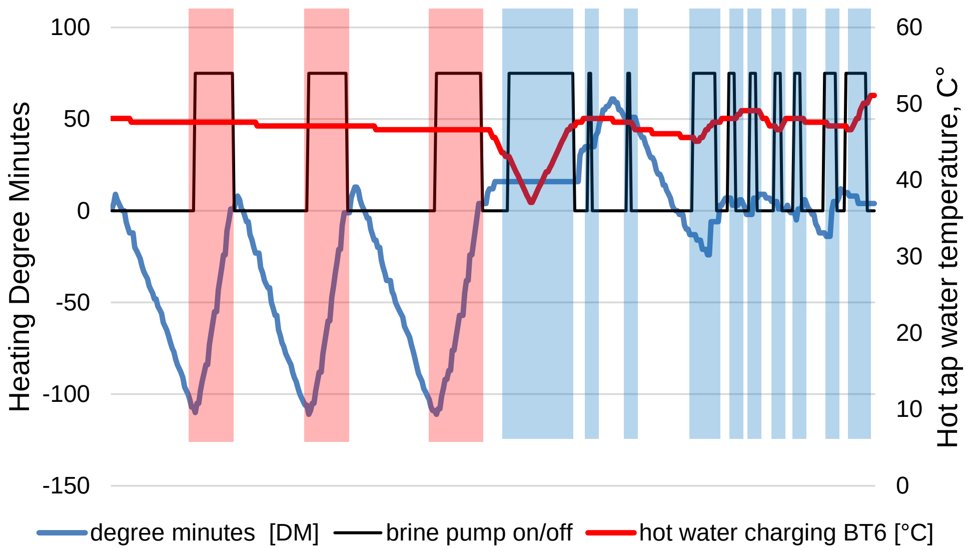

Figure 22 Heat pump functioning in the space heating mode (red area) and in the hot tap water production mode (blue area) (Publication 2) © 2020 IEEE

By contrast, the time constants for hot tap water (blue area) are much smaller. Using hot tap water, for example, taking a shower, requires a huge amount of power in a relatively short period of time. To meet the heat need, the heat pump must react as fast as possible.

That is most probably the reason for the fact that controlling the hot tap water production resulted in a faster response.

After finding the best parameter to control for the quickest response in power consumption, several tests were conducted to investigate if the speed was enough to meet the requirements of the FCR markets operated by Fingrid. It soon became obvious that the reaction time of the heat pump is not short enough to meet the FCR-D requirements as 50% of the capacity should be provided within 5 s. The results also showed that the heat pump cannot always meet the requirements of FCR-N either. For some reason, the heat pump reacted faster to “on” commands compared with “off” commands, as illustrated in Figure 23.

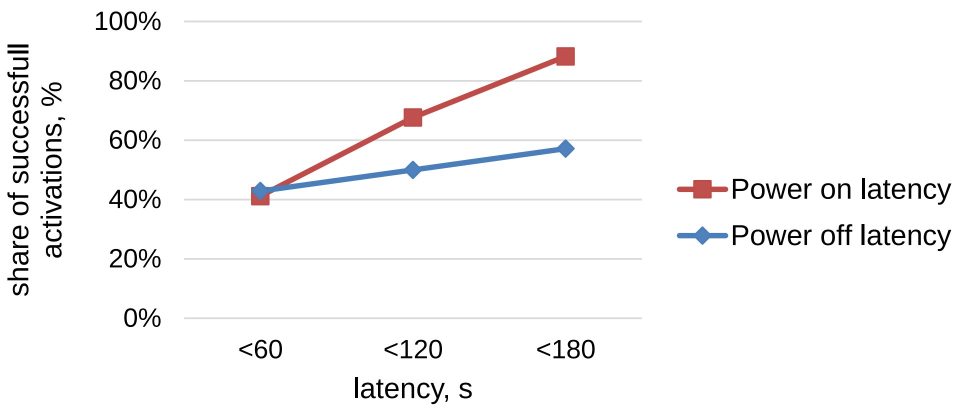

Figure 23 Number of successful commands over time (Publication 2) © 2020 IEEE

The results indicate that the heat pumps do not perform well in the FCR-N markets either without the help of other assets that could provide supporting capacity. Another option to use heat pumps as FCR-N capacity would be to investigate the statistical behavior of heat pumps and apply commands accordingly to comply with the FCR-N requirements. However, the monetary benefit from the FCR would be significant if the heat pump capacity could be used in these markets. The simplified economic simulation shows (Table 4) that the economic potential of heat pumps in the FCR markets is indeed considerable if the identified latency issues could be solved.

Table 4 Market income in FCR-N (in k€/a) with different availabilities and numbers of DR-controlled heat pumps (Publication 2) © 2020 IEEE

<table>
<tr><th colspan="2" rowspan="2"></th><th colspan="4">Proportion of qualifying sites (sensitivity analysis), %</th></tr>
<tr><th>25%</th><th>50%</th><th>75%</th><th>100%</th></tr>
<tr><td rowspan="5">DR-controlled heat pumps, pcs</td><td>5 k</td><td>60</td><td>120</td><td>181</td><td>241</td></tr>
<tr><td>25 k</td><td>301</td><td>602</td><td>903</td><td>1204</td></tr>
<tr><td>50 k</td><td>602</td><td>1204</td><td>1806</td><td>2408</td></tr>
<tr><td>75 k</td><td>903</td><td>1806</td><td>2709</td><td>3612</td></tr>
<tr><td>100 k</td><td>1204</td><td>2408</td><td>3612</td><td>4816</td></tr>
</table>

5.3 Discussion and conclusions

As the electrification of heating is accelerating, so is the number of internet-connected heat pumps. The connectivity enables remote controllability, and further, DR activities by an aggregator. The research suggested that heat pumps are not as fast as direct electric heating loads (resistive loads) to respond to aggregators' commands and are thus not suitable for the FCR markets as such. However, they could be used in these markets if blended with faster-reacting loads. They also react fast enough for energy-based secondary or tertiary reserve markets where the reaction time requirement is 5 min or more. Hence, the research provided information for the following research questions:

- What are the technical, regulatory, and economical limitations of the electric loads of Finnish households on the participation in the primary frequency regulation markets?
- Is it possible to establish any techno-economically proven concepts to control the major electric loads of Finnish households within primary frequency regulation?

However, it should be noted that the research was limited to only one type of heat pump from a single manufacturer. The manufacturer has developed their cloud solution after the empirical tests were conducted. Hence, additional research is needed to validate the results with the new system. Furthermore, additional tests with other manufacturers' solutions would improve the reliability of the results and provide a more holistic view on the topic. The FCR market requirements are changing in the Nordic countries, which will also affect the applicability of the results. It seems that heat pump systems have not been designed to be operated in the primary frequency regulation markets even if they would have theoretical capabilities to do so. It would be highly beneficial to design new heat pump systems with their potential utilization in fast-reacting energy markets also taken into account to enable this valuable contribution to our energy systems.

5.4 Impact assessment

As the number of heat pumps is increasing rapidly, so is their potential as a source of primary frequency regulation capacity. There are already over 100 000 x-to-water heat pumps in Finland that are considered suitable for DR. However, as the tested heat pumps had challenges in providing primary frequency regulation capacity, their potential could be better utilized in the slower-reacting reserve markets like the secondary and tertiary markets or hourly spot markets. In any case, heat pumps could play a significant role in the balancing of the system, especially when they are connected to a cloud service, and hence, could be harnessed through digital arrangements without the need for retrofit installations.

6 Domestic electric water heater loads (Publication III)

In addition to electricity-based space heating (direct electric space heating and heat pumps), hot tap water production is also a major contributor to the total electricity consumption. Contrary to the heat pump water heating, hot tap water is usually produced with separate electric water heaters in homes with direct electric heating. In Finland, the basic operating principle of these water heaters is to heat the water tank at night (with a cheaper night tariff) so that there is enough heat for a whole day. Compared with heat pump water heating, this buffering of hot water provides far more flexibility, as there is a large storage of hot tap water. This flexibility could also be used for primary frequency regulation.

In around 10% of the electrically heated homes, the heat of both the space heating and the hot tap water heating is stored in a common large water-based accumulators to enable the heat to be generated at night when the price of electricity is lower (for customers that have a night tariff pricing). The size of the accumulator (water tank) in the latter case can be several cubic meters, whereas the volume of normal buffer tanks for hot tap water only is usually 100–300 L. In countries without a night tariff system, the buffer tank is usually smaller as there is no need to store heat for a whole day.

As the hot tap water production consumes around 4 MWh per annum per household, it provides a significant economic opportunity to be used in the primary frequency regulation markets as a source of aggregated demand response capacity. Again, as the per asset revenue potential can be considered low, simple and economically efficient solutions must be developed to provide a reasonable business opportunity. Hence, the focus of the research in Publication III was to find a techno-economically viable concept for the existing water heaters to be harnessed to the use of primary frequency regulation markets.

6.1 Concept, methods, and assumptions

To meet the challenging economic limitations, simple and scalable solutions should be developed. It soon became apparent that solutions incorporating extensive retrofit installations to the electric water heaters was out of question. The costs of a multihour installation quickly ruin the feasibility of the concept. Hence, the focus shifted to the existing infrastructure that electrically heated sites usually have in Finland. Luckily, in Finland, the homes that are heated with direct electric heating have usually implemented the night tariff control infrastructure. A common wiring scheme for the night tariff control was proposed by the Association of Finnish Electric Utilities (Sähkölaitosyhdistys, SLY), and it has been widely adopted for the night tariff control in Finland. In the SLY setup, domestic heating loads, including electric water heaters, are supplied through contactors that are, again, controlled by the night tariff relay, which is controlled by the night tariff signal provided by the local DSO.

The use of this setup to control electric water heaters was tested in a proof of concept pilot where a simple cloud-connected device was installed in series with the original night tariff control wire according to Figure 24.

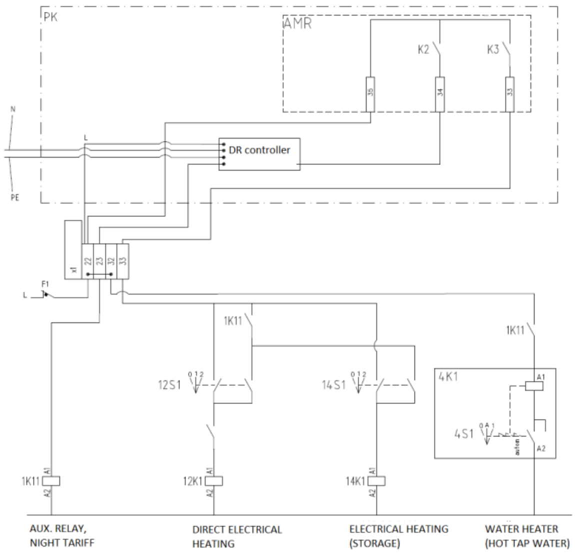

Figure 24 Schematic of the mDR controller in the night tariff control system (Publication 3) © 2022 IEEE

In order to investigate the effect of the DR control, power measurements must be recorded. The measurements are needed for the aggregation algorithms to know the status of a controlled site and for possible verification purposes by the market operator, the local TSO. The measurements are acquired by either installing current clamps to the main phases of the site or with a specially designed LED reader attached on a consumption-indicating blinking LED in the smart meter on the site. In Finland, the smart meters are obligated to have a consumption indicator, which is, in practice, a blinking LED light in the meter visually indicating the consumption level for the consumers.

One of the greatest concerns and a focus of this study is the activation time requirements of the primary frequency markets. In the FFR market, the required activation time is 1.3 s at the maximum, which is a relatively short time for a centrally controlled concept. However, the FCR markets, where the minimum activation time is 5 s (50% of the capacity in the FCR-D) is assumed to be the target market in this study.

The economic feasibility of the concept was simulated with the average nightly (22:00–07:00 hours) FCR price information from the past few years. As not all the units might not be available for DR operations, three different scenarios were included to reveal the effect of availability on the economic potential.

6.2 Results

The real-life experiences from the concept show that the existing night tariff control setup can, indeed, be used to make electric water heaters to contribute as units in a centrally controlled aggregate. One of the greatest concerns was the response time from the cloud command to the effect on the consumption on a remote site. The empirical findings also show that the concept complies with the tight latency requirements of the FCR markets as most of the activations happen in 5 s. Further, as it usually takes hours to heat the water in the tank, the activation duration is not an issue considering the FCR markets.

To calculate the economic feasibility, the average nightly FCR prices were calculated first. As it can be seen from Table 5, the prices vary significantly and the best target market for the EWH capacity can change over time.

Table 5 Average nightly FCR and FFR market income in different years (Publication 3) © 2022 IEEE

	Average reserve market prices, €/MW,h		
Year	***FCR-D up***	***FCR-N***	***FFR***
2017	3.15	17.02	
2018	4.64	21.70	
2019	4.69	20.28	
2020	6.22	22.04	19.50
2021	5.68	13.51	13.70
Average, 2017–2021	4.88	18.91	16.60

In order to evaluate the profitability of the concept, also the cost side had to be taken into account. As with the installation cost, the hardware costs should also be minimized. Based on the features required for the concept, the material costs were estimated for the hardware. Owing to the modest requirements, it was concluded that the hardware costs could be pushed to as low as 50 €/pcs if produced in larger quantities. On top of the initial costs (hardware and installation), running the service also entails some costs. Among such costs are the data communication costs related to the device–cloud connection. There may also be some other unexpected costs occurring during the service life. Hence, an extra cost component “other” was also included in the calculation. The costs are presented in Table 6.

Table 6 Cost components related to the concept (Publication 3) © 2022 IEEE

Cost source	Cost type	Initial cost, €	Recurring cost, €/month
Hardware	one-time	50	
Installation	one-time	100	
Telecommunication	operational (monthly)		1.5
Other	operational (monthly)		1

Finally, the economic potential of the concept in the FCR-N was calculated over a lifetime of 10 years using the net present value formula (1). The variable C_t denotes the net cash flow during the lifetime T (10 years), and C_0 is the initial investment. 5% was used as the interest rate r in the calculation.

$$NPV = \sum_{t=1}^{T} \frac{C_t}{(1+r)^t} - C_0 \qquad (1)$$

The economic potential was calculated for all scenarios in which the sensitivity of the availability rate was evaluated. The simulation shows that the availability rate has, indeed, a significant impact on the economic feasibility of the case as the concept is not profitable within 10 years if only a half of the units are providing capacity as seen in Figure 25.

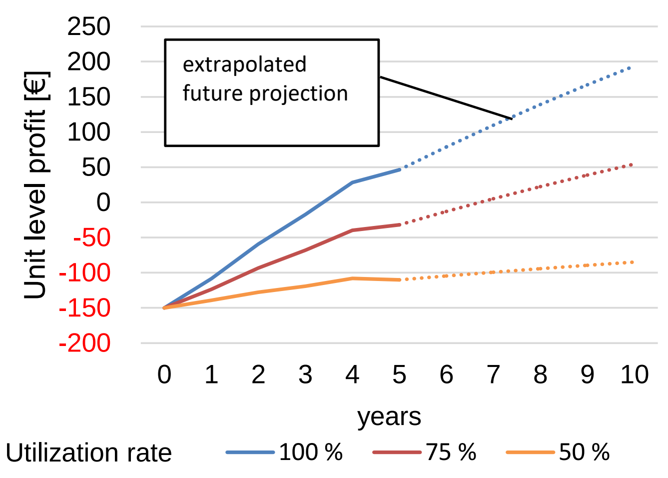

Figure 25 Projected income for the EWH concept in ten years (Publication 3) © 2022 IEEE

6.3 Discussion and conclusions

Electric water heaters (EWHs) are relatively small loads, but they hold a valuable property, namely the capability of storing energy. In this case, the energy is stored as heat, but as EWHs are heated by electricity, this capacity can be used for DR purposes. As EWHs have resistive heating elements, they do not have any latency incorporated when adjusting the power. In fact, there is only a mechanical relay and thermostats controlling the heating element. This makes them a perfect candidate for utilization in primary frequency regulation. This research presented a concept to control EWHs. The concept takes advantage of the existing night tariff control setup to control EWHs and demonstrates its economic potential. The results suggest that there is an economically viable way to harness existing water heating with a retrofit solution and answer the following research question:

- Is it possible to establish any techno-economically proven concepts to control the major electric loads of Finnish households within primary frequency regulation?

As new EWHs are increasingly equipped with online services, the implementation becomes even easier through cloud-to-cloud solutions between an aggregator and the manufacturer.

6.4 Impact assessment

As part of the direct electric heating setup, EWHs are being used for hot tap water production in almost all cases. As there are roughly 500 000 electrically heated homes in Finland that have EWHs usually equipped with 2–3 kW resistive heating elements, there is theoretically over 1 GW of EWH capacity that could potentially be used for DR purposes. Of course, not all the sites have a night tariff control in use, but even if only a third of this capacity could be used for DR, it would cover a significant proportion of the FCR markets at least at nighttime when they are operated.

7 Electric vehicle charging loads (Publication IV)

In addition to electricity-based heating, there will be a new kind of domestic asset that is considered a major contributor to the primary frequency regulation market, namely EV charging. EVs are widely acknowledged as a potential source of flexibility. The number of EVs is increasing rapidly, and EVs will account for a significant proportion of the total domestic energy consumption. Charging of EVs can be controlled by digital solutions, which provides considerable opportunities for DR. Usually, the capacity harnessed from EVs is employed in implicit DR, for instance, based on day-ahead prices. There are already many services and applications providing charging optimization for EV users. However, price optimization is not the only use case for the EV DR; for example, the charging capacity can be used for purposes of primary frequency regulation. EV charging DR for primary frequency regulation as such is already a widely acknowledged opportunity in the research community. However, it is not yet verified if the charging capacity could be used for extremely fast-reacting new markets like the FFR, where the activation should happen in less than 2 s.

This chapter focuses on the research conducted to verify the technical compliance of EV charging in the FFR markets and on its business impact in Finland. The research in Publication IV was conducted with a type 2 AC charger with modified firmware. The firmware was modified by the manufacturer by our request to trip the charging power in case the supply frequency dropped below 49.7 Hz. The main focus was to evaluate the activation time and correct the behavior of the charger as an FFR capacity-providing asset. The proof of concept was carried out using real EVs, but the concept can be further expanded to other cases where batteries are being used in such a way that short interruptions are not critical to the process they serve.

7.1 Concept, methods, and assumptions

EV charging capacity could be harnessed and used in the primary frequency regulation markets if it meets the prequalification specifications. The most difficult challenge related to the prequalification process is the activation time requirement. Hence, the research focused on the verification of the activation time of the charger under test. As noted in Chapter 3, the previous research has focused on slower-responding primary frequency regulation markets or some other purposes.

To participate in the FFR market, the capacity-providing asset must meet the tight prequalification requirements. The Nordic TSOs use similar Entso-E based requirements for the FFR, presented in Chapter 2. The key requirement is the extremely fast reaction to possible severe underfrequency situations. As severe underfrequency events are of rare occurrence, a test setup with a laboratory microgrid had to be built. The microgrid consisted of a drive-controlled motor rotating a synchronous generator that fed electricity to the EV charger (Figure 26). To increase the frequency stability of the microgrid, additional idling motors were added to the system. The rotating mass of these motors increased the inertia in the test system. An isolation transformer was also used in the test setup before the actual EV charger to create a TN network.

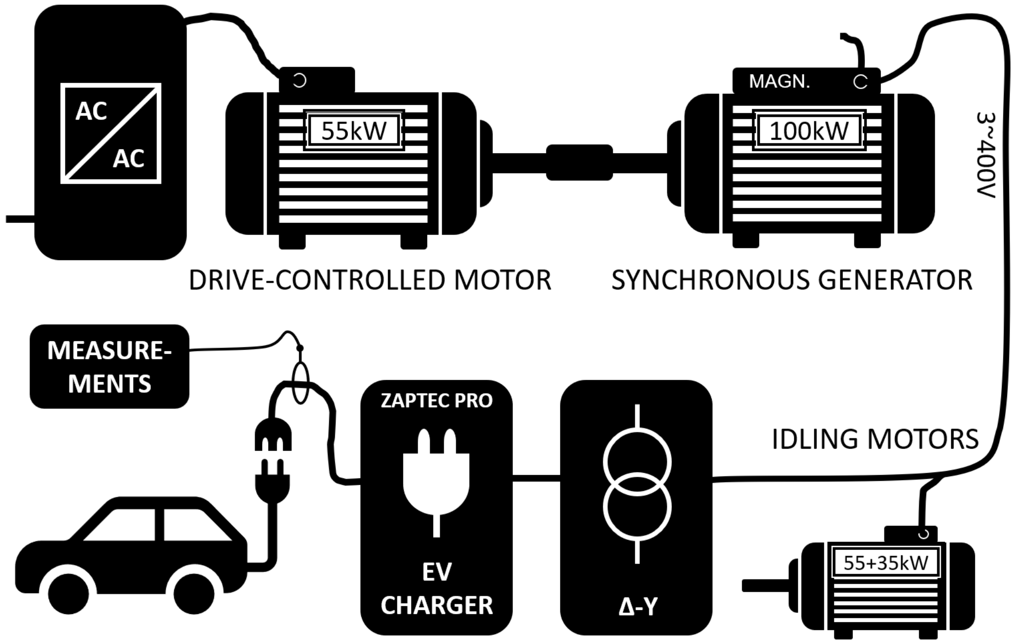

Figure 26 Laboratory microgrid setup for the FFR tests (Publication 4) © 2023 Wiley

The idea of the setup was to provide the ability to change the frequency of the electricity supplied to the EV charger. This is because the rotational speed of the synchronous generator determines the output frequency. By changing the speed of the drive-controlled motor, the system frequency also changes. The tests were conducted by charging an EV in the microgrid with the FFR-enabled charger and by altering the microgrid frequency according to the official test specification (option 2, frequency ramp test) for the FFR (Statnett, 2022) illustrated in Figure 27. The second option would have been to conduct the FFR tests with a stepwise frequency change, which would have been impossible with the microgrid setup.

The test procedure was as follows: First, the frequency was kept at nominal, 50 Hz, for 2 min. Then the frequency was gradually lowered below 49.7 Hz (the activation threshold) and kept there for another 2 min, and finally increased back to the nominal level. The main objective was to find out if the charger tripped at the required reaction time (1.3 s). The test procedure is shown in Figure 27.

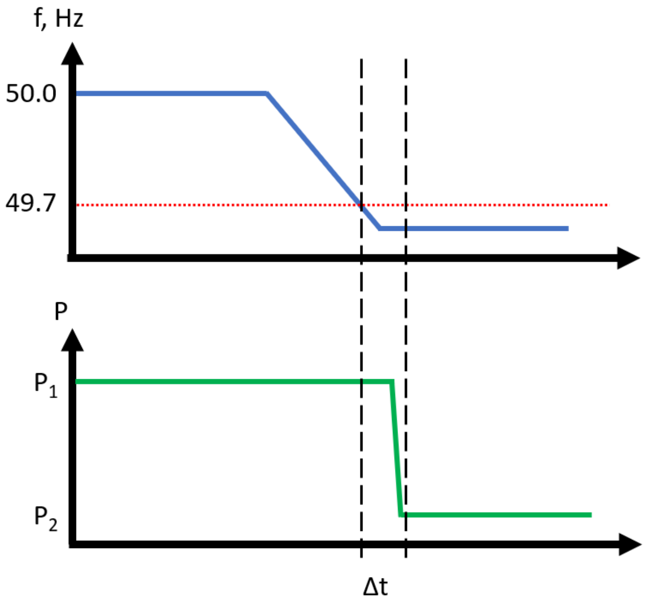

Figure 27 Test frequency ramp and power measurements (Publication 4) © 2023 Wiley

Three different car models from different brands were used in the tests to evaluate if there are differences in the behavior in the underfrequency event. The tested EVs included Tesla Model 3, Mazda MX-30, and Peugeot e-2008.

7.1.1 **Results**

The proof of concept laboratory tests showed that an EV charger can, indeed, be used to provide FFR capacity. The tested charger met the most critical requirement of providing the capacity within the required activation time of 1.3 s after the system frequency dropped below the chosen activation threshold of 49.7 Hz (Figure 28). The test data also show that the activation lasted at least 60 s, which is more than the required activation duration in the FFR prequalification requirements (Figure 29). The figure shows that the charger tries to restart charging around 60 s from the activation. This is presumably a pre-coded feature of the charger to retry fast after a failure. A generator rush phenomenon is also visible in Figure 28. The spike occurred because of the limited amount of inertia in the laboratory microgrid.

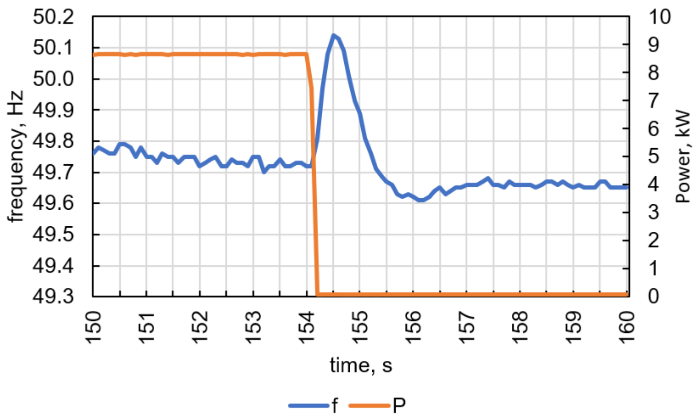

Figure 28 Behavior of power during an activation (Publication 4) © 2023 Wiley

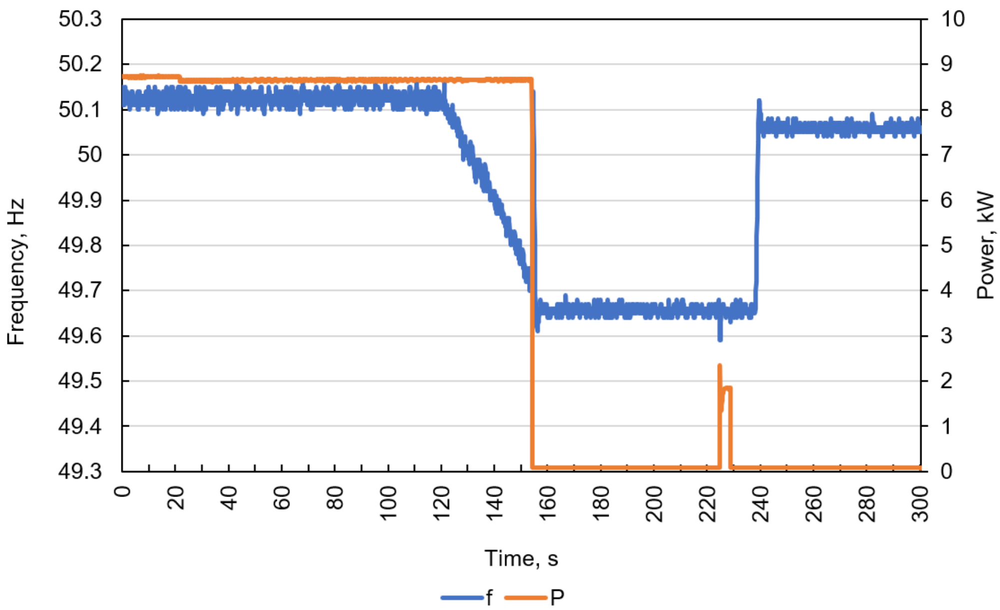

Figure 29 Frequency and power during the tests with Peugeot e-2008 (Publication 4) © 2023 Wiley

The other car makes and models also met the tight activation time. However, the Tesla model 3 had an internal droop control mechanism that was activated when the frequency was reduced with a moderate speed (Figure 30). When the frequency was reduced faster or slower, the droop control was not activated.

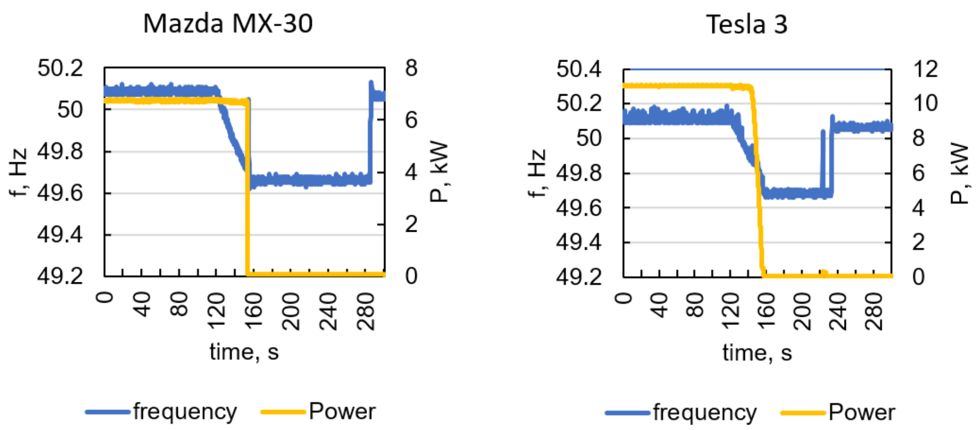

Figure 30 Frequency and power during the tests with Peugeot Mazda MX-30 and Tesla 3 (Publication 4) © 2023 Wiley

7.2 Economic simulation

The second important objective was to evaluate the available capacity and business potential of the concept. The potential of the concept is, of course, dependent on the total energy and power of EVs connected to a charger capable of providing the FFR. Further, the amount of power and energy can be estimated from the number of EVs and the average annual consumption and charging power of an EV. The numbers of EVs and PHEVs were acquired from the national vehicle statistics, maintained by the Finnish Transport and Communications Agency, Traficom (Traficom, 2022).

It is obvious that not all the EV users will participate in this kind of DR activity for various reasons. For example, not all the EVs are plugged in all the time, and many users do not want to take part in these kinds of DR programs. Hence, a parameter called "availability rate" was used in the simulation. Further, three different availability rates were included in the simulation to evaluate the sensitivity of the parameter. The numbers of controllable EVs and PHEVs with different availability rates are presented in different scenarios in Table 7. It is also assumed that the EVs and the PHEVs are always charged at nighttime (22:00–07:00 hours). The simulation was conducted by using the FFR market data from the years 2020–2021, published in (Fingrid, 2023d).

Table 7 Selected scenarios and the number of controllable EVs and PHEVs © 2023 Wiley

Scenarios	Availability	Controllable EVs	Controllable PHEVs
Scenario 1, optimistic	15 %	4134	12641
Scenario 2, moderate	10 %	2756	8427
Scenario 3, pessimistic	5 %	1378	4214

Charging capacity

One of the limiting factors in the economic simulation is the available charging capacity. In this research, an average charging power of 6 kW for EVs and 3.6 kW for PHEVs (plugin-hybrid EVs) was used. This is because PHEVs often have only a single-phase internal charger, which limits the charging power to 3.6 kW (with 16 A rating). The "full" EVs have, on the other hand, a 3-phase internal charger in most cases. A typical home charger is rated for 11 kW charging, but in many cases, this capacity cannot be used to its full potential because of old cabling infrastructure or limitations in the main fuses, and therefore, the power output of the charger is manually limited in the installation configuration. The total DR capacity of EV charging can be calculated by multiplying the assumed average charging power of EVs and PHEVs by the corresponding number of available vehicles in different scenarios.

Charging energy

As the FFR market is an up-regulating market, the consumption-side assets providing capacity for the market must reduce the power intake when activation is needed. This means that the FFR-providing EV chargers must be charging all the time when their capacity is offered to the market. Hence, it is necessary to evaluate the average charging energy need in the participating EVs and PHEVs. In more practical terms, the vehicles connected to the FFR-enabled chargers should not be fully charged if they should provide FFR capacity.

To evaluate whether the charging energy is sufficient for the market needs, the amount of energy must be compared with the market need. The amount of charging energy is calculated by dividing the annual energy consumption of EVs and PHEVs into daily consumption. In the simulation, the average consumption of a PHEV is assumed to be half of the "full" EV consumption. To further calculate the total amount of energy, the daily consumptions are then multiplied by the number of EVs and PHEVs in different availability scenarios. These daily consumptions are then compared with the amount of daily FFR purchases (during hours from 22:00 to 07:00).

Economic potential

The economic potential of the concept can be evaluated by multiplying the aggregated available hourly DR capacity by the hourly FFR price data time series, also published by Fingrid (Fingrid, 2023), taking into account the aforementioned limitations in charging energy and power. The total value of the concept (*DRvalue*) is calculated using Equation (2), where P_{bid} is the sold FFR capacity and *FFRprice* is the FFR price for each hour. The purchased FFR capacity is limited by either the maximum available capacity P_{dr} or the maximum bought FFR capacity P_{ffr} by Fingrid.

$$DRvalue = \sum_{t=1}^{T} FFRprice_t * P_{bid}(t)_t \tag{2}$$

$$P_{bid}(t) = \begin{cases} P_{dr}, & P_{dr} \le P_{frr} \\ P_{frr}, & P_{dr} > P_{frr} \end{cases} \tag{2.1}$$

7.2.1 Results of the economic simulation

The objective of the economic simulation was to evaluate the business potential and the potential limitations of the concept. The identified possible limitations were the amounts of charging capacity and energy. The simulation showed that the amount of charging energy does not limit the utilization of EV charging for the FFR market. The amount of daily EV charging energy exceeded the amount of energy that is needed to be able to provide the FFR capacity that was bought during the simulation period (2020–2021, 22:00–07:00 hours). However, the charging power was found to be more limiting. The market needs could not be met with the EV capacity if the availability rate was below 15% (scenarios 2 and 3) leaving room for other assets to contribute to the FFR. Figure 31 shows how the availability limits the utilization when the FFR need is extremely high. It should, however, be noted that even with the most pessimistic scenario (3), 80% of the market value could have been captured (Table 8).

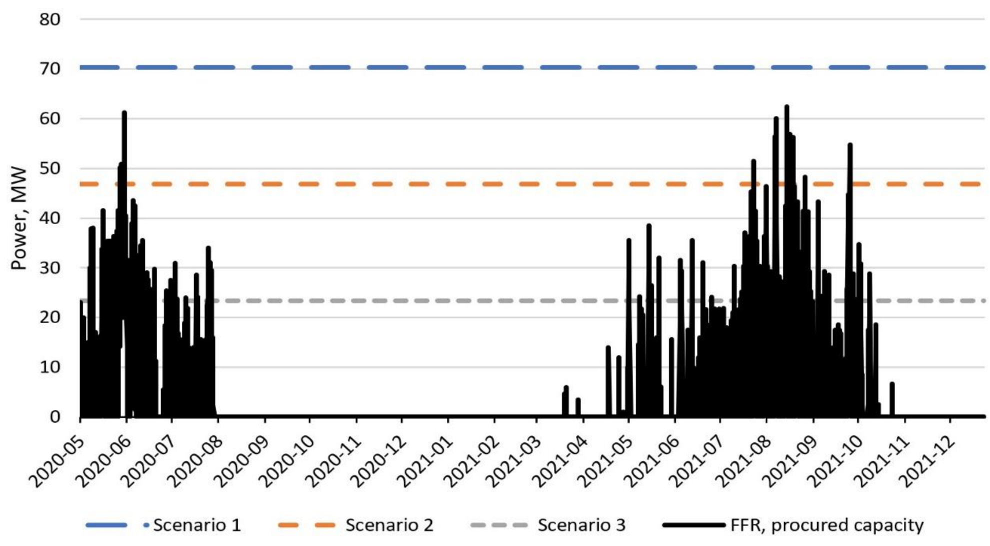

Figure 31 Amount of procured FFR capacity and available EV charging DR capacity (Publication 4) © 2023 Wiley

Table 8 Value of the DR concept with different scenarios (Publication 4) © 2023 Wiley

	Scenario 1 Optimistic, €/a	**Scenario 2 Moderate, €/a**	**Scenario 3 Pessimistic, €/a**	**Procured FFR volume, MW, h**	**Average FFR price, €/MW,h**
Controllable EVs/PHEVs, pcs	4134/12641	2756/8427	1378/ 4214		
2020	781 192	778 827	676 530	9 549	29
2021	807 703	793 095	630 639	16 844	23
AVERAGE	794 447	785 961	653 585	13 196	

Table 8 also reveals the volatile nature of the market. The average hourly price of the FFR has decreased, but the procured volume has increased at the same time. This keeps the monetary potential of the concept at the same level in the optimistic scenario (Scenario 1). However, in the pessimistic Scenario 3, a slightly greater reduction in the monetary potential can be seen. Still, the concept provides significant business value as there is no hardware investment needed to untap this capacity—only software changes are needed to the charger.

7.3 Discussion and conclusions

This section discusses the results of the research related to the utilization of EV charging in demand response for the FFR market. The following research questions were answered:

- Can aggregated domestic EV charging provide FFR capacity?

The results of the research showed that domestic EV chargers can, indeed, provide FFR capacity for TSOs if aggregated in sufficient quantities. It was demonstrated that the EV chargers can interrupt the charging process within the required activation time (1.3 s), and the activation was sustained over the required duration of 30 s.

The economic simulation showed that the business potential is substantial, even though there are limitations on the charging capacity in the most pessimistic scenarios related to the availability of participating chargers or EVs.

7.4 Impact assessment

As the climate change is pushing also car manufacturers to produce more environmentally friendly models, the number of EVs is growing with a rapid pace. This provides an opportunity also for energy market stakeholders to use EVs as a source of frequency regulation capacity. At the same time, the need for regulating capacity is increasing rapidly as the power electronic applications isolate the inertia from the system. This research demonstrated that EV chargers can contribute significantly to the solution of the problem. In fact, the whole FFR market can be covered with EV charging capacity only, at least at night when EVs are mostly being charged. In addition to the FFR market, the capacity from EV charging can be used in other primary frequency regulation markets. If the chargers can meet the tight prequalification requirements of the FFR, they will also meet the requirements of other markets.

8 Discussion

The main objective of the research covered in this doctoral dissertation was to evaluate new DR concepts that are implementable in real life for primary frequency regulation markets. Despite the ample research, the literature lacks information on concepts that have been demonstrated in real life and focus on primary frequency regulation. These studies are mostly concentrated on complex theoretical models considering various data sources like in (Dong et al., 2023), (Marnell et al., 2020) and (Haakana et al., 2023), or forecasting the availability of these assets (Paull et al., 2010). Many of the studies also focus on implicit demand response, like energy arbitrage in (Su et al., 2020) or other use cases like network congestion management (Vivian et al., 2020), which is usually not a problem in Finland where the networks are usually well dimensioned.

In this research, the evaluated technical and economic potential of the most electricity-consuming domestic appliances in the Finnish context. The idea was to evaluate if the potential concepts can meet the prequalification requirements of primary frequency regulation in real life. Hence, the technical proof of concept demonstrations were chosen to ensure the correct functioning of the concepts. In practice, the focus was on the activation time of the markets as it was considered the most demanding requirement.

The results show that the evaluated concept developed for direct electric heating and electric water heaters can indeed meet the latency requirements of the FCR markets. By connecting the direct electric heating devices to the aggregator's cloud solution, a significant amount of capacity can be provided to the primary frequency regulation reserves, as presented in Figure 15. Of course, not all of this capacity can be harnessed in practice for various reasons.

Although the results of the empirical technical tests suggest that electric space and water heating can be harnessed to primary frequency reserve capacity with an economically viable way, aggregation capabilities and market access are also needed. These are typically services that an aggregator provides. From an aggregator's point of view, the low latencies and predictability of the behavior of the assets are highly important. The retrofit solutions evaluated for the resistive loads in this study provided adequately low latencies, especially for the FCR-N markets, but the control of heat pumps was more challenging because of the internal refrigeration cycles incorporated. Hence, it is reasonable to consider if these assets would suit better for secondary or tertiary frequency regulation markets (aFRR and mFFR), where longer activations times are accepted. The techno-economic results of the suitability of the assets are presented in Table 9. A more detailed analysis of the techno-economic feasibility is provided in Appendix A.

Table 9 Suitability of the residential asset DR for the FCR and FFR markets per type

	FFR	FCR-D up	FCR-N
Direct electric space heating	Not studied	Economically challenging	Suitable
Heat pump space & water heating	Technically not suitable	Technically not suitable	Technically and economically challenging
Electric water heating	Not studied	Economically challenging	Suitable
Electric vehicles	Suitable	Suitable	Challenging from users' perspective

As there was already existing literature related to the DR of EV charging against FCR-types of markets, for example (Mu, 2013), the research conducted here focused on the fast-reacting FFR markets, which is a relatively unresearched area when considering studies that include practical demonstrations. The results show that EV chargers could meet the activation time requirement of the FFR market, and the concept was later also officially approved to provide FFR capacity for the Norwegian TSO as a type-prequalified asset. This is a significant result as the whole FFR market need in Finland could be covered at nighttime if only 15% of the EVs and the PHEVs participated in this DR (Figure 30).

Another objective was to evaluate the business potential of the tested concepts. The results show that all the developed concepts have a considerable business potential as the concepts were proven to be economically cost-effective, the market income being reasonable at the same time. Figure 32 shows the annual per unit income of the studied concepts in the Finnish primary frequency markets together with the total number of existing assets (like the number of electrically heated houses Finland) with the assumption that 75% of the loads would be available for DR.

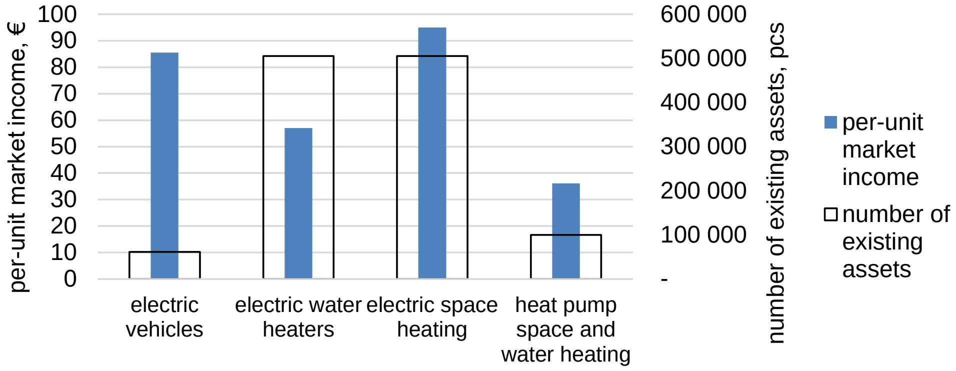

Figure 32 Annual per unit market income from the assets (left axis) and the total number of existing assets in Finland (right axis)

The figure shows that the potential is greatest in the electric space and water heater cases as the number of existing sites is high and the income is still reasonable compared with the heat pump case. However, the need for a retrofit solution in these cases makes them trickier for a company to harness compared with cloud-integrated concepts with EVs and heat pumps. As noted previously, the heat pumps were not considered to meet the FCR requirement, and they are presented in the figure for illustrative purposes only.

It should also be noted that the owner of the concept (company) must have enough motivation to operate a service that incorporates retrofit installations. They require more practical arrangements and effort compared with fully digital services (that do not need any installations). But on the other hand, retrofit products might increase customers' commitment to stay with the service provider and to possibly buy additional services (including electricity) from the same supplier.

As the inertia in the system is decreasing, more regulating capacity is needed for the frequency stability. From TSOs' perspective, the results show that residential assets can contribute significantly to the primary frequency regulation markets, reducing the procurement costs as the supply increases. Another beneficial effect is that the current assets contributing to the markets can be reallocated for some other purpose if it is more profitable. Similarly, the assets considered here could likely be used for other purposes. One such service could be the temporary reduction in power if there is a national-level shortage of production in peak consumption hours. Thus, intentional blackouts or rolling power cuts could be avoided. As the residential electric consumption accounts for 7% of the total consumption, a huge amount of consumption could be shifted to hours with a lower demand of electricity.

9 Conclusions

The research conducted in this doctoral dissertation focused on the demand response (DR) opportunities of residential energy consuming assets. The focus was on the primary frequency regulation reserves in the Finnish context, but the results also provide valuable information for other power system areas with different market requirements, because the challenge of frequency stability is universal. In cold climate areas, like Finland, the heating loads play an essential role in energy consumption. Hence, they also introduce a significant potential source of flexible capacity if they can be controlled according to the market requirements.

The approach taken in this research was to find and evaluate technically and economically viable solutions that are feasible for practical implementation. Hence, the work focused especially on demonstrations in real life. The research covered the most electricity-consuming domestic assets existing in Finnish households: direct electric heating devices, heat pumps, and electric water heaters. Domestic electric vehicle (EV) charging was also addressed, as based on the recent growth statistics, EVs will most likely play a significant role in the domestic electricity usage in the future.

To conclude, this doctoral dissertation answered the following questions:

- **Main question**: Can the major electric loads in Finnish households contribute to the primary frequency regulation in a technically and economically feasible way?

The underlying problem with the existing solutions is related to the scalability and costs. The existing retrofit solutions are usually mainly made for generic smart home purposes, which means that their initial costs (hardware and installation) are too high for large-scale deployment. This does not mean that they are not necessarily economically viable in their niche-targeted customer segment. To develop a large-scale service for mainly automated DR purposes, extremely cost-effective solutions must be created. Based on the research conducted, there are technologically and economically sound ways to implement DR solutions that run in the background without the need for any customer interaction. These novel concepts are presented and evaluated in this dissertation, providing new information for society and the scientific community.

When considering resistive-heating-based domestic appliances, the results show that a light retrofit solution employing the existing infrastructure, like night tariff and home-away controls, enable easy implementation and thereby also low initial up-front costs. This, again, enables scalability and thereby viable business opportunities. The technical demonstrations in real environments verified that the usage of these already-existing local control interfaces together with the simple cloud-connected controllers provide a sufficiently fast remote control of the domestic loads to be qualified in the FCR markets.

In the case of heat pumps, using the manufacturers' cloud solutions bring the up-front costs to almost zero as only a couple of clicks are needed to pair the aggregator's DR service to a heat pump. However, the results suggest that because of the operating cycles of heat pumps there is still too much latency in command-to-action when controlling heat pumps. EVs, on the other hand, are already identified sources of primary frequency regulation capacity. Hence, the research conducted in this dissertation focused on the new extremely fast-reacting FFR capacity, where the capacity must be provided within 1.3 s at the maximum. By implementing changes to the chargers' firmware, this tight reaction time requirement can be achieved. Also here, the focus was to find a practical and easily implementable solution. Hence, the real-life demonstrations were carried out with a commercially available EV charger and EVs, which is not the case in the previous studies.

- What are the technical, regulatory, and economical limitations of the electric loads of Finnish households on the participation in the primary frequency regulation markets?

The most demanding technical requirement is the latency from the frequency deviation to the provision of balancing capacity. Within the FCR markets (FCR-D and FCR-N), the market requirement for activation time varies between 5 and 180 s. The research conducted in this dissertation suggests that a sufficiently fast DR control with domestic heating appliances that use resistive heating elements is achievable. The latency requirements can be met with a simple centrally controlled remote unit connected straight to the devices or local control interfaces. In the case of the FFR, local control logics must be used as the latency requirement is roughly a second. By adding an underfrequency relay functionality to a charger, an adequate reaction time is achieved.

The original use case of the controlled assets may significantly limit the DR potential. In the case of heating applications, the main operational limitation is the indoor temperature level or hot tap water temperature that ultimately affects the comfort of the inhabitants. However, based on the results of the research on the space heating DR, no significant changes to the indoor temperature level were observed even with an activation duration of 3 h on a cold winter day. This observation, combined with the fact that the activation durations in the DR operations against FCR markets are typically short, means that the effects of DR on the room temperature are negligible. Similarly, the EV charging DR for the FFR markets can be considered to have negligible effects on the amount of energy charged as the activation duration is 30 s at the maximum in the FFR.

The results of the economic analyses show that the annual per unit profits of the concepts are marginal. Therefore, economically light solutions had to be found to reach economically feasible concepts. A good example of the challenge is the case of electric water heaters (EWHs). There, the theoretical per unit average annual income is 76 €/a, which leaves very little room for up-front and operational expenses. Hence, the installation should be as easy and fast as possible (as the installation work accounts for most of the up-front costs). In cases where existing cloud connections can be used (like the heat pump and the EV concepts in this dissertation), such challenges do not exist as no installations are required to enable DR. On the other hand, the more capacity is introduced in the markets, the lower the price levels should go. Furthermore, if implicit DR (for example spot control) becomes more popular, it can also affect the availability of the analyzed resources, as these use cases might have conflicting control needs. However, there are possibilities to optimize implicit and explicit DR so that it creates even more revenue. For example, it is possible to offer up-regulating FCR-D capacity when the assets are turned on and down-regulating capacity when they are turned off. The saturation effect and simultaneous use of implicit and explicit DR are not covered in this work, which could be an interesting area of future research.

As the energy systems are changing rapidly, the regulation must also adapt to these changes. The research conducted in this dissertation was tested against the current FCR and FFR requirements in force in Finland during the period of 2000–2022. However, for example Fingrid has published information that the FCR rules will change. A new stability requirement will be added to the prequalification criteria, which has not been taken into account in this dissertation.

- Can aggregated domestic EV charging provide FFR capacity?

The number of EVs in our society is increasing rapidly. This is not only a challenge to our energy system but also a huge opportunity. EVs can provide substantial amounts of capacity for primary frequency regulation as they can basically be considered “mobile batteries.” The capabilities to provide governor type of frequency following the “droop” capacity is widely acknowledged. Additionally, this research demonstrated that they can also provide extremely fast reacting capacity as is required in the FFR market.

As stated above, this dissertation provided more knowledge in the area of practical applications of residential DR in the Finnish power system. The main contributions were related to real-life demonstrations of these DR concepts and their business potential. The main contributions are the following:

- Presenting and evaluating techno-economically viable residential DR concepts (on most electricity consuming assets like space and water heating and EV charging) that can be considered to be implementable in real life
    - Technical verifications of the concepts by empirical demonstrations
    - Evaluation of the business potential of the concepts

However, the number of tests conducted was relatively limited. More empirical research would thus be required to improve the reliability of the results. As the number of cloud-connected appliances is growing rapidly, the focus could, correspondingly, be on these concepts using APIs (Application Programming Interfaces). Furthermore, the statistical allocation of domestic appliances in a larger pool of aggregated resources would be an interesting topic of future research. Another topic that deserves more attention is the hourly matching and optimization of these residential assets. The assets studied here were mainly covering the nighttime (EWHs and EVs). The electricity-based space heating mainly covered the wintertime when heating is needed. Hence, further research is clearly needed on time optimization of these assets.

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Appendix A: Suitability of residential assets for primary frequency regulation markets in Finland

	FFR			FCR-D up			FCR-N		
	Technical compatibility with market requirements	Economic feasibility	Effect of DR activations on users	Technical compatibility with market requirements	Economic feasibility	Effect of DR activations on users	Technical compatibility with market requirements	Economic feasibility	Effect of DR activations on users
Direct electric space heating				Meets the requirements but latencies are at a critical level	Challenging as the historical market value is low compared with costs	Effect of DR activations on users negligible as the activations are usually small and short	Meets the requirements	Good as the historical market value is better than in FCR-D, latencies do not cause issues	Effect of DR activations on users negligible as the activations are symmetrical
Heat pump space & water heating	Not suitable as the latencies from the heat pump refrigeration cycle are too long			Not suitable as the latencies are too long			Very challenging and needs support from other assets	Effect of DR activations on users negligible	Effect of DR activations on users negligible
Electric water heating				Meets the requirements but latencies are at a critical level	Challenging as the historical market value is low compared with costs	Effects on users are negligible as the buffer tank for hot tap water is being used	Meets the requirements	Good as the historical market value is better than in FCR-D, latencies do not cause issues	Effects on users are negligible as the buffer tank for hot tap water is being used
Electric vehicles	Meets the requirements with a remotely configurable local activation logic	Good as the costs are negligible compared with the historical market value	Effect on users negligible as there are only a few short activations per year	Meets the requirements as the latency requirements are less strict than in FFR but requires more advanced control from an aggregator	Good as the costs are negligible compared with the historical market value	Minor effect on users as there are many activations per year	Meets the requirements as the latency requirements are less strict than in FFR	Good as the costs are negligible compared with the historical market value	Major effects on users as the FCR-N market is symmetrical (the capacity must be adjustable in both directions)

Publication I

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A novel method to utilize direct electrical space heating for explicit demand response purposes – proof of concept

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A novel method to utilize direct electrical space heating for explicit demand response purposes – proof of concept

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***Abstract*—The potential of demand response (DR) in its various forms has recently been widely investigated. This paper focuses on residential direct electric space heating (DESH) and introduces a novel way to enable DR that deploys the temperature decrease feature available in many thermostats and heating units. This deployment of the temperature decrease function was tested in a small-scale technical proof of concept pilot. It was verified that the concept is technically viable, does not cause significant changes in the indoor temperature, and the achieved controllable capacity can be used as capacity even for primary frequency regulation purposes. An economic analysis revealed that the concept has a positive business case even with a retrofit installation.**

Keywords—Demand Response, space heating, primary frequency regulation

I. Introduction

The increasing renewable energy production presents challenges for the balance management in the power system. The intermittent production introduces forecasting errors in generation and increases the need to use demand-side resources also in balancing and ancillary services, in addition to implicit demand response (DR) use. Implicit DR (where the customers react to varying electricity prices) is gaining popularity among consumers, because it is easy to understand. It has also been a popular topic of research; previous studies have often concentrated on peak shaving or day-ahead optimization [1]-[4].

Explicit DR, however, provides significantly higher expected revenues than implicit DR [5], and larger loads (e.g. data centers) have already been identified as potential providers of capacity for the purpose [6].

Heating loads have also been recognized as potential providers of explicit DR services, such as primary frequency regulation [7]-[9]. However, the major unanswered question is: Is there a means to control DESH systems in a simple and economically scalable way? This paper introduces a novel concept that enables explicit DR for sites with a DESH system – with a positive business case. Results of a proof-of-concept pilot are also provided.

There are roughly 600 000 electrically heated homes in Finland [10]. The majority of them have a heating system that can be categorized as "direct electric heating" meaning that the heat is not stored anywhere before the actual usage. Approximately 10% of the sites are heated by producing and accumulating heat in large boilers and then distributing it to different parts of the building by circulating water either in a heating network with wall radiators or in a dense network of underfloor heating pipes [10]. There are also systems where the heat is produced directly in underfloor concrete slabs by electric heating cables.

The present DR services [11]-[13] for these kinds of sites with the ability to store heat are usually used for implicit DR, controlled for instance based on day-ahead prices. To the best knowledge of the authors, for the time being, there are no credible systems for controlling direct electric heating in households for explicit DR.

Owing to the economic constraints of controlling such a small site-specific capacity, a simple and efficient local solution has to be found. Furthermore, the concept shall not jeopardize the comfort at home, and the control must be fast enough to meet the strict requirements of marketplaces, such as primary frequency regulation.

The focus of the paper is on the technical proof-of-concept pilot built to verify the developed concept. Furthermore, an economic analysis is provided to demonstrate the potential monetary value of the concept. Because of the piloting costs, the pilot consists of only two houses. Therefore, the results only allow to verify the functionality and feasibility of the concept, but not, for instance, the acceptability for a larger group of customers or how an aggregate of participating sites would be controlled by an aggregator.

The technical focus of the pilot is on studying the effect of the option of temperature reduction on power consumption. Room temperatures were also monitored to ensure that the effect on the comfort of living is taken into account. The residents were also instructed to give feedback related to the indoor temperature during the tests. The thermodynamics of houses is outside the scope of the paper.

The introduction and second section of this paper provide the background information of space heating in general and the motivation of the paper. The third section describes the technical aspects and control methods of space heating. The key contribution of the paper is presented in the fourth section, which introduces a novel and efficient concept that allows space heating to be harnessed for explicit DR markets, such as primary frequency regulation markets. The section also explains how the setup was tested in a proof-of-concept pilot. The fifth section shows the technical results of the proof-of-concept pilot and also addresses the economical side of the case. The key deliverables and future considerations are explained in the sixth section.

II. Residential Demand Response

Since the liberalization of the power markets in the Nordic countries and the rapid decrease in the price of electronics, utility-driven load control has been phasing out and new service providers have arisen. These companies, usually startups, mostly offer implicit DR services, such as day-ahead spot price optimization, for consumers' direct benefit.

An alternative to spot price optimization is to deploy the controllable capacity for explicit DR purposes. One of the most valuable markets recently has been primary frequency regulation, i.e., frequency containment reserves (FCR) [14]. In Finland, there are two separate markets for FCR; FCR-N for normal operation and FCR-D for disturbances [15] FCR-N is active all the time, while FCR-D is activated when the grid frequency drops below the range of FCR-N. The purpose of FCR-N is to keep the grid frequency stable in normal conditions, maintaining the balance between production and consumption in the short term. Thus the provided capacity must be increased or decreased proportionally to the frequency deviation. Fig. 1 and Fig. 2 illustrate the activation boundaries for the reserves against the grid frequency [16].

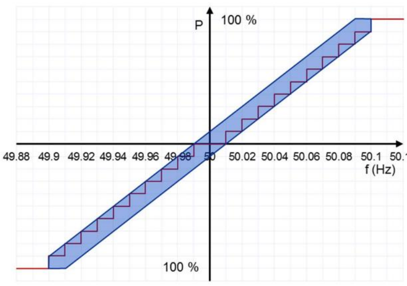

Fig. 1. Piecewise linear control curve, FCR-N [16]

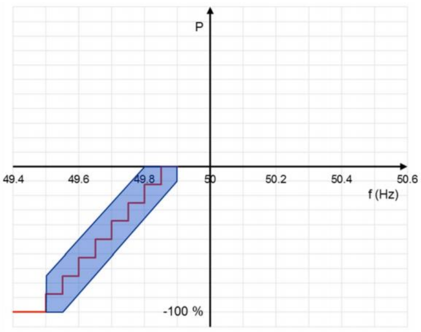

Fig. 2. Piecewise linear control curve, FCR-D [16]

III. Heating Load Control Technology

The DESH has been traditionally implemented with wall-mounted heating convectors or with underfloor resistive heating cables and room thermostats. Most of the installations in the past have been wall-mounted heaters, but today, almost all of the systems installed are underfloor cables.

Typically, both wall heaters and room thermostats, which adjust the underfloor or ceiling heating, have an in-built feature that enables a reduction in the set temperature. This feature has been developed to enable energy savings when the home is not used, for instance when a family is having a vacation somewhere else.

In the wall heaters, the temperature reduction is enabled by sending voltage signal into one of the input connectors of the heater unit. Fig. 3 illustrates a basic implementation of such a setup. A control signal could be connected to connector 4 enabling and disabling the reduction feature.

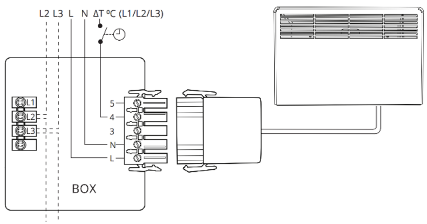

Fig. 3. Ensto panel heater wiring diagram [17]

The same logic usually applies to room thermostats. There are also thermostats that have a local wireless connection or even internet connection through Wi-Fi. As a result of changes in legislation, this feature will be more common in the future. The latest EU Ecodesign Directive [18] requires manufacturers to have at least a weekly heating scheduler and some other smart energy saving features available. Provided by the directive, the newest thermostats have usually a Bluetooth or Wi-Fi connection and a dedicated mobile app that enable the obligatory features (see [19]).

The temperature reduction feature is usually enabled from a home-away switch. The switch can be wired to a contactor in the fuse board, or it can directly feed signal to heater units. In newly built homes, the switch is usually replaced with a smart home system with a virtual switch.

In the future, heating controls will shift toward mobile and web applications, and the control signals will be produced and processed on cloud platforms.

IV. Technical Pilot

Inspired by the experiences of the startups providing implicit DR services as part of their smart home offerings, a new cost-effective concept was designed. The concept incorporates a remote control signal fed to the temperature reduction connector to enable control of heating loads. Because the potential DR value from a single site is quite marginal, the setup with a device and an installation must be kept very simple and fast to keep the up-front costs low and the business case viable.

For that purpose, the device shown in Fig. 4 was used. The device has a relay output and an ability to measure power from either the blinking kWh led of the power meter or by current clamps on the main phases. The device also has a “tariff-in” connector that allows fallback to the original ToU control in case of malfunction.

Fig. 4. Control device

To verify the technical functionality and the operating boundaries of the concept, a small-scale technical proof-of-concept pilot was conducted. The main objective in these tests was to investigate the effect of temperature reduction option activation on power consumption and room temperatures. Other measured variables were latencies, human reactions, and the effect of the users’ daily activities on the measured values. The technical tests were carried out by reducing the heating of the houses for 1 h, 2 h, and 3 h. The tests were conducted almost every night between January and April 2018, starting with the 1 h tests. For feasibility of the resource use in the DR market, a live control test against the FCR-N market was made.

The tests were made at night to minimize the possible negative effect on the comfort of living and to maximize the need for heating (because it is usually colder at night). The nighttime also provided an excellent opportunity to reduce the effect of possible human factors related to temperatures and electricity consumption in the home, such as cooking and using other electrical appliances, which could bias the results.

The pilot consisted of two homes located in southern Finland. One of the buildings is a relatively new wooden building, built in the 2010s. Owing to the present tight energy efficiency regulations in Finland, the building is very well insulated. The home also has a fireplace with a relatively large capacity to store heat, and it is used quite regularly. The use of the fireplace affected the tests during the pilot period. The pilot was conducted during winter in 2018.

The second home is an older wooden house built in the 1980s. The site has an old heating control system with a home-away switch that controls the ceiling heating units in the building.

V. Results

A. Effect on temperatures and consumption

Enabling the temperature reduction feature for 1 h did not result in a significant decrease in the room temperature. Naturally, the newer well-insulated house 1 kept the indoor temperature better than the older one. The room layout also played a significant role in the indoor temperature drop. In house 2 (the older house), the residents kept the bedroom doors closed, which made the room temperatures sink more rapidly as the warm air from other rooms could not level off the temperature differences. House 2 had also ceiling heaters which caused uneven heat distribution inside the room 1 and thus affected the measurements (the orange line in Fig. 5, house 2).

The effect of other electronic appliances on temperature was considered insignificant, as the tests were carried out at night when there is less human activity in the home.

The 2 h reduction also did not significantly decrease the indoor temperatures in either house. It was finally the 3 h control during a very cold weather (< −20°C) that made the residents of house 2 report feeling slightly cold at night. This was when the room 1 sensor in house 2 measured a room temperature of 19 °C. However, the indoor temperatures usually remained above 20 °C.

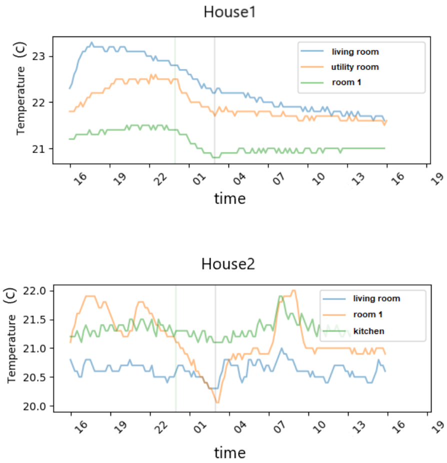

Fig. 5. Effect of reducing the heating on indoor temperatures in the 3 h test

The consumption dropped as expected in most of the tests. Typically, the heaters cause “ripple” in the consumption. This is due to the frequent switching of the thermostats in the heaters. During the reduction, it can be clearly seen that most of the fluctuation has disappeared (Fig. 6). A payback effect is also visible after the reduction when the heaters try to achieve the previous temperature setpoint. These spikes add complexity to the control of aggregated capacity (e.g. to retain certain power level). Luckily they are predictable and can thus be compensated with other resources and spread timewise.

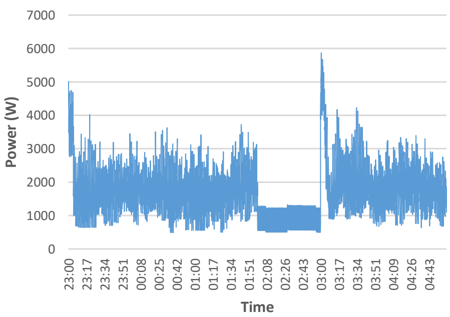

Fig. 6. Power consumption during the 1 h reduction test, house 1

The outdoor temperature naturally played a role in the achieved controllable capacity (Fig. 7). There are variations in the responses, caused by other loads (e.g. electric water heater) turning on or off during the test, as only the overall consumption of the houses was measured.

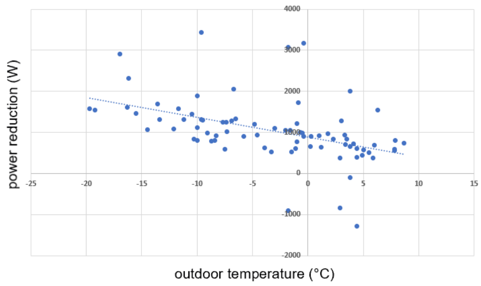

Fig. 7. Correlation of controllable capacity vs. outdoor temperature

The tests showed that the indoor temperature decreased very slowly even in the 3 h reduction tests. This result combined with the Fingrid historical data on frequency deviation durations [20] indicates that the measurement of indoor temperature may not be even necessary—the frequency practically never remains below 50 Hz for hours; see Fig. 8.

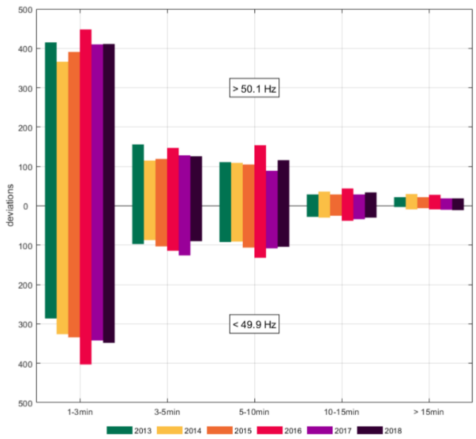

Fig. 8. Duration of frequency deviations [20]

However, applying heating control for markets with longer reduction times could affect the comfort in homes. Obviously, the control algorithms could then be configured to mitigate the issue. The payback effect can also be compensated by intelligent control algorithms.

B. Latencies

The total latency of the heating control system consists of many elements. There is latency in the cloud system, telecommunication, and possibly in the equipment on site. The latency in the cloud is at a sub-second level, and it can be improved at any time by applying more resources virtually. The main latency comes from the aging 2G technology chosen for the device-to-cloud communication (as the worst-case scenario). The latencies on site can be caused by ramp-up or ramp-down cycles of the heating equipment. In this case, it can be assumed that there is no latency, because resistive loads are controlled. Despite the 2G latency, all of the piloted units responded within 5 s, which meets the requirements of both FCR-N and FCR-D (Table I) [21]. At larger volumes, the risk of greater latencies in the communication system can be mitigated by using faster telecommunication technologies. Also a small proportion of the achieved controllable capacity can be kept as a backup reserve for any disturbances.

TABLE I. FCR REQUIREMENTS IN FINLAND [14]

	Minimum size	**Full activation time**	**Other**
FCR-N	0.1 MW	in 3 min after frequency step change of ± 0.1 Hz	Dead band max ±0.01 Hz
FCR-D	1 MW	5 s / 50 %, 30 s / 100 %, after frequency step change of −0.50 Hz	

C. Economic feasibility

The value of flexibility is at highest in primary regulation markets, such as FCR in the Nordic countries [21]. The economic value of the DR control was simulated when it is enabled at night (8 h) and in the case of whole-day control (24 h). To estimate the economic value in general, it was assumed that the total amount of heating per year is 10 MWh/site, which was distributed across the year by the heating indices provided by the Finnish Meteorological Institute [23]. To keep the analysis conservative, it was assumed that 85% of the heating load could be used for DR. Table II shows the value of control toward FCR-N and FCR-D with 2019 hourly market prices [22]. Assuming that the installation and device cost can decrease to €200 (€100/ device, 1–2h of work) in larger volumes, there is a viable business case especially when constantly using the capacity for FCR-N. The payback time of a single site is less than 2 years in that case.

TABLE II. VALUE OF CONTROLLING A SITE IN THE FCR MARKETS

	Capacity value			
	night control (22:00-07:00)		***whole-day control (24h)***	
month	***FCR-N value***	***FCR-D value***	***FCR-N value***	***FCR-D value***
Jan	7.64 €	1.00 €	21.47 €	2.28 €
Feb	4.40 €	0.51 €	12.18 €	1.02 €
Mar	5.49 €	0.66 €	15.16 €	1.57 €
Apr	2.90 €	0.42 €	10.45 €	1.35 €
May	4.01 €	3.52 €	14.92 €	14.02 €
Jun	0.00 €	0.00 €	0.00 €	0.00 €
Jul	0.00 €	0.00 €	0.00 €	0.00 €
Aug	0.00 €	0.00 €	0.00 €	0.00 €
Sep	1.83 €	0.11 €	5.21 €	0.15 €
Oct	5.05 €	0.46 €	16.10 €	1.00 €
Nov	3.64 €	0.10 €	10.83 €	0.51 €
Dec	7.60 €	0.31 €	20.48 €	0.91 €
TOTAL	**42.56 €**	**7.09 €**	**126.81 €**	**22.81 €**

VI. SUMMARY AND CONCLUSIONS

To tap the potential of residential DESH capacity in explicit DR markets, simple solutions must be found. This paper introduced a simple and cost-effective concept that enables the direct electric space heating capacity to be utilized in historically valuable power markets, such as primary frequency regulation, without significantly affecting the indoor temperature levels in homes. The solution deploys the existing temperature reduction setup originally provided for energy savings purposes. Because the indoor temperature decreases slowly after the heating has been controlled off, the same feature can now be used in a smarter way, thereby enabling valuable DR activity.

The developed concept was verified with a proof-of-concept pilot. The results show that the control did not significantly affect the indoor temperatures. The results also indicate that the indoor temperature monitoring is not necessarily even needed in practice when applying the concept for short-term markets, such as FCR. The economic analysis indicates that the concept also has a positive business case.

This paper focused on technical aspects of the introduced concept; the economic aspects would require a more detailed analysis of their own. There is a need for a more detailed analysis on the scalability, for instance the number buildings with the home-away feature enabled. Furthermore, the market prices (e.g. FCR) have a significant impact on the feasibility of the concept. Further, a larger pilot is needed to enhance the accuracy of the economic calculations and the assumptions made. It would also better reveal the characteristics of aggregated direct space heating capacity controlled toward primary frequency regulation. There is also a need for customer acceptance-related future research that focuses on aspects other than temperature (e.g. customer communication).

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Publication II

Manner, P., Alaperä I., and Honkapuro S.

Domestic heat pumps as a source of primary frequency control reserve

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Domestic heat pumps as a source of primary frequency control reserve

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***Abstract*—Demand response applications have been extensively studied to provide the capacity needed for grid support. However, research projects have typically focused on peak shaving or similar applications with longer latency requirements and duration. This paper introduces a method to enable heat pumps to provide primary frequency regulation services in the Nordic regulatory framework, without producing major disturbances to the primary use of the heat pumps—heating and cooling.**

With the developed method, the Internet-connected heat pump capacity can be acquired with fully digital solutions, without the need to have a retrofit installation on site. A proof of concept pilot was conducted to verify the functionality of the method in practice. An economic analysis revealed that the business side of the case is positive, as there are practically no costs for enabling the feature in existing or newly installed heat pumps.

Keywords—Demand response, Heat pump, Primary frequency regulation, Value of flexibility

I. INTRODUCTION

The power markets are in a transition phase. The increasing intermittent and scattered renewable production challenges the traditional ways to operate the grid and increase the balancing capacity need. Furthermore, the traditional source of inertia in the grid is decreasing because of the increasing number of frequency converters installed for applications with a rotating mass. The aforementioned challenges lead to problems in the availability of balancing power. New sources of flexibility are thus needed, and the focus is shifting towards the consumption side. There is already established demand response business around industrial sites with heavy electricity consumption, like the forestry and the metal and chemical industries [1].

Recently, the focus has been shifting to smaller consumption units like data centers. There are already very promising results on research into demand response with data centers [2]. There is also established business related to residential demand response. The challenge associated with the implementation of these demand response concepts is in their accessibility, upfront costs, and the effect on the normal use (i.e., service level and customer comfort).

Demand response (DR) or demand side management (DSM) is currently a known and popular topic in the academic world. Many researchers have investigated consumption-side capacity to provide the much-needed capacity to mitigate the growing grid balancing problem. However, many of the previous studies have focused on implicit demand response [3][4], where the owner or the user on the consumption side is reacting to given prices. This approach is suitable for forecastable issues like congestions in the distribution networks during peak hours. Distribution system operators (DSO) can provide pricing models where they offer cheaper prices during off hours and higher prices to tackle issues with high loading. This leaves it up to the customers to react to the prices and achieve possible savings.

In explicit DR, reacting is left to the operator, often an aggregator. This is because the capacity is usually used for something that cannot be forecasted, and it requires fast reactions or otherwise cannot be left for the customer to respond. A typical such purpose is the primary frequency regulation, where the capacity must be activated within seconds in the worst case. Commonly, the aggregator shares the gained value with the resource owner by paying monetary compensation or providing a price reduction on a service.

Explicit demand response is currently a popular subtopic among researchers. Recent studies have focused especially on battery-based solutions [2], [5]. Typically, the batteries have a primary purpose, while demand response is a value-adding secondary purpose. There are also studies on the capability of heat pumps to participate in explicit DR markets; however, these studies often lack an experimental part [6], require a new local retrofit solution [7][8], or focus on markets with longer latency requirements than those required in primary frequency regulation markets [7], [9]. However, large-scale heat pumps have already been shown to provide primary frequency capacity [10]. Direct electrical heating systems and water heaters have also been studied [11], [12]. These loads can be easily controlled because of their purely resistive loads and thus utilized in explicit demand response. At the moment, their major obstacle is that they are usually not connected to any cloud solutions. Recent research has, however, introduced novel methods to capture their capacity to be controlled in an economical way [13].

Domestic heat pump systems could be a promising source of balancing capacity. These systems are often controlled with online solutions. By connecting to heat pump manufacturers' cloud services, thousands of sites could be reached automatically. The advantage of connecting through cloud services is on the cost side. It only requires a one-time development to access the resource while the operational cost remains minimal.

There are also emerging standardized ways to control devices locally. Many new devices are equipped with "SG Ready" (Smart Grid Ready) connectors that allow external local control for the device [14]. In the future, also the increasing number of devices have an Internet connection. This is a result of new energy savings directives [15] but also

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the target to add on features for customers to make a product more attractive. The capacity of the connected devices can then be harnessed for demand response purposes with a low operational cost.

In this paper, the focus is on a proof of concept pilot of Internet-connected heat pumps already present in many residential buildings. A novel concept is introduced and tested that would allow heat pumps to be controlled with a low reaction time enabling them to be used as capacity in even the most challenging explicit DR power markets. The objective of the study is to answer the following questions: 1) What is the fastest way to control a heat pump? 2) Is the response time adequate for the primary frequency regulation capacity? 3) Are there some limitations (e.g. pump state) that affect the controllability? The paper also provides a rough analysis of the economic potential of the connected heat pump capacity in the Finnish primary frequency regulation markets. The possible additional wear and tear caused by DR commands is not included in the analysis.

Today, there are already over a million sold heat pumps in Finland [16]. The majority of them are air-to-air heat pumps, which are usually not connected to the Internet and are thus left outside the scope of this research. However, there are still over 100 000 of heat pumps that have circulating water as the heat distribution method [16]. Usually, these types of heat pumps can be connected to the Internet. This makes them a huge potential source of capacity to be utilized in power markets. Typically, the option of Internet connection is implemented to enable remote control for heat pump users for instance during holidays and to facilitate remote maintenance for professionals.

Some advanced models already have demand response functionalities. For example, the heat pump manufacturer Nibe has an implicit demand response feature called “Smart Price Adaptation” in their current heat pump models [17]. The feature controls the pump so that as much power as possible is used during cheapest day-ahead spot hours. To benefit from that, a customer should, of course, have an hourly based electricity contract. These types of contracts are quite common among consumers in the Nordic countries [18].

II. Background

A. Heat pumps

Heat pumps are a great option to reduce primary heating energy consumption in general. The proportion of heat pumps chosen as the primary heating method in new houses built in Finland is growing rapidly [19]. The increasing popularity of heat pumps is explained by the fact that they usually provide the lowest life cycle costs to their owner. This is due to their ability to draw excess heat from the surroundings (soil, bedrock, water, or air) instead of burning fuel or using energy transferred to the house. The amount of imported energy to a heat pump is only a fraction of the heat energy output.

The operation principle of the heat pump is fairly simple (see Fig. 1). The key idea is to compress a refrigerant so that it is condensed to the liquid state. The compression heats the refrigerant, and the heat is then transferred from the system to be used for heating, in this case the house or hot tap water. After passing the hot side the refrigerant is decompressed, which makes the fluid to evaporate. The evaporation process requires energy, which is taken from a chosen source. Typically, the heat to and from the process is transferred by circulating fluid in heat exchangers connected to the hot and cold sides of the system.

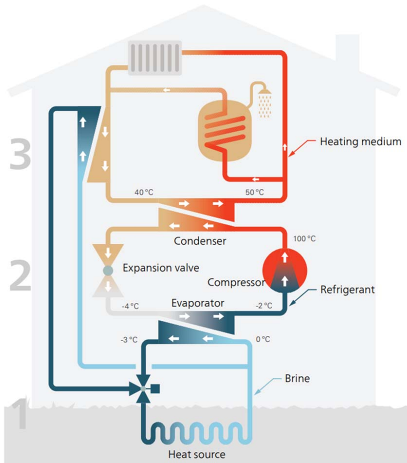

Fig. 1. Operation principle of a domestic heat pump [20]

The compressor compressing the refrigerant starts to operate only when certain set threshold values are achieved and stops when the limits are reached. The running time, starts, and stops are the main factors affecting the lifetime and condition of the compressor. To reduce the number of starts and stops, buffer tanks are used. A buffer tank stores the acquired heat allowing the compressor to run longer, thereby reducing the number of starts and stops. Some units also have an extra resistive heating element to back up or cover potential exceptional heat demand.

In domestic applications, the heat is used for two purposes: to heat (or cool) the house and to produce hot tap water. Heat pumps analyze the need for the both and decide where to use the heat. The hot tap water need is determined simply by the buffer tank temperatures. For the heating, the heat pump control system calculates the difference between the set and actual temperature in the water flowing in the heating circuit.

Heat pumps control their compressor motor either by simply turning the power on and off or controlling the running speed by an inverter. The latter improves the efficiency of the device but is usually more expensive.

B. Demand response markets

Currently, there are many potential DR markets for residential loads. In the past, primary frequency regulation markets have been identified as the most valuable one [21]. In Finland, the primary regulation market is called frequency containment reserves (FCR) and has two different products [22]; FCR-N for normal operation and FCR-D for disturbances. The FCR-N is operational when the frequency is between 49.9 Hz and 50.1 Hz i.e., in normal conditions. When the frequency drops below 49.9 Hz, the FCR-D starts to operate. The basic principle for the operation is that the amount of capacity used increases in proportion to the frequency deviation (see Fig. 2).

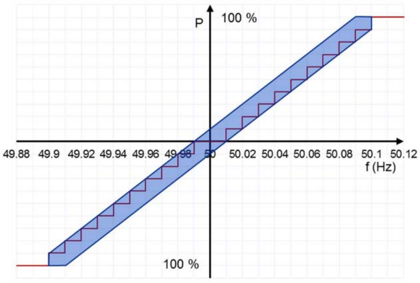

Fig. 2. Stepwise linear control curve of FCR-N [23]

Because the FCR capacity is the primary balancing power, the requirements for latencies are very short (see Table 1). This is especially the case for disturbances, when the FCR-D is activated. 50% of the capacity must be activated in 5 s and 100% in 30 s [22]. These time constraints bring challenges to the possible usage of heat pump capacity for this purpose.

TABLE I. FCR REQUIREMENTS IN FINLAND [22]

	Minimum size	Full activation time	Other
FCR-N	0.1 MW	in 3 min after frequency step change of ± 0.1 Hz	Dead band max ±0.01 Hz
FCR-D	1 MW	5 s / 50 %, 30 s / 100 %, after frequency step change of −0.50 Hz	

III. PROOF OF CONCEPT

The original key idea of the concept is to use API interfaces to enable a cloud-to-cloud control mechanism for heat pumps. Thus, they can be merged to a pool of various other DR-controlled loads with intelligent algorithms. By connecting the aggregator's control cloud to a cloud solution built for the heat pumps, a vast amount of heat pump capacity can be harnessed.

The most critical technical challenge with heat pumps is the response time or latency from command to reaction in the power intake. There are several sources of latency in the process. There is latency in the cloud service (usually <1 s), the communication networks (usually <5 s depending on the chosen technology), and the heating device itself. In this case, the heat pump causes most of the delay. The heat pump delay is mainly caused by the local control system that controls the operation of the compressor. The control system tries to maintain an adequate temperature in the building and an adequate level of hot tap water. At the same time, the system tries to protect and maximize the lifetime of the most vulnerable part of the system, the compressor.

To verify the capabilities of heat pumps, a small-scale proof of concept pilot was made. The main objective of the tests was to analyze the command-to-action latencies on two types of heat pumps. The first tested heat pump is an inverter-controlled model F1255-6 manufactured by Nibe. The other heat pump is an on-off type model F1245-8, also manufactured by Nibe. Both of the pumps are connected to the manufacturer's cloud service through a local Internet connection available on the sites.

To know where to focus in the tests, different parameters were altered to see which parameter would provide the fastest response (space heating curve set points and hot tap water modes). After finding the most promising parameter, a series of control tests were performed. The aim was to compare the latency results against the requirements of the FCR markets.

Owing to the lack of resources to build a cloud-to-cloud-based test setup, manual tests were carried out. The tests were conducted by using the manufacturer's cloud interface [24]. The interface provided a good way to control the parameters of the tested heat pumps. The solution also provided access to the logs of the heat pumps. An Internet-connected power metering device was installed on the site with an on-off type heat pump to measure the effect of control actions on electricity consumption. The device has an optical reader to read the consumption data from the original DSO-owned smart meter with a resolution of 1 s.

IV. RESULTS

A. Latencies

In the proof of concept tests, it was found that the fastest way to affect the power consumption of the device is to control the hot tap water production. The space heating side responds slower because of the heat pump system logic. This is natural because the heating side does not typically need fast reaction times owing to the high thermal time constants in space heating.

It was discovered that controlling the hot tap water to a luxury mode provided the fastest reaction times. The luxury mode changes the temperature set point of the hot tap water buffer to a higher value, thus providing more hot tap water for the user. This feature is available in most of the heat pumps, but it can have different names depending on the manufacturer.

The site with an additional electricity metering device installed was chosen for more detailed testing. A total of 34 tests were made on the on-off type heat pump. From the very first steps it was obvious that the heat pumps are not able to meet the latency requirements of the FCR-D, and thus, the focus shifted to the FCR-N. The results in Fig. 3 show that almost all of the "luxury on" commands made the consumption to rise within 3 min, which is the maximum full activation time allowed in the FCR-N. However, only 57% of the "luxury off" commands produced the desired reaction (power down) in 3 min. This is unfortunate because it defines the actual qualifying capacity.

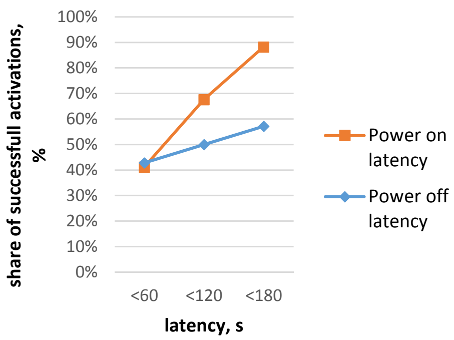

Fig. 3. Proportion of commands that resulted in a power increase and decrease with different latency levels

Based on test results, it can be concluded that the tested heat pumps alone cannot provide capacity for primary frequency regulation purposes with the present online systems (see Table 2). However, it is still possible to use the capacity harnessed from these heat pumps to some extent as "bulk capacity" if they are aggregated together with more controllable capacity in real time. Such capacities could be for example batteries in distribution grids or data centers or resistive loads like electric water heaters or space heaters. Their task is to secure the linearity in the aggregated response.

TABLE II. RESULTING LATENCIES COMPARED AGAINST THE FCR MARKET REQUIREMENTS

	Activation time	**Latency**	**Conditions**
FCR-N	100 % in 3 min	Partially meets the requirement	If used together with more controllable resources
FCR-D	5 s / 50 %, 30 s / 100 %	Does not meet the requirement	-

There is also a notable issue with the control of heat pumps to the luxury mode. When the luxury on command was sent, it was usually impossible to switch it off before the actual start of the compressor (and the increased power consumption). However, the luxury off commands went through quite fast after that. There were also cases where the heat pump refused to switch off the compressor despite the off commands. This was probably caused by a simultaneous heat need on the space heating side.

B. Economic feasibility

A financial calculation was made to estimate the theoretic economic potential of the concept. Based on the results of the latency test, different scenarios were simulated with a fleet of 100 000 devices aggregated together with more controllable load. The main parameters were the usability (how well the capacity could be controlled in the required time) and the available share of DR-enabled units. It was assumed that a heat pump is statistically available for external control for 7.5 min in an hour. The rest of the time the heat pump is considered to be in an unfavorable state, for instance, needing recovery time for possible next activation. It was also assumed that the average heat pump electrical power intake is 2 kW and that the feature is always available.

The potential monetary value of the concept was calculated with Fingrid's 2019 hourly FCR-N prices [25]. Table 3 shows that the potential is fairly good even if a small proportion of the installed fleet is controlled and used as the FCR-N capacity. However, it should be noted that the market saturation effect is not taken into account in this analysis. The prices could possibly drop when more capacity is introduced to the markets. Possible penalties are not considered in this research, either. It is up to the aggregator to determine the optimal risk vs. revenue balance.

TABLE III. HEAT PUMPS' SHARE OF THE CONCEPT'S FCR-N INCOME CALCULATED WITH 2019 HOURLY MARKET PRICES

		Proportion of qualifying sites (sensitivity analysis), %			
		25%	***50%***	***75%***	***100%***
DR-Controlled Heat Pumps, pcs	***5 k***	60 k€	120 k€	181 k€	241 k€
	25 k	301 k€	602 k€	903 k€	1204 k€
	50 k	602 k€	1204 k€	1806 k€	2408 k€
	75 k	903 k€	1806 k€	2709 k€	3612 k€
	100 k	1204 k€	2408 k€	3612 k€	4816 k€

As the concept has practically no operational costs, only the development cost determines the payback time.

V. CONCLUSIONS AND DISCUSSION

Internet-connected heat pumps are a potential source of flexibility for the power system. Their per unit controllable capacity is low, but the number of heat pumps is enormous. Taking advantage of the existing connectivity provides a huge business opportunity for the aggregators. One of the most potential areas for the harnessed capacity is to use it as capacity for primary frequency regulation. However, the requirements in these markets are very strict. The main challenge in the requirements is the latency from a grid frequency deviation to a response at the aggregated capacity level.

In this paper, the focus was on testing the latencies associated with the control of heat pumps. The technical test showed that there are difficulties in controlling heat pumps alone as a capacity for primary frequency regulation purposes. However, they could still be useful if they were used together with other more controllable loads.

A. Future research topics

The aggregation of residential heat pumps with other loads would be an interesting topic of future research. There is also a need for an empirical research with a larger number of heat pumps, preferably from multiple manufacturers. The proof of concept pilot was carried out with only one heat pump brand (although a very common one in Finland). Other heat pump brands might have different properties and behavior. Other possible limitations of heat pumps could also be revealed in a larger scale pilot. In this study, the tests were carried out during a warm period when there was not high demand for space heating. The effect of cold and hot outdoor temperatures should thus be further investigated. The customer consumption behavior and pump sizing strategy also affect the usability of the concept.

Despite the limitations and difficulties in the heat pump control, the potential value of using heat pumps for DR purposes encourages to develop the setup further and to conduct a more extensive research on the topic. Even though the monetary value of a single site is low, the number of existing remote controllable heat pumps is enormous.

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Publication III

Manner, P., and Honkapuro S.
Electric Water Heaters Contributing to the Primary Frequency Regulation Markets—Finnish Case

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Electric Water Heaters Contributing to the Primary Frequency Regulation Markets—Finnish Case

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***Abstract*— As the renewable generation continues to increase its share in our power systems, the need for balancing power is also increasing. The intermittent, increasingly unpredictable production mix poses challenges for the energy system. Transmission system operators (TSOs) are in need to acquire more balancing power to mitigate the increasing fluctuations in the generation vs. consumption equilibrium.**

This paper introduces a concept to harness domestic electric water heaters (EWHs) to contribute to primary frequency regulation markets. The paper focuses on the technical concept incorporating a retrofit control device that takes advantage of the night tariff control wiring scheme already implemented in more than 500 000 homes in Finland. In addition, an economic simulation, applying real-life data, shows that the concept has business potential and, in fact, is already being used in thousands of homes in Finland providing FCR-N (frequency containment reserve for normal operation) capacity for the Finnish TSO, Fingrid.

***Index Terms*— Aggregation, demand response, electric water heater, primary frequency regulation.**

I. Introduction

The renewable production plays an ever more important role in our energy system. To phase out fossil fuel in the energy system, a vast amount of clean production must be brought in. Another major, or currently perhaps the most important driver, is the security of supply. Energy production must be available at all times, and the production must meet the demand. This is not only a long-term issue but also the case for continuous power balance in time resolutions of seconds. This is because the frequency in the system is determined by the amount of production compared with consumption. When the consumption is exceeding the production in power, the frequency decreases, and vice versa. Traditionally, there is dedicated flexible generation that is used to control the production so that the frequency stays at acceptable levels.

Today, the focus on flexible capacity is starting to shift toward the consumption side and energy storages. By controlling the energy-consuming assets, the same effect can be produced, providing much-needed flexibility into the system.

The flexibility provided from the consumption side, also known as demand response (DR) capacity, can be used directly for customers' benefit as savings in electricity procurement costs, or indirectly through a stakeholder controlling the assets, such as an aggregator, who rewards the customer for DR activities. The former DR activity is called implicit demand response and the latter explicit demand response. A comprehensive overview of these is presented in [1].

One potential use case for DR is found in congestion management in distribution grids. Distribution system operators need to ensure that the lines and other network components do not overload, thereby jeopardizing the stability of the network. Typically, they have managed this challenge by network reinforcement, which is costly and slow to implement. Another typical use case for DR is the optimization of customers' energy usage against day-ahead spot markets. In domestic applications, electric water heaters (EWHs), heat pumps, electric vehicle charging, and other energy-consuming appliances are controlled to consume electricity at the cheapest spot hours to create savings for the homeowner.

The aggregated DR capacity can also be used for the momentary power balance in the system. Transmission system operators (TSOs) are responsible for continuous power balance. This balance or imbalance can be seen as the frequency in the system. TSOs could handle the problem by dedicating own generation for the purpose but also by having open market mechanisms for acquiring such capacity elsewhere. TSOs have created various frequency regulation reserve markets for the market players to sell capacity and energy for balancing purposes. By trading capacity from consumption or production side, companies can earn monetary value for flexibility.

Some of the domestic appliances are known to have potential as flexible controllable capacity. Multiple studies have presented concepts to harness, e.g., electric heating [2]–[3], heat pumps [4]–[6] and EWHs [7]–[11] as sources for flexible capacity. However, there is a lack of studies about practical implementations of such concepts in primary regulation. This paper presents a real-life implementation of such a concept and an economic simulation that shows the monetary side of the concept.

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II. Background

A. Domestic energy usage

The households account for 20% of the total energy consumption in Finland [12][13]. Most of that energy (64%) is used for heating. The share of electricity as the primary source of energy used for household heating is 25% (not including the electricity used in heat pumps) [13]. This is roughly 9.8 TWh per year of energy that is consumed directly in resistive heaters. Considering the consumption of a single home, the production of hot tap water constitutes a large share of the household's total energy consumption. According to the statistics [13][14], in an average electrically heated Finnish household, the average total consumption of domestic hot tap water is 4 MWh/a. This is 11% of the average energy consumption of electrically heated homes. There are almost 600 000 homes in Finland that have "direct electrical heating" as the primary heating method [14].

Because the standard temperature of hot tap water is high, its production requires quite a high momentary power. To avoid power peaks and excessive heating elements, heat accumulators are being used to store the hot water to be used when needed. Another reason for buffer storages has been the night tariff scheme, which has driven consumers to schedule their electricity usage to nighttime when the price of electricity has usually been lower. In electrically heated homes in Finland, the size of the boiler is usually large enough to cover the whole tap water usage of a day. As it does not take the whole night to heat up the water in the tank, there is room for scheduling the heating. This creates an opportunity for DR aggregators to control the EWH so that it serves as a source of flexibility to be traded further as part of aggregated capacity.

B. Demand Response

Demand response or demand side management is becoming more and more important for our energy systems. Instead of using or investing in generation assets, demand-side assets are a cost-effective solution for providing controllable capacity. Usually, generation assets dedicated for balancing purposes require heavy investments or their operational costs are high. The assets consuming fossil fuels are usually both expensive to build but also expensive to operate. Hydropower plants are a good source of balancing power, but the amount of hydro capacity is limited, and they usually have limitations when operating in ancillary services markets.

In this study, we focus on the hourly primary frequency regulation markets, as they are currently providing the highest value for flexibility assets [15]. In Finland there are three markets covering the primary frequency regulation. These are the frequency containment reserve market for normal operation (FCR-N), the frequency containment reserve market for disturbances (FCR-D), and the fast frequency reserve market (FFR) [14]. The FFR and FCR-D markets react to frequency levels that are considered abnormal, while the FCR-N market is used constantly to keep the frequency within normal frequency levels (50 ±0.1 Hz). The FCR-D market has also both, up and downward regulation markets.

The FFR market is dedicated to activate reserve capacity extremely fast in case the frequency is about to drop drastically in a low-inertia situation. There are three different frequency levels when the FFR capacity should be injected. The required response time depends on the frequency, as presented in Table I.

TABLE I. FFR ACTIVATION TIME REQUIREMENTS [16]

Activation frequency (Hz)	Max. activation time (s)
49.7	1.3
49.6	1.0
49.5	0.7

FCR-D capacity is activated when the frequency goes outside the boundaries of the normal frequency level where the FCR-N capacity is being used. The reaction time requirement for the FCR-D is not as strict as in the FFR but considerably faster than in the FCR-N as it is a "disturbance reserve." The activation speed requirements are presented in Table II.

TABLE II. FCR PREQUALIFICATION REQUIREMENTS [15]

	Minimum size	Full activation time	Other
FCR-N	0.1 MW	in 3 min after frequency step change of ± 0.1 Hz	Dead band max ±0.01 Hz
FCR-D	1 MW	5 s / 50 %, 30 s / 100 %, after a frequency step change of ±0.50 Hz	Up and down markets

In Finland, Fingrid Oyj is the TSO that is responsible for keeping the balance in the system and thus organizes the aforementioned markets. The markets are operated transparently and are open for everyone that can provide capacity according to their specifications. Because the markets are free and open, the price is determined by supply and demand. As it is more difficult to provide capacity for the markets that have stricter requirements, the prices in these markets are usually higher than in the markets where, e.g., the required response time is lower. In addition to the response time requirement, the activation duration and number of activations have great impact on the value of flexibility.

The value also depends on the availability of assets providing capacity for these markets. For example, hydropower cannot provide flexibility if there is no water available to rotate the turbines. Furthermore, in springtime, when the snow melts, the hydropower plant must occasionally run at the maximum capacity to avoid exceeding the water level limits in the reservoirs upstream.

III. Proposed Demand Response Concept

The objective of the study was to evaluate the suitability and economic feasibility of domestic EWH utilization as a demand response capacity for primary frequency regulation purposes in Finland. In order to achieve a commercially viable concept, there should be low upfront costs and high enough profit from the primary frequency regulation market. Hence, the research focuses on the technical setup and its costs as well as on the market analysis of the primary regulation markets in Finland.

A. Technical concept

Because the asset is considered to be very small compared with traditional assets participating in the primary frequency regulation markets, the upfront costs must be as low as possible. Hence, a technical concept of "minimal Demand Response" (mDR) was developed. The idea was to create a retrofit concept that should be as cost-effective as possible. This means that the hardware (HW) should be very limited and cannot have any advanced features. Simply put, the device cannot be a general-purpose off-the-shelf device, but it has to be a low-cost device that is designed specifically for this purpose.

For this reason, a device with in-built current-withstanding relays was out of the question because the relays cost too much. An alternative solution was found that uses the existing infrastructure available in many Finnish houses with electrical heating, that is, the night tariff control scheme. In the night tariff control setup, the electrical switchboard of a building is equipped with contactors dedicated to switching on and off the energy-intensive loads according to the signal sent by the local DSO. The idea of the night tariff control is to shift some of the loads from daytime to nighttime when the consumption is usually lower. For end-users convenience, the DR activity in this concept happens also during the night tariff period (22-07) in order to avoid increasing the customers' electricity costs.

Thus, a device for mDR was developed (Fig. 1). The device had only two in-built relays, where one of the relays was dedicated as a "fail-safe" relay that could deactivate the demand response control and turn back on the original night tariff signaling. The other relay was dedicated to the actual demand response control. In order to reliably identify the state of the water heater and to measure the effect of the DR control on consumption, power measurements were needed. This was achieved by implementing an optical reader to the device capable of sensing the blinking light of a smart meter installed to every home in Finland. In case there would not be any smart meters on site or they could not be otherwise used for the measurements, an option to attach current clamps to the device was also implemented. The frequency is not measured locally as it would require more sophisticated (costly) components.

Figure 1. Simple controller unit "mDR"

The idea of the technical concept is that this low-cost device can be used to control the contactor connected to the original night-tariff-controlled loads. Usually, these loads have included an EWH and possibly some heating loads that are able to store heat for the daytime use. A more detailed illustration of the setup can be found in Fig. 2.

The devices exchange measurements and settings with an aggregator cloud service. The service uses the measurements and the grid frequency as inputs for the aggregation control logic. The system monitors the status of individual sites automatically and schedules them to be ready for DR so that the required capacity is always provided. The assets are turned either on or off, depending on the direction of the frequency deviation and balancing need. Thanks to this centrally controlled concept, the remote units can be just simple remote-controlled actuators, with measuring capabilities.

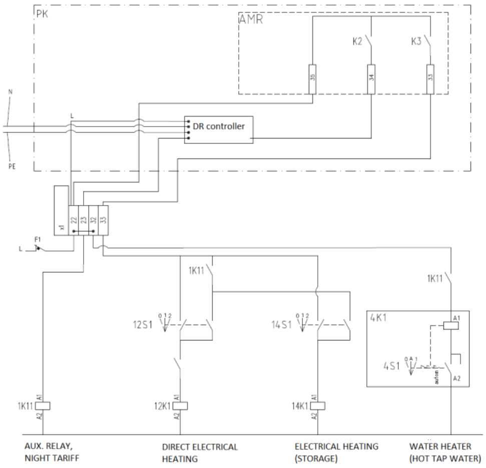

Figure 2. Wiring diagram for the night tariff control

Because only a low-current relay was needed, the HW costs were low. With this setup, the HW costs can be driven down to roughly €50 when procured in high volumes. Another major cost component in the concept is the installation cost. The installation cost actually covers the largest share of the total costs. However, in this concept, also the installation costs can be minimized, thanks to the existing night tariff control wiring already present on sites.

B. Economic simulation

In order for the concept to have a positive business case, the income from the reserve markets has to be greater than the operational and initial start-up costs within a reasonable period of time. In this study, we use a time period of ten years. To be able to identify the economic potential, the theoretical DR income per unit of the EWHs in each primary frequency reserve markets has to be calculated. The average prices for 1 MW capacity in different hourly markets in nighttime (22–07) are presented in Table III. It should be noted that there are no data for FFR market prices for the period of 2017–2019 because the market was introduced in 2020. Average prices from 2017–2019 are used as future projections of the reserve market prices in the simulation.

TABLE III. NIGHTLY (22–07) AVERAGE RESERVE MARKET PRICES [15]

	Reserve Market Prices, €/MW,h		
Year	***FCR-D up***	***FCR-N***	***FFR***
2017	3.15	17.02	
2018	4.64	21.70	
2019	4.69	20.28	
2020	6.22	22.04	19.50
2021	5.68	13.51	13.70
Average, 2017-2021	4.88	18.91	16.60

Naturally, not all the theoretical capacity can be bid as is to the markets. There is always some unexpected behavior occurring for normal everyday reasons; for instance, the residents may be on holiday or they may have some visitors, which affects the consumption of hot tap water. There may also be some technical issues related to the device or its communication. For the aforementioned reasons, a safety margin is always left to the actual bid compared with the theoretical maximum capacity. This margin can be taken into account by using a parameter "capacity utilization rate."

The other critical factor determining the commercial feasibility is the cost side. As described in the previous section, the hardware and the installation are the most important cost components in the concept. Finally, the profitability of the concept for a period of ten years was calculated using the net present value formula (1) where the variable C_t is the net cash inflow during period *t* and C_0 is the initial cost (investment). An interest rate (*r*) of 5% and investment lifetime (*T*) of 10 years was used in the calculations.

$$NPV = \sum_{t=1}^{T} \frac{C_t}{(1+r)^t} - C_0 \qquad (1)$$

It should be noted that the market saturation effect was not taken into account in this simulation. The saturation effect will reduce the price level if the amount of procured capacity is not increasing accordingly.

IV. RESULTS

The concept enables the utilization of EWHs as primary frequency regulation capacity in reserve markets. The greatest concern is the latency requirement in the FCR-N and FCR-D markets, which devices fulfill as they react to commands usually in less than 5 s. However, the concept does not meet the requirements of the FFR market because of the extremely tight latency requirement. In the FFR market, the capacity must be delivered in 0.7, 1, or 1.3 s, depending on the activation frequency level chosen. This is practically impossible without a local logic with a frequency sensing device. As a conclusion, EWHs were found to be technically good assets for the aggregation system because they are not sensitive to momentary power changes. It is enough that the EWHs are fully charged (i.e., the water has been heated) during a night.

The economical simulation was conducted by first calculating the income of a single site from the reserve markets. The income was simulated using real-life price information from Fingrid with different scenarios of capacity utilization rate. Table IV presents the results in more detail.

TABLE IV. UNIT LEVEL RESERVE MARKET INCOME WITH DIFFERENT CAPACITY UTILIZATION RATES

	FCR-D up, €/a			FCR-N, €/a		
capacity utilization rate	***100 %***	***75 %***	***50 %***	***100 %***	***75 %***	***50 %***
avg. nighttime price 2017	13	9	6	68	51	34
avg. nighttime price 2018	19	14	9	87	65	43
avg. nighttime price 2019	19	14	9	81	61	41
avg. nighttime price 2020	25	19	12	88	66	44
avg. nighttime price 2021	23	17	11	54	41	27
avg. nighttime price 2017–2021	20	15	10	76	57	38

The cost side of the concept can be divided into four categories: HW cost, installation cost, telecommunication cost, and other operational costs, including customer service and all other minor costs occurring during the lifetime of the product. The installation and the HW costs are onetime initial costs, while the telecommunication and "other" costs are operational costs that occur recurringly during the whole lifetime of the product. In addition to these, there are costs associated with the development of the aggregation platform and the device design, but they are not taken into account in this study. The costs used in the simulation are presented in Table V.

TABLE V. UNIT LEVEL COSTS IN THE CONCEPT

cost source	**cost type**	**initial cost, €**	**recurring cost, €/month**
hardware	onetime	50	
installation	onetime	100	
telecommunication	operational		1.5
other	operational		1

By calculating the income and costs together over the years, we can conclude that the concept is economically viable within approximately 3–6 years of operation in FCR-N when the capacity utilization rate is over 75% (Fig. 3). However, it should be noted that there is a high uncertainty in the FCR price development. In this simulation, we used realized prices for the first five years and the average value of those as projected future prices. The dotted lines represent future values. The net present value calculation reveals that the concept can produce roughly €200 profits per unit in a time period of ten years.

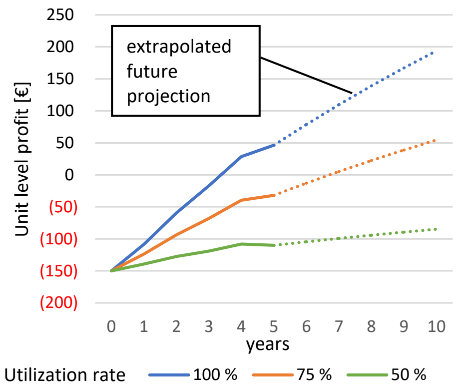

Figure 3. Unit-level profitability in ten years

V. Conclusions

The aim of this study was to evaluate the technical and economic feasibility of a concept where EWHs are being controlled remotely with a simple retrofit solution to produce demand-side capacity for primary frequency regulation. The results of the study show that the concept is indeed technically and economically feasible. The key factor to this is the simple installation employing the existing night tariff control setup traditionally implemented in Finnish households with electrical heating. A simple and standard installation is crucial for the concept, because the complexity and variation usually present in ordinary smart home installations would make the installation too expensive and turn the economic feasibility negative.

EWHs can provide primary frequency regulation capacity in certain markets in the Nordic countries. The EWHs comply with Fingrid's current requirements at least for FCR-N and FCR-D when aggregated together to produce the desired effect. However, the concept cannot provide FFR capacity because of the tight latency requirements. Also, the possible changes in the market requirements pose challenges to the concept [17].

New target use cases for the harnessed capacity could also emerge. A great example is the FCR-D down market introduced by Fingrid in January 2022. There could also be some more feasible use cases for the capacity among energy companies in, e.g., correcting the internal energy balance errors in trading.

Even though the concept is economically already viable as a retrofit solution, in the future, the cost side can be even further optimized. Because electricity consuming assets are being increasingly implemented with remote "smart" functionalities, the initial costs will be decreasing if not disappearing altogether. In the future, the DR functionalities could already be implemented in the hardware setup and taken into use by the end customers by simply clicking a button in an app.

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Electric vehicle charging as a source of Nordic fast frequency reserve—proof of concept

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ORIGINAL RESEARCH

Electric vehicle charging as a source of nordic fast frequency reserve—proof of concept

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Abstract

Demand-side flexibility or demand response (DR) has long been recognized as a potential source of balancing capacity. The charging of electric vehicles (EVs) is a known source of flexible capacity, and the vast amount of charging capacity available can be utilized for valuable applications, including ancillary power markets, by controlling the charging sessions according to the needs of the power system. One identified and unexplored potential market for EV DR capacity is the Fast Frequency Reserve (FFR) market for the Nordic system area. This article proposes and demonstrates that a home charger can participate in this extremely fast reacting ancillary service market with only software modifications made to the charger. The biggest challenge in the FFR market is the response time requirement for capacity activation. When a certain frequency limit is exceeded, the activation must happen within 0.7 s in the worst case. In this study, a laboratory test setup was constructed to test the capabilities of the FFR-enabled EV charger. The tests were conducted by building a laboratory microgrid capable of changing the grid frequency. Additionally, an economic feasibility study was carried out to evaluate the business potential of the concept in Finland. The economic study included an analysis of the concept's potential with different levels of DR service availability. The laboratory tests demonstrated the FFR capabilities of the charger and as a final outcome of the research, the Norwegian transmission system operator (TSO) approved the tested charger as a type-prequalified FFR-providing entity. The economic study revealed that the approach has good business potential, primarily because of the almost non-existent cost side even if the availability rate decreases significantly.

1 | INTRODUCTION

Rapidly increasing use of intermittent renewable production and reducing levels of natural inertia are challenging the resilience of power systems. Today, renewable energy production comprises a significant share of the generation portfolio and is even replacing some old fossil fuel-based production. Renewable production is inherently more unpredictable and less controllable, which creates increasing volatility in the balancing mechanisms handled by transmission system operators (TSOs). Furthermore, renewable production is almost always connected to the grid through power electronics, preventing possible natural inertia from entering the grid. Large generation units traditionally provided substantial amounts of inertia simply by their huge rotating mass resisting change in rotational speed.

TSOs are responsible for keeping the grid frequency stable, and in the Nordic countries, primary frequency regulation has mainly been handled commercially through TSO marketplaces such as Frequency Containment Reserves (FCR) [1]. Natural inertia has traditionally kept the frequency oscillations manageable with moderate efforts, but diminishing natural inertia is prompting TSOs to explore new solutions. For example, a new primary reserve market called the Fast Frequency Reserve (FFR) was introduced in Finland in 2020 [2]. This new market in the Nordic system area is meant to be activated in the case of severe frequency dips, and capacity offered to the FRR

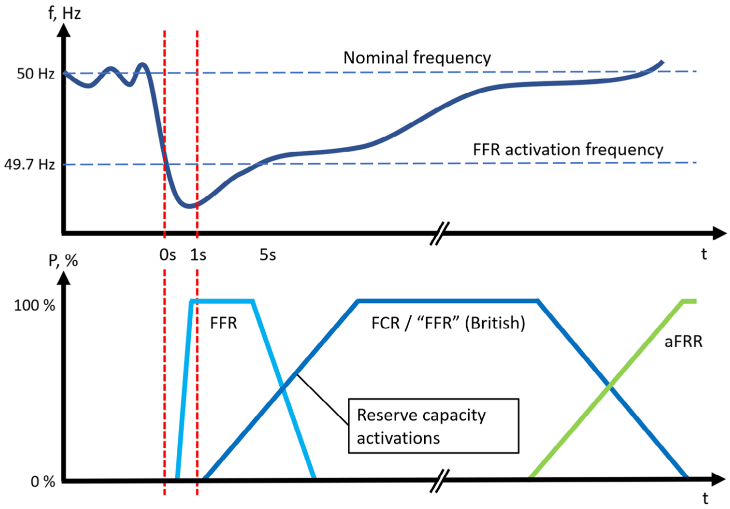

FIGURE 1 **Activations** of different frequency reserves in frequency events.

market is meant to react extremely fast (within 0.7 s in the worst case) compared to traditional reserves. Abrupt frequency changes requiring access to the FFR market can be caused by, for example, a failure in the transmission network or a large power plant. Such failures occur a couple of times per year. It should be noted that there are many reserve markets with the acronym 'FFR' which differ from the Nordic type of FFR referred to in this paper.

The decreasing inertia is a serious global phenomenon and similar mitigation actions are being taken in many countries. In addition to existing FFR services in the US and Ireland, the Australian NEM and the Italian TSO Terna are proposing similar ancillary service markets [3] and [4]. The role of these new reserves is to arrest or slow down the frequency drop before traditional primary frequency regulation resources (like FCR/British 'FFR') are able to respond to the situation (Figure 1). The less inertia there is in the system, the steeper the frequency drop, and the more substituting fast-reacting capacity is needed.

Instead of focusing only on the generation side, TSOs are now accepting capacity also from the consumption side. There are multiple known sources of demand response (DR) capacity, and DR can be harnessed from assets that have either in-built flexibility or from assets that suffer very little from possible power reductions. Thermostatically controlled residential heating or cooling loads are examples of such sources, as momentarily reducing the power used for heating or cooling does not affect the indoor temperature dramatically. This controlled reduction of heating, ventilation and air conditioning (HVAC) loads can be harnessed by DR aggregators using sophisticated control systems and used as capacity for primary frequency regulation markets, as described in [5], for example.

Batteries are an obvious asset type to use as a source of primary frequency regulation capacity as they can release or capture energy extremely fast. Depending on the mode, they can be used for up and/or down regulation. The use case of grid-connected batteries varies a lot depending on the country. In California, for example, batteries are used mainly for price optimization [6], whereas in the Nordic area, they have been used for primary frequency regulation markets [7]. In the Finnish context, these markets are not usually sufficiently valuable to support battery investment alone, and DR concepts where the batteries have another primary purpose have been invented. In such cases, the battery has the secondary purpose of acting as a source of capacity for primary frequency regulation markets. For example, the uninterruptable power supply (UPS) systems of data centres can provide ancillary services without jeopardizing their original duty of keeping the data centre operational during possible interruptions in the power supply [8].

Batteries in electric vehicles (EVs) are smaller in size than those used for data centre UPSs, but the number of EVs is rising rapidly. For example, the International Energy Agency report that sales of new EVs have doubled in 1 year [9]. At its simplest, EVs can be considered batteries on wheels, which is particularly true for vehicle-to-grid (V2G) EVs that are capable of feeding energy back to the grid. It should, however, be noted that there are not many commercially available V2G EVs; hence, a more practical approach is to treat EVs as normal consumption-side DR assets whose charging can be reduced or interrupted momentarily without causing significant harm to their users. Clearly, other factors also affect the performance and usability of EVs in DR applications. For example, they are not always connected to a charger, that is, they are not always available for

DR purposes, and EV users might wish to have a say in how their vehicle can be controlled.

1.1 | Literature review

Research has traditionally focused on distribution system level bottleneck optimization; in recent years, however, studies have increasingly examined possible use of flexible charging capacity for ancillary services of TSOs. One such case is primary frequency regulation. For example, the authors in [10] evaluate the benefits of EVs in providing primary frequency capacity and the authors in [11] investigate the utilization of EVs as sources of synthetic inertia. The main idea in these studies is to control the charging processes such that they produce an effect that mimicks natural inertia, that is, the capacity produced reacts to the deviation and/or the rate of change of frequency (RoCoF).

Similarly, bi-polar charging DR can be used for frequency support, as discussed in [12]. Marinelli et al., in [13], note that the delay in providing primary frequency capacity should be less than 1 s in order to maintain system stability in the grid area analyzed. In [14], the authors propose an autonomous V2G control scheme as in [15], where the authors take also the charging scheduling into account.

Much research related to controlled charging capacity focuses on theoretical concepts and approaches. The authors in [16] and [17], on the other hand, present concepts that they have verified in real life with proofs-of-concepts and real-life demonstrations. Additionally, in [18] and [19], the customer or user is also taken into account, which is a viewpoint that is often neglected.

In addition to studies of synthetic inertia, some works have focused on FFRs. For example, Muhssin et al. [20] propose an EV charging control method capable of providing FFR capacity in Great Britain. However, it should be noted that much research has considered 'FFR', but the acronym typically refers to other markets such as the 'Firm Frequency Reserve' [21]. The requirements and specifications of these markets vary depending on local regulations, and they often contain a dynamic and a static response component. As mentioned, previous research on 'FFR' has commonly referred to the dynamic FCR-type of reserves and is thus not directly comparable to the static, bulk response type of 'FFR' examined in this article. The authors in [22] and [23] conducted research that also covered the utilization of EV capacity for fast reacting frequency control. However, the laboratory tests in [22] were conducted with an 'EV prototype' that was actually a specially made inverter-and-battery setup representing an EV capable of bi-directional charging. Using a separate prototype inverter differs significantly from using commercially available EVs and chargers, as 'pure' inverter-connected batteries are already widely acknowledged sources of fast reacting capacity. Further, it should be noted that the authors in [23] base their conclusions on simulations only.

Although a vast amount of research has been done on controlled EV charging, to the best knowledge of the authors, the existing literature lacks information on EV charging providing ENTSO-E (European Network of Transmission System Operators for Electricity) qualifying FFR capacity for the Nordic power system area. Additionally, little research has been done that tests concepts and approaches successfully in real-life contexts. A summary of the literature review is presented in Table 1.

TABLE 1 Summary of the literature review (EVs as DR capacity).

	Primary frequency regulation		**Other**		
	Nordic FFR or similar	**FCR/FFR/PFR (droop)**	**Analyses considering**		
Ref	***Activation in < 2 s***	***Activation in > 2 s***	***Generation mix***	***V2G***	***Empirically verified***
[10]		x	x		
[11]		x		x	
[12]		x		x	
[13]		x		x	
[14]		x		x	x
[15]		x		x	
[16]		x			x
[17]		x			x
[18]		x		x	
[19]		x		x	
[20]		x		x	
[22]	x	x		x	x
[23]	x	x		x	
This paper	x				x

Abbreviations: DR, demand response; EV, electric vehicles.

The key contributions of this paper are:

- We propose and demonstrate that EV charging can be used to provide ENTSO-E qualifying FFR capacity with a commercially available (TRL9) hardware (both charger and EV) with only minor software changes made to the charger. The technical compliance to FFR requirements is validated by conducting multiple empirical tests in laboratory microgrid environment. Using real-life chargers and EVs differs significantly from earlier simulation-based studies and empirical research where inverter and Li-ion battery packs were used to approximate a V2G capable EV. The upside of using EV charging capacity for FFR rather than for droop control type-of reserves is the negligible effect on battery state of charge and degradation (as there are only few FFR activations per year in the Nordic system area)
- Our market simulation also provides evidence that the impact of this new feature in chargers is significant as the FFR-enabled charging capacity can cover a major part of the whole market need even with modest implementation rates. This new capacity is a very welcome addition to the current fast reacting frequency regulation capacity source mix as the amount of natural inertia is decreasing universally. The simulation also indicates that there is reasonable business value.

These new insights can together trigger not only new research on fast reacting EV DR but also spur further development in EV chargers, leading eventually to partly mitigating the diminishing inertia problem. To our best knowledge, this work is the first scientific techno-economic proof-of-concept of EV charger DR in a fast-reacting FFR market (with an activation time requirement of less than 2 s) using commercially available hardware.

The rest of the paper is structured as follows: Section 2 describes challenges related to the FFR market and the characteristics of utilization of EV charging in DR. Section 3 provides an overview of the technical proof-of-concept and economic analysis done in this study, followed by Section 4, where key findings are presented, focusing in particular on the reaction speed of the tested charger at FFR-triggering frequency levels and the economic potential of the concept with different numbers of controllable EVs. The impact of the concept on the FFR market and the importance of the concept is discussed in Section 5, and the research is concluded in Section 6.

2 | CHALLENGES OF EV CHARGING CONTRIBUTING IN FFR

The rapid increase in distributed energy production and power electronic interfaces in the power system has caused the amount of electrically connected rotating mass to reduce drastically. The decreasing amount of natural inertia was a major contributor to the decision to introduce a new reserve capacity market called the FRR in the Nordic system area in 2020 [2]. The FFR aims to respond as quickly as possible to large drops in the grid frequency, which can be caused by a large power plant or power transmission line tripping from the system. This drop in production causes a huge imbalance in the production vs. consumption equilibrium, which changes the frequency level.

TSOs need to purchase an ever-growing amount of FFR capacity as the natural inertia diminishes. EVs, on the other hand, are a known source of flexibility since they can store electrical energy and do not need to be charged all the time. Thus, EVs could relieve the need of TSOs for fast-reacting FFR capacity if EV chargers could be used technically, economically, and practically as qualifying assets for the reserve market.

2.1 | Availability of EV capacity for FFR

One aspect affecting the practical usability of the concept is the availability of grid-connected EVs, that is, EVs that are being charged. EV charging can happen in many places, such as at home, during a visit to a shopping centre, at an EV fast charger at a service station etc., and the characteristics of DR with EVs depend heavily on the type of charging session. Basically, the key properties affecting the availability of DR capacity from EV charging are the number of controllable EVs, the charging power or energy, the criticality of the charging, and the general acceptability of participation in DR activities.

For normal users, the most natural place for charging to occur is at home overnight. It is also probably the charging type providing the best opportunities for DR. Typically, the car is plugged into the charger when a person comes home and unplugged when leaving for work. Naturally, there is some uncertainty during the evening when people use their cars occasionally but in most cases the car stays parked and connected at night. This gives DR aggregators an opportunity to use the charging capacity as flexible capacity in their operations. However, the charging power of most home EV chargers is fairly limited compared to fast chargers. A typical 3-phase home charger in Finland is rated for 11-kW power. Similarly rated chargers can be found also in shopping malls and other public areas. However, the availability and acceptability of reducing the amount of charged energy is clearly lower with public chargers since users might need to charge their EV as much as possible during the stop. A clearly more difficult situation for DR is fast charging. Although the power of fast charging is usually high, those who use fast charging stations have usually arrived at the charger primarily to charge their vehicle, which means that the charging is critical for their trip and reducing the charged energy will limit the range and hence jeopardize continuation of their journey. Public chargers also introduce much more uncertainty since they tend to be used more randomly than home chargers.

Of course, with some reserve markets, DR activations do not reduce the amount of charging energy significantly, making DR activities more acceptable and suitable for charging sessions that have higher demand for availability. One such reserve market is the FFR market because it has an extremely short activation duration (which would reduce the amount of charged energy) and a low number of activations per year. Indeed, DR activities for the FFR market can be considered to have negligible effects on consumed energy. Furthermore, the market is still reasonably priced compared to other frequency regulation markets [24], making it a perfect target market for DR using EV charging applications.

2.2 | Requirements for FFR capacity providing assets

In order to contribute in the FFR market, EV chargers need to meet stringent prequalification requirements defined by TSOs. TSOs in the Nordic countries have agreed to use common ENTSO-E specifications for FFR purchases [25], [26], and [27]. The specifications give three optional grid frequency activation levels that determine the activation time (Table 2) [27]. The greater the frequency dip, the faster the activation should happen.

The FFR has two ways to deactivate capacity. In the first method, the capacity should be deactivated with a ramp response. With this method, the full activation needs only last for 5 s (Figure 2, allowed response inside the area marked with diagonal lines). The idea of the ramp response is to minimize sudden dramatic power changes during the frequency dip in order to reduce oscillations during the abnormal frequency event [27].

TABLE 2 Activation steps and corresponding activation speeds in FFR [27].

Frequency level, Hz	Reaction speed, s
49.7	1.3
49.6	1.0
49.5	0.7

Abbreviation: FFR, fast frequency reserve.

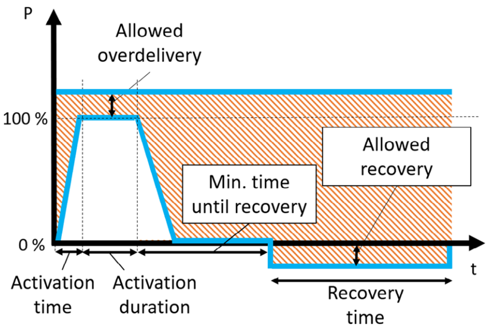

FIGURE 2 **Required** activation pattern in short FFR activation [27]. FFR, fast frequency reserve.

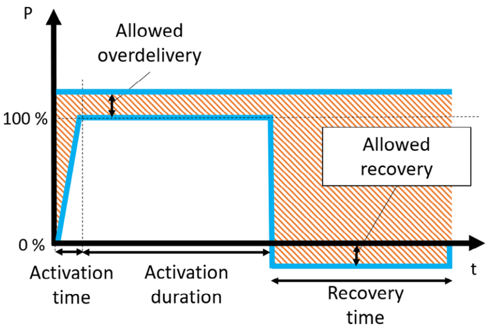

FIGURE 3 **Required** activation pattern in long FFR activation [27]. FFR, fast frequency reserve.

The second capacity deactivation method allows an immediate stepwise power change (Figure 3). However, the full activation capacity must be provided for a longer time (30 s) when using this method. With either approach, the asset should be capable of performing another activation after 15 min. An overshoot of 20% is allowed and the assets are also allowed to recover with 20% power intake in order to be available for the next possible activation. This permitted recovery mainly applies to batteries or other assets that feed energy to the grid rather than just stop using energy during an activation [27].

If EV charging could be verified as complying with the FFR requirements, as proposed in this paper, a huge amount of valuable capacity could be released for use to mitigate problems TSOs might face in sudden frequency imbalance situations, making the concept also attractive to DR aggregators.

3 | PROPOSED METHODOLOGY

3.1 | Empirical tests with a laboratory microgrid

To verify the functioning of the concept in practice, a series of laboratory tests were conducted in a laboratory microgrid with a charger unit with modified firmware to see if the charger could qualify as an FFR-capacity providing entity. An activation frequency of 49.7 Hz was chosen as the triggering value, meaning that the activation should happen in 1.3 s, according to the FFR specifications [27]. Modifications were made to the charger's firmware in order to get the safety relays to trip if the supply frequency drops below 49.7 Hz. The idea in the microgrid test setup was to emulate an under frequency situation in the grid that would activate FFR capacity. This approach was adopted because frequency levels triggering FFR resources are very rare in real power systems. Moreover, the prequalification specifications state that the FFR-providing entity should be tested with synthetic frequency signals [27].

There are several alternatives for conducting the prequalification tests. The prequalification documents state that tests should be conducted on single assets providing at least 1 MW of FFR capacity. However, there is also a possibility to conduct type qualification tests on control units that are less than 0.1 MW in power. Thus, the TSO and FFR capacity provider can save resources by avoiding multiple similar tests with control units that have already been qualified for FFR [27].

The main aim in the FFR prequalification tests is to verify the activation speed and power. Two alternative methods can be used to measure the correct activation. The first approach is to use an artificial external frequency signal fed into the control system controlling the asset providing the FFR capacity. The same frequency signal should also be fed to the measuring device that logs the activation power. From the acquired data, it is possible to measure the latency from the time the frequency drops below the chosen frequency level to the time when the promised FFR capacity is supplied. In this case, no power is supplied back to the grid, but rather the stable consumption is interrupted, resulting in the desired effect.

The second method is to use an internal synthetic frequency to trigger the activation. In this method, the test frequency is pre-defined and pre-coded to the control device. The test frequency signal is also logged by the measuring device together with the effect on the power of the FFR-providing entity. With this method, however, the correct behaviour of the FFR-providing unit must also be complemented with tests against natural frequency in the range of 49.9 and 50.1 Hz with

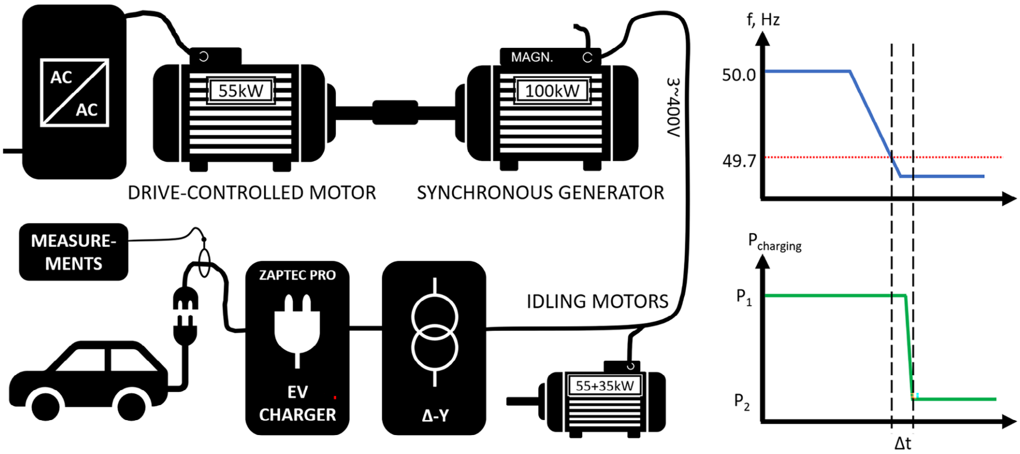

FIGURE 4 **Laboratory** setup for the EV charger FFR type tests and the test procedure. EV, electric vehicle; FFR, fast frequency reserve.

higher set tripping frequency. The idea is to verify the correct behaviour with an external or non-predefined signal, which rules out the possibility of pre-defined fake activation.

Two alternative test frequency signal patterns can be used to verify the FFR capabilities of an asset: a step response test and a ramp test. In the step response step, the frequency is reduced to just above the targeted activation frequency after a 2-min steady-state period and then to just below the activation frequency. In the ramp test, the test frequency is gradually decreased at a steady pace past the chosen activation frequency. The idea of the aforementioned methods is to create a clear point where the activation should have happened for an accurate activation time evaluation.

Since it was very challenging to program or feed a synthetic signal to the charger unit, the under frequency had to be produced manually in the tests in this study. This under frequency event was implemented by generating the feeding power with a laboratory microgrid, illustrated in Figure 4, comprising a 100-kW rated three-phase synchronous generator. In the setup, the generator torque is provided by a 55-kW rated induction motor powered by a three-phase frequency converter (ABB ACS880). This setup allowed the grid voltage to be controlled by the synchronous generator excitation circuit control and the frequency by the induction motor rotational speed control. The inertia of the test microgrid was increased by adding a 35 and a 55-kW rated motor idling to provide additional rotating mass. Increased inertia on the grid aided maintenance of grid frequency stability under rapid load changes.

The main benefit of using such a network in testing is that the voltage and frequency can be controlled. It is also worth mentioning that such a test network is nearly free of harmonics and other noise typically seen in actual distribution grids. An isolation transformer was added to the system before the charger to generate a TN-network with a grounded neutral-phase. The charging setup was monitored by utilizing power analyzers on the charger feeder side and charger output side.

Testing with such a method can be considered testing with a 'synthetic natural frequency' signal. Although this kind of testing is not explicitly described in the FFR prequalification document, it is in line with the specified method of using a synthetic external test frequency.

Because of the setup, the FFR prequalification test with a frequency ramp was the only practicable way to conduct the tests. The individual tests were conducted by altering the supply frequency according to the required test program (Figure 4, right side). First, the frequency was kept constant for 2 min and then it was slowly decreased (approximately −0.01 Hz/s) to reach the predetermined limit (here 49.7 Hz). The idea was to determine how fast the charging load dropped to idle level after the frequency limit was reached. The tripping time (activation time) of the charging load was then calculated from the point where the frequency reaches the chosen activation threshold to the time when the charging load reached the idle load level. The measurements (frequency, voltages, and currents of the feeding network) were recorded using a precision power scope (Yokogawa PX8000) connected to measuring instruments (including Hitec B200 current sensors (1:100A) located between the charger and the car (Figures 4, 5)). The laboratory data were also compared to data gathered from the charger manufacturer's cloud service, as the charger measures also the grid frequency and charging power. Of these values, the power value is sent to the cloud system, via a mobile network, where it can be stored for FFR verification.

Several tests were done to establish whether the car model and charging power affect the charging behaviour and functioning of the FFR feature. The main focus of the tests was to ascertain if the charger could fulfill the activation time

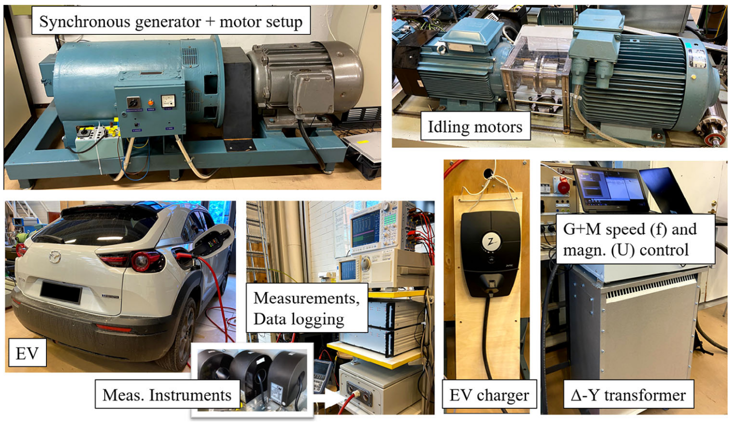

FIGURE 5 **Laboratory** test setup.

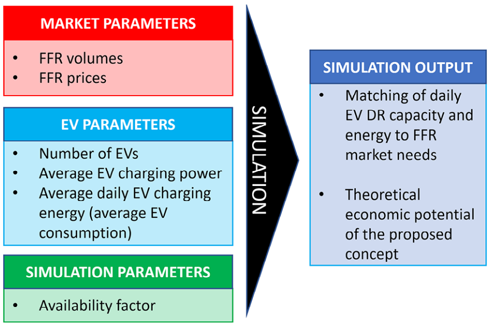

FIGURE 6 **Economic** simulation model.

requirement of the FFR market. The tested cars included a Peugeot e2008, Mazda MX-30 and Tesla Model 3.

3.2 | Economic analysis with different EV availability

An economic simulation (Figure 6) was carried out to evaluate the business and market potential of the studied concept in Finland using historical FFR price and volume data from 2020 to 2021 [28]. Availability and the price development of the FFR market are the most uncertain parameters affecting the economic feasibility. Hence, a series of scenarios with different availability percentages was included in the simulation. It is assumed in the simulation that the availability contains the uncertainty of charging behaviour, that is, whether the EV is being charged at home, at a public charger, or whether the EV is left unplugged at night. Availability also includes uncertainty related to user preferences; sometimes a customer does not want to take part in smart charging activity due to a possible range-critical journey the next day. It also includes the assumption that only a minority of EV users want to take part in a DR-enabled charging program for various reasons [29].

The number of EVs is also a vital parameter affecting the economic potential of the studied approach. In recent years, the number of EVs in Finland has grown at roughly 100% p.a. [30], that is, the number of EVs has doubled every year from 2017 onwards. There has been a slight decrease in the rate of increase of plugin hybrid electric vehicles (PHEVs), but the number of full EVs is growing at an even faster pace.

To analyze the economic potential of the concept, the hourly EV capacity must be multiplied by hourly FFR prices (data available in Fingrid's portal [28]). In this simulation, it is assumed that the chargers participating in FFR-enabled smart charging would participate between 21:00 and 07:00 h every night.

Firstly, the amount of available charging energy must be compared to the purchased FFR capacity during the DR-enabled charging session to establish whether the charging energy is enough to cover all the energy that would have been needed for the FFR during the simulation period (years 2020–2021, hours from 21:00 to 07:00 h). The amount of energy needs to be calculated because the chargers should be charging all the time the DR service is offered in order to be ready for possible FFR activations (power reduction). Naturally, when the EVs are fully charged, charging capacity is no longer available for utilization in the FFR.

In this simulation, we assume that the electrical energy consumed by PHEVs is 50% of the total 'full EV' energy consumption. The official WLTP-based consumption information of the most common PHEVs suggests that average annual electrical consumption would be much higher, but real-life consumption

TABLE 3 Availability scenarios used in the simulation.

Scenarios	Availability	Controllable EVs	Controllable PHEVs
Scenario 1, optimistic	15%	4134	12,641
Scenario 2, moderate	10%	2756	8427
Scenario 3, pessimistic	5%	1378	4214

Abbreviations: EV, electric vehicles; PHEV, plugin hybrid electric vehicle.

analyses in [31], for example, suggest lower electricity/petrol ratios. The average yearly electricity consumption of an EV can be calculated by multiplying the statistical yearly mileage to the average electricity consumption. The average yearly mileage of an EV is assumed to be the average (2010–2017) yearly mileage of the category 'other fuel car' in the Finnish Agency for Transportation and Communication (Traficom) statistics [32]. The average consumption of an EV per kilometre is assumed to be 0.2 kW/km, as in many other studies, for example, [33].

The second limiting factor is the maximum DR capacity. It is assumed that the average home charging power is 6 kW for full EVs and 3.6 kW for PHEVs. A charger of 11 kW is common for full EVs, while single-phase 3.6 kW chargers are a common choice for charging a PHEV. However, not all EV owners can install or fully utilize 11-kW chargers because of limitations in existing electrical infrastructure in their properties. The assumed charging powers are multiplied by the number of EVs and the availability rate to give the maximum DR capacity for the FFR. To calculate the monetary potential, the maximum theoretical aggregated available DR capacity is compared to the data series of hourly purchased FFR capacity and price, Equation (1). The total DR value (*DRvalue*) is the product of the purchased FFR capacity (P_{bid}) and price (*FFRprice*) for each hour (t) taking into account that not all the FFR market needs can be fulfilled when there are limitations in the maximum DR capacity (P_{dr}) in different scenarios. Similarly, if the available capacity exceeds the amount of purchased capacity (P_{ffr}), some of the available capacity cannot be used, Equation (2). The parameter T represents the total number of hours of the chosen test period.

$$DRvalue \ = \sum_{t=1}^{T} FFRprice_t * P_{bid}(t)_t \tag{1}$$

$$P_{bid} \ (t) = \begin{cases} P_{dr}, \ P_{dr} \leq P_{frr} \\ P_{frr}, \ P_{dr} > P_{frr} \end{cases} \tag{2}$$

Because of the high uncertainty of availability, three different scenarios were investigated to demonstrate the sensitivity of the parameter (Table 3). It should be also noted that FFR prices follow the law of supply and demand. The more capacity that is available compared to the market needs, the lower the price, and vice versa. This dynamic is not taken into account in the simulation.

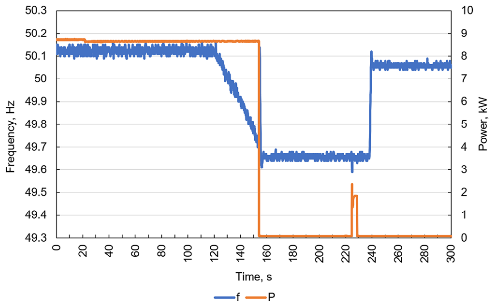

FIGURE 7 FFR ramp test with the charger charging a **Peugeot** e2008. FFR, fast frequency reserve.

TABLE 4 Compliance of the results with the main FFR requirements.

Car model	Activation speed ≤ 1.3 s (max tripping time, s)	Activation duration ≥ 30 s	Reactivation capability ≤ 15 min
Mazda MX-30	Pass (1.3 s)	Pass	Pass
Tesla model 3	Pass (1.3 s)	Pass	Pass
Peugeot e2008	Pass (1.0 s)	Pass	Pass

Abbreviation: FFR, fast frequency reserve.

4 | NUMERICAL AND EXPERIMENTAL RESULTS

4.1 | Laboratory tests

The results of the technical proof-of-concept tests show that the charger tripped inside the required activation time after the grid frequency dropped below 49.7 Hz with all tested car models. The activation also lasted over the requirements of the FFR activation duration (> 30 s). As the charger tries to re-start the charging after at least 1 min from the FFR activation (which can be seen in Figure 7), it would have been ready for the next activation within 15 min as required by the FFR specification. Although there was noise in the frequency measurements of the testing environment, which caused some of the verifications to fail, it can be concluded that the charger fulfills the technical type-prequalification requirements of the FFR. However, further testing could be done to increase the reliability of the results. The results of successful tests are summarized in Table 4.

One interesting finding visible in the results was the generator rush phenomenon. Since the inertia of the laboratory microgrid setup was low, the rush effect could be seen. When the charger stopped the charging (the FFR tripped) the sudden change in the loading caused the generator to temporarily gain a too high speed, which can be seen in Figure 8 as a spike in the frequency. However, the spike occurred, of course, after the tripping and the results can thus still be considered valid.

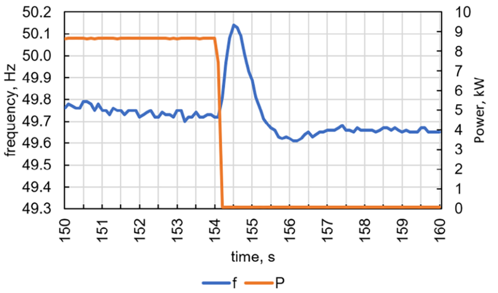

FIGURE 8 **Activation** of the charger charging a **Peugeot** e2008.

Another interesting finding was that the Tesla Model 3 had an internal mechanism to lower the charging power according to the rate of change in grid frequency. This mechanism only occurred when the frequency was lowered at moderate speed. When the frequency was reduced at fast speed (which is usually the case in events activating the FFR and required in the stepwise test procedure), no power ramp down effects were visible. Also, if the frequency was lowered slowly, the charging stopped, as expected, at the set threshold. The behaviour of Tesla 3 and Mazda MX-30 can be seen in Figure 9.

Finally, the measurements gathered by the charger itself were compared to the values of the laboratory measurements. It was noticed that the power values followed the laboratory values well even though the smallest fluctuations were not stored. The average difference between the power measurements in the tests was 98 W (1.48%), which is probably partly explained by losses occurring between the two measuring points.

4.2 | Economic analysis

In the economic analysis, the amount of daily EV charging energy was first compared to the energy required to fulfill the statistical FFR needs. The simulation showed that the amount of EV charging energy does not limit the availability for DR as the aggregated average daily charging energy is more than any of the daily FFR purchases made in the simulation period (years 2020–2021, hours from 21:00 to 07:00 h). The maximum DR capacity was, on the other hand, more limiting (Figure 10 and Table 5).

From Figure 6, we can see that in Scenarios 2 and 3, the available controllable capacity would limit the potential. However, even with Scenario 3, over 80% of the monetary potential would be already covered (Table 6). It should be also noted that Scenario 1 would already cover the whole FFR market capacity need and higher availability rate or number of controlled chargers would not produce any extra benefit.

An interesting finding that can be seen in Table 6 relates to the volatility of the FFR market. The statistics [28] show that the amount of FFR capacity procured in 2021 increased from the previous year. However, the price for the capacity decreased at the same time. This decrease in price reduced the economic potential in Scenario 3 even though the total market value remained stable. Nevertheless, the results show that the concept has good business potential even if FFR prices were to decrease in the future. The approach benefits from the almost non-existent additional costs related to its implementation in EV chargers. If a charger can react to the highly demanding latency requirements, the only investments needed are software-related investments to the aggregation platform and the chargers.

5 | DISCUSSION

This work has focused on EV charging and its potential as an aggregated capacity source for the FFR reserve market. EVs are considered a promising source for primary frequency regulation, but according to the best knowledge of the authors, their utilization for the extremely fast reserve market has not been verified empirically earlier. In summary, the results confirmed that from the technical and economic standpoint, EV chargers can be utilized as type prequalified FFR-providing assets to deliver much needed fast-reacting flexible capacity to the power system when aggregated together by an aggregator who ensures that bid capacity is always available.

The most important factor affecting the availability and, further, bidding optimization is the predictability of the charging

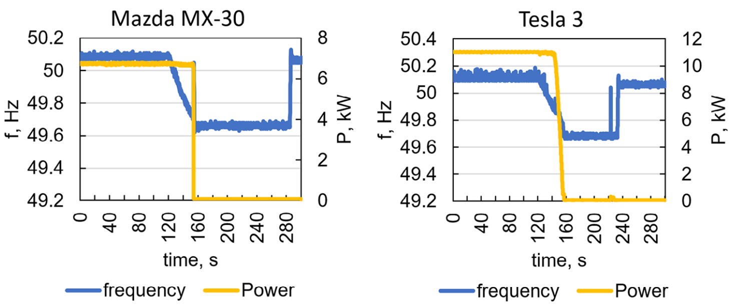

FIGURE 9 **Activation** with **Mazda** MX-30 (left) and **Tesla** 3 (right).

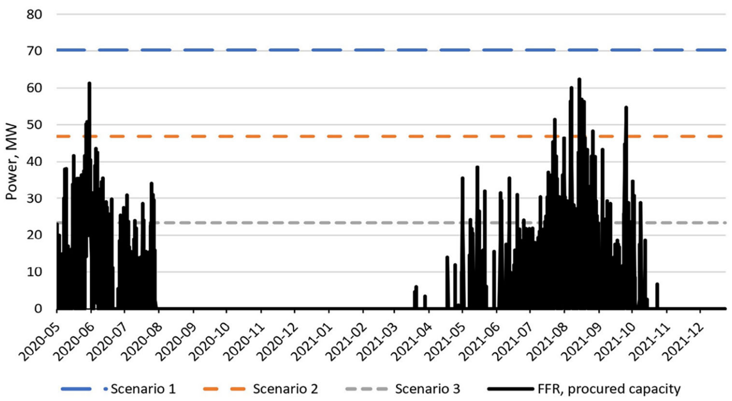

FIGURE 10 **Theoretical** charger DR capacity and actual FFR purchases in 2020 to 2021 (hours from 21:**00** to 07:**00 h)** with different scenarios of availability. DR, demand response; FFR, fast frequency reserve.

TABLE 5 Maximum available FFR capacity from EV charging with different scenarios.

Scenarios	EV DR availability	Max. EV charging (DR) capacity, MW	Max. procured FFR capacity, MW
Scenario 1, optimistic	15%	70.31	62.4
Scenario 2, moderate	10%	46.87	62.4
Scenario 3, pessimistic	5%	23.44	62.4

Abbreviations: DR, demand response; EV, electric vehicles; FFR, fast frequency reserve.

sessions. For example, the state of charge and the usage patterns of the EVs as well as customer willingness to enroll in a DR program play a crucial role when predicting the usable capacity. These factors are generalized in this study as the availability rate.

Naturally, when a bid has been placed, a matching amount of capacity must be also delivered when requested. This can be ensured by monitoring the consumption of the chargers in real time and enabling FFR functionality in a large enough number of chargers to match the bid size. Risks related to unavailability can be mitigated by reserving an adequate amount of back-up capacity. These tasks could be done automatically by an aggregator using cloud-based software. Testing a larger fleet of FFR-enabled charging sessions in real power system would be a good subject for future study to further validate the concept.

Harnessing the charging capacity through cloud solutions ensures the economic feasibility of the concept even if FFR prices were to decrease significantly. However, the results also revealed that the market will saturate quite fast as the number of connected chargers increases. It is very plausible that the whole FFR market might be covered by EV charging capacity, at least during nighttime, which could be the case in countries with a high number of EVs. For an aggregator, this saturation will mean that some of the chargers cannot join the aggregated pool of FFR-enabled chargers. Yet, this does not necessarily mean that the chargers cannot join DR activity in general. As the chargers meet the tight requirements of FFR prequalification specifications, they will certainly qualify for markets with slower reaction times. However, more advanced aggregation methods must then be developed to be able to perform the more delicate control required in, for example, FCR markets.

The theoretical economic value of the approach in countries other than Finland (with existing FFR or similar market) is, of course, highly dependent on the number of EVs in the country and FFR prices. In countries with high EV penetration, the approach provides more capacity, which, of course, affects the total value as not all available FFR capacity from FFR-enabled chargers can be utilized. As the number of EVs is growing all the time, and because of the volatility of FFR markets, reliable estimation of the future value of the approach is very challenging.

TABLE 6 Total yearly economic value of the concept with different scenarios of EV DR availability, years 2020 and 2021.

	Scenario 1 optimistic, €/a	Scenario 2 moderate, €/a	Scenario 3 pessimistic, €/a	Procured FFR volume, MW, h	Average FFR price, €/MW,h
Controllable EVs/PHEVs, pcs	4134/12,641	2756/8427	1378/4214		
2020	781,192	778,827	676,530	9549	29
2021	807,703	793,095	630,639	16,844	23
AVERAGE	794,447	785,961	653,585	13,196	

Abbreviations: DR, demand response; EV, electric vehicles; FFR, fast frequency reserve; PHEV, plugin hybrid electric vehicle.

The approach has negligible effects on the charging experience of EV users, since according to Fingrid's frequency quality reports [34], levels activating FFR capacity have historically been rarely reached in the Nordic power system (16 times in 2022). Moreover, the unavailability of a charger in the case of an activation lasting less than a minute is short compared to the overall length of the charging session. It can thus be stated that the concept has no real negative impacts on the EV user in practice. Indeed, the opposite may be the case as the aggregator can even share with the EV user a portion of the FFR revenue gained.

An important topic that deserves more research is customer acceptance of this kind of concept. Would customers accept DR activity without any compensation for participation? And if compensation is required, how much should it be? Additionally, the economic feasibility of the concept in other countries could be studied because there could be other fast reaction capacity reserve markets elsewhere which could benefit from the approach presented in this work.

6 | CONCLUSIONS

As many previous EV DR studies have focused on other use cases or markets for demand capacity, there was a clear need to conduct practical research on fast-reacting (activation in < 2 s) DR for primary frequency regulation. One such market is the FFR market in the Nordic power system area. Since natural inertia in the power system is decreasing, the FFR market was introduced in 2020 to help the system cope with fast frequency drops. In this article, we propose and demonstrate in real life that a typical EV charger can participate in this ancillary power market as a type-prequalified FFR resource with only software modifications made to the charger.

The biggest technical challenge in the ENTSO-E specified FFR market for the Nordic system area is the response time requirement to activate capacity when a certain grid frequency level is exceeded. A series of laboratory tests were conducted to reveal the actual capabilities of the FFR-enabled charger. The tests were done by setting up a laboratory microgrid with the possibility to alter the system frequency. By lowering the microgrid frequency, it was possible to see if the charger reacted appropriately to an underfrequency that should normally trigger FFR capacity. An economic simulation was also conducted to evaluate the business impact of the concept.

The laboratory tests revealed that the tested FFR-enabled charger reacted properly to the underfrequency situations and hence meets the FFR requirements. The economic simulation demonstrated that the value of the concept is significant. It should also be noted that the FFR-enabled charger was later accepted by a Nordic TSO as a type prequalified asset for aggregation as FFR capacity. To the authors' best knowledge, this is the first of a kind scientific proof-of-concept work demonstrating an EV charger with FFR capability (Nordic type of FFR where the activation must happen in 1.3 s or less), and the first time an EV charger has been type prequalified for utilization in the (Nordic) FFR.

AUTHOR CONTRIBUTIONS

Pekka Manner: Conceptualization, Methodology, Writing- Original draft. Ville Tikka: Methodology, Investigation, Data curation. Kyösti Tikkanen: Investigation. Samuli Honkapuro: Supervision, Writing—review & editing. Jamshid Aghaei: Writing—review & editing.

CONFLICT OF INTERESTS STATEMENT

The authors declare no conflict of interest.

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DATA AVAILABILITY STATEMENT

The data produced during the research work is not publicly available.

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