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Mobile base station site as a virtual power plant for grid stability

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ABSTRACT

Energy grids and markets are in transition. Increased use of renewable energy sources (RES) introduces new stability challenges for power grids. Despite the substantial electrical consumption of mobile networks, they are yet to harness their inherent flexibility for aiding in the stability of the power grid. A noticeable research gap exists concerning measuring full activation time for fast frequency reserve (FFR) product while using batteries from mobile network base stations. Our objective is to demonstrate that mobile operators could use their existing infrastructure to participate in the reserve market of a contemporary power grid. Furthermore, it seeks to determine if the full activation time can meet the requirements of an FFR product. The system consists of a live mobile base station site with a mobile connection to the site, local controller, an existing battery, and a power system that, in combination, can function as part of a power grid balancing system. Our main finding indicates that the rectifier reaction time within an installed base station site infrastructure ranges from 5 to 8 s, and the time when the base station is entirely off from the grid varies from 7 to 10 s. This finding is significant since the activation time is too long for the base station power system controller to be used for FFR. The required full activation time for FFR is less than 1.3 s. In conclusion, power system vendors should investigate improvements for their equipment and software products to enable fast reserve market entry for their existing customers and stay competitive.

1. Introduction

The journey to net zero emissions in the Nordic countries requires a significant transition of the current power grids. For this journey, power grid providers need all the help from all grid participants. Grids face multiple challenges: market, political, legislative, grid development, and stability. According to a report by Svenska Kraftnät, Energinet, Fingrid, and Stattnet in 2023, grid stability is one of the most urgent challenges. The report states, “With increased devices connected to the grid via power electronics (wind, solar, batteries), the power system may become unstable in several ways not experienced before.” [1].

The mentioned new stability challenge mainly relates to decreasing inertia in power grids due to the rapidly increasing share of RES. Therefore, it is time for mobile network operators to step up and do their part in stabilizing grid frequency by providing a virtual power plant (VPP) solution covering all feasible reserve market products.

Renewable wind and solar power generation are crucial to the world. These new power sources help reduce reliance on combustion based electricity generation, thus decreasing greenhouse gas emissions, air pollution, and health problems. In addition, they provide economic growth and increase self-sufficiency. Renewables combined with nuclear power (fossil-free grid mix) will provide most of the world’s electricity by 2030, according to the International Energy Agency (IEA), published by the World Economic Forum [2]. Despite all the positive impacts, the increased usage of renewable sources contributes to the challenge of decreasing inertia in power grids.

The primary motivation to conduct this study stems from the lack of precise data regarding the latency characteristics of the novel Fast Frequency Response (FFR) reserve product, particularly within the context of mobile network infrastructures. No articles were found where

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measurement setup would have been described or what are actual delay times for reaction time. This research gap is especially important given the increasing integration of mobile technologies in grid stability mechanisms and the critical nature of response times in frequency regulation services. Fig. 3 at the end of the introduction is visualizing article content and scope.

For to be able to fill this gap in the industry will analyze the most recently launched FFR product, covering aspects such as how it can be implemented around mobile network base stations with live traffic by using the on-site equipment and how well such setup meets the requirements of the FFR product. Based on our knowledge, no publicly available research has been done on the FFR product. This lack of FFR test results reveals a clear research gap for VPP usage with FFR in mobile network space.

A Recent study published in International Journal of Electrical Power & Energy Systems [3] studied distributed control of a virtual storage plant for frequency restoration services. This research provides valuable information related to communication delays and synchronization and demonstrates the importance of this aspect [4].

In Chapter 3.7, Methods for Testing, we provide a detailed description of the experimental setup to ensure reproducibility by other researchers using comparable equipment. The testing was implemented on an operational network site under real-world conditions. Our analysis revealed significant latency issues and identified specific optimization opportunities within the existing power controller software to reduce response times.

Due to the EU directive's targets, all industries increasingly focus on energy consumption and replacing fossil energy with RES, such as wind and solar power. The directive (EU) 2023/2413 sets a target of 42.5 % of the EU's total energy consumption covered by the combined solar and wind energy contribution by 2030. Their share in 2021 was 19.5 %, as shown in Fig. 1.

To meet the target of 2030 within the next six years, the EU must more than double the share of wind and solar energy produced [5]. Fig. 2 illustrates a discernible trend: wind and solar energy are emerging as the predominant power sources on the upswing. These two sources do not possess natural kinetic energy and, therefore, will decrease inertia in power grids [6].

Based on the trends presented, the increasingly popular RES continues introducing challenges to the power grid, and the inherent volatility of renewables makes it harder to maintain a stable and functional power system. As stated, the most challenging feature is the lack of inertia in the electricity generated by the inverters of wind turbines

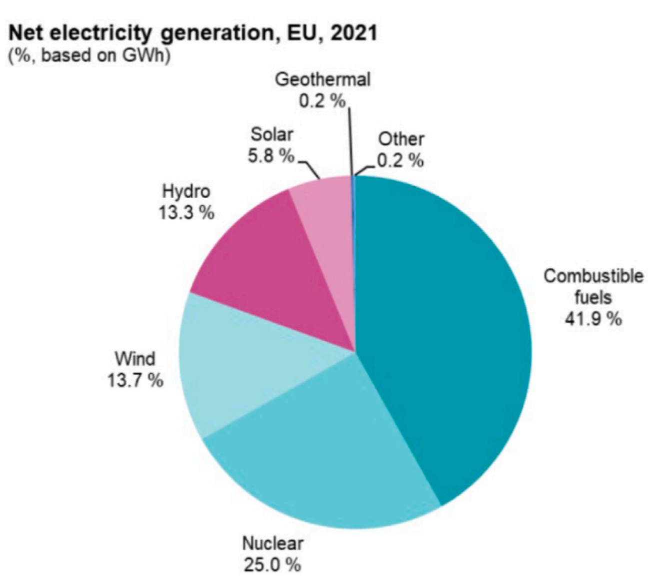

Fig. 1. Net electricity generation in the EU (2021).

and photovoltaic arrays and the increased use of more efficient electric drives in heavy industry. The European Network of Transmission System Operators for Electricity (ENTSO-E) defines the inertia of a power system as follows: "Inertia of a power system is defined as the ability of a system to oppose changes in frequency due to resistance provided by the kinetic energy of rotating masses in individual turbine-generators" [7].

Despite challenges in inertia, RES production is still predictable, as weather forecasting can accurately forecast wind and solar power generation for two to three days ahead of the target [8]. This capability enables VPP providers to anticipate demand and engage in market activities as required.

In addition to wind and solar energy, there is some adjustable power generation capacity from hydro and gas turbines. Those can be used based on weather forecasts to balance the systems with a large share of RES, but as seen from the trends provided by Ember, the share of gas is declining, and hydro has remained stable [9].

Considering these facts, the growing share of RES has increased the demand for balancing. However, the current balancing mechanisms are inadequate, and power grids will encounter significant challenges if new balancing methods, such as VPPs, are not widely adopted by all industry stakeholders, including mobile network operators [10].

Our study investigates the full activation time of FFR product. FFR was chosen as the focus due to the lack of publicly available data on reaction times in the mobile operator environment. Notably, the ENTSO-E report titled 'Fast Frequency Reserve – Solution to the Nordic inertia challenge' from 2019 identifies FFR as the most promising mitigation measure for addressing low inertia [11]. FFR is used widely with different names but the same logic worldwide, which increases the importance of the results from this article [12].

Results from our test demonstrate that the full activation time for the base station to fully use power from the batteries instead of using it from the grid is too slow. The requirement for end-to-end delay for full activation for FFR product is 1.3 s, and in our results, full activation time ranged between 7–10 s.

Following Fig. 3 provides holistic overview of the article contribution and main aspects.

The rest of the paper is structured as follows. In Chapter 2, we review the relevant literature and summarize the findings in the table. In Chapter 3. "Material as methods used in the research," test methods are explained in detail. Pictures from the setup and system diagrams are used to visualize the research setup. Chapter 4 summarizes the results found based on the field measurements. Chapter 5 discusses the main findings and possible future research; in Chapter 6, we conclude this article.

2. Literature review

Rasmus Sjöholm's thesis examined the application of VPP to a mobile network operator use case: "Engineering Virtual Power Plant – Implementation in Radio Base Stations Analysis of the World Situation of Virtual Power Plants and Feasibility of Implementing Them in Radio Base Stations". The thesis covers essential implementation aspects for a base station based VPP [13].

Ilari Alaperä, Pekka Manner, Johan Salmelin, and Heli Antila conducted a study using base station batteries, analyzing the motivational background and pilot results. Although the study does not directly relate to virtual power plants, it provides insights into using base station batteries and helps understand the feasibility of implementing virtual power plants in base stations [14].

Satoshi Sugita, Takahasi Shodai, Shigemichi Watanabe, Yousuke Nozaki, and Yuji Kawagoe studied overall telecom energy trends and how the usage of VPP contributes to the increased demand of decarbonizing society. This study helps understand the feasibility of implementing VPPs in the telecom industry, including mobile operator virtual power plants. [15].

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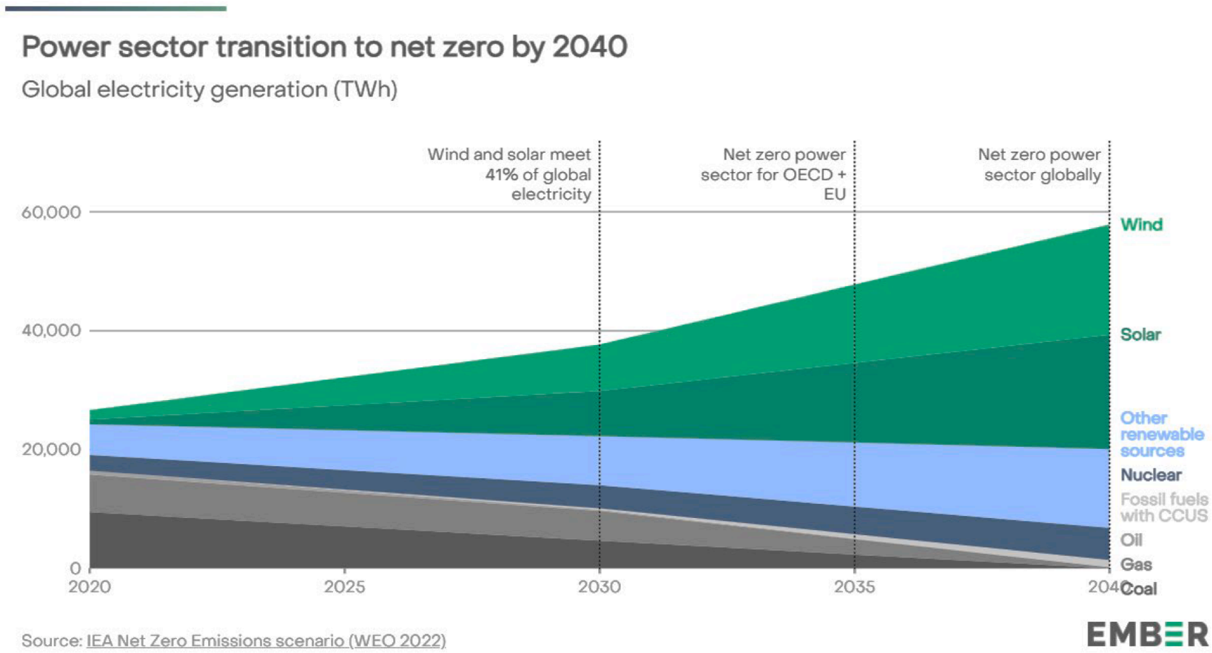

Fig. 2. Power sector transition to net zero by 2040.

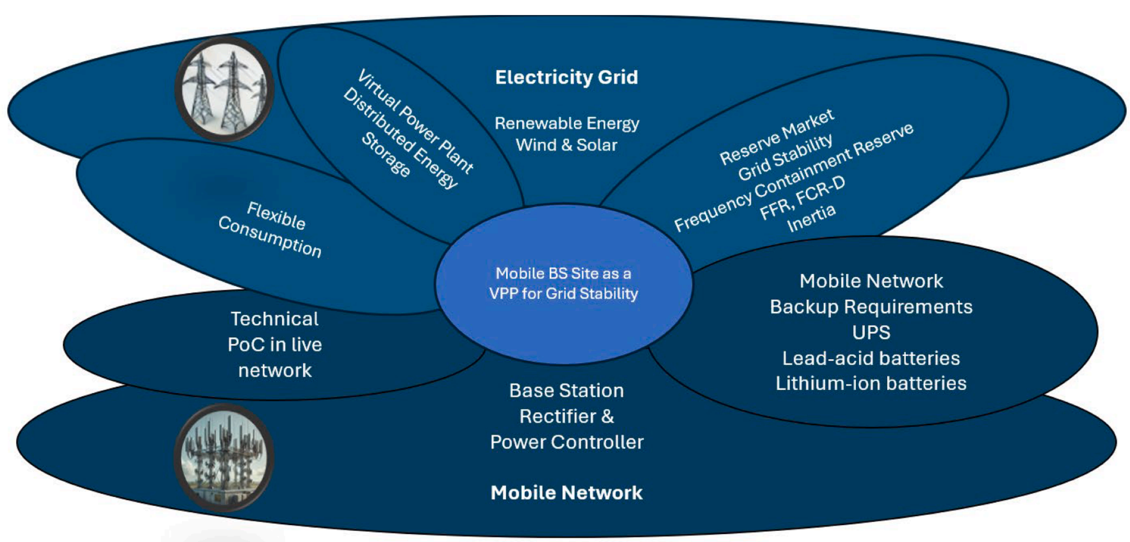

Fig. 3. Research position in the landscape of reserve markets.

Manner, and Eva Pongracz pointed out an essential aspect of safe usage of the battery based VPP. It is crucial to understand base station energy usage with live traffic. Without up-to-date information about electricity consumption, it is impossible to ensure that batteries always have enough energy for the base station to stay functional. The article shows base station energy use measurements with live traffic [16].

Tomasz Poplawski, Sebastian Dubzik, Piotr Szelag, and Janusz Baran researched how data provided by VPPs during usage can forecast and analyze the future of power sources and the grid. The article offers valuable insight into a broader understanding of different VPP implementation methods. An energy storage option related to our research is also covered. In addition to the infrastructure, the article covers software applications needed to control and monitor a VPP implementation [17].

Özge Pınar Akkaş and Ertuğrul Çam investigated the significance of reacting to the power grid market as a crucial aspect of deriving value from VPP solutions. In addition to the technical aspect, understanding the market demand for VPP is valuable [18].

Maciej Swierczynski, Daniel Loan Stroe, Irina Ana Stan, Remus Teodorescu, and Henrik Vikelgaard studied the integration of lithium-ion batteries, emphasizing that used batteries play a central role in VPP implementation and that the supported reserve products depend on the types of batteries used [19].

Ya-Chin Chang and Rung-Fang Chang conducted a study on how VPP implementation can be used to save power. Their research indicated that maximum benefits, besides stabilizing the power grid, can be achieved when batteries are charged during lower electricity rates and discharged when higher rates are higher. Although cost saving is not a central aspect, mobile network operators should implement VPP because it makes the overall business case more viable [20].

Sang-Yoon Park, Sung-Won Park, and Sung-Yong Son examined the potential issues of an approach focused solely on cost-saving and compared different VPP types and implementation methods. In addition to the previous study, this provides a more comprehensive justification for VPP implementation in the mobile operator segment [21].

Muhammad Bilal Ali, Syed Ali Abbas Kazmi, Abdullah Altamimi, Zafar A. Khan, and Mohammad A. Alghassad covered other more environmentally friendly power generation options for remote sites. As demonstrated, VPP is only one possible alternative method for telecom operators' contribution to modern power grids [22].

Jianpei Han, Hian Liu, Yujing Huang, and Zhenyu Zhou conducted a study on collaborative optimization of distribution networks and 5G mobile networks with renewable energy sources in smart grids. Their analysis reveals the challenges of increased RES use, as we have raised in our study. They indicated that having a demand response solution in a mobile network would benefit both parties and mobile and distribution network operators. VPP solution proposed in this study could also be used for demand response in addition to grid balancing [23].

Matej Krpan, Xiao Wang, Mateo Beus, Alessandra Parisio and Igor Kuzle analyzed distributed control of a virtual storage plant. This paper discusses the challenges and results of implementing a distributed control framework for a virtual storage plant, including the impact of communication delays and synchronization issues, which are relevant to the operation of virtual power plants in mobile network environments [4].

Sasan Pirouzi conducted study on network-constrained unit commitment-based virtual power plant model in the day-ahead market according to energy management strategy. This study introduces a novel hybrid model for energy regulation in a virtual power plant (VPP). The model combines stochastic and robust optimization methods, aiming to minimize the difference between the expected operating costs of generators and the expected revenues of the VPP in day-ahead energy and reserve markets. The VPP consists of a wind farm, energy storage, and demand response. The model takes into account the uncertainty factors of day-ahead market prices, demand load, and wind farm power output. The study also presents several simulation results, which demonstrate that the proposed VPP model can enhance both economic and technical benefits that can be achieved by utilizing the virtual power plant concept[24].

As can be seen from Table 1, our article takes a unique approach to VPP research by using actual field measurement results for the FFR product. Nothing has been published with the same combination. The literature review covers multiple aspects of VPP usage and provides a solid baseline for our studies.

3. Materials and methods

This chapter explores the critical aspects of the VPP implementations. We begin by summarizing the use case of virtual power plants in the mobile operator industry and the current state of implementation by Finnish operators in Chapter 3.1. Chapter 3.2 explains the operators' requirements from authorities relating to battery backup. Chapter 3.3 provides an overview of high-level reserve market products in Finland. Batteries are crucial in VPP implementation, which is covered in Chapter 3.4. Chapter 3.5 covers reserve markets, and Chapter 3.6 introduces the primary solution providers. Finally, Chapter 3.7 concludes the study by explaining the methods used for the selected test scenario.

3.1. *Virtual power plants and finnish mobile network operators*

VPP is a flexible and distributed power consumption or storage unit that aggregates the capacities of heterogeneous distributed energy resources (DER). VPP supports generating energy or trading power on the electricity market and demand-side options for load reduction [22] has been available as a concept for over a decade, and many types are attainable.

The main objective of VPP systems is to maintain the power grid's stability and generate additional revenue from the asset. Power systems are subject to continuous impacts that may interfere with their balance; for example, overproduction due to windy weather or if a big consumer, such as a paper factory, has a service break. Other examples of imbalance include when RES fails to provide enough power, or there are issues with traditional power providers. The power system must possess sufficient reserves (primary, secondary, and tertiary) to deal with unbalanced consumption and production. The market mechanisms determine the procurement of the reserve products on a need basis [25].

The principle of reserve markets and products remains consistent despite the differences in reserve product offerings across global and European markets, even when the same abbreviations have different meanings. Cooperation between markets is increasing rapidly to harmonize systems and processes even further. For example, Fingrid, a Finnish transmission system operator (TSO), belongs to the ENTSO-E, which harmonizes European offerings, especially in the Nordics [26]. Mobile network operators can implement a VPP solution to provide reserve products, such as FFR and automatic frequency restoration reserve (aFRR). As mentioned in this article, we focus on FFR.

There are two types of VPP implementations: power unit and consumption based. Power units consist of generators that can feed the grid with additional power. Consumption based VPP comprises a battery array that can adjust the power demand according to the grid conditions by switching between local and grid sources [26,27]. In this article, we employed the consumption based approach for the experimental design.

Due to the authorities' power backup requirements, mobile network operators need batteries for each station site. This requirement allows operators to implement consumption based VPP, which is also the case in Finland. Based on publicly available information, the Finnish operator DNA does not have a VPP solution in use. Still, the two other incumbent operators, Telia and Elisa, are actively working with VPP implementations. Elisa has even introduced their VPP solution for an aFRR product using EU funding. Elisa targets other operators to implement VPP

Table 1
Literature review comparison.

REF ID	Mobile Operator	FFR	VPP	Batteries	Field measurements	Business aspect
[4]	No	No	Yes	Yes	No	No
[13]	Yes	No	Yes	Yes	No	No
[14]	Yes	No	No	Yes	Yes	No
[15]	Yes	No	Yes	Yes	No	Yes
[16]	Yes	No	Yes	Yes	No	No
[17]	No	No	Yes	No	No	Yes
[18]	No	No	Yes	No	No	Yes
[19]	No	No	Yes	Yes	No	Yes
[20]	No	No	Yes	No	No	Yes
[21]	No	No	Yes	No	No	Yes
[22]	No	No	Yes	No	No	Yes
[23]	No	No	Yes	No	No	Yes
[24]	No	No	Yes	No	No	Yes
Our article	Yes	Yes	Yes	Yes	Yes	Future

solutions as a service [28]. In addition to Elisa's offering, the market offers various products from different sources, including prominent mobile network element vendors, battery providers, and power supply providers. For an aFFR product, the activation time requirement is between 2 and 15 min and, therefore, significantly slower than the required FFR full activation time. As the first step towards more efficient usage of backup batteries, in January 2022, Telia, Fortum, and ABB collaborated by connecting an extensive data center uninterrupted power system (UPS) to the electricity market [29]. Fortum provided the aggregation and VPP controller functions, and ABB was the UPS vendor. In addition, Telia conducted a pilot study with the energy storage solution provider Polarium [30]. The pilot aimed to enhance the energy efficiency of the mobile network, lower the electricity expenses, and improve the reliability of the electricity infrastructure. The experimental design excluded the base station based VPP solution tests despite their relevance to the research question in this article. However, these tests still yielded valuable insights about the article's topic.

This article analyzes a VPP implementation on one of Telia's base station sites. Research assumes that FFR and frequency containment reserve during disturbance (FCR-D) are best-fit base station battery based VPP with legacy lead acid batteries. The demand for battery cycle loading and stored energy is well within the capabilities of current UPS's and does not disturb the regulatory requirements for mobile network resiliency and operation. The limiting factor is the total activation time to activate battery operation. More details about FFR and other reserve products are presented in Chapter 3.3.

In addition to the reaction time, a VPP provider must have a specific power capacity to offer to the market. For an FFR product, the minimum is 1 MW. The methods chapter states that the average single base station power consumption is around 3–15 kW. Therefore, to reach the minimum power required to participate in the market, around 300 distributed base stations are needed to qualify as participants in the reserve market. The replacement of lead-acid batteries with lithium-ion batteries and the addition of battery capacity will facilitate the involvement in the reserve markets that require more energy storage and have lower time constraints. Elisa has decided to replace lead-acid batteries while rolling out a VPP solution. This will ensure they meet the authorities' requirements in all conditions, enabling them to participate in other energy markets.

3.2. Power backup requirements for mobile operators in finland

To meet the power backup needs of mobile operators, the Finnish Transportation and Communication Agency (Traficom) has set a requirement for communication network operations during electricity breaks. Fig. 4, "The principle of a power supply with accumulators and a UPS device as an emergency power supply", presents a high-level power grid layout with an emergency backup [26]. The grid's alternating current (AC) power is first fed into an inverter/rectifier. An inverter is used if there is a need to feed power to the grid, but a rectifier is usually sufficient for backup power. Batteries and communication network components are connected to the inverter/rectifier over 48 V direct current (DC). If grid power is lost, communication network components still receive DC power from batteries.

The regulatory standards for base stations vary according to their categories. Importance classification determines how well the power supply of a base station must be secured and which devices are needed for the implementation. The backup time requirement specifies the operating time of the base station site during a power outage or equipment failure. Table 2 shows the backup time requirements for different classes of importance and the technologies they include. The most common one is Class 5, which requires three hours of basic coverage for most sites and allows other higher frequencies to go offline 15 min after

Table 2
Requirements for battery backup.

Requirements for battery backup in Finland by Traficom			
	Technologies		
	2G/3G/4G 700/800/900 MHzor lowest 4G frequency	2G/3G/4G 700/800/900 MHzor lowest 4G frequency	4G 1800/2100 MHz 4G 2600 MHz 5G 3.5 GHz
Class of Importance	Tower Site	Real Estate Site	General Requirement
5	3 h	2 h	15 min
4	6 h	2 h	15 min
3	12 h	2 h	15 min
2	6 h	2 h	15 min
1	3 h	2 h	15 min

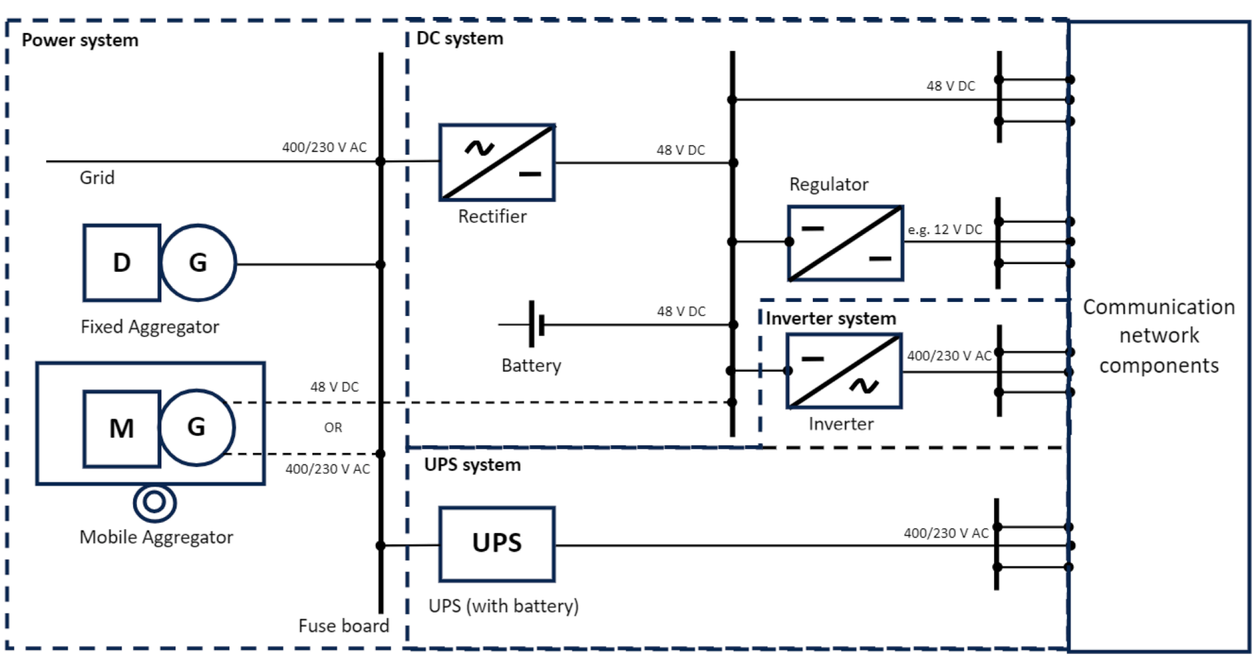

Fig. 4. The principle of a power supply with accumulators and a UPS device as an emergency power supply.

a power outage. The so-called 15-minute service outage drop, meaning the power cutoff, is designed to prevent the need for unreasonably oversized batteries and devices from unnecessarily shutting down during short power outages. The latter can prevent potential equipment failures, such as in freezing conditions [27,31] For these reasons, it is important to consider possible VPP usage when designing the site's battery capacity.

3.3. Reserve products in operator environments

In addition to the detailed measurements for a selected FFR product, in this chapter, we will briefly explain the main logic for all available products and evaluate product feasibility in the mobile network operator business. Available products are listed below in Fig. 5 [28,32,33].

Reserve products include automated and manual products, as shown in Fig. 5. Products can be divided into four main categories based on their reaction time [33].

1. Fast frequency reserve product for frequency containment in low inertia situations. Reaction time is below 1 s, and full activation time is below 1.3 s.
2. The frequency containment reserve (FCR) controls the grid's frequency. The reaction time ranges from a few seconds to 3 min.
3. Frequency restoration reserve (FRR) for returning frequency to the normal range (49.9 – 50.1 Hz). Reaction time: 5 to 15 min.
4. Replacement reserve RR for releasing activated (FFR) product. Therefore, this product is not used in the Nordic power system and is not explained further in this article.

Fast frequency reserve (FFR) is a new product launched in the Nordics in May 2020. Technical requirements vary slightly by region, but the main logic is the same. In Finland, local TSO Fingrid has defined FFR requirements in the document "The technical requirements and the prequalification process of Fast Frequency Reserve (FFR)." [34]. The increasing share of RES is setting a lack of inertia challenge to grid providers. With less inertia, the system becomes less capable of resisting changes in frequency. Due to this challenge, FFR was established to better handle low-inertia situations on the grid. FFR was also needed since aFRR, and FCR-N/D products were too slow to react when inertia gets too low [35]. The demand for power systems is influenced by their prevailing inertia and the size of the reference incident. The highest need for procurement for FFR occurs in spring, summer, and autumn when solar and wind power systems produce higher amounts of electricity.

FFR activation is done by automatic local control, and Fingrid does not send a control signal. The reserve unit needs a controller that adjusts the VPP behavior based on frequency measurements. The same controller can also alter the size of the base station fleet based on demand.

FFR automatic balancing must be triggered when frequency falls below a specific value, but the balancing service provider can select the trigger frequency from three options with different activation times. The values are in Table 3.

The second primary category comprises frequency containment reserves (FCRs), which have two distinct products: FCR for regular operation (FCR-N) and FCR for disturbances (FCR-D). Both products serve as active power reserves and automatically respond to frequency deviations. Their purpose is to keep the frequency within normal limits. FCR-N operates between 49.9 – 50.1 Hz, and FCR-D aims to limit frequency deviation between 49.5 Hz and 50.5 Hz when normal thresholds are violated. An FCR-N product must be capable of up- and down-regulation. Upregulation, in practice, means either increasing power production or decreasing consumption, whereas downregulation means decreasing power production or increasing consumption. FCR-D is divided into separated up- and down-regulation products. More detailed technical requirements can be found on Fingrid product pages [36]. A mobile operator base station based VPP-only consumption-based approach is feasible since base stations cannot generate power. Reducing consumption is much simpler than increasing it. Decreasing can be done by directing base stations to use batteries instead of the grid. For the increasing option, operators would need to run a certain number of sites with partial battery charge levels to charge them when needed,

Table 3
Triggering options for FFR product.

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

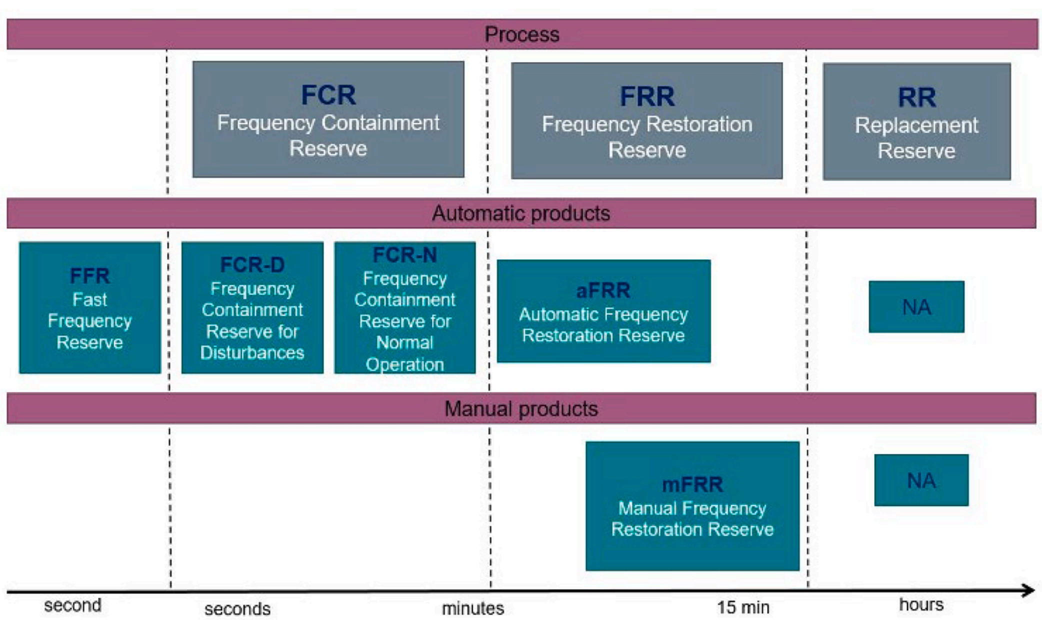

Fig. 5. Fingrid reserve products.

thus increasing load. This approach introduces risk to normal operations during a power outage. Alternatively, operators would need to oversize base station batteries. Therefore, the challenging implementation of downregulation excludes FCR-N entirely and the FCR-D downregulated product from base station-based VPP implementations.

The third main category, the frequency restoration reserve, is divided into two products: the automatic frequency restoration reserve (aFRR) and the manual frequency restoration reserve (mFRR). The aFRR product aims to return the frequency to the grid's nominal value of 50 Hz. An activation request signal from the TSO does activation. With aFRR, the product provider can bid for up and downregulation or only for one. This supports aFRR usage in base station based VPP solutions. The minimum capacity for aFRR is 1 MW, and full activation must occur within 5 min from the TSO's request signal. Also, these requirements can be fulfilled by base station based VPP. Finnish operator Elisa has aFRR available in their product [37].

Manual restoration products have the same principal purpose as automatic products, with the difference being that the operation is entirely manual. TSO owns manual RR products, and therefore, this product is not an option for operators or any other external company [32].

FFR product was selected for this article due to the following reasons: 1) It is a good fit technically to base station-based VPP in an operator environment, and 2) by being a new product, there is no publicly available research data about FFR-based VPP implementation in mobile network operator segment, and 3) operator base station fleet can adjust size, duration and reaction time based on the need on the market [38]. Other reserve products like FCR were excluded from this study since we wanted to focus only on FFR. FCR products also demand more battery capacity and are, therefore, more challenging for mobile network operators to implement.

3.4. Battery technologies

Lead-acid batteries have provided communications resilience to mobile telecommunication networks for decades. Lead acid is heavier and less durable than lithium based systems when deep-cycled [39]. In Finland's urban environment, deep cycles are exceedingly rare as the urban electricity grid consists of underground cabling protected against disturbances. Valve-regulated lead acid (VRLA) batteries with absorbed glass mat (AGM) constructions are the most common battery type used. The main advantage of these batteries is that they do not require constant maintenance except cleaning and regular functional testing during normal annual site maintenance operations.

Li-ion batteries have several different chemistries for different applications [27]. For electric vehicles (EV) and battery energy storage systems, the most common options are lithium batteries with ferro phosphate as cathode (LFP) and lithium batteries with nickel manganese cobalt oxide as cathode (NMC). These chemistries have different performance characteristics regarding energy density, cycle life, depth of discharge, safety, and cost. Even if NMC has a much higher energy density than LFP, space, and weight are not usually the most critical factors in energy storage applications. Cycle life, battery safety, and long-term costs are essential selection factors. In those aspects, LFP has a clear advantage over NMC. LFP also has advantages with higher flexibility to the depth of discharges as it can tolerate a full 100 % state of charge for a long time if needed [40].

According to latest IEA report [41] it seems that for battery storage applications LFP chemistry covers majority of the additional capacity by 2030. When comparing environmental factors, such as global warming potential, across different battery chemistries, there is still no definitive evidence to suggest the best solution for energy storage. However, up-to-date primary data is crucial when making such comparisons [42].

3.5. Power system reserve markets

The role of reserve markets in global energy systems has grown significantly with the increasing role of renewable power in the electricity mix [14]. To balance deviations, TSOs procure different kinds of reserves from reserve markets. Reserves are power plants, consumption resources, and energy storage, which adjust their electric power according to the power system's needs. VPP has the potential to have a significant role in the market. One study estimates the potential of VPP to be around 6,5% of the total Finnish FCR-D market (2017) [14].

Fully functional reserve markets can be found in the following:

- Nordic synchronous area TSOs
  - o Finland – Fingrid
  - o Sweden – Svenska Kraftnät
  - o Norway – Statnett
- Entso-e (TSOs from eight countries)
  - o Austria (APG),
  - o Belgium (Elia),
  - o Switzerland (Swissgrid),
  - o Germany (50Hertz, Amprion, TenneT DE, TransnetBW),
  - o Western Denmark (Energinet),
  - o France (RTE),
  - o the Netherlands (TenneT NL),
  - o Slovenia (ELES)

All TSOs are also working together to enable the EU Commission Regulation (EU) 2017/1485 of 2 August 2017[43] establishing a guideline on electricity TSO common market for procurement and exchange of FCR (FCR Cooperation) [7,25,26,44–54].

3.6. System providers for vpp solutions

Fig. 7 presents the VPP implementation architecture. It shows that multiple functions are needed for a fully operational installation. VPP providers can be divided into three categories: software (SW) providers, hardware (HW) providers, and a combination of SW and HW providers.

SW VPP providers offer components for control functions for data processing and automation, bidding functions, site controllers, and communications. Ventyx, an ABB subsidiary, exemplifies this type of software-only vendor. Other examples include Enbala, which focuses on battery optimization, and Autogrid, which specializes in managing and optimizing distributed energy resources.

HW providers are mainly focused on the power control and battery management aspects of the VPP. They are typical vendors who would be present at the site even without VPP solutions. Delta Power is an excellent example of an HW-only provider.

Combined SW and HW providers provide both software to collect data and manage VPP implementation and HW to store and sometimes even produce electricity. These vendors include ABB, Tesla, SolarEdge, Enel X, and Alpha-ESS.

In addition to power industry vendors, traditional telecom network equipment providers like Ericsson, Nokia, and Huawei have started offering VPP solutions to their customers. Ericsson's solution enables energy providers to connect and manage DES, such as solar panels, batteries, electric vehicles, and intelligent appliances using LTE and 5G connectivity [55]. Nokia provides an SW solution to remotely control and monitor base station backup batteries for VPP. In addition to VPP, the solution also supports load shifting. The VPP solution by Nokia incorporates the aggregator function. Huawei also has offerings for site power management that support distributed power systems (DPS) and hybrid power and site energy management [56].

Elisa is one of the rare mobile network operators who also has VPP product offering for other operators. Elisa's subsidiary, Elisa Polystar, offers VPP, which they sell and use internally in Finland [28].

3.7. Methods for the testing

Test setup with VPP using base station batteries was built on Telia's dense urban site with live traffic. A high-level overview of the VPP implementation can be found in Fig. 7. The general architecture of VPP in a mobile network site Off-loading tests included three tests where external power feed from the grid was cut off for 2–3 min, and the base station used power from batteries. The purpose of the offload is to measure reaction time to power-off, impact on the state of charge (SoC), and return delay when the base station is again fully consuming power from the grid. All these three aspects are essential for the VPP production feasibility and the selection of the reserve product. To comply with FFR requirements for full activation, the delay in state changes must be sufficiently rapid to achieve full activation within the required 1.3 s.

Tests relating to this article were conducted with Aalto University, Telia, and Nokia between April 5th, 2023 – May 23rd, 2023 (weeks 13–21). The latency test took one hour on 13th April between 10–11 AM. Test equipment was installed in one live mobile network base station in Southern Finland. The base station has a 3*25 Ampere (A) grid connection and several generations of mobile networks, including LTE & 5G in different frequency bands. The maximum theoretical power for the site is 5,8 kW (kW), whereas the average power consumption of the site varied between 3–5 kW, as seen in Fig. 6. The x-axis is the time in April 2023 in days, and the y-axis is site power consumption in kilowatts (kWh). We measured consumption using Delta power and Acuvim measurements, which are different frequency bands.

The set-up described in Fig. 7 consists of a telecommunications rectifier, a battery controller, eight 12 Volts (V) each 125-ampere hour) VRLA batteries in two strings of 48 V provide a total capacity of 12 kWh. The controller on the rectifier includes a battery test function, which was used to set the site off-grid remotely using an industrial computer called MOXA in Fig. 7a with a 4G LTE modem.

In the test site, Fig. 7b alternating current (AC) metering in data was observed to reference the total site electricity consumption. Also, mobile network key performance indicator (KPI) data, including uplink and downlink data volume and utilization rate, was monitored. Data was collected from the whole test duration, and the measurement resolution was one hour. KPI collection was made to ensure that power off-loading tests did not impact regular cell operation. Off-loading tests included three where external power feed from the grid was cut off for 2–3 min, and the base station used power from batteries. In this article, we do not analyze KPI measurements in detail. Also, the systemic impacts of VPP on energy production and business aspects of the tested VPP implementation in mobile network operator business will be analyzed in a separate article.

Power-off reaction speed and duration of the full activation are the main factors for FFR reserve product. It was tested and measured both ways, going from grid feed to batteries and back to grid. A set of activations was performed, and the input current of the rectifier was measured to investigate how fast the rectifier reacts to remote power-off commands.

Fig. 7e shows the power controller. Different types of sites have slightly different setups regarding power supply, batteries, and air ventilation described in Fig. 7d. The selected site presents one common type of site that provides good insight into wider VPP usage.

We used the power system for the site from Delta Power with the Orion controller. Delta Electronics is one of the significant power supply providers [57].

The batteries used on site were lead-acid batteries presented in Fig. 7c. Lead-acid batteries can only be considered for power-off cycles, not grid feeding.

Nokia has built a measurement setup to monitor the power consumption results remotely. This remote monitoring is not needed for the production usage of the VPP. The test system included AC coil measurements, presented in Fig. 7b, and measurements and remote over-the-air connection using a 4G modem called MOXA, presented in Fig. 7a. MOXA also collects direct current (DC) power consumption, temperature, and frequency measurements from the site. MOXA has an ethernet connection to the Orion power controller to control the power feed presented in Fig. 7e and Fig. 7f.

The following measurements were conducted: an offloading test, an impact on batteries test, a reaction latency test from the power grid to the battery, and a reaction latency test from the battery to the power grid.

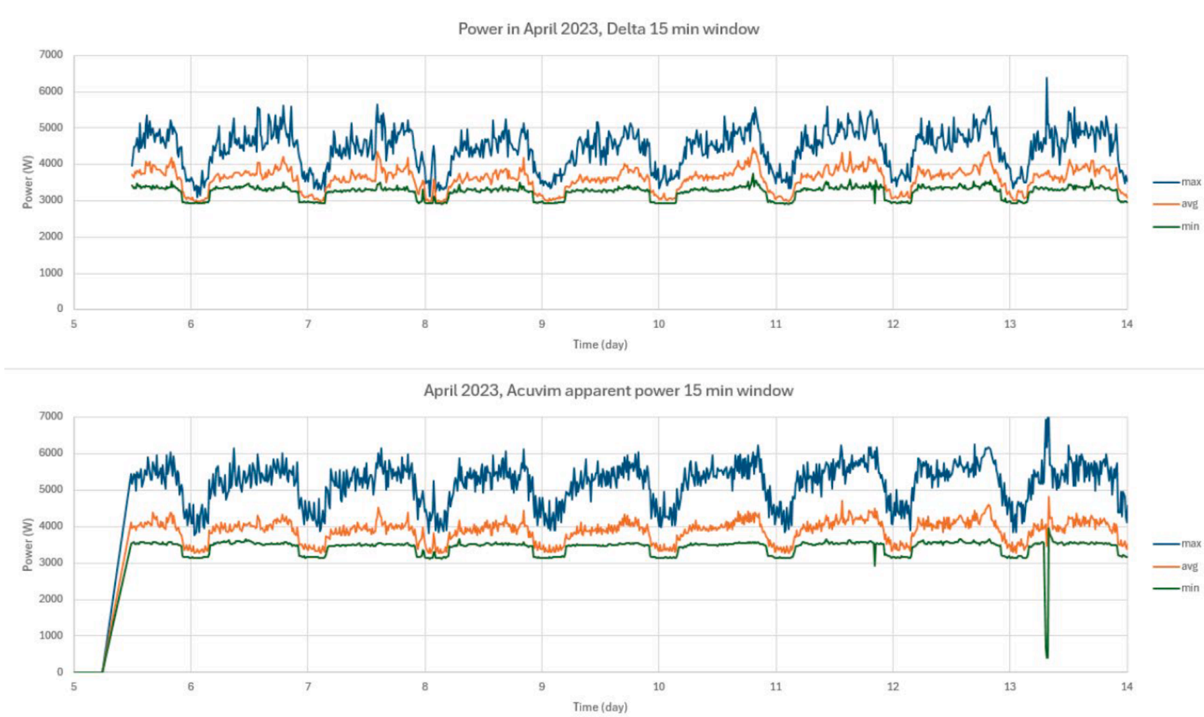

Fig. 6. Site power controllers.

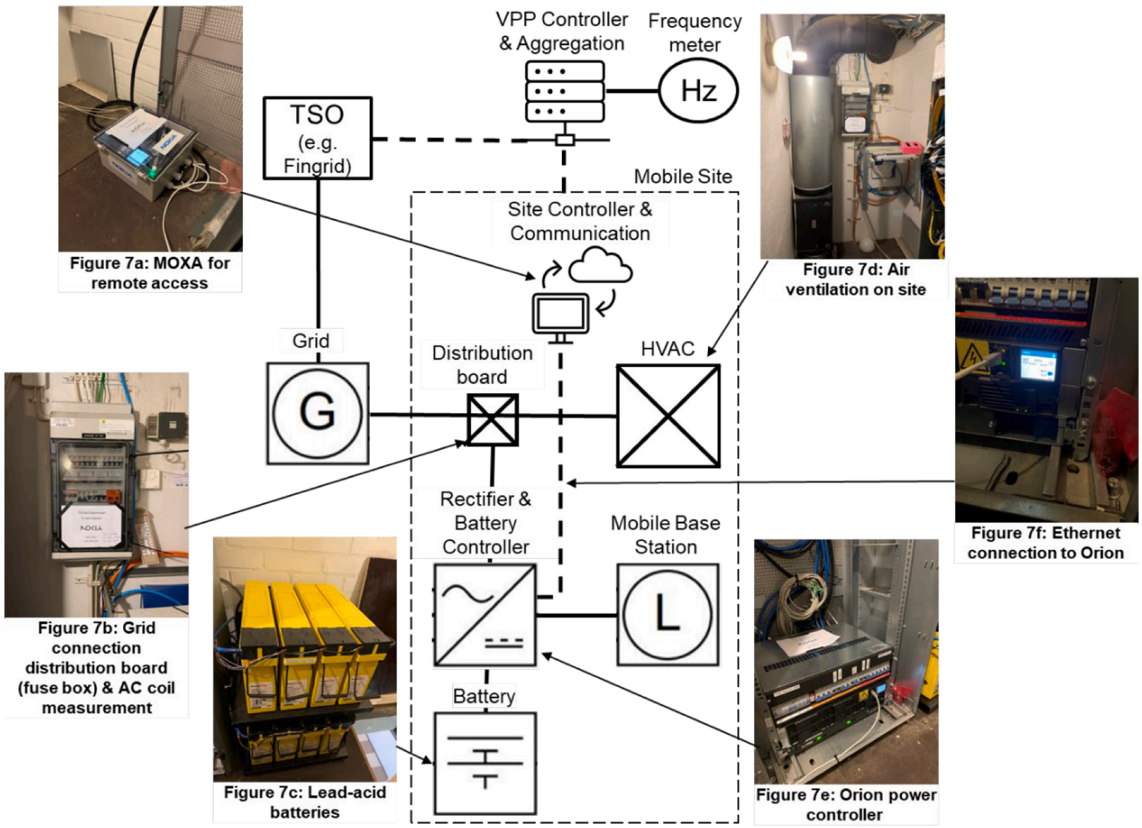

Fig. 7. The general architecture of VPP in a mobile network site.

A battery's depth of discharge (DoD) describes the difference between a fully charged battery and the charge of the same battery after usage. State of Charge (SoC) is defined as the ratio of the remaining charge in the battery divided by the maximum charge that the battery can deliver. It is expressed as a percentage (%). The power system provided SoC value; therefore, separate calculation was unnecessary [54].

4. Results

Full activation time to power off means how fast the base station stops completely consuming energy from the grid from the command

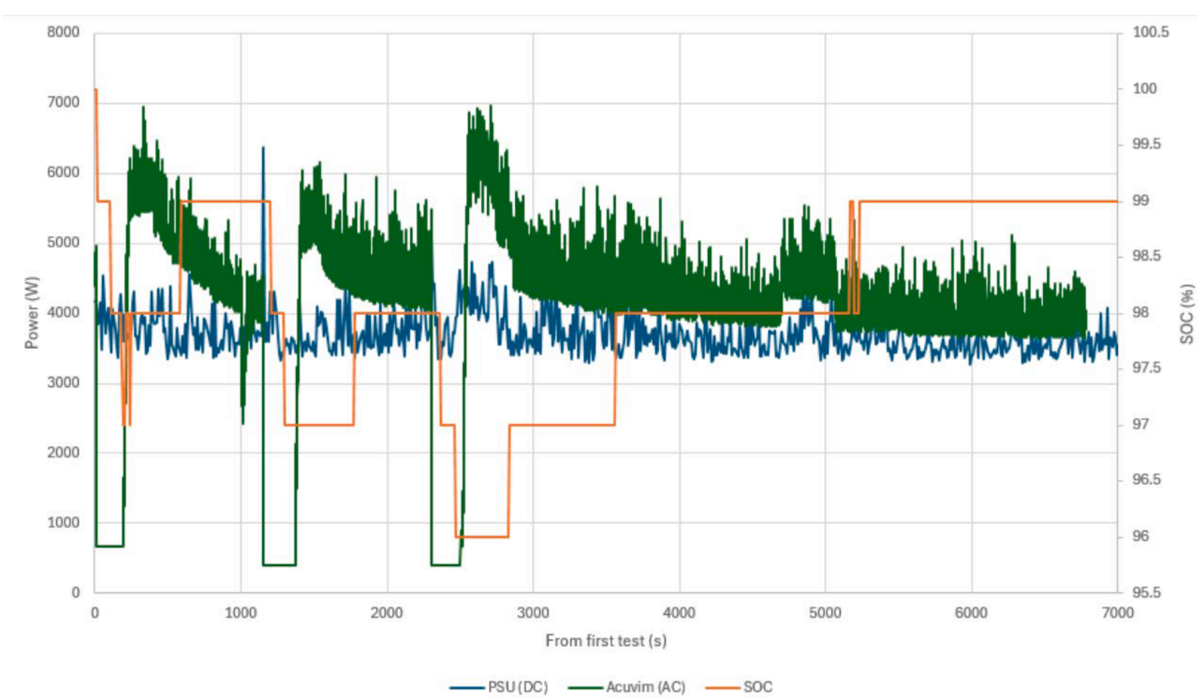

Fig. 8. Power off and State of Charge measurements.

signal. Fig. 8, the x-axis represents the duration of the power consumption and shows how long each of the three off-load tests lasted. Time is measured in seconds (s). The y-axis represents power consumption in Watts (W) for both DC and AC. DC is used for base stations, and AC is used for additional power needs on-site, like lights and site cooling. In Fig. 8, the blue line shows the DC consumption, which is not offloaded, and the green line shows the impact of AC power-off loading. What can be observed is the drop in the AC consumption for each of the three power-off cycles. The power-off does not impact the blue line with DC since the PSU uses batteries during the power break. A drop in the power consumption for the AC power indicates that the power controller configuration is working, and the base station is not consuming energy from the power grip during the off cycle. As soon as the cycle is over, the base station starts to consume energy from the grid again.

As can be seen, in addition to power consumption from Fig. 8, power-off cycles impact also SoC. After the third cycle, three cycles reduced the SoC by only four units, from 100 % to 96 %. The red line in Fig. 8 presents the battery's state of charge.

Fig. 9 shows the most important finding from the executed tests. The Y-axis shows the power consumption in W, and the x-axis shows the duration in seconds (s). On the left-hand side, the chart delay from trigger to start using batteries instead of grids shows that the start delay is 5 – 8 s after the command. Full activation when the base station fully uses battery power varies between 7—10 s.

The delay was also measured in other directions when the base station was controlled to start using power from the grid. This can be seen in Fig. 9, right-hand side chart. Full power usage was restored roughly 1 min after the trigger. The base station reacts to the trigger command between ~ 16 and 21 s, and then power consumption grows until the needed level is reached and power consumption is stabilized.

Table 4 presents the time in seconds (s) when the base station's power consumption began to decrease, as indicated by yellow markings. In Table 5, we observe the point at which the base station ceased drawing power from the grid, leaving only consumption from auxiliary systems such as air cooling.

To estimate power measurement accuracy, three different power consumption metrics were compared, and the results can be seen in Fig. 10. The Y-axis shows the power consumption value in W, and the X-axis shows the sample points of one hour. Consumption was measured using Delta power, Acuvim, and AC Meter systems. Based on measurement results, all three power measurement methods provide corresponding results.

In Figs. 11 and 12, plots with energy consumption are presented on the y-axis in Watthour (Wh) versus DL volumes on the x-axis in Gigabytes. Hours 2:00–5:00 are in "power save" mode, and 8:00–1:00 are in "no-save" mode. As can be seen, there is an excellent correlation coefficient. Correlation coefficient values are close to 1 in both modes, as expected. This can be easily understood as the power consumption of a base station is dominated by the DL. The power-saving feature is easily

Table 4
The exact time when the power consumption of the base station from the grid started to decline.

TEST 1		TEST 2		TEST 3	
Time from trigger (s)	Power (W)	Time from trigger (s)	Power (W)	Time from trigger (s)	Power (W)
4,88	1759	4,85	1719	4,92	2017
5,04	1746	5	1718	5,08	1960
5,2	1709	5,16	1681	5,23	1810
5,36	1788	5,32	1611	5,37	1685
5,55	1740	5,47	1575	5,53	1567
5,7	1757	5,64	1447	5,69	1406
5,86	1831	5,8	1339	5,84	1248
6,02	1756	5,94	1225	6	1124
6,18	1650	6,09	1103	6,17	1076
6,32	1653	6,24	958	6,32	896
6,48	1774	6,4	850	6,46	543
6,64	1778	6,56	666	6,62	333
6,79	1654	6,72	456	6,76	216
6,93	1694	6,88	336	6,91	189
7,09	1653	7,05	226	7,07	171
7,25	1596	7,22	180	7,23	166
7,41	1633	7,36	168	7,39	165
7,59	1546	7,52	166	7,55	164
7,73	1515	7,68	167	7,71	164
7,87	1520	7,83	167	7,87	163

Table 5
The exact time when the power of base station consumption from the grid stopped.

TEST 1		TEST 2		TEST 3	
Time from trigger (s)	Power (W)	Time from trigger (s)	Power (W)	Time from trigger (s)	Power (W)
7,73	1515	7,68	167	7,71	164
7,87	1520	7,83	167	7,87	163
8,03	1437	7,97	167	8,02	163
8,19	1484	8,13	166	8,17	163
8,35	1285	8,29	163	8,32	163
8,5	1211	8,45	163	8,48	163
8,66	1035	8,61	163	8,62	163
8,82	882	8,77	163	8,78	163
8,98	719	8,93	163	8,94	163
9,16	579	9,09	163	9,1	163
9,32	364	9,25	163	9,26	163
9,48	257	9,39	163	9,42	163
9,64	184	9,54	163	9,6	163
9,8	167	9,7	163	9,76	163
9,94	163	9,88	163	9,92	162
10,1	162	10,02	163	10,06	162

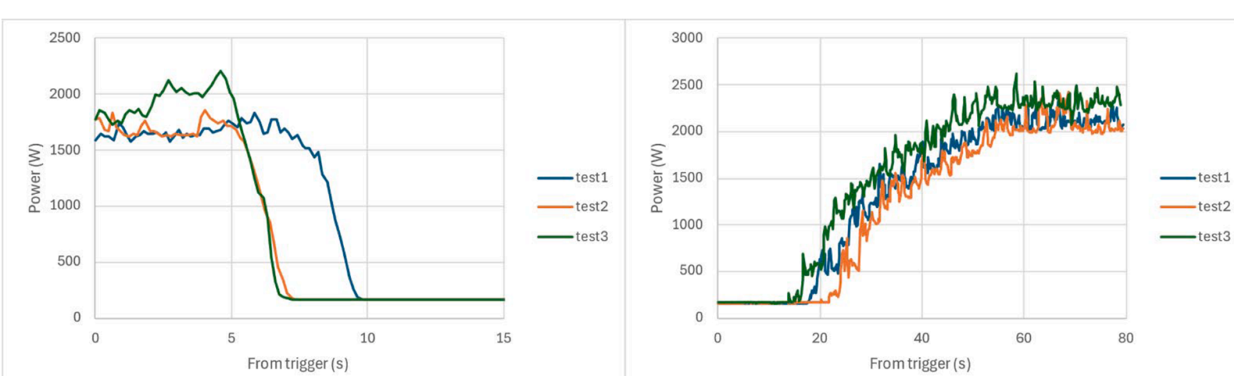

Fig. 9. Latency from the grid to batteries and back to the grid.

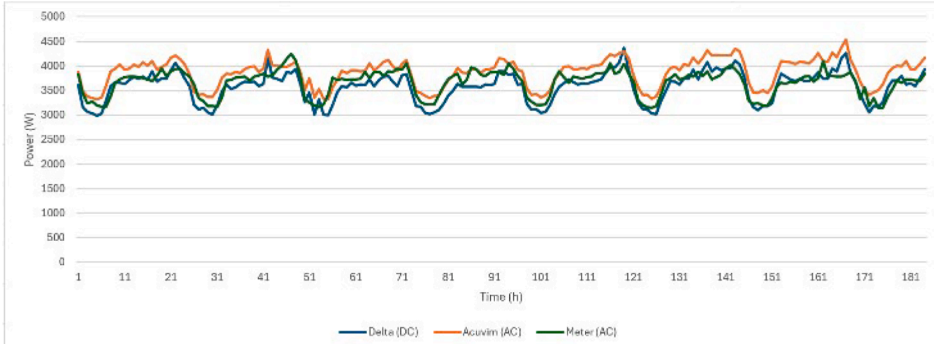

Fig. 10. Power measurement comparison.

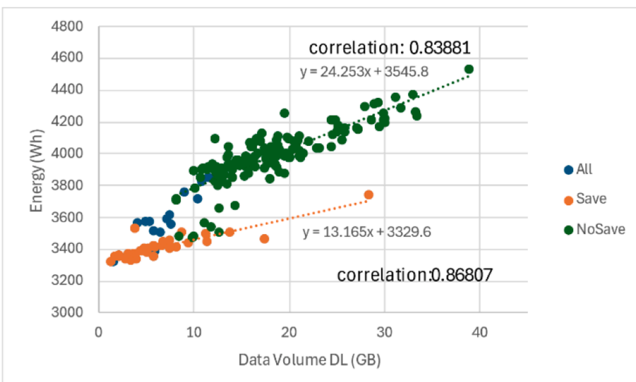

Fig. 11. Power consumption vs. transferred downlink (DL) data volume with Acuvim.

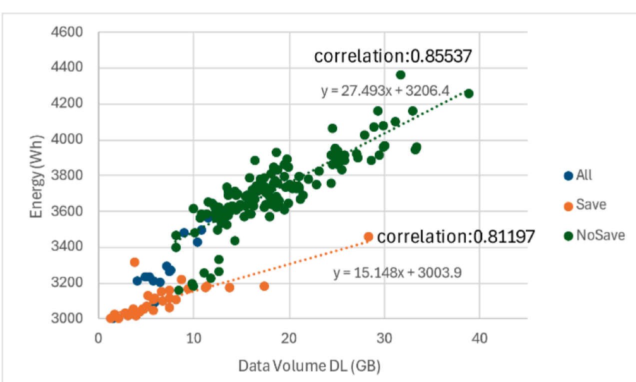

Fig. 12. Power consumption vs. transferred downlink (DL) data volume with Delta Power.

recognizable in the plots, as it follows a somewhat different slope than the regular "no-power saving" trend.

The power consumption of the air ventilation system was measured to assess its influence on the experimental results. Fans run periodically in 6-minute lengthy periods; 35-minute repeat cycles with 450 W additional power consumption. The air ventilation system's activation depended on the site temperature, as shown in Fig. 13. In the diagram, the blue y-axis is the temperature in Celsius (C), the red y-axis is the electricity consumption in Watts, and the x-axis is time in seconds. The diagram also shows that the fan was triggered when the site temperature reached 21.6 °C.

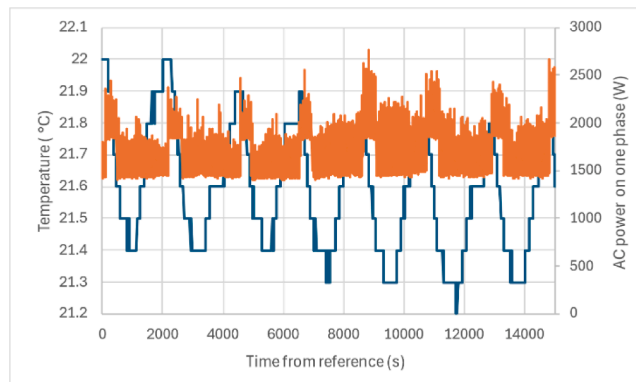

Fig. 13. Fan usage with power consumption.

5. Discussion

Tests were executed as planned and provided unmistakable evidence that VPP can operate in a live base station without interferences to normal operations or physical changes to the current infrastructure. There are two main takeaways from this research. The primary discovery, utilizing the designated equipment, revealed the actual delay measured during the transition from the power grid to battery power was too long for FFR usage. Time back to the grid is not the entry criteria for market participation. Only when the load is off from the grid is mandatory. The 7–10 s complete activation delay exceeded the slowest level of 1.3 s. The delay analysis indicated a causal relationship between the polling cycle duration of the power source and the response time. In addition to the start delay, there is a delay in how fast power consumption is fully transferred from the grid to the batteries. To meet the FFR product entry criteria that stipulate a response time of less than one second, it is imperative to increase the frequency of the polling cycle. The secondary outcome of this study is to provide a detailed description for any mobile network operator to build a similar test setup at their sites and, in this way, speed up VPP implementations in the market.

The main target for future research is to contact power controller vendors and test reaction times with a modified polling cycle. By assessing the same setup with the new modified controller software, we could prove that the setup is feasible for FFR products. In addition to the improved software target, we will conduct more tests with simulated environments to have more scientifically solid statistics. The current article focuses on the technical aspects of VPP implementation. In future studies, we will also study business aspects of VPP implementation in mobile network environments.

In addition to power controllers, another key target for future research is base station batteries. As demonstrated in the test setup, the use of current lead-acid batteries is feasible in the FFR. By utilizing the existing batteries, operators can begin implementing the VPP solution on top of their current infrastructure. This allows for a smooth transition and provides the opportunity to enhance the system's capabilities based on needs gradually. This strategy enables a cost-effective path for full VPP implementation.

The rollout of modern technology is always a combination of business and technical aspects. Although business aspects were not included in the current research, one requirement for wider production usage is that the setup is functional with minimum or preferable without any additional HW at the base station site. It is much harder to achieve a profitable business case if a site visit is required for VPP activation. Site visits cannot be avoided since an ethernet cable connection needs to be connected for the power controller remote connection or, optionally, a separate controller device placed on the site. These slight changes can be made during regular maintenance visits to the sites so that the VPP footprint can be gradually extended.

Additional infrastructure-related services like VPP should not jeopardize the quality of the end-user services. Quality needs to be carefully analyzed by continuous measurement. Service impact analysis during VPP usage will be addressed with additional tests and a separate article. In addition to the possible quality impact of the VPP, the correlation of the volume to the traffic versus energy consumption needs to be considered.

All these mentioned business and quality aspects need to be carefully studied. For the grid provider, the advantages are clear, but the business case must be positive for operators. Additional value on top of the VPP-generated income for the operators could come from possible savings from using batteries during high-cost hours. Business and technical evaluation is also needed to combine battery types versus reserve products. One aspect to consider is the size of the VPP fleet. An assumption that needs to be studied is how many base stations must be controlled simultaneously to have enough reserve available for selected products. The size of the VPP fleet also has a business impact. Costs and benefits both correlate with the number of base station sites.

6. Conclusion

Since FFR is a novel product in the grid balance reserve market, there is limited publicly available information about it. During our experiments, the live base station was equipped with remote access to the power controller, and we measured the reaction times for initiating battery usage. Reaction time emerges as a critical distinction between reserve products and is a pivotal factor for successfully entering the market with a fast frequency reserve product. The requirement for end-to-end full activation time for FFR is below 1.3 s. Our quantitative analysis confirms that a measured 7–10 s delay, including reaction and full activation time, is a bottleneck for FFR utilization.

Therefore, it is evident that software development for the controller SW is needed to meet FFR requirements. Since no other limiting factors were found, the next step is to contact power controller companies to have software with a faster polling cycle for the remote command. When a new version of the software is available, new measurements need to be conducted, and business evaluation is required to prove that implementation is fully functional and profitable.

In addition to the delay measurements commanding the power system remotely, the collection of measurements was successful. As explained in the methods section, measurement, and remote-control unit, MOXA was used to collect measurements for the testing. For an actual production setup, this additional equipment is not needed. Triggering of the VPP will be handled centrally for the whole fleet. Before production usage, the VPP operator must perform the necessary installations to remove fleet management, measure grid frequency, and participate in market bids.

The article's results can be utilized in any market where an FFR reserve product or similar product with a fast reaction requirement is used, and operators have battery backup for the base stations. Additionally, any industry with a large enough battery fleet could utilize their findings.

As further studies in the following articles, we will first focus on the new version of the software with the faster polling cycle to verify the fully functional setup for the FFR product. Furthermore, business aspects of the VPP, such as detailed implementation costs, optimum size of the base station fleet, return on investment, and overall feasibility for large-scale deployment, need to be studied. In the business aspect article, we also aim to conduct simulation on bidding model as a stochastically optimization problem, instead of relying on deterministic forecasts and optimize over probability distributions. More and more VPP implementations will be required to meet the growing demand for reserve products.

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CRediT authorship contribution statement

Jussi Laimio: Writing – review & editing, Writing – original draft, Software, Methodology. **Mika Keski-Heikkilä:** Writing – review & editing, Writing – original draft, Validation, Resources, Project administration, Methodology, Investigation, Conceptualization. **Matti Pärssinen:** Writing – review & editing, Writing – original draft, Validation, Supervision, Methodology, Conceptualization. **Roope Lahti:** Writing – review & editing, Methodology. **Olli Salmela:** Writing – review & editing. **Topi Volkov:** Software, Methodology. **Jari Collin:** Writing – review & editing, Supervision, Resources. **Petri Rannikko:** Supervision. **Henri Koskela:** Software, Methodology, Data curation. **Jukka Manner:** Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available on request.

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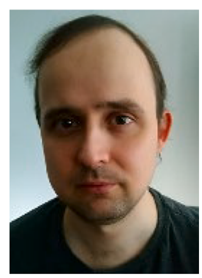

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