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Research Article

Evaluation of greenhouse gas emission reduction potential of a demand–response solution: a carbon handprint case study of a virtual power plant

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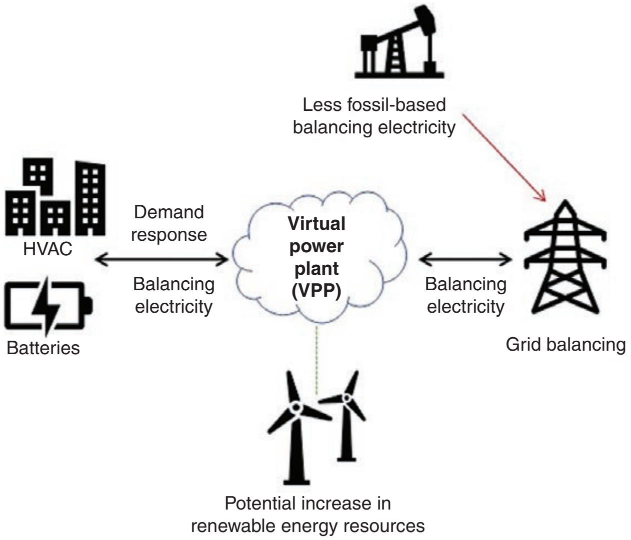
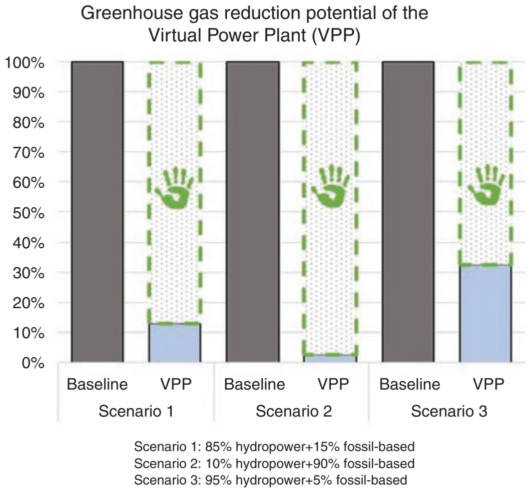
Abstract

The transition towards zero-carbon energy production is necessary to limit global warming. Smart energy systems have facilitated the control of demand-side resources to maintain the stability of the power grid and to provide balancing power for increasing renewable energy production. Virtual power plants are examples of demand–response solutions, which may also enable greenhouse gas (GHG) emission reductions due to the lower need for fossil-based balancing energy in the grid and the increased share of renewables. The aim of this study is to show how potential GHG emission reductions can be assessed through the carbon handprint approach for a virtual power plant (VPP) in a grid balancing market in Finland. According to our results, VPP can reduce the hourly based GHG emissions in the studied Finnish grid systems compared with the balancing power without the VPP. Typical energy sources used for the balance power are hydropower and fossil fuels. The reduction potential of GHG emissions varies from 68% to 98% depending on the share of the used energy source for the power balancing, thus VPPs have the potential to significantly reduce GHG emissions of electricity production and hence help mitigate climate change.

Graphical Abstract





Keywords: virtual power plant; demand–response; carbon handprint; greenhouse gas emissions; electric grid

Introduction

Climate change is a major challenge, and limiting global warming to 1.5°C or 2°C above pre-industrial levels calls for a considerable reduction in greenhouse gas (GHG) emissions. In 2020, the electricity sector accounted for 36% of the global energy-related CO_2 emissions [1]. To cut emissions from this sector, transitioning from fossil-based to zero-carbon energy is required. Investment in renewables, such as wind and solar energy, is one of the key mitigation procedures. Annual growth rates of wind and solar energy generation were, on average, 17.0% and 22.3% worldwide

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in 2021, respectively [2]. Eventually, our energy systems could become 100% renewable, which has been shown to be feasible technically and economically [3, 4]. However, wind power and solar power are fluctuating energy sources in nature; thus, there should be a wide implementation of different technologies capable of balancing the grid in 100% renewable-energy systems [5, 6].

Electricity generation must always be equal to consumption and the increasing share of intermittent renewables makes the maintenance of this balance an increasingly challenging task. The energy systems should be smart to regulate the frequency of the grid [7, 8]. There are several different definitions of a smart grid [9]. In this paper, the smart grid is understood as defined by the European Committee for Standardization [10]. The short definition is: 'A smart grid is an electricity network that can intelligently integrate the actions of all users connected to it—generators, consumers and those that do both—in order to efficiently deliver sustainable, economic and secure electricity supplies' [10]. A smart grid enables several types of technologies to balance the system by controlling the demand for electricity based on variations in generation. This type of demand–response (DR) may be facilitated, for example, by the use of batteries [11]; water electrolysis solutions called Power-to-X solutions, such as power-to-gas or power-to-liquid solutions capable of transforming excess energy to something else [12, 13]; or buildings by integrating DR solutions for their heating, ventilation and air-conditioning (HVAC) systems [14].

Virtual power plants (VPPs) have been shown to be feasible systems to aggregate energy production from distributed energy resources. The idea of the VPP is to combine the DR potential of multiple end users and be a part of energy storage systems [14–16]. Consequently, VPPs can help eliminate peak loads and maintain the stability of the power grid. For example, the VPP can connect the automation systems of a group of buildings under a cloud-based platform, by which the energy consumption of the buildings can be remotely and automatically controlled [17]. Aggregating HVAC systems under the VPP enables the adjustment of the electricity consumption by reducing or increasing the required energy in buildings instantaneously based on frequency in the electricity grid without causing noticeable changes in the indoor air quality [14, 18]. In addition to grid management, DR solution providers can join the electricity market as electricity providers, which may also enable economic profits [19].

Because the increasing number of DR solutions enables the increasing share of renewables in energy systems and possibly reduces the necessity for fossil-based balancing power, the impact on GHG emissions is of interest. However, the calculation of possible GHG emission reductions of DR solutions is challenging because they do not necessarily directly reduce energy consumption or GHG emissions. DR solutions store, reduce or increase the energy consumption according to the frequency or demand of the grid, or transform the energy to other products or services, such as heat storage. The possible GHG emission reductions are supposed to be from product substitution because the fossil balancing power is avoided due to the down-regulation, which reduces the energy consumption in the grid, via the DR solution. In addition, VPPs enable an increase in the share of renewables in the grid, which might reduce GHG emissions [20]. Traditionally, the life-cycle climate impacts of products and services have been assessed with attributional life-cycle assessment (A-LCA), but this approach is not suitable for modelling possible consequential environmental impact reductions of DR solutions without making a system expansion. Milovanoff *et al.* [21] studied the implementation of an hourly based dynamic LCA model for demand-side management programmes but did not consider local grid responses or consequential environmental impacts. Stoll *et al.* [22] studied how to calculate the carbon footprint for the hourly based energy consumption of DR tariffs but did not calculate the carbon footprint for a DR solution.

By using a consequential LCA (C-LCA), modelling the impacts when an activity is expected to change the surroundings is possible [23, 24]. However, one challenge of C-LCA is to choose and estimate which products or services are affected, changed or substituted and in what quantities over time. The challenges arise from uncertainties of future predictions on how markets behave [25, 26]. The choices of the products or services affected can significantly influence the impacts [27, 28]. For overcoming the problem of choosing and avoiding the relevant products or services, the LCA-based carbon handprint approach developed by Grönman *et al.* [29] and Pajula *et al.* [30] can be applied. The handprint concept has been adopted by the scientific literature in recent years and, although still emerging, there is a consensus that the handprint thinking underlines the actions with positive impacts and development towards sustainability goals [29, 31–35].

The carbon handprint approach with its guided steps enables a fair and transparent comparison of the lifetime carbon emissions between a business-as-usual (BAU) solution and a new product or service introduced in the same market area and to the same customers. Principally, climate change impacts of products or services are assessed through carbon footprints, which measure absolute carbon emissions produced throughout the lifetime of the product or service [36]. However, the carbon handprint approach provides means to consider the relative positive climate impacts of offerings when used by a customer, which is crucial for climate change mitigation. It should be noted that the idea of the introduced approach is to provide means to communicate with customers about the possible emission reductions in a consisted scientific manner; thus, it is a separate evaluation approach apart from footprint accounting. In addition, the handprint is not necessarily formed even if the actor has previously performed poorly from a climate point of view but improves their operations. For example, when the changed operation does not reduce customers' BAU impact, the handprint is not formed [29]. As there is increasing need to communicate how positive actions, such as those of a DR solution provider, reflect on sustainability goals in a trustworthy way, the authors chose to use the carbon handprint approach. According to our review of the literature, no studies have evaluated the lifetime climate impacts of a DR solution and considered potential GHG emission reductions through the carbon handprint method.

In this study, we aim to show how to assess the lifetime climate impacts of a DR solution and, to achieve that objective, we use as an example a VPP in different grid systems. The concept of a VPP and the case example are introduced in Sections 1.1 and 1.2, respectively. The carbon handprint approach (please see Section 1.2.1) was used to estimate the possible emission reduction potential compared with that of the baseline solution. The remainder of our paper provides information on the significance of VPPs as a climate mitigation action in the energy sector, explains how to measure the lifetime impacts of a DR solution and discusses the role of response providers in this cause (please see Sections 2 and 3). The gained information can be applied for investigation of GHG emissions of other DR solutions, which is becoming a more and more important issue due to the ongoing energy transition, and provides a means to communicate the good that the DR solution provider can do for the grid operator from a climate point of view.

1 Materials and methods

In this section. we present the concept of a VPP and related power markets in Finland, and then the carbon handprint method and the case for handprint calculation are described.

1.1 VPP concept

The idea of VPPs is not new [37, 38] and ongoing research has practical and theoretical implications. For instance, Ran *et al.* [39] simulated the possibility of including a self-adjusting water flow supervisor as a part of HVAC systems, which can result in power reduction; Vedullapalli *et al.* [14] simulated how HVAC systems and storage batteries can be used as a DR solution; Yoon *et al.* [40] proposed integrating an artificial neural network for determining optimal retail prices as a part of DR HVAC systems; and Elgamal *et al.* [41] studied how to optimize the profit of VPPs. The VPP analysed in this study consisted of a combination of multiple DR solutions in buildings on a cloud-based platform, where they could be operated automatically and simultaneously. However, it should be noted that a VPP can consist of several DR solutions other than those in buildings (Fig. 1). In addition, the operator of the VPP can consider local weather conditions, the frequency of the local grid and conditions of the building through HVAC systems.

VPPs have been successfully piloted. For example, in Finland, aggregated resources, including DR, are eligible for all the electricity marketplaces operated by the transmission system operator Fingrid (Table 1) to maintain the grid system in balance. An example is that the City of Lappeenranta, University Properties of Finland Ltd (SYK) [42] and Sello shopping centre [43] have implemented VPPs that provide services to Fingrid.

Currently, in Finland, VPPs are designed to operate in frequency control markets because their power capacities are still small. Frequency containment reserves (FCRs) are active power reserves automatically controlled based on the frequency deviation in the grid in Finland. The minimum size for reserve capacity in these markets varies from 0.1 to 1 MW, whereas joining balancing markets (mFRR) would require 5 MWh of reserve capacity [44]. In the near future, some operators of VPPs might have the capacity to shift their markets into balancing capacity markets. For instance, Helsinki alone has ~1100 public service buildings in which the air ventilation power is sufficient to be used for DR solutions with total power for ventilation of >11 MW [45]. When a VPP operates in balancing capacity markets, it can be used to substitute energy production from peak power facilities. Grids traditionally use gas turbines with carbon-intensive fuels such as light oil for balancing purposes; therefore, gaining energy and emissions savings by implementing high-capacity DR solutions such as VPPs is possible. Of course, hydropower is another typical means to balance the grid, if the location can have such reservoirs. In addition, VPPs might enable an increase in fluctuating renewable electricity production by providing reserve capacity.

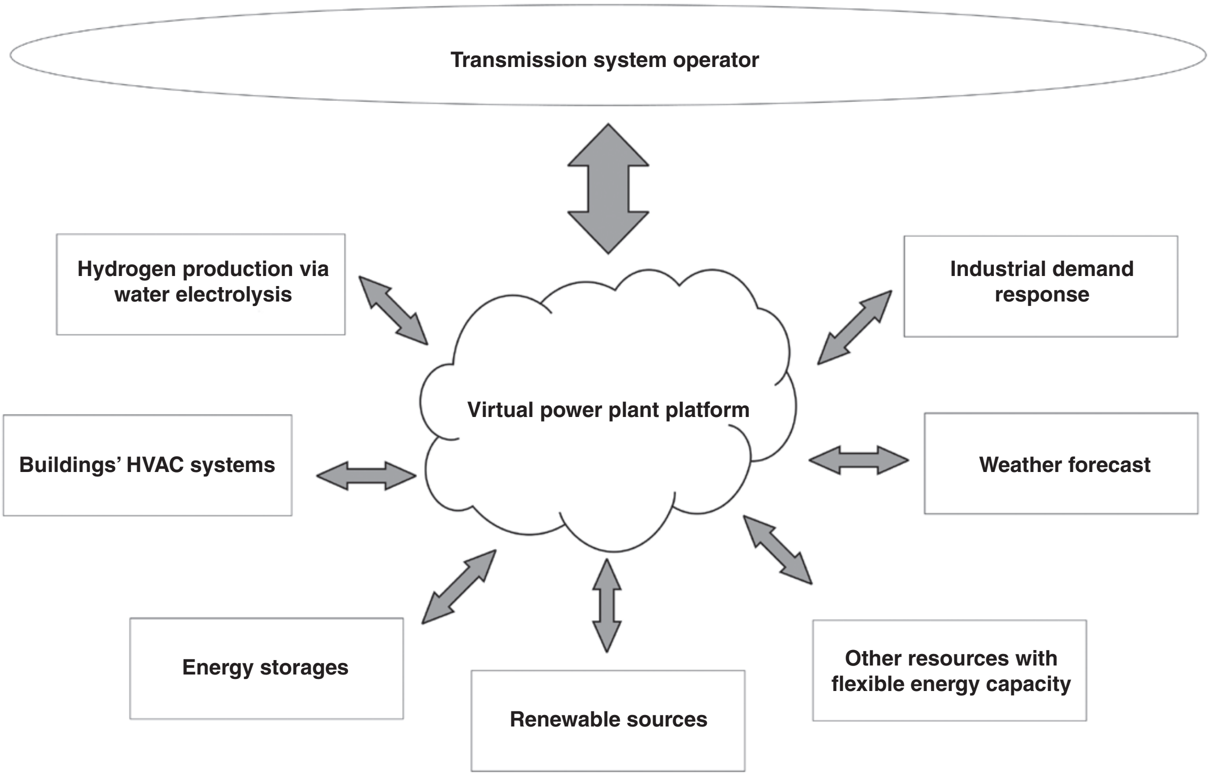


Fig. 1: Simplistic scheme of the idea of VPP [37,38,40]

Table 1: Reserve products in Finland [46, 47]

	Frequency containment reserve for normal operation (FCR-N)	Frequency containment reserve for disturbances (FCR-D)	Automatic frequency restoration reserve (aFRR)	Manual frequency restoration reserve (mFRR)	Fast frequency reserve (FFR)
Purpose	Constant control of frequency		Returning frequency to its normal range and releasing activated FCR back into use		Managing low inertia situations
Minimum bid size	0.1 MW	1 MW	5 MW (used only during certain hours)	5 MW	1 MW

1.2 The case study: GHG reduction potential of a VPP when connected to HVAC systems of buildings and batteries

In the case study, the impact of the HVAC system of the SYK buildings and the batteries connected to the VPP impact on the life-cycle GHG emissions of electricity production is evaluated, when upscaled to reach the minimum capacity of 5 MWh required in balancing markets. The information of the operated VPP of SYK is used as an example for the upscaled version of VPP. SYK joined the VPP platform in September 2020 and, since then, SYK has integrated ~500 objects that can be used for power regulation as a part of the VPP, which consists of 100-kWh lithium-ion (Li-ion) batteries and 430 kWh of HVAC systems, and operates in FCR-N markets. The VPP operational data from April to June 2021 show that using the system at its full capacities is possible (Table 2), thus here we upscale the system for minimum requirement to achieve balancing markets. As the introduced VPP acted in FCR-N markets, where FCR-N is a symmetrical product used to keep the frequency in the normal frequency range of 49.9–50.1 Hz, with the restricted period, the typical up- and down-regulations are similar. The upscaled VPP consists of a battery capacity of 940 kWh and the remainder is from different DR solutions in buildings. The GHG reduction potential was calculated by using the carbon handprint approach for four different grid systems, which are described in Section 1.2.2. To form a handprint, the product or service needs to be used [28, 29]. As the idea of the case study is to evaluate how possible GHG reduction potential is formed, it is assumed that the upscaled VPP is economically competitive.

For integrating a building into a VPP platform, one required action is to integrate HVAC systems with variable-frequency drive (VFD) equipment. VFD makes it possible to adjust the energy consumption with the frequency and voltage. Typically, modern buildings with large HVAC systems have VFDs installed [48], even if they are not a part of the VPP platform for energy efficiency reasons. As VFDs are already installed in many buildings with modern HVAC systems, we excluded the lifetime impacts of VFD and HVAC systems from the model. The same cannot be said for batteries, although they have been demonstrated to lower the stress for power peaks in the grid [49]. As the batteries can considered to be installed for the purpose of being a DR solution in the buildings, their lifetime emissions are included in the model.

1.2.1 *Carbon handprint approach*

As a promising indicator to assess and communicate positive impacts, several handprint approaches aiming at guiding in assessments have been developed, mainly based on existing guidelines on LCA modelling. The Sustainability Health Initiative for NetPositive Enterprise (SHINE) approach introduced by Norris *et al.* [50] provides a framework to assess handprints related to all three aspects of sustainability: environmental, economic and social. In the SHINE approach, positive changes implemented by a defined actor are estimated by comparison to the BAU scenario by utilizing footprint-related metrics. In the SHINE approach, there is a net-positive concept meaning that the handprint is bigger than the footprint of BAU in the defined impact category. The SHINE approach has been used to estimate the handprint to the actors making the change to BAU in several studies [51, 52]. In the handprint approach by Kühnen *et al.* [34], the focus is on assessing positive contributions towards the sustainable development goals set by the United Nations [53]. Closely related to handprint thinking, the Avoided Emissions Framework also aims to capture climate benefit solutions compared with BAU [54].

Table 2: Average increase (up-regulation) and decrease (down-regulation) in power consumption of the VPP during the operational time of 3 months in FCR-N markets. Data were derived from personal communications with SYK.

	HVAC systems (kWh)	Batteries (kWh)
Maximum capacity	430	100
Typical down-regulation of power	150	30
Typical up-regulation of power	150	30
Up-regulation of power (max)	435	100
Down-regulation of power (max)	435	100

This study applies the LCA-based carbon handprint approach introduced by Grönman *et al.* [28] and Pajula *et al.* [29] and further modified by Pajula *et al.* [55] and Lakanen *et al.* [56]. According to Grönman *et al.* [28], handprints refer to the beneficial environmental impacts that organizations can achieve and communicate by providing products or services that reduce the footprints of customers. In the carbon handprint approach, the gained handprint cannot be subtracted from the carbon footprint. The carbon footprint of a commonly used solution in certain areas is compared with the carbon footprint of a new, or as referred to in the framework, the offered, solution. Therefore, tracking the emission reductions achieved by the proposed solution is possible. The selected handprint approach allows attention on the real operation environment by the use of a functional unit, defined beneficiary and a baseline, thus providing realistic estimates on handprints. Additionally, step-by-step guidelines are provided as a difference to other approaches [28, 29].

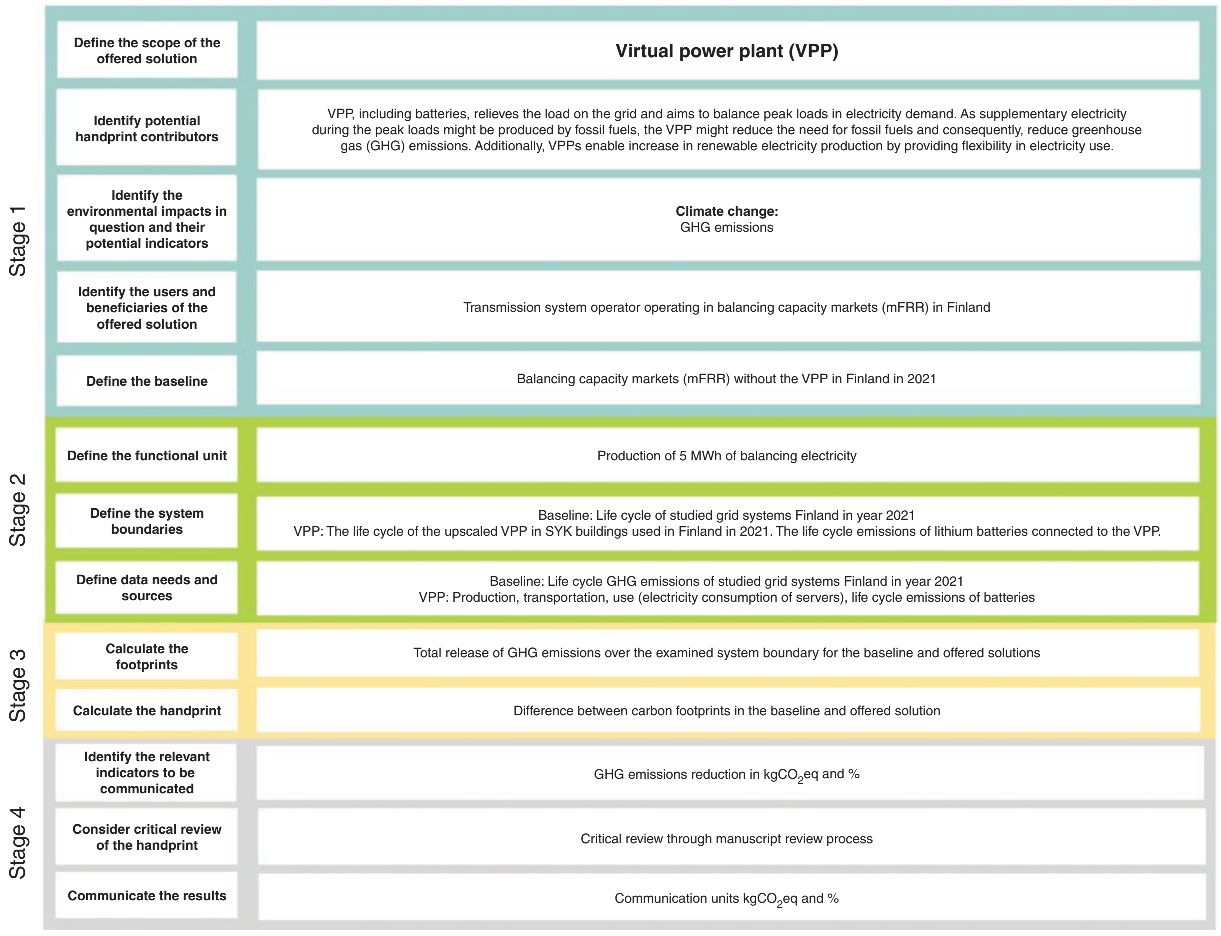
As the idea of the examined VPP concept is to provide means to lower the emissions of the energy generation while at the same time balancing the grid, it is relevant to know what kind of handprint can be formed per MJ. This is relevant as it is unclear what kind of total balance capacity the VPP could provide when comparing the service of the VPP to the BAU solution. LCA was applied to determine the carbon footprints of the VPP and four different grid systems, which were identified as baseline solutions. Lifetime carbon emissions were calculated using the LCA software GaBi 10.5. The global warming potential (GWP100s) was calculated using the CML 2016 impact assessment method [57].

The carbon handprint framework for the VPP in the SYK buildings is shown in Fig. 2. The framework presents a step-by-step process of identifying the offered solution with GHG emission reduction potential, in this case, the VPP; the customers who potentially benefit from the VPP; and the relevant baseline solution if the VPP is not in use in the examined market area. Stages 2–4 are a guide to conducting the LCA-based carbon footprint calculation and how to measure and communicate the carbon handprint.

In Finland, VPPs operate mainly in the FCR electricity markets; hence, historical data from VPPs working in balancing capacity markets are not available. According to the carbon handprint guidelines, statistical or average data must be used if actual users are not known, but potential beneficiaries of the offered solution can be identified [55]. In the case study, potential GHG emission reductions were calculated based on the annual average emission factors of balance power generation. The energy consumption of the VPP has been excluded as it can be considered negligible. In addition, we assume that the VPP replaces an amount of energy produced to balance the grid that is similar to the capacity of the VPP through up- and down-regulation. The system boundaries of the carbon handprint calculation for the VPP are shown in Fig. 3.

According to Fingrid [58], in 2020, the average balancing energy per hour used was 21 MWh for up-regulation and 23 MWh for down-regulation; thus, we can assume that the maximum capacity of the VPP can be fully utilized most of the time when there is a need to regulate energy production or consumption. In addition, we assumed that increasing the energy generation while charging the batteries is unnecessary because of the times when the demand side is lower than the generation side. Hence, the amount of energy generation remains the same as that of the system without a VPP, which does not affect GHG emissions. Because the idea of the studied VPP system is to function in grid balancing markets, avoiding the activation of balancing power is possible by regulating batteries and HVAC systems of the connected buildings with the VPP. In this study, balancing capacity markets without a VPP was chosen as the baseline. The potential carbon handprint was assessed using four alternative scenarios representing different electricity grid mixes as baselines.

Typically, most of the activated balancing power of the Finnish grid system consists of hydropower, but the public information on the sources and shares of activated balancing power sources is limited. In addition, the amount of activated hydropower varies by the season, annual weather conditions and grid



Stage 1	**Define the scope of the offered solution**	**Virtual power plant (VPP)**
	Identify potential handprint contributors	VPP, including batteries, relieves the load on the grid and aims to balance peak loads in electricity demand. As supplementary electricity during the peak loads might be produced by fossil fuels, the VPP might reduce the need for fossil fuels and consequently, reduce greenhouse gas (GHG) emissions. Additionally, VPPs enable increase in renewable electricity production by providing flexibility in electricity use.
	Identify the environmental impacts in question and their potential indicators	**Climate change:** GHG emissions
	Identify the users and beneficiaries of the offered solution	Transmission system operator operating in balancing capacity markets (mFRR) in Finland
	Define the baseline	Balancing capacity markets (mFRR) without the VPP in Finland in 2021
Stage 2	**Define the functional unit**	Production of 5 MWh of balancing electricity
	Define the system boundaries	Baseline: Life cycle of studied grid systems Finland in year 2021 VPP: The life cycle of the upscaled VPP in SYK buildings used in Finland in 2021. The life cycle emissions of lithium batteries connected to the VPP.
	Define data needs and sources	Baseline: Life cycle GHG emissions of studied grid systems Finland in year 2021 VPP: Production, transportation, use (electricity consumption of servers), life cycle emissions of batteries
Stage 3	**Calculate the footprints**	Total release of GHG emissions over the examined system boundary for the baseline and offered solutions
	Calculate the handprint	Difference between carbon footprints in the baseline and offered solution
Stage 4	**Identify the relevant indicators to be communicated**	GHG emissions reduction in kgCO$_2$eq and %
	Consider critical review of the handprint	Critical review through manuscript review process
	Communicate the results	Communication units kgCO$_2$eq and %

Fig. 2: Framework for the carbon handprint calculation in the case study of SYK

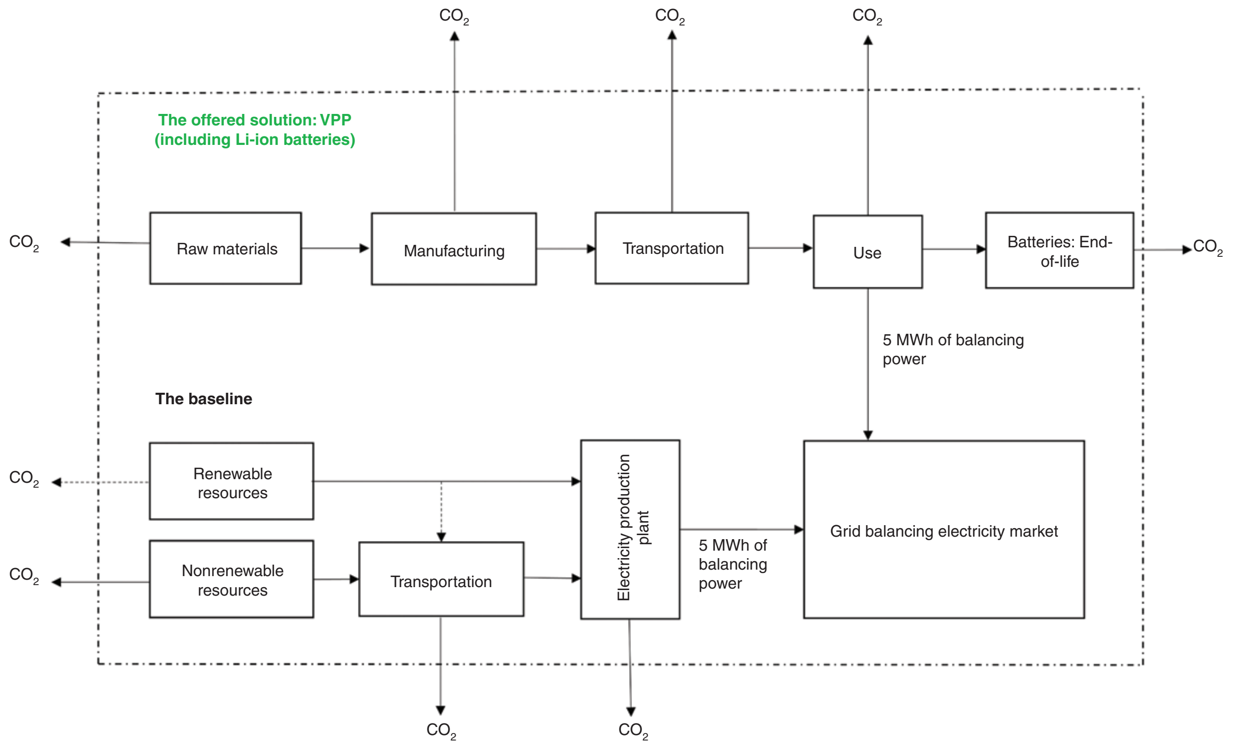


Fig. 3: System boundaries of the carbon handprint calculation for the VPP

functions; thus, simplifications are required. Here, we assumed that balancing power includes 85% hydropower, which was achieved in 2018 [59]. The remainder was assumed to consist of energy from fossil-based liquid fuel. The emission factors of different energy generation sources were derived from the GaBi databases.

1.2.2 *Carbon handprint calculation for the transmission system operator*

The carbon handprint for the VPP was modelled for four different grid systems (Table 3). Each scenario acted as an alternative baseline (BAU) for the VPP. The baseline situation for Scenario 1 is a current Finnish grid that produces the average carbon emissions derived from the electricity generation of the annual grid balance. Here, we assumed that the possible energy savings from the demand side was due to the VPP substituting the average energy mix from the balancing markets.

Public data were unavailable for determining the hourly requirement for the energy source used to balance the grid; thus, we could not calculate the exact energy substitution possibilities for different seasons. The commonly used solutions for grid balancing are fossil fuel-powered gas turbines and hydro storage. However, in many grid systems, hydro storage is not a feasible option because of geographical conditions. In addition, it is possible that the energy savings due to the VPP can reduce the need to produce energy for peak power gas turbines in peak power times in Finland, such as cold winter periods. Thus, the second scenario assumes that the energy produced for grid balancing consists of a 90% fossil-based source and 10% hydropower. In many cases, balancing can be achieved mostly by using hydropower, such as in rainy summer seasons; thus, the third scenario assumes that the energy produced for grid balancing consists of a 5% fossil-based source and 95% hydropower. Overall, the examples show how different grid systems can influence the results of GHG emissions.

Table 3: Differences in modelled grid systems acting as a baseline for handprint calculations

Baseline	Substituted electricity sources for grid balancing	Amount of new wind power
Scenario 1	4.25 MWh hydropower 0.75 MWh fossil-based	–
Scenario 2	0.5 MWh hydropower 4.5 MWh fossil-based	–
Scenario 3	4.75 MWh hydropower 0.25 MWh fossil-based	–
Scenario 4	4.25 MWh hydropower 0.75 MWh fossil-based	16.25 MWh

There is no acute need to increase DR solutions to increase the capacity of fluctuating renewables in the Finnish grid system. However, if the capacities of fluctuating renewables continue to increase, the situation may change. Several studies have estimated the need for reserve requirements when increasing the capacity of wind power. The requirement can vary between 1% and 20% of the installed wind capacity depending on the grid system and the timescale of the forecast horizon [60–62]. Here, we assumed that a 10% more reserve requirement is necessary per installed wind capacity; thus, 5 MWh of new reserve power makes increasing the wind capacity by 50 MWh in the grid possible. However, as the annual wind energy generation is not 100% efficient, e.g. due to wind conditions, a region-specific capacity factor should be used to provide information on the quantity of power generation. To calculate wind power generation, we used a Finnish average capacity factor of 32.5% [63]. Thus, the fourth scenario models the carbon handprint if the DR solution makes increasing the wind power in the current energy grid possible. The handprint of the wind turbine was calculated by comparing the emission factors of the average grid mix in Finland. To calculate the handprint containing both potential emission reductions caused by additional wind power and substituted grid balancing reservoirs, we used system expansion (Fig. 4). System expansion can be used to divide the impacts between a product and a co-product without allocation. As the VPP does not generate electricity and it functions in a different market segment than wind energy providers, economic or energy allocation is not feasible. Here, extra wind power capacity can be considered as a possible co-product.

1.2.3 *Influence of the capacity and function of the battery system on the carbon footprint of the VPP*

In the case study, the VPP of SYK included Li-ion batteries of 100 kWh to increase the capacity of the system for down- and up-regulation. Several LCA studies on different Li-ion-based batteries have been conducted [64–66], but the authors found only one that estimates the impacts for the DR perspective. Varlet *et al.* [67] estimated that the lifetime global warming potential (GWP) per kWh delivered by Li-ion batteries varies between 0.02 and 0.18 kg CO_2-eq kWh^{-1} for those designed for residential storages. The variation is dependent on the frequency of charging and emptying of the battery. The greater the number of charge and energy releases, the lower the lifetime GWP. The lifetime impacts consider transportation, infrastructure requirements, material and energy inputs and waste outputs. Here, we assumed that the same impacts were applied in this study and that of Varlet *et al.* [67]. For the baseline situation, the average emission factor for the Li-ion batteries was used.

The lifetime GWP of Li-ion batteries depends on the number of charge and release cycles. Based on the public information provided by Fingrid, sometimes there are no charges or releases during a day. However, on other days, more than one cycle of charge and release occurs [58]. Because no historical data are available on the intensity of the cycles for VPP application in grid balancing markets, to estimate the influence of the grid fluctuation on the GWP of batteries, a different number of cycles are investigated on sensitivity analysis. As the batteries contribute most of the GHG emissions and the capacity of batteries can vary in different DR systems, the battery capacity is also investigated. The number of cycles is 0.5 per a day and 4 per a day, and the capacity of the battery system is decreased to 50 kWh.

2 Results

The carbon handprint is formed if the carbon footprint in the baseline situation is higher than that in the case of a VPP. In every modelled scenario (Table 4), a carbon handprint was generated. The share of renewable energy should be near 100% in balanced markets, when the handprint is not formed for VPP. In other words, utilizing the VPP results in GHG reductions compared with the studied baseline scenarios. The highest handprint is formed in Scenario 2, even when compared with Scenario 4, in which the extra handprint from system expansion is included. Then again, if the CO_2 intensity of the average grid mix would be similar to the energy production of the baseline in Scenario 2, the formed handprint in Scenario 4 would be many times higher than that of Scenario 2. In addition, when the energy used for grid balancing consists solely of renewable energy sources, the system expansion can be a decisive factor for handprint formation. Thus, depending on the used energy source to provide grid balancing reserve power or the energy palette in the grid, the greatest GHG reduction potential can come either from reducing the need to balance the grid via VPP or from the extra renewables that the VPP enables.

As Fig. 5 shows, the carbon handprint is the highest in Scenario 2, namely 3 918 kg $CO_{2\text{-eq}}$ h^{-1} or 98% in the studied case. In Scenarios 1 and 3, the carbon footprints of the baseline are significantly lower because of the higher share of hydro power;

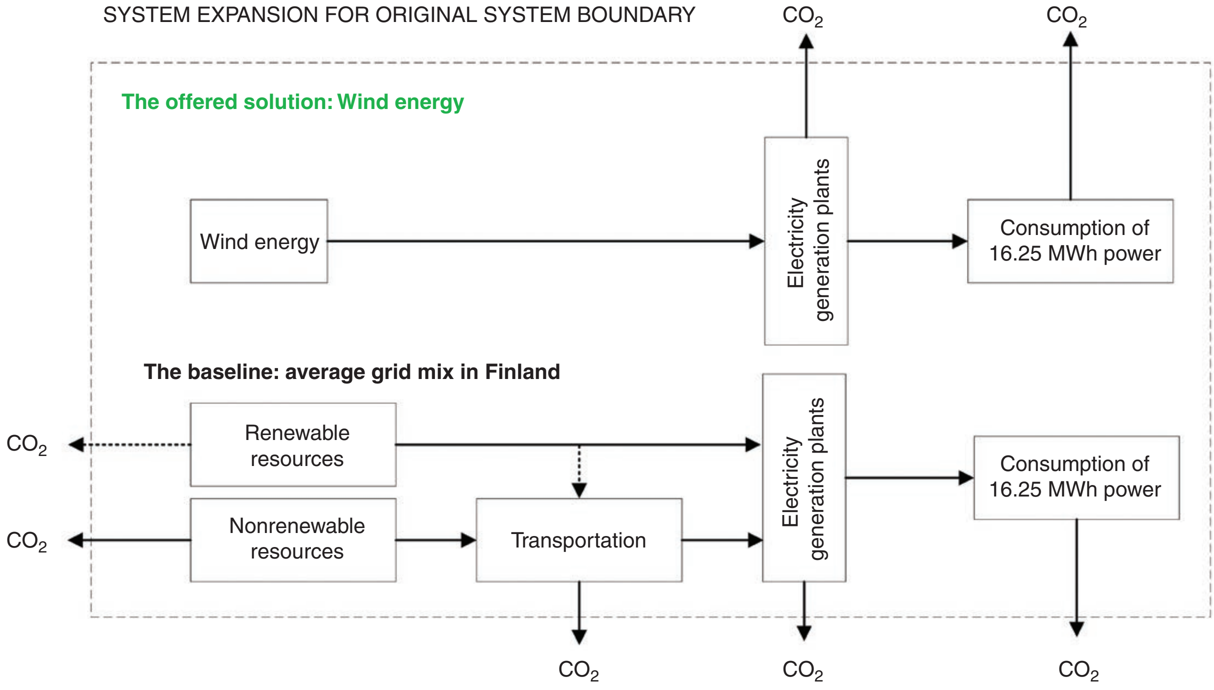


Fig. 4: System expansion for considering the possible renewable-energy increase due to implementation of VPP in Scenario 4. Dashes in arrows show that renewables can also cause GHG emissions in similar phases than non-renewables, but not necessarily.

nevertheless, carbon handprints are formed. In Scenario 1, the provider of the VPP can communicate handprints of 634 kg $CO_{2\text{-eq}}$ h^{-1} or 87%, and in Scenario 3, 196 kg $CO_{2\text{-eq}}$ h^{-1} or 68%.

Fig. 6 illustrates the results from Scenario 4. In Scenario 4, the carbon footprint of the baseline consists of two separate carbon footprints: the carbon footprint of balancing energy of 5 MWh and the carbon footprint of electricity production without wind energy. Hence, the total carbon footprint in Scenario 4 is 3854 kg $CO_{2\text{-eq}}$ h^{-1}. In the offered solution, including the VPP, the total carbon footprint is 233 kg $CO_{2\text{-eq}}$ h^{-1}. Consequently, a handprint of 3 621 kg $CO_{2\text{-eq}}$ h^{-1} or 94% can be communicated in this scenario.

2.1 Sensitivity analysis

As the emissions of VPP consist solely of emissions from battery systems, the GWP of the VPP also halves when the capacity of the batteries halves (Table 5). As a result, the VPP will have a handprint even if only hydropower is used for grid balancing. However, if the number of cycles of batteries is low, at only 0.5 times per day, the GWP of VPP is almost doubled. If the cycles are four times per day, the GWP of the VPP is decreased by ~80%. Thus, the highest sensitivity to VPP is related to how the batteries are used rather than the capacity of the batteries in the studied sensitivities.

3 Discussion

In this paper, we showed how the GHG emission reductions of a DR solution can be estimated by using a VPP as a case example with the Finnish electricity grid. Our results show that a significant reduction in GHG emissions is possible, especially if the grid system uses a high share of fossil-based energy generation for grid balancing. This information might become increasingly relevant because it has been shown that a high share of wind energy in the grid is not as sufficient for emission reduction than thought when the grid is balanced by energy derived from fossil fuels [68]. Most of the energy sources used are already low-carbon in Finnish energy systems; thus, different grid systems can result in higher handprints than in modelled scenarios. Additionally, as the results show, VPPs may enable an increase in the use of renewable electricity by providing balanced electricity to the grid, generating indirect emission reductions. The results further outline the importance of using the carbon handprint approach in these types of systems, where potential emission savings are from a use-phase of the service or product, because typical LCA studies do not estimate emissions savings via product substitution with guidelines on how to determine a comparable system [69].

Table 4: GWPs ($kg_{Co2\text{-eq}}$ h^{-1}) of grid systems and handprints of different systems

System	Baseline in different scenarios	VPP	Handprint	
Scenario 1	728	94	634	
Scenario 2	4012	94	3918	
Scenario 3	290	94	196	
System expansion	Baseline in different scenarios	VPP	Handprint from extra wind energy	Total handprint
Scenario 4	728	94	2988	3622

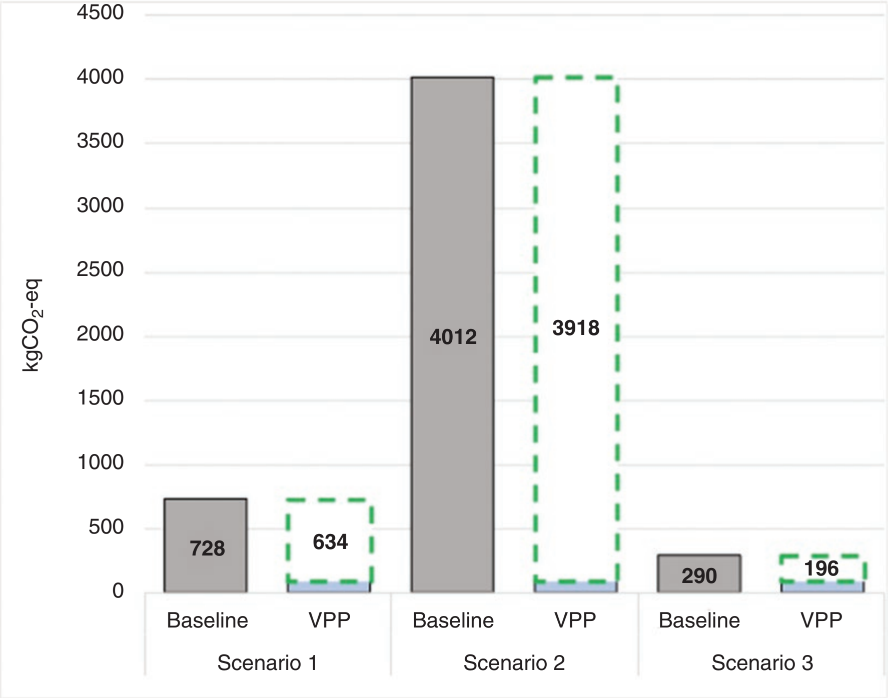


Fig. 5: Carbon footprints and carbon handprints of three studied scenarios

3.1 Validity and generalization

The possible errors of the results are related to assumptions due to limited public information on energy generation for grid balancing, historical data about how the VPP functions and the upscaling of the case example. Hence, the GWP was modelled based on energy generation per hour. The hourly based modelling does not require historical data on how the VPP functions in grid balancing markets, such as the annual GWP estimation, which improves the validity. Similarly, there is a validity issue related to the use of historical data of the number of cycles in batteries in VPP per day, and the usage of different emission factors of batteries used in this study as the used data for the GWP of different commercially available battery systems are from a single literature source. To improve the validity, the impact on GWP caused by the number of cycles and battery capacity were examined in the sensitivity analysis. By modelling different scenarios and sensitivities of two key factors affecting the GWP of the VPP, the handprints show how to model the impacts of DR solutions and what factors increase the validity of the results. By using the emission factors of different grid systems and calculating the GWP of production of a DR solution, the introduced example can be used to estimate emission reductions of other DR solutions in different grid systems than that presented. In addition, because the technology of VPPs can be implemented in all developed grid systems that are smart, there is a major potential for scaling-up, which can result in emission savings worldwide.

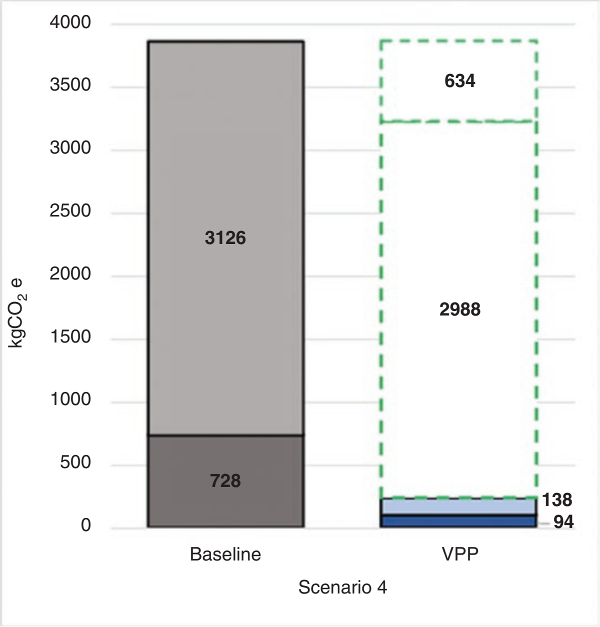


Fig. 6: Carbon footprints and carbon handprints in Scenario 4. Carbon footprints and handprints includes the emissions and avoided emissions from grid balancing and energy generation.

The handprint formation in Scenario 4 via the increase in wind energy should be viewed with caution. Although the assumptions made in Scenario 4 are justified, determining whether the specific DR solution enables a certain amount of renewable energy to increase in the grid is difficult. However, when estimating the impacts at a systemic level for several DR solutions simultaneously or when the capacity of a solution is significantly higher than that studied, the approach in Scenario 4 becomes relevant.

In this study, we assumed that the buildings already had VFD equipment for managing the installed HVAC systems; thus, the equipment was not considered in the models. An argument could be made that the main reason for installing the VFD is not to join the VPP platform, because they are typically installed afterwards to conserve energy [70, 71]. However, if the VFDs are installed to join the VPP platform, an assumption can be that the handprint for the building increases more than the GHG emissions caused by the manufacturing and installation of the VFD equipment due to energy savings. In addition, if the number of buildings and/or other DR solutions drastically increases in the VPP platform, the operation of the VPP can become relatively energy-consuming. In this case, the energy consumption of the servers should be included in the handprint calculations.

3.2 Communication of the handprint

The idea of the handprint is to communicate the potential emission reduction for the customer when providing a service or a product, not to calculate the absolute footprints of the BAU. Thus, it is important to know how to properly communicate the handprint. According to the handprint guidelines, the provider of the offered solution may communicate handprints [55]. However, in the case study, the provider of the VPP is not straightforward because several actors are involved, and all of them are necessary to ensure the function of the VPP in the electricity market. For example, in the case study, the owner of the buildings, the provider of the VPP technology, the operator (of the VPP) in the electricity market and the transmission system operator are significant stakeholders of the system. Kasurinen *et al.* [72] recommended that the carbon handprint be transparently communicated for each customer and function. They also concluded that shared handprints are possible in system-level examinations. In our study, the actors ensuring the function of the VPP are the operators of the VPP, the technology provider and the grid provider, who can communicate the total handprint of all connected capacities given the customer remains the same. The other actors, such as the separate building owners that are a part of the VPP, can only gain the handprint based on their capacity and emissions delivered from their equipment when communicating the handprint to the transmission system operator, and the actor provides added value to the emission reduction in a studied value chain. However, if the customer for the building owner would be a VPP, the handprint must be recalculated. In that case, the operational environment defining the baseline is different, which highly impacts the handprint formation. The transparent evaluation of the potential handprint for every actor involved

Table 5: Sensitivity of the capacity of the battery system and the intensity of cycles of charges and releases of batteries per day

	The average GWP for VPP	Maximum capacity of batteries decreased	Number of cycles is 0.5 times per day	Number of cycles is four times per day
VPP (GWP kg$_{CO2\text{-}eq}$ h^{-1})	94	47	170	19

separately is important to ensure correctness in the calculations and communications.

3.3 Further research and limitations

The handprint calculation of the case example was based on a theoretical situation in which the VPP was upscaled to fit into balancing markets. In further research, if historical data on VPP with energy generation sources exist in balancing markets in Finland, calculating the annual energy savings derived from the VPP is possible. In this case, using primary data to model a more valid baseline for calculating GHG emission reduction potentials can be done when estimating future investments in different DR solutions. In addition, this study used only battery and building HVAC systems to form a VPP. As shown in Fig. 1, including several different DR solutions than those studied in the VPP platform is possible and might require a different approach when modelling the impacts of VPP. For instance, if the DR solution is designed solely to function in a VPP, the lifetime impact of the DR solution should be wholly included in the model.

In the future, with building modernization, energy efficiency improvements make including more buildings into VPPs possible, and because the VPP is scalable into different grid systems in different regions, investigating emission reduction potential savings in different regions is of interest. The emission reduction potential can be much higher than that of the studied system in areas with high fossil-based energy generation for grid balancing, such as regions with low hydro storage capacities.

This study focused on GHG emission evaluation by using the carbon handprint approach, although the energy sector contributes to several impact categories, such as water and land use. Hence, further research should attempt to recognize and evaluate other possible impact categories and possible reduction potentials in these categories. The literature has shown that the handprint approach can also be used to evaluate impact categories other than GHG emissions [55].

4 Conclusions

According to our study, VPPs may enable greenhouse gas reductions and help mitigate climate change. However, the magnitude of reduction is highly dependent on the studied grid system, especially sources of electricity production, i.e. if the system is balanced using fossil fuel-based generation, VPPs may reduce the emissions significantly, whereas if the system can be balanced using low emission generation such as hydropower, the emission reduction potential is smaller. The higher the share of fossil fuels in the baseline system, the higher the GHG emission reduction potential when the VPP is included. Our study shows that potential GHG reductions of demand–response solutions can be assessed using the carbon handprint approach, which provides valuable information for further studies of GHG reduction potential calculations for VPPs and other DR solutions. Our results show that the significant emission reduction potential of VPPs can also help provide insights into the relevance of DR solutions in climate change mitigation. Additionally, our study helps DR providers understand their role in reducing GHG emissions in the energy sector and encouraging consumers, companies and property management to implement VPPs.

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Conflict of interest

None declared.

Data availability

The data underlying this article cannot be shared publicly, because some of the data used for modelling (LCA software GaBi 10.5) were provided by third party under licence.

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