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The contribution of smart buildings to low-carbon built environment

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Abstract. Decarbonizing the energy sector is one of the most significant challenges of our time. Accordingly, the electrification of the energy system, deployment of renewables, and implementation of smart electricity control in the built environment is at the core of the in-force European Union policy actions. Recently, the European Commission released the Smart Readiness Indicator (SRI) for buildings framework. The SRI intends to raise awareness of the benefits of demand-based smart electricity control in energy- and carbon-intensive buildings. However, it is unclear whether implementing SRI-compatible smart electricity control technologies truly reduces carbon emissions in the built environment. This study modeled an SRI-compatible smart electricity control to every ground-source heat pump heated building in the Helsinki Metropolitan area. The study evaluated the climate mitigation implications before and after the smart electricity control using hourly-level energy consumption data. The study revealed how the climate mitigation potential of smart electricity control was only 0.02% annually. The reason for such a slight decrease in emissions appeared to be Finland's relatively clean electricity network. Accordingly, the results questioned whether the SRI delivers its primary objective – i.e., decarbonizing the electricity grid – in northern European countries.

1. Introduction

The more efficient and flexible use of existing resources will play a vital role in the future. The efficient utilization of resources is especially crucial in carbon-intensive building and energy sectors. In the coming years, electrification is expected to enable a fundamental transition from a highly centralized and fossil fuel-based energy system to a decentralized energy network [1]. Accordingly, as electricity is becoming the main energy carrier, it will also positively affect the efficient deployment of renewable energy resources (RES) [2]. However, the increasing uptake of RES will set some challenges for future energy supply reliability. In an electricity-based energy network, the energy production and demand must be balanced at all times. However, this is often not the case with RES due to their fluctuating energy production profile [3]. Thus, to support the electricity grid against failures, increasing flexibility in the energy system is mandatory, especially on the demand side [4].

Over 80% of the global emissions are energy-related, and most of the emissions are produced by building heating and cooling [5]. Buildings' role in providing flexibility services for the electricity grid has been widely discussed during the past decade [2,6,7]. It has been found that energy-intensive buildings not only provide a great opportunity for energy savings but can also act as short-term reserves for the grid [8]. Accordingly, due to the energy system electrification, it has become more crucial to implement such energy-efficient heating appliances, which are power-to-heat and smart control (SC) compatible. Such heating appliances are heat pumps (HPs), which can be operated according to the grid signals and, for instance, cut the power grid load during peak hours [9]. In the Nordics, one especially appealing HP technology is the ground-source heat pump (GSHP) heating/cooling system [10]. GSHP is equipped with a power-to-heat functionality designed for buildings that use HP technology to transfer heat to or from the ground [11]. The technology takes advantage of the relative constancy of the earth's temperatures through the seasons.

Today, the EU enhances SC-compatible building technologies through the smart readiness indicator (SRI) framework. The key focus areas of the framework appear to be decarbonizing the building heating and cooling sector and raising awareness of the benefits of demand-based electricity control in the built environment [12]. Accordingly, the SRI rating scale is constructed based on 54 predefined building services, and nearly half are somewhat heating-related. Besides those services related to heating/cooling, other domains covered in the framework are ventilation, lighting, dynamic building envelope, on-site (renewable) electricity production, and monitoring and control. In the framework, each service is enabled by a combination of smart-ready technologies with various degrees of smartness, referred to as functionality levels [13]. Generally, the highest functionality levels are obtainable only if the service control happens based on the demand set by the building, user, and the grid. However, the maximum SRI rating appears to require a building unit's ability to actively adapt its electricity usage based on the grid signals [14].

The main aim behind the development work of the SRI framework is to encourage investments in smart buildings, which can support the energy system transformation towards a low carbon economy. Thus, the building unit's smart grid compatibility is at the core of the framework. However, the northern European countries are already known for a fairly clean electricity system today. It is still unclear whether the SRI carries out its original purpose as a climate mitigation activity also in the Nordics. Furthermore, the SRI rating scale evaluates only one building unit's ability to provide flexibility for the grid. However, a single building's capability to provide any flexibility services for the grid is often restricted, for instance, to a heating unit's capacity. This study aims to discuss whether the SRI-compatible smart building, equipped with smart heat load control of a cold climate-appropriate heating technology (i.e., GSHP), truly leads to reduced carbon emissions in the Nordic building stock.

2. Research design

In this study, we model SRI-compatible smart heat load control to every building in the Helsinki Metropolitan Area (HMA), where a GSHP heating solution has been implemented. In addition, the GSHP heated buildings in the area are pooled together due to a single heating unit's limited capacity, and the pool's shared potential to decrease carbon emissions is evaluated.

HMA is a 1.19 million population capital city area (including Helsinki, Espoo, and Vantaa) in Finland. In total, 6 403 buildings (i.e., 1 913 989 sqm) fulfilled the study criteria and formed the GSHP pool for this study. The final data included building type, size, volume, and construction year. The energy model applied in this study uses hourly-level energy consumption data for 2019. The energy model, originally introduced by Vimpari [15], is based on the same data applied by Janhunen et al. [16]. Thus, a more detailed description of the dataset can be found therein.

In the present study, the developed energy model was set to estimate the climate mitigation implications of the GSHP pool before and after the implementation of SC. The SC followed the SRI-compatible service functions, and in this study, the service Heating-4 – Flexibility and grid interaction – was further studied. Heating-4 is divided into five functionality levels introduced in Table 1.

Table 1. The applied SRI-compatible smart heat load control features, retrieved from [13]

SRI-compatible service	Functionality level	Smart Control	Description
Heating-4: Flexibility and grid interaction	Level 0	No	No automatic control
	Level 1	Yes	Scheduled operation of the heating system
	Level 2	Yes	Self-learning optimal control of heating system

Level 3	Yes	Heating system capable of flexible control through grid signals
Level 4		Optimized control of heating system based on local predictions and grid signals (e.g., through model predictive control)

In this study, we applied the functionality levels 0 and 4 to evaluate the climate mitigation implications of the GSHP pool without (level 0) and with (level 4) the SC. First, we calculated the heating emissions of the pool by multiplying the estimated energy consumption with GSHP-specific carbon emission coefficients, as described by Vimpari [15]. The base scenario introduced by Vimpari equals the pool's electricity control without SC. Secondly, the SC was modeled to remove two peak hours per day, as Janhunen et al. [16] described. The two-hour peak shaving was selected based on expert interviews so that peak shaving would have a minimal influence on the comfort of the building user and indoor climate. Accordingly, the third-highest hour of the day was the new daily peak power hour. The daily energy consumption was not reduced from the SC actions as the energy required for the peak hours was returned to other hours of the day (i.e., the energy consumption curve was flattened). This modeling was done for every day of 2019. Finally, we estimated the climate mitigation potential from the reduced power usage during peak hours, as the power peak periods tend to possess higher negative climate implications than other hours of the day.

3. Findings and discussion

The study evaluated the climate mitigation implications of the EU-driven SRI compliant smart electricity control in the Nordic building stock. Accordingly, we studied the influence of SC on one of the most potential power-to-heat appliances, i.e., GSHPs. HPs, in general, are expected to have a vital role in low-carbon heating markets. Today, 2% of the heated floor area in the studied HMA building stock is covered with GSHP. The share is expected to dramatically increase during the coming decade due to the heating solution's extraordinary technological features.

This study modeled smart electricity control to restrict the GSHP buildings' peak power consumption during the two peak hours per day. Accordingly, we analyzed the results from the climate mitigation point of view. Table 2 represents the GSHP pool's carbon emissions before and after the SC and their difference in peak consumption and produced carbon emissions.

Table 2. Estimated GSHP emissions before and after the SRI-compatible SC

Floor area (sqm)	Peak consumption (MW)			Emissions (kgCO$^{2)}$		
	No SC	SC	Difference	No SC	SC	Difference
1 913 989	24.9	22.9	92%	6 382 471	6 381 086	99.98%

The study results revealed a surprisingly low climate mitigation implication of the SC on the studied GSHP pool. The difference before and after SC activation was only 0.02%, even though the peak power consumption with SC decreased by 8%. The results of this study seemed not to fully support the expected implication of smart electricity control's climate mitigation potential as outlined in the most recent in-force EU policy decisions [17].

Generally, smart electricity control's climate mitigation implications are perceived as the main driver of smarter buildings. Accordingly, the advanced SC activities in the built environment contribute positively to climate mitigation through energy conservation and more efficient renewable energy utilization [18,19]. However, to enable decarbonization of the energy system, the more flexible use of energy resources is required on the demand side. Therefore, implementing various smart grid-ready heating appliances, such as HPs, is essential. Furthermore, due to the HPs' high coefficient of performance – at best, one heating unit can generate three times more thermal energy than the consumed electricity – they are perceived as appealing low-carbon solutions [20]. However, the climate mitigation implications of power-to-heat appliances are always related to the carbon emissions of the electricity utilized to generate heat [6]. Moreover, the current state of the power system affects the emissions, as the present study results revealed.

In power markets, where electricity is still mainly produced by burning fossil fuels, the climate mitigation potential of GSHPs' SC would be much more significant. However, that is not the case in the Nordic power system, where today, 90% of the electricity is produced with renewables [21]. Especially renewable hydropower has a significant role in Nordic electricity production since it is used as regulating power to counterbalance the fluctuating production profile of other intermittent renewables, such as wind and solar. In this study, only two daily power peak hours were shifted, which could potentially cause the minor climate mitigation implications of the GSHP pool's SC shown in Table 2. However, due to the relatively clean power system in the Nordics, a greater number of reserve hours would not have significantly affected this study's results. Moreover, a greater number of reserve hours could negatively affect the post-heating peaks and indoor climate conditions during the heating season [22]. Even though the SC did not lead to significant environmental benefits in the studied GSHP pool, implementing GSHPs is an economically and environmentally appealing solution in the built environment [10,23].

Today, the SRI framework aims to strongly promote the uptake of smart building technologies by raising awareness of the benefits of smartness from the building's, users', and energy grid's perspectives. Nevertheless, the key driver behind the framework is the global demand to reduce carbon emissions generated by the energy system. In the SRI framework, a high level of smartness is obtainable only if the building provides flexibility for the energy grid [14]. Thus, even though the framework evaluates the smart technologies' potential to improve the overall efficiency of the building (energy savings and maintenance) and support user wellbeing (occupant informing and maintaining indoor conditions), the most crucial dimension in the SRI framework is the demand-side flexibility, i.e., SC as referred in this study. Accordingly, the main aim behind the development work of the SRI framework is to increase the building stock's readiness for participating in the reserve markets without compromising the user wellbeing and building's operational efficiency.

Currently, the SRI only evaluates the building smartness on a property level [12]. Still, a single building's reserve potential is limited to a single heating unit's capacity. Thus, it is questionable whether the SRI framework should broaden its scope of smartness from a property level to a city level. In the coming years, electricity usage is expected to increase, but the energy system will be more fragile due to the intermittent production of RES. Therefore, an increasing need for smart electricity control is expected, especially in the built environment. Accordingly, the need to increase the readiness of the building stock and awareness of the users for smart resource sharing is crucial today, even though the results of this study did not show direct benefits between SRI-compatible smart electricity control and carbon emissions in the Nordics.

4. Conclusions and further research

The results of this study highlighted the difference between the Nordic power market and the SRI's baseline design. The results indicated that the highest level of smartness does not necessarily lead to reduced carbon emissions. Based on the earlier studies, it has appeared that high SRI scores are possible only if the building's smart electricity is controllable based on the grid signals. However, the climate mitigation implications – one of the main drivers behind the SRI rating system's development work – are not fully fulfilled in the Nordics. This aspect within the scope of the SRI framework should be further studied since the other energy grids in Europe are gradually moving away from carbon-intensive electricity production.

Originally, the SRI framework for buildings was more like an ultimate definition of smartness. The rating system aimed to consider other resource-sharing dimensions, such as those relating to people flow, rather than focusing only on energy sharing. However, in its current form, the SRI mainly supports flexible energy resource sharing based on the need set by the user, the building, and the grid. It is questionable whether the SRI should be framed to support other resource-sharing challenges of future urban networks. Such resources are, for instance, the building facilities and spaces.

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