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RESEARCH ARTICLE

Hedging Investments of Grid-Connected PV-BESS in Buildings Using Cryptocurrency Mining: A Case Study in Finland

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ABSTRACT In recent decades, there has been a growing global focus on solar power as a renewable energy source (RES) to supply local energy demands and reduce greenhouse gas emissions. Rooftop solar photovoltaic (PV) system provides a small-scale utilization of solar energy on the roofs of apartment buildings. Investment in this system and its profitability depends on several factors, including geographic conditions, electricity price, and local load profiles. However, in Finland, the maritime and continental climates and electrically heated residential buildings present unique challenges to the investment and utilization of rooftop PV systems. Common solutions to incentivize the investment of grid-connected PV in apartments are battery energy storage systems (BESSs), demand side management (DSM), and power-to-x (P2X) approaches. Nevertheless, the value of these solutions is limited in Finland due to the seasonal variation of solar PV generation and customers' energy consumption. This paper presents a novel and practical control and hedging mechanism to encourage investments in rooftop solar PV-BESS systems by investing in cryptocurrency mining devices (CMDs) as dispatchable and flexible loads, which facilitate the use of excess renewable energy for producing cryptocurrency, such as bitcoin (BTC). This mechanism can optimally switch the output of excessive renewable energy between exporting to the main grid and mining cryptocurrency. The proposed mechanism is studied using a dataset obtained from a residential apartment building in Helsinki, Finland, and its effectiveness is demonstrated through several practical scenarios. The results of a case study employed in this work demonstrate that the proposed hedging mechanism can provide sufficient encouragement for investors to invest in a PV system, with a return on investment equal to 57.7%. This mechanism also reduces the annual cost of residential apartments by 68.1%.

INDEX TERMS Battery energy storage system, building energy management, cryptocurrency mining, renewable energy, photovoltaic.

NOMENCLATURE

A. INDICES AND SETS

t	Index for time.
T	Set of time.

B. PARAMETERS

A_{PV}	Total surface area of solar arrays (m^2).
DC_t^{BESS}	Depreciation cost of BESS ($/h).
DC_t^{CMD}	Depreciation cost of CMDs ($/h).
DC_t^{PV}	Depreciation cost of PV ($/h).
E^{max}/E^{min}	Maximum/Minimum energy capacity of BESS (kWh).

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ir	Interest rate (%).
I_t^r	Solar irradiance (kW/m^2).
MPF^{BTC}	Cryptocurrency mining pool fee (%).
$N_{in}^{CMD-max}$	Maximum number of CMDs.
P_{PV}^{cap}	PV capacity (kW).
P_D^{CMD}	Power consumption of a CMD (kW).
P_l^{max}	Residential complex line limit (kW).
$P_{ch}^{max}/P_{dch}^{max}$	Maximum charging/discharging rate of BESSs (kW).
P_t^{PV}	PV unit output power (kW).
P_t^{res}	Demand of residential apartment building (kW).
PP^{CMD}	Purchase price of a CMD ($).
TC^{BESS}	Total cost of BESS ($/kWh).
TC^{PV}	Total cost of PV ($/kW).
UL_{year}^{BESS}	Useful life of BESS (year).
UL_{year}^{CMD}	Useful life of a CMD (year).
UL_{year}^{PV}	Useful life of PV (year).
α^{BTC}	BTC block reward (BTC/block).
$\beta_t^{BTC,CMD}$	Profit factor of mining loads ($/kWh).
$\gamma^{cooling}$	Cooling factor of mining (%).
δ_t^{BTC}	BTC mining difficulty level (TH/block).
λ_t^{BTC}	Price of 1 BTC at time t ($).
$\lambda_t^{ex}/\lambda_t^{im}$	Purchase/Retail price of electricity at time t ($/kWh).
μ^{max}/μ^{min}	Maximum/minimum flexibility of demand response programs (%).
ρ^{CMD}	Hash rate of a CMD (TH/s).
η_{ch}/η_{dch}	Charge/Discharge efficiency of BESSs (%).
η_{PV}	PV Module Efficiency (%).
θ_t	Angle of incidence at time t.
Δt	Time step (hr).

C. VARIABLE

E_t^{BEES}	Stored energy of BESSs at time t (kWh).
I_t^{ch}/I_t^{dch}	Binary charging/discharging decision of BESS at time t.
N_{in}^{CMD}	Number of installed CMDs.
N_t^{CMD}	Number of running CMDs at time t.
P_t^{DR}	Demand of apartment building with considering demand response programs (kW).
P_t^{CMD}	Total demand of CMDs at time t (kW).
P_t^{ch}/P_t^{dch}	Charge/Discharge power of BESS at time t (kW).
P_t^{ex}/P_t^{im}	Exported/Imported power to/from the main grid at time t (kW).
Rev_t^{BTC}	Income of the cryptocurrency mining business at time t ($).
$ROI_{SC,i}$	Return on investment for scenario i (%).

I. INTRODUCTION

Following the global financial crisis in 2009, financial markets experienced a new phenomenon known as "cryptocurrency", such as bitcoin (BTC) [1]. Due to the benefits of blockchain-based cryptocurrencies, including transparency, accessibility, decentralization, immediate settlement, anonymity, and global recognition; they are rapidly spreading and attracting the interest of enterprises, startups, entrepreneurs, economists, as well as common people worldwide [2]. Therefore, they have enormous potential to serve as an alternative form of currency soon. Blockchain technology in the smart grid provides infrastructure for improved communication, electricity trading within the microgrid (MG), transparency, smart contracts, automation, and resource sharing in the smart grid. It not only facilitates close interaction between participants and the exchange of both data and energy transfer, but also enables access to various large-scale distributed energy resources, ensuring supply-demand equilibrium, and providing a private and secure trading platform [3], [4]. However, the significant energy consumption of this technology may pose challenges to the grid.

Technically speaking, cryptocurrency mining is a process in which cryptocurrency miners validate blockchain-based cryptocurrency transactions by solving a computational problem using cryptocurrency mining devices (CMDs). Miners with their application-specific integrated circuit (ASIC) devices verify the dates and validity of each transaction and receive block rewards as motivation based on their ability to solve computational problems [5]. However, there are two critical obstacles that challenge miners: the high energy consumption of CMDs and the resulting environmental pollution due to their energy-hungry nature [6]. The electrical energy consumption, the installed electricity capacity, and greenhouse gas emissions of the BTC network in 2022 were estimated to be about 95.41 TWh, 10.88 GW, and 48.35 million metric tons of carbon emissions, respectively [7]. These values increase when considering other cryptocurrencies such as Ethereum (ETH), Tether (USDT), etc. To overcome these challenges, miners can use renewable energy sources (RESs) such as solar and wind for mining cryptocurrency.

Today, there is a growing global focus on renewable energy due to targets for limiting the use of fossil fuels and advancements in energy generation technologies using RESs. However, high installation and investment costs, as well as the intermittency of energy production due to the non-controllable and non-dispatchable nature of RESs such as wind or sunlight, geographic limitations, etc., pose technical and economic challenges to the widespread adoption of RESs [8]. This means that the utilization of RESs presents challenges, and without further technological advancements and changes to the current energy system, it is not possible to meet all energy requirements from RESs. In addition to the challenges mentioned above, in some countries such as Finland, small-scale utilization of solar energy faces another challenge. Peak loads occur in winter, while peak power generation from solar photovoltaic (PV) systems occurs in summer. This time difference limits the full utilization of PVs [9].

The literature presents widely used solutions for small-scale solar energy utilization on apartment building roofs. These solutions aim to add flexibility to energy systems with significant renewable energy source (RES) penetration and address related problems. Some of these solutions include using energy storage systems like battery energy storage systems (BESS) [10], implementing demand side management (DSM) programs such as demand response (DR) [11], and utilizing power-to-x (P2X) approaches such as power-to-hydrogen [12]. However, employing these solutions increases the investment costs of RES deployment and poses substantial risks to investors. Successful implementation of these solutions also requires remuneration policies, government incentives, and risk reduction mechanisms. Motivated by these challenges, this paper proposes a control and hedging mechanism that could encourage more investment in rooftop solar PV systems. The mechanism involves mitigating risk by investing in cryptocurrency mining facilities to store excessive renewable energy (energy surplus) from solar power as cryptocurrency value.

A. LITERATURE REVIEW

As residential retail electricity prices continue to rise, rooftop PV emerges as a potential low-cost RES alternative for customers. While BESS can increase self-consumption and reduce customers' billing costs, the high investment costs associated with them must be considered. Thus, it is essential to examine scenarios and conduct economic studies to determine the feasibility of implementing this system. References [12] and [13] present the optimal capacity of solar PVs and BESSs for households connected to the grid, using actual annual data to minimize electricity costs. The authors in [15] and [16] develop a techno-economic performance model of a rooftop solar PV system with BESS for residual buildings in different regions and climate zones in India and Saudi Arabia, respectively.

Reference [17] presents an intelligent power management system for solar PV systems in buildings, using an adaptive neuro-fuzzy inference system to maximize the utilization of solar power. In [18], an economic analysis is presented to evaluate the profitability of a grid-connected PV-BESS system for residential applications. In order to implement grid-connected PV-BESS systems in apartment buildings, it is essential to employ energy/power management systems for monitoring and controlling the energy/power flow within them. In this regard, the authors in [19] propose a method based on current control to improve the energy management strategy and effectively manage the active power flow among PV units, the electric grid, and various loads.

Cryptocurrency mining has become a popular and lucrative industry in recent years. However, it has faced criticism for its high energy consumption and contribution to carbon emissions. To address this issue, numerous researchers have explored the feasibility and potential benefits of using RESs for cryptocurrency mining. In [20], a DC-DC direct connection from a solar panel to a CMD is developed, and the financial feasibility of this system is determined. Reference [21] describes a method of mining cryptocurrency that uses solar energy to maximize profits while minimizing the carbon footprint and reducing electronic waste. The authors in [22] present a risk-aware energy management strategy for an MG that includes RESs, BESSs, cryptocurrency miners, and responsive loads. In [23], the optimal planning and operation of a cryptocurrency mining farm integrated with electrolyzers, BESSs, fuel cells, hydrogen storage tanks, and heat pump are proposed to assess the economic benefits of using curtailed renewable energy.

Reference [24] introduces an approach to investigate a cogeneration system of electricity and cryptocurrency mining using a rooftop solar PV system. This approach considers technical, economic, and environmental analyses. In a paper closest to ours, study [25] investigates a wind farm investment model that involves simultaneous investment in a cryptocurrency mining farm to hedge against electricity price risk and create an incentive for early investment in wind farms. The results presented in the paper demonstrate that investing in a cryptocurrency mining farm behind the behind-the-meter of a wind farm can significantly increase the generator's revenue while simultaneously reducing the risk of anticipating the wind farm's construction. However, the power capacity of the cryptocurrency mining farm is considered fixed, and no optimization has been done to calculate it, which is different from our study.

The research literature discussed above has mainly focused on the strategy of using renewable energy for cryptocurrency mining from the perspective of the miners' owners while assuming a constant load. However, there has not been an in-depth study on optimizing the cryptocurrency mining capacity and its consideration in energy management studies from the perspective of the MG owner. This paper aims to fill this gap by proposing an approach that encourages investment in RESs and optimizes the cryptocurrency mining capacity. Specifically, we propose a hedging mechanism to encourage investment in rooftop solar PV systems with BESSs and mitigate the risk of investing in cryptocurrency mining facilities.

B. CRYPTOCURRENCY MINING IN APARTMENT BUILDINGS: PROS AND CONS

This paper demonstrates how the application of cryptocurrency mining provides economic benefits for grid-connected apartment buildings with PV-BESSs, besides its effect on the motivation of customers to utilize RESs. The use of this strategy can result in several advantages and disadvantages. One of the primary advantages is the potential to offset the cost of the PV-BESS systems through cryptocurrency mining, which can increase the overall return on investment.

Cryptocurrency mining can also provide a hedge against energy price volatility, as any excessive renewable energy generated by PV systems can be used to mine cryptocurrency, providing an alternative revenue stream. This can demonstrate the feasibility of its application to the building owners, to invest in this type of RESs. However, there are also several potential disadvantages to consider. For example, the income generated from cryptocurrency mining may not be stable or predictable, and it may not always be sufficient to offset the cost of the PV-BESS system. Additionally, there are significant regulatory and compliance risks associated with cryptocurrency mining that must be carefully managed to avoid legal and financial consequences. Overall, the decision to hedge investments of grid-connected PV-BESS in apartment buildings using cryptocurrency mining will depend on a variety of factors, including the cost of the system, the expected return on investment, and the volatility of the cryptocurrency market.

C. MOTIVATIONS

In the following, the motivations for performing this study are presented.

- The importance of using RESs to supply cryptocurrency mining loads in the power system is one of the key criteria to improve environmental sustainability and cost savings.
- Encouraging investment in RESs is important for transitioning toward a sustainable and low-carbon energy system. Cryptocurrency mining using excess renewable energy can be a sustainable and profitable strategy to offset the costs of investing in RESs.
- Existing research primarily focuses on cryptocurrency mining from the perspective of miners, with less emphasis on considering these loads as an encouragement for investment in RESs. Therefore, there is a need to consider these loads in the energy management of MGs to hedge the investment in RESs.
- Current research treats cryptocurrency mining loads as common loads, overlooking their specific characteristics. Therefore, it is necessary to model these loads as dispatchable/controllable loads, considering the potential benefits derived from their flexible operation.

D. MAIN CONTRIBUTIONS

The main contribution of this paper is to introduce a practical controlling and hedging mechanism to encourage investments in rooftop solar PV-BESS systems by investing in CMDs, and other contribution can be summarized as follow:

- The profitability of cryptocurrency mining is investigated in grid-connected apartment buildings consisting of rooftop solar PV systems, BESSs, and loads under various practical scenarios.
- An intelligent control process is integrated into energy management systems for cryptocurrency mining loads, taking into consideration their profitability function.
- A new building energy management system (BEMS) formulation is introduced to model cryptocurrency mining loads in the optimal operation of a grid-connected apartment building.
- The proposed BEMS formulation can be used to evaluate the optimal number of CMDs in the apartment building.
- A practical mechanism is proposed to optimally switch the output of excessive renewable energy between exporting to the main grid and mining cryptocurrency.

E. PAPER ORGANIZATION

The rest of the paper is organized as follows. Section II reviews the literature on renewable energy, with a focus on solar energy in Finland, as well as solar PV systems in apartment buildings. Section III is devoted to describing the system model. Section IV introduces the proposed energy management system for an apartment building. Section V and VI represent the results and discussion, respectively. Finally, concluding remarks and future works are presented in section VII.

II. RENEWABLE ENERGY IN FINLAND

A. POTENTIAL OF RENEWABLE ENERGY IN FINLAND

Finland is one of the industrialized countries in the world, which requires high energy due to its energy-intensive industry, cold climate, and high standard of living. Based on the Paris Climate Agreement in 2015 and the Finnish government's goal of achieving carbon neutrality by 2035, Finland has emerged as a world leader in utilizing RESs as an alternative solution to reduce greenhouse gas emissions and shift away from fossil fuel-based energy systems [26]. In this country, RESs have presented about 40% of the energy consumption in 2022, and the National Energy and Climate Strategy aims to increase this to over 50% by 2030 [26]. The most significant forms of RESs in Finland include bioenergy, hydropower, wind power, ground heat, and solar power [9].

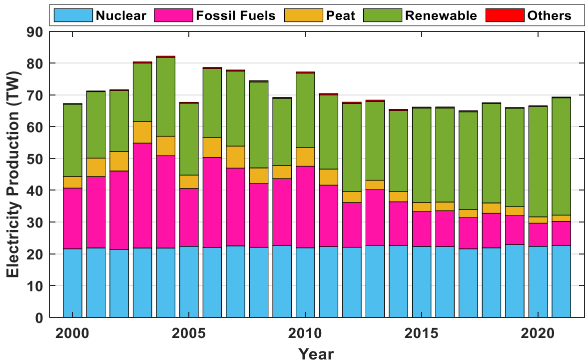

FIGURE 1. Total energy consumption in Finland in 2000 to 2021.

Fig. 1 depicts the total energy consumption in Finland from 2000 to 2021 [27]. As shown in this figure, the share of RESs in Finland's total energy consumption has been increasing steadily. This is agreeing with the Finnish government's decision to realize its net zero carbon plans, by providing technologies for the transition toward renewable energy by 2035 and making wind and solar energy the largest sources of electricity in Finland [9]. In order to achieve a carbon-free electricity system, it is necessary to present mechanisms along with the technological advancements of wind and solar energy so that these RESs become the most competitive forms of electricity generation in Finland.

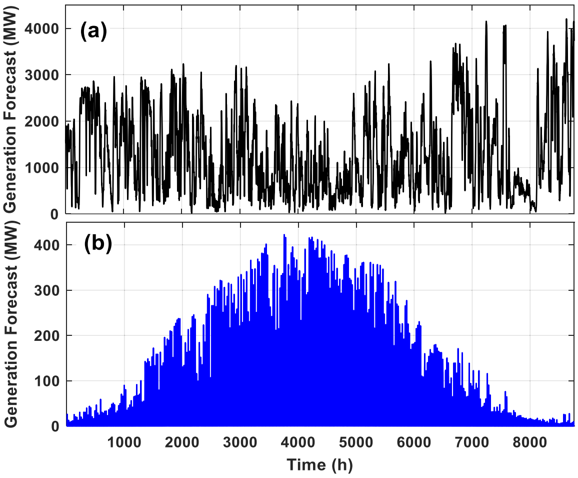

FIGURE 2. Power generation in Finland in 2022: (a) wind power and (b) solar power.

In 2022, Finland charged 12% of the electricity demand with wind and solar power generation, and the share of wind and solar energy were estimated at 10.9% and 1.1%, respectively [9]. Finland has a lot of windy coastlines making wind power a very affordable investment in RESs. Fig. 2 shows the annual power generation from wind and solar energy in Finland in 2022 [28], [29]. The figure reveals that wind energy is already commercially viable in Finland, whereas the utilization of solar energy is not yet fully developed. The focus of this study is to investigate the reasons for this discrepancy and propose methods to expand the use of solar energy.

B. SOLAR POWER IN FINLAND

Finland's unique geographical location and climate present several unique challenges to the utilization of solar power in this country. Due to the seasonality of solar radiation, this country receives significantly lower irradiation in winter compared to summer, as shown in Fig. 3 [30]. This figure depicts the average monthly sunshine duration in Helsinki, Finland, in 2022. In Helsinki, more than 90% of residential buildings are heated by electricity in winter. These apartment buildings are called "electrically heated residential buildings" [26]. As a result, electricity consumption by residential customers in Finland is considerably higher in winter than in summer.

The dramatic increase in residential retail electricity prices over the last decade in Finland along with the opportunity for employment of local distributed energy resources (DERs) has made Finnish households increasingly interested in employing rooftop solar PV systems to generate and consume renewable energy and reduce their electricity bills. However, the electricity generation from rooftop solar PV systems is more concentrated in summer than in winter. Non-simultaneity of PV generation and consumption has presented some challenges for these customers. Among them, the most significant factors to consider are the rising levels of excessive renewable energy, the curtailment of renewable energy, and the declining profitability of investments in RESs. These aspects will be thoroughly examined in the following subsection.

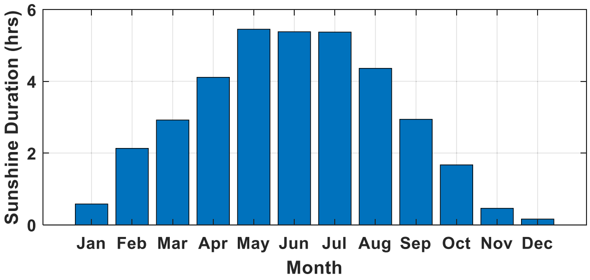

FIGURE 3. The average value of monthly sunshine duration in Helsinki, Finland in 2022 (sun hours per day).

C. SOLAR PV IN APARTMENT: OPPORTUNITIES AND CHALLENGES

Apartment building owners can employ rooftop solar PV systems to reduce their electricity costs and have an opportunity to reduce their environmental impact. However, investing in rooftop solar PV systems to produce renewable energy has created new challenges due to the lack of electrical energy storage systems to store excessive renewable energy (when solar irradiation is at its peak). The excessive renewable energy produced in an apartment building can be sold to the main grid. However, as more and more apartment building owners install rooftop solar PV systems and more solar energy plants come online, the generated energy due to a higher supply may become worthless and can be sold at a relatively lower electricity price. This trend reduces the revenue from selling electricity and, as a result, reduces the tendency of consumers to utilize RESs. In the worst-case scenario, customers may pause exporting renewable energy to the main grid or DERs can even be switched off temporarily. At this stage, a huge amount of excessive electricity is wasted or curtailed and cannot be fully utilized in the grid.

As mentioned before, the three most common solutions for customers to reduce renewable energy curtailment are using DSM, electrical energy storage systems, and P2X approaches. The concept of DSM is not new, but its implementation is faced challenges compared with traditional approaches. These challenges include a lack of information and communication technology infrastructures, a lack of understanding of the benefit of DSM solutions, not being competitive, increasing the complexity of the system operation, and inappropriate market structure [31].

In the electrical energy storage system approach, apartment building owners can use a storage element, such as BESSs to reduce renewable energy curtailment and increase the self-consumption potential of PV power and add flexibility to their energy systems. They can reduce their dependency on grid electricity which has high costs and taxes imposed by the electricity suppliers and service providers. Although BESSs could be used to solve many of the mentioned problems, they have not been yet widely used because of the poor investment returns compared with the high investment and maintenance costs [13].

The concept of P2X is the most promising alternative to solve the problem of renewable energy intermittent production. This key technology can potentially convert or store excessive renewable energy into renewable synthetic fuels, such as hydrogen, natural gas, and other liquid fuels. Although P2X technologies provide sustainable solutions for infrastructure conversion of renewable energies, a small-scale feasibility study has shown that their application can bring technical and economic barriers such as long start-up preparation and high investments and maintenance costs [12].

D. THE MAIN TECHNICAL CHALLENGES OF SOLAR POWER IN FINLAND

In Finland, the peak electricity demand of households occurs in winter while the peak power generation of PV happens in summer. This non-simultaneity has presented some challenges for Finnish customers including the increase in excessive renewable energy, energy curtailment, and the decrease in the profitability of RESs investments. In the following, the mentioned challenges are examined by presenting a real-world measurement for an electrically heated residential building in Helsinki, Finland in 2022. The building has 24 flats with 2-4 bedrooms and each flat has a contracted demand of 7 kW. The roof area of this building is assigned to solar panels with a power capacity of 30 kW. Figs. 4(a) and (b) show the hourly load profile of the apartment building and the power generation profile of its corresponding rooftop solar PV system in 2022, respectively. In these figures, the non-simultaneity of peak PV generation and peak demand can be clearly seen in summer and winter. By subtracting the residential load profile from the PV generation profile, the residual PV generation profile is obtained, as shown in Fig. 4(c). In this figure, positive values represent renewable excessive energy, when PV generation is higher than energy consumption.

For more details, Fig. 5 depicts a sample profile curve of power consumption and PV generation of this building during a summer day. As seen in this figure, the peak of generated power, the red dotted line, even reaches about 20 kW in some hours while the peak demand is about 12 kW. Fig. 6 shows a histogram of the yearly excessive renewable energy of this apartment building in 2022. In this apartment, the annual energy consumption and solar PV energy generation are estimated at about 77 and 37 MWh, respectively. Therefore, the total hours with excessive energy and the total amount of excessive renewable energy are calculated as 1659 hours, and 15 MWh in 2022, respectively. In fact, about 40% of the total PV generation is considered excessive energy due to the non-simultaneity of PV generation and energy consumption in this building.

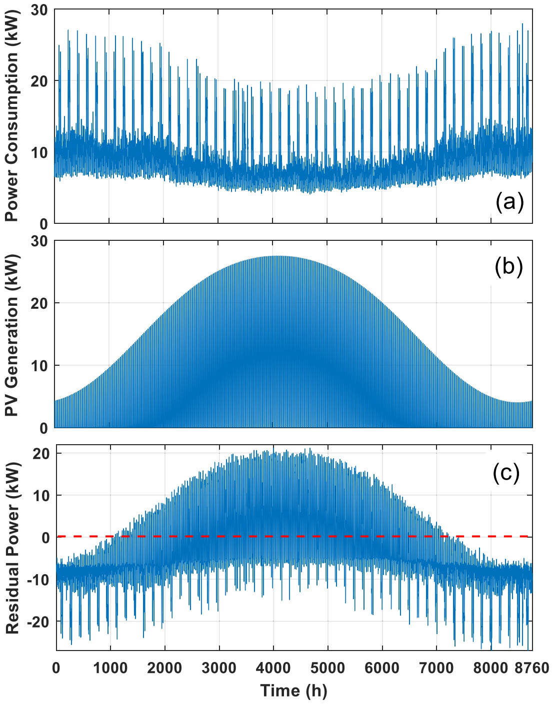

FIGURE 4. (a) Hourly load profile, (b) solar power generation, and (c) residual power of the apartment building.

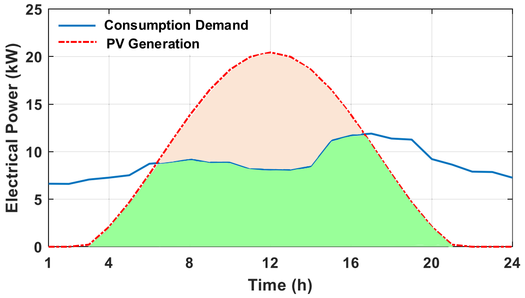

FIGURE 5. Power consumption of the apartment building and the PV production in a summer day.

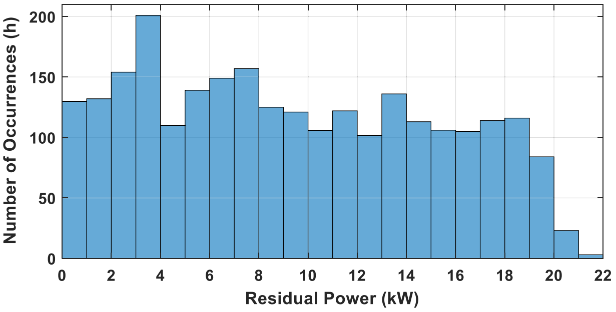

FIGURE 6. Excessive renewable energy histogram for the residential apartment building in 2022.

As mentioned earlier, the surplus energy can be either sold into the main grid or stored in a BESS. The low price of selling electricity to the main grid in Finland has made the first option not economical. Regarding the application of the second option, a BESS with a high energy capacity is needed because of the non-simultaneity of generation and consumption which occurs seasonally; however, the BESSs are usually employed for daily generation and consumption shift or daily peak shaving, not seasonal shifts. In fact, this excessive energy cannot be stored in one season and consumed in another one. The reason is that the maintenance cost of the solar PV system to preserve its stored energy for such a long time is so expensive. These costs have made the owners of the apartment forgo the storage and decide to curtail the excessive renewable energy.

This paper proposes a novel method to store the excessive energy of RESs as follows. Apartment owners can consume excessive renewable energy by employing CMDs and storing them in the form of cryptocurrency value and reducing their generation uncertainty. This method, unlike BESSs, allows customers for unlimited energy storage, as a result, enables apartment building owners to make the most efficient use of excess energy generated by their PV systems. In other words, they can either sell it to the grid or store it as cryptocurrency, depending on which option is more valuable at the time.

III. MODELING AND DESCRIPTION OF THE SYSTEM

In this section, a mathematical model of a grid-connected PV-BESS system for a residential building is formulated. The PV-BESS system includes a cryptocurrency mining load unit, PV panels, a BESS, and residential loads.

A. CHARACTERISTICS OF CRYPTOCURRENCY MINING LOAD

As mentioned before, a common solution to increase the efficiency of RESs involves employing energy programs, such as DR, which facilitate the efficient utilization of RESs [32]. In DR programs, customers are motivated to shift their electricity consumption from peak hours to off-peak hours through monetary rewards or incentives. Additionally, customers have the opportunity to shift electricity loads to time slots with renewable energy generation to minimize costs [33]. To implement DR programs effectively, loads are categorized into two groups: dispatchable and non-dispatchable loads [32]. Dispatchable loads, such as electric vehicle charging, offer flexibility in terms of their consumption timing, and their control does not cause inconvenience to consumers. However, managing non-dispatchable loads, such as lighting systems, can present challenges as controlling their usage may disrupt consumer activities or comfort. Furthermore, small-scale dispatchable loads, such as apartment buildings, are classified into manual scheduling loads and automatic scheduling ones [34]. The authors in [35] considered two categories of electric appliances as automatic dispatchable loads: the first category consists of appliances with flexible start times, such as dishwashers, while the second category comprises appliances with flexible power usage, such as heating, ventilation, and air conditioning (HVAC) systems.

Cryptocurrency mining loads can be considered dispatchable loads with the economic benefit of flexible start time and flexible power usage. These loads can be scheduled to initiate mining operations at specific times, taking advantage of periods when the electricity price is lower or when there is excess renewable energy available. Additionally, the power consumption of cryptocurrency mining units can be adjusted based on the overall demand and supply of electricity, allowing for flexibility in response to grid conditions and optimizing energy usage. The following subsection introduces the load model for cryptocurrency mining load, based on its profitability function.

B. CRYPTOCURRENCY MINING LOAD MODEL

By considering cryptocurrency mining operations as flexible loads, miners have the ability to adjust their energy consumption based on market conditions and profitability. The profit function plays a crucial role in this control mechanism, considering factors such as electricity price, mining difficulty, and the value of the mined cryptocurrency. With this approach, miners can dynamically control their loads, scaling them up or down to align with fluctuations in electricity prices or the availability of RESs. By leveraging the flexibility of cryptocurrency mining loads and incorporating a profit function, miners can enhance their overall profitability and encourage investments in RESs.

As mentioned before, miners mine digital currencies such as BTC by employing CMDs. Since BTC is the most popular cryptocurrency by market capitalization, this cryptocurrency is considered in this work. Assuming that at time t, a set of CMDs (with similar specifications) consumes P_t^{CMD} kWh of electrical energy, which includes the power consumption of devices and cooling power, the amount of revenue gained from cryptocurrency mining can be calculated as follows [36]:

$$Rev_t^{BTC} = (1 - MPF^{BTC}) \times \beta_t^{BTC,CMD} \times P_t^{CMD} \tag{1}$$

where, $\beta_t^{BTC,CMD}$ is the profit factor of cryptocurrency mining loads depending on the parameters of the BTC network and the characteristics of the installed CMDs. This factor is calculated as follows [36]:

$$\beta_t^{BTC,CMD} = \frac{3600 \times \alpha^{BTC} \times \rho^{CMD} \times \left(1 - \gamma^{cooling}\right) \times \lambda_t^{BTC}}{2^{32} \times \delta_t^{BTC} \times P_D^{CMD}} \tag{2}$$

The number of running CMDs at this time can be evaluated as follows:

$$N_t^{CMD} = \frac{\left(1 - \gamma^{cooling}\right) \times P_t^{CMD}}{P_D^{CMD}} \tag{3}$$

To reach this revenue, the owner of CMDs must also pay some costs. Part of these costs is related to the cost of supplying electrical energy to run the CMDs, and another part is related to the depreciation cost of CMDs. The depreciation cost of a CMD is the cost paid by the owner over a certain period to earn revenue from it. At the end of the useful life (UL) the aggregated depreciation cost is equal to the purchase price of the CMD. Therefore, the depreciation cost of a CMD can be calculated as follows [37]:

$$DC_t^{CMD} = \frac{ir \times N_{in}^{CMD} \times PP^{CMD}}{8760 \times \left(1-(1+ir)^{-UL_{year}^{CMD}}\right)} \tag{4}$$

Finally, based on the actual measurement data presented in [38], the power consumption of CMDs in idle mode is negligible compared to their power usage during active mining operations. Therefore, this paper assumes that when the CMDs are not powered by the rooftop solar PV systems and are lying idle, there is no running cost or energy utilization.

C. PV GENERATION MODEL

The intermittent nature of solar radiation causes uncertainty in the power generation output of the solar PV system. In a certain meteorological condition with a specific level of solar radiation, ambient temperature, and wind speed, the predicted output power of a typical PV unit can be calculated as follows [39]:

$$P_t^{PV} = \eta_{PV} \times A_{PV} \times I_t^r \times \cos\theta_t \tag{5}$$

where, θ is the angle between the incoming solar radiation ray and the normal line perpendicular to the PV module surface. Solar irradiance is an uncertain variable and highly depends on atmospheric conditions, seasons, radiance angle, *etc*. Historical data for solar irradiance corresponding to Helsinki, Finland in 2022 is employed to estimate the output power of a rooftop solar PV system. The depreciation cost of this system can be calculated as follows:

$$DC_t^{PV} = \frac{ir \times TC^{PV} \times P_{PV}^{cap}}{8760 \times \left(1-(1+ir)^{-UL_{year}^{PV}}\right)} \tag{6}$$

where, TC^{PV} is the total cost of the PV per kW including investment, operating, and maintenance costs.

D. BESS MODEL

The hourly stored energy in the BESS and its operational constraints can be modeled in the following equations [36]:

$$E_t^{BESS} = E_{t-1}^{BESS} + \eta_{ch} \times P_t^{ch} \times \Delta t - \frac{1}{\eta_{dch}} \times P_t^{dch} \times \Delta t \tag{7}$$

$$E^{min} \leq E_t^{BESS} \leq E^{max} \tag{8}$$

$$0 \leq P_t^{ch} \leq I_t^{ch} \times P_{ch}^{max} \tag{9}$$

$$0 \leq P_t^{dch} \leq I_t^{dch} \times P_{dch}^{max} \tag{10}$$

$$0 \leq I_t^{ch} + I_t^{dch} \leq 1 \tag{11}$$

The depreciation cost of BESS can be calculated as follows:

$$DC_t^{BESS} = \frac{ir \times TC^{BESS} \times E^{max}}{8760 \times \left(1-(1+ir)^{-UL_{year}^{BESS}}\right)} \tag{12}$$

where, TC^{BESS} is the total cost of BESS per kWh including investment, operating, and maintenance cost.

E. RESIDENTIAL LOAD MODEL

As mentioned in section II.F, the hourly load data is considered for a residential apartment building in Helsinki, Finland in 2022. The building has 24 apartments. Fig. 7 shows the energy consumption of this residential apartment during one week of winter and summer in 2022. As can be seen in Fig. 7, the energy consumption of this apartment building in winter is more than in summer.

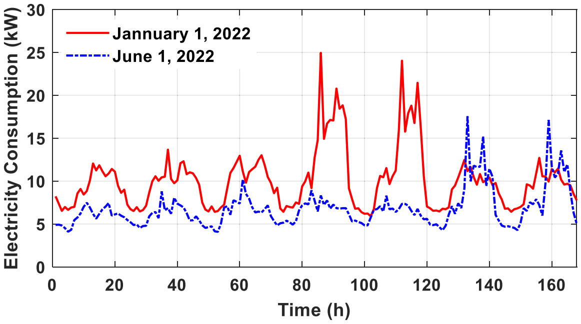

FIGURE 7. Energy consumption of the 24-unit residential apartment during one week of winter and summer.

F. ELECTRICITY PRICE MODEL

In Finland, the electricity price is based on the Nordic electricity market which is known as the Nord Pool day-ahead spot market. In this country, the total electricity price includes three parts: the price of electrical energy, the price of electricity network service (transfer fee), and the energy tax. For residential electricity prices, in most cases, each part of the price is approximately one-third of the total electricity price [40]. Usually, the electricity purchase price from the main grid is higher than the selling price to one.

The energy tax and distribution price are included in the electricity purchase price from the main grid or retailer, but not in the selling price to the main grid. Therefore, it represents a significant difference between these prices. In the case study of this paper, hourly historical data for the electricity market price of households in Finland in 2022 is employed. Fig. 8 shows a sample of this dataset for several days in 2022 [41]. As seen in this figure, in colder seasons, the electricity market price is usually higher than that in warmer ones because of the higher energy consumption of electrically heated residential buildings.

G. INTEGRATION OF ALL COMPONENTS

Fig. 9 depicts a complete system architecture of an apartment building connected to the main grid including rooftop solar PV systems, residential loads, BESSs, and cryptocurrency mining loads. Also, this system contains a communication network and control units that ensure the safe and optimal operation of the system. In this system, the apartment building central controller (ABCC) coordinates the local controllers by employing micro source controllers (MCs) and load controllers (LCs). MC is a local controller responsible for controlling and monitoring the local power generation or

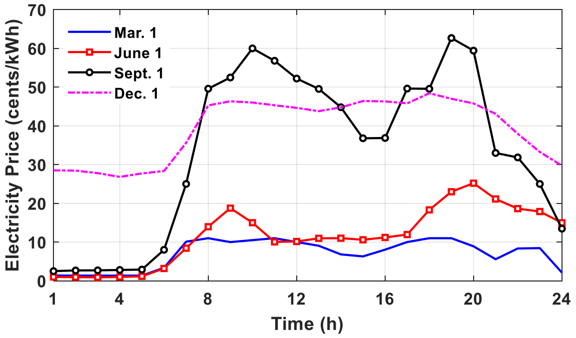

FIGURE 8. Electricity price for households in different days in Finland in 2022.

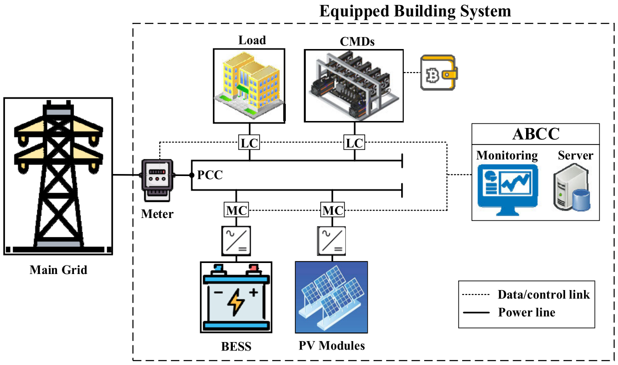

FIGURE 9. Proposed system integrated with RESs, BESS, residential loads, cryptocurrency mining load and control units.

energy storage units. LC is a local controller responsible for controlling and monitoring the local load. This sample system will be used as optimization problem input in the following section.

Apartment buildings, like the MGs, to convey their purpose, energy delivery with a guaranteed level of power quality and reliability, must be operated under the control of apartment owners/operators. Apartment owners/operators, by employing their assets properly and running an optimization problem, try to minimize total electricity cost and reduce the dependence on the main grid. This process is called a building energy management system (BEMS), as depicted in Fig. 9. Implementing the BEMS for an apartment building is formulated by a cost-based optimization problem trying to minimize the cost. The output of the problem determines the flow and quantity of power of the main grid, RESs, and the BESS' charge/discharge state at every time.

H. APPLICABILITY AND ENABLERS OF THE PROPOSED SYSTEM

The applicability and enablers of using excessive renewable energy of rooftop solar PV systems in apartment buildings for cryptocurrency mining will depend on several factors such as the availability of renewable energy, the cost of electricity, the availability of specialized CMDs, the profitability of cryptocurrency mining, etc. However, employing this technology can have some applicability aspects in Finland. Firstly, there is a huge amount of excess solar energy due to the non-simultaneity generation and consumption which is resulted from peak power consumption in winter and the peak power generation of solar PV systems in summer. Secondly, this technology allows for the utilization of excess solar energy that would otherwise be curtailed or exported to the main grid at a low electricity price. This not only reduces the customers' billing costs but also encourages the use of RESs in apartment buildings. Furthermore, recent advances in cryptocurrency mining technology, such as the use of ASICs, have made it feasible to conduct small-scale mining operations in apartment buildings.

In order to make this technology applicable, advanced energy management systems need to be employed to monitor and control the energy flow of apartment buildings. Therefore, the next section presents a novel BEMS optimization model for a grid-connected PV-BESS system to optimally switch the output of excessive renewable energy between exporting to the main grid, storing in BESSs, and mining cryptocurrency.

IV. PROPOSED BUILDING ENERGY MANAGEMENT SYSTEM

Fig. 9 shows an apartment building consisting of DERs (solar panels and BESSs), and residential loads. As mentioned before, the excessive renewable energy in the apartment building is usually sold to the main grid at a relatively lower electricity price, which reduces income and, as a result, decreases the motive of consumers to utilize RESs. To solve this problem, the following subsections present different practical strategies/scenarios to encourage investments in rooftop solar PV-BESS systems by employing CMDs to store excessive renewable energy in cryptocurrency value such as BTC. This paper presents five possible and practical scenarios/strategies for investing in and implementing methods to enhance revenue and reduce costs associated with the deployment of rooftop solar PV systems in apartment buildings.

In the following subsections, at first, the typical BEMS formulation for a grid-connected apartment building without the installation of BESS and CMDs is introduced as the first scenario. Then, four operational scenarios shown in Fig. 10 are considered along with related BEMS frameworks to minimize the cost of an apartment building. Respectively, Fig. 10 depicts the system configuration for all operational scenarios for a grid-connected apartment building with a rooftop solar PV system. In each of the proposed scenarios, the optimization problem will determine the optimal operation of BESS, the power exchange between the apartment building and the main grid, and the optimal number of CMDs.

A. SCENARIO I: PV ONLY (BENCHMARK SCENARIO)

In the first scenario, the owners of the apartment building decide to supply their electricity demand by investing in a rooftop solar PV system and the remainder of the energy by importing from the main grid. In this case, the PV power is

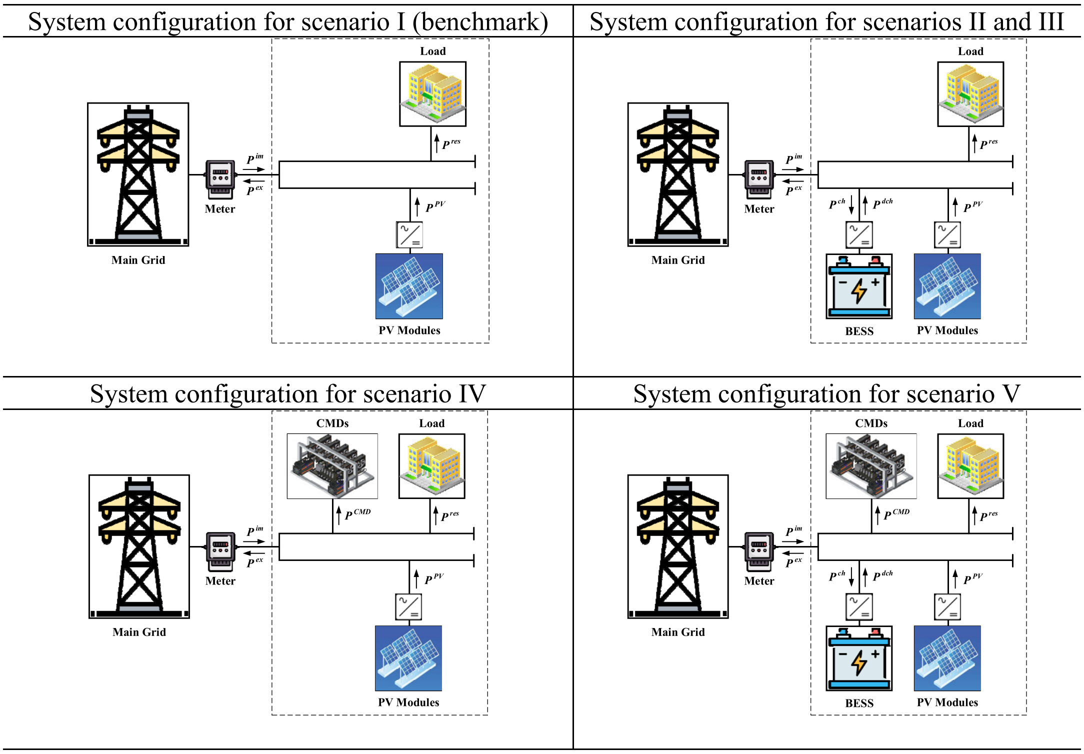

FIGURE 10. System configuration for different proposed scenarios of a grid-connected apartment building with rooftop solar PV systems.

the main supplier of electricity for the building and when the PV power exceeds the demand of the building, the excessive power is exported/sold to the main grid. In this situation, the BEMS formulation is an optimization problem to minimize the cost of building as follows:

$$F_{SC,I}^{obj} = Min\left[\sum\nolimits_{t=1}^{T}\left(\lambda_t^{im}\times P_t^{im} + DC_t^{PV} - \lambda_t^{ex}\times P_t^{ex}\right)\right] \tag{13}$$

The operational constraints include the load balance and the transmission power limit as follows:

$$P_t^{im} + P_t^{PV} = P_t^{ex} + P_t^{res} \tag{14}$$

$$-P_l^{max} \leq P_t^{im} + P_t^{ex} \leq P_l^{max} \tag{15}$$

In (13), the first term represents the cost of purchasing power from the main grid. The second term deals with the depreciation cost of the rooftop solar PV systems including investment, operation, and maintenance costs. The third term denotes the income of the apartment owner by exporting excessive renewable energy to the main grid. Equation (14) represents the power balance in the apartment building's point of common coupling (PCC). The maximum exchange power between the apartment and the main grid is constrained by the building-to-grid line loading limits as (15). This maximum exchange power limit is the same for all other proposed strategies.

B. SCENARIO II: PV AND BESS

In the second scenario, a BESS is added in parallel with the rooftop solar PV system. In this case, the BESS can be charged or discharged depending on the amount of excess energy generated from the PV system and the electricity price. The state of the BESS is determined from the optimization results of the BEMS as follows:

$$\begin{aligned}F_{SC,II}^{obj} &= Min\left[\sum\nolimits_{t=1}^{T}\left(\lambda_t^{im}\times P_t^{im} + DC_t^{PV} + DC_t^{BESS} - \lambda_t^{ex}\times P_t^{ex}\right)\right]\end{aligned} \tag{16}$$

In this strategy, the constraints of the objective function include the load balance, exchange power limit, and EESS requirement. Equations associated with the BESS are presented in subsection III-C and the load balance equation is modified as follows:

$$P_t^{im} + P_t^{PV} + P_t^{dch} = P_t^{ex} + P_t^{res} + P_t^{ch} \tag{17}$$

In fact, in this strategy, the depreciation cost of the BESS and the charge/discharge power are added to the objective function and load balance equation of the previous strategy, respectively. This paper proposes the return on investment (ROI) as an index for the profitability analysis of the presented scenarios. The *ROI* index is defined by dividing the profit earned on an investment by its costs. The following equation is employed to evaluate the *ROI* index for this scenario:

$$ROI_{SC,II} = \frac{F^{obj}_{SC,II} - F^{obj}_{SC,I}}{\sum\limits_{t=1}^{T} DC^{BESS}_{t}} \tag{18}$$

C. SCENARIO III: PV, BESS, AND DEMAND RESPONSE PROGRAM

In this scenario, rooftop solar PV systems are combined with a BESS and a simple DR program. The DR program enables the system to communicate and coordinate with electricity consumers, encouraging them to reduce or shift their electricity usage during periods of high demand or grid instability. By integrating demand response, the system can better manage peak loads and improve overall grid reliability and stability. In this paper, the following equations are considered to model a simple DR program [42].

$$(1-\mu^{min})\times P^{res}_{t} \leq P^{DR}_{t} \leq (1+\mu^{max})\times P^{res}_{t} \tag{19}$$

$$\sum\nolimits_{t=1}^{T} P^{DR}_{t} = \sum\nolimits_{t=1}^{T} P^{res}_{t} \tag{20}$$

Equation (19) defines the range of demand variations, while equation (20) states that the total energy consumption of the consumer does not change over the operating horizon. In this scenario, both the objective function of the BEMS and the *ROI* index remain similar to the previous scenario. However, the load balance equation is modified as follows:

$$P^{im}_{t} + P^{PV}_{t} + P^{dch}_{t} = P^{ex}_{t} + P^{DR}_{t} + P^{ch}_{t} \tag{21}$$

D. SCENARIO IV: PV AND CMDS

In scenario III, the electrical energy storage and demand response program are used to add flexibility to the energy system of an apartment building to reduce the energy consumption and the associated cost of the building; however, the BESSs are not yet widely employed in Finland because of the high investment cost and their limited energy capacity. Therefore, to address this issue, this paper proposes a control and hedging mechanism that could encourage investments in rooftop solar PVs with BESSs and reduce the risk by investing in cryptocurrency mining facilities.

In this scenario, the system integrates PV systems and controllable CMDs as a dispatchable and profitable load in all seasons. The proposed control framework can manage and coordinate CMDs to adjust their power consumption and start time flexibly. This scenario allows for optimizing the profitability and energy utilization of the CMDs throughout the year. By incorporating control capabilities, the system can dynamically adjust the power consumption and starting time of the CMDs based on system conditions, energy availability, electricity price, and profitability function. This flexibility enables the system to align the cryptocurrency mining activities with the optimal utilization of PV generation and stored energy from the BESS, resulting in improved efficiency, profitability, and overall system performance across all seasons. In fact, the proposed solution allows apartment building owners to optimally switch excessive renewable energy between exporting to the main grid and mining cryptocurrency depending on the relative values of each one. In this strategy, the objective function of the BEMS and the load balance equation are modified as follows:

$$F^{obj}_{SC,IV} = Min\left[\sum\nolimits_{t=1}^{T}\left(\lambda^{im}_{t}\times P^{im}_{t} + DC^{PV}_{t} + DC^{CMD}_{t} - \lambda^{ex}_{t}\times P^{ex}_{t} - Rev^{BTC}_{t}\right)\right] \tag{22}$$

$$P^{im}_{t} + P^{PV}_{t} = P^{ex}_{t} + P^{res}_{t} + P^{CMD}_{t} \tag{23}$$

The presented objective function in (22) includes five terms. The first, second, and fourth terms were explained before. The third term presents the depreciation cost of CMDs. The last term presents the revenue of apartment building owners employing CMDS as shown in (1). Also, the power demand of CMDs is added to the load balance equation. Finally, to limit the amount of power and number of CMDs, two constraints should be considered in the BEMS model as follows:

$$0 \leq P^{CMD}_{t} \leq (1+\gamma^{cooling})\times N^{CMD}_{in} \times P^{CMD}_{D} \tag{24}$$

$$0 \leq N^{CMD}_{in} \leq N^{CMD-max}_{in} \tag{25}$$

Constraint (24) imposes limits on the power consumption of cryptocurrency mining facilities that can be installed by apartment building owners to minimize building costs via the proposed BEMS optimization problem. In (24), $\boldsymbol{\gamma}^{cooling}$ and P^{CMD}_{D} represent the power ratio used for cooling down cryptocurrency mining facilities and the power consumption of a single CMD device, respectively. Constraint (25) bounds the optimal number of single-type CMDs, considering the space limitations of the building's roof. The following equation is employed to evaluate the *ROI* index for this scenario:

$$ROI_{SC,IV} = \frac{F^{obj}_{SC,IV} - F^{obj}_{SC,I}}{\sum\limits_{t=1}^{T} DC^{CMD}_{t}} \tag{26}$$

E. SCENARIO V: PV, BESS, AND CMDS

In this proposed scenario, the owners of the apartment building decide to supply their electricity demand by investing in a rooftop PV system, a BESS, and importing from the main grid. Also, to hedge the investment of PV and BESS, cryptocurrency mining facilities are employed. The objective function of the BEMS and the load balance equation are modified as follows:

$$F_{SC,V}^{obj} = Min\left[\sum_{t=1}^{T}\left(\lambda_t^{im}\times P_t^{im}+DC_t^{PV}+DC_t^{BESS} + DC_t^{CMD}-\lambda_t^{ex}\times P_t^{ex}-Rev_t^{BTC}\right)\right] \tag{27}$$

$$P_t^{im}+P_t^{PV}+P_t^{dch} = P_t^{ex}+P_t^{res}+P_t^{CMD}+P_t^{ch} \tag{28}$$

In this strategy, two constraints (24) and (25) are considered to limit the amount of power or the number of CMDs, similar to scenario IV. Finally, the following equation is employed to evaluate the *ROI* index for this scenario:

$$ROI_{SC,V} = \frac{F_{SC,V}^{obj}-F_{SC,I}^{obj}}{\sum\limits_{t=1}^{T}\left(DC_t^{BESS}+DC_t^{CMD}\right)} \tag{29}$$

The following section presents a practical case study to demonstrate the effectiveness of the proposed hedging mechanism in more detail.

V. CASE STUDY AND NUMERICAL RESULTS

In order to investigate the effectiveness of the proposed hedging mechanism, this section studies a practical test system with grid-connected PV-BESS in a residential apartment building in Helsinki, Finland which includes real-world data, and it presents the implementation results of this mechanism in 2022.

A. DATA PREPARATION

In this subsection, the input data used in this case study are explained. These data include different datasets: economic and technical data of components, data of main grid (electricity rate), residential load data, and meteorological data. In this work, real-world measurement data of a residential building apartment in Helsinki (Finland) have been employed to investigate the effectiveness of the proposed mechanism. The building has 24 apartments. Approximately, half of the roof area is assigned to solar panels with an efficiency of 21% and a total power capacity of 30 kW. Note that as the study aims to investigate the application of BESSs and cryptocurrency miners in a renewable energy-based system, the investment cost of solar panels is not considered in the case study.

To conduct a more precise analysis, the power demand of the apartment was recorded with a one-hour sampling resolution in the year 2022. Fig. 4(a) shows the demand profile of the apartment building. For more details, Fig. 11 illustrates the average load profile of the apartment building during four periods of the year 2022. The power exchange limitation between the apartment and the main grid is assumed to be 40 kW. To obtain the actual electricity pricing rate of buying from the main grid, day-ahead electricity prices for households in Finland in 2022 are employed which includes all components of the electricity bill such as the cost of power, distribution, and taxes. For example, Fig. 8 depicts the electricity rate for different days of the year 2022. As mentioned in Section III, the price of selling electricity to the main grid is assumed to be one-third of the price of buying electricity from it.

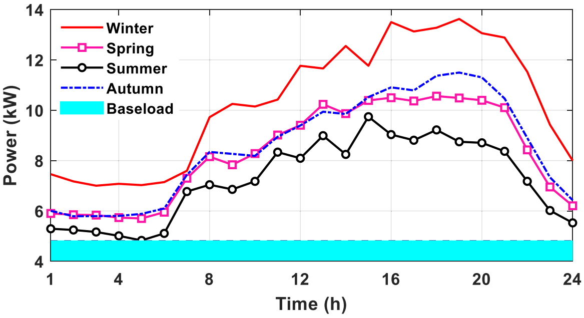

FIGURE 11. **Seasonal load profiles during four periods of the year (Jan. 2022 - Dec. 2022).**

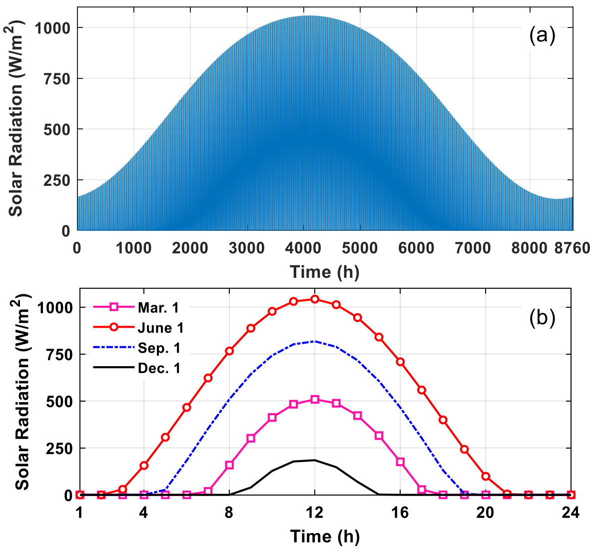

FIGURE 12. **Solar radiation in Finland in 2022: (a) yearly data and (b) daily data.**

Actual historical data of solar radiation and angle of incidence in Helsinki in 2022 have been employed to evaluate the PV power generation as shown in Fig. 12(a). For more details, Fig. 12(b) shows the daily solar radiation in different seasons in Finland.

Tables 1 and 2 present characteristics of the CMDSs [43] and BESS [44] used in the case study, respectively. As shown in Table 1, the three most popular CMDs with different characteristics and prices have been considered to mine the cryptocurrency. In addition, Table 3 presents the values of the other selected parameters for analysis. In the case study, the difficulty level of the BTC network and the BTC price are obtained from [45] over one year, from January to December 2022. Besides, the block reward value of the BTC network and Cryptocurrency mining pool fee are

TABLE 1. Characteristics of the CMDs used in the case study.

Parameter	CMD 1	CMD 2	CMD 3
Mining device	AvalonMiner 1246	Antminer S19j Pro	Whatsminer M50S
Manufacturer	Canaan	Bitmain	MicroBT
Power (W)	3420	2832	3276
Hash rate (TH/s)	90	96	126
Efficiency (Gh/J)	26.3	36.7	38.46
Release date	January 2021	August 2021	July 2022
Price ($)	1900	2650	3500
Lifetime (years)	3	3	3

TABLE 2. Characteristics of BESS used in the case study.

Parameter	Value
BESS capacity (kWh)	13.5
Maximum energy capacity of BESS (%)	80
Minimum energy capacity of BESS (%)	20
Charge rate (kW/h)	5
Discharge rate (kW/h)	5
Lifetime (years)	10
Total cost ($/kWh)	800

TABLE 3. Parameters fixed for simulation and analysis.

Parameters	Values	Parameters	Values
T	8760 hours	P_l^{max}	40 kW
A_{PV}	77.36 m^2	TC^{PV}	0
ir	1.5 %	α^{BTC}	6.25 BTC/block
MPF^{BTC}	5 %	$\gamma^{cooling}$	0
$N_{in}^{CMD-max}$	30 #	η_{PV}	21 %
P_{PV}^{cap}	30 kW	μ^{max}/μ^{min}	10%

assumed to be 6.25 BTC and 5%, respectively. Finally, according to the geographical conditions and climate of Finland, the cooling factor of mining is considered zero. The proposed BEMS optimization problem has been solved for each strategy/scenario separately using the CPLEX solver in the GAMS (Generalized Algebraic Modeling System) software [46], while the machine possesses Intel®coreTMi5-11600 CPU2.80 GHz and 32GB of memory.

B. OPTIMIZATION RESULTS

This subsection presents the output results of the proposed mechanism to hedge investment of the grid-connected PV-BESS system in a residential apartment building in Helsinki, Finland in 2022. Table 4 presents the output results of operating four proposed scenarios. In the scenarios with CMDs, the results for employing different CMDs are also depicted. In this table, for each scenario, the first line presents the optimized number of CMDs for each device, and the most profitable candidate can be employed for doing cryptocurrency mining business by the building owners. The next two lines are related to the annual income of the building due to cryptocurrency mining and the sale of electricity to the main grid.

In the third line, the optimized number of CMDs for each device is presented, and the most profitable candidate can be employed for doing cryptocurrency mining business by the building owners. In the fourth line, the annual cost of buying electricity from the main grid is depicted. In the fifth and sixth lines, the annual investment cost of BESS and CMDs are presented, respectively. Finally, the three last lines of the table present the annual total cost of the apartment building and the *ROI* economic index for participating in each of the proposed scenarios. It should be noted that in using this index for economic analysis, all scenarios are compared to the benchmark scenario.

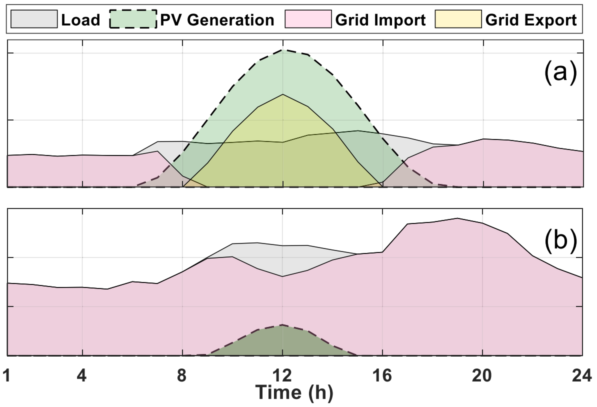

FIGURE 13. The electrical power dispatch of apartment in benchmark scenario on: (a) Summer day and (b) winter day.

The results presented for the benchmark scenario show that as expected, the excessive renewable energy is exported to the main grid. Figs. 13(a) and (b) depict the economic electrical power dispatch for a sunny summer day and a winter day in 2022, respectively. As seen in Fig. 13(a), due to the excess PV generation and the low energy consumption of the apartment building in the summer day, a part of the PV generation is exported to the main grid between 08:00 AM and 04:00 PM, while the rest is consumed by the apartment. In these hours, the power imported from the main grid remained at the least possible amount. Apartment building owners can employ BESSs, DR programs, and CMDs instead of exporting/selling this excessive renewable energy to the main grid at a low price to reduce their costs. These solutions will be examined in the next scenarios.

The winter day power dispatch is quite dissimilar to the summer day as shown in Fig. 13(b). Due to the low PV power generation and the high energy consumption of the electrically heated residential buildings in the winter day, a major portion of the electricity demand is supplied from the main grid. With this condition in mind, in this scenario, the revenue of the building covers only a small part of its annual cost. Such a result highlights the importance of the BESS or CMDs in parallel with rooftop solar PV systems, which presents a hedging mechanism for apartment building owners to optimally utilize their RESs.

TABLE 4. The results of the proposed hedging mechanism for residential apartment building in finland in 2022.

Parameter	SC I	SC II	SC III	SC IV			SC V		
				CMD1	CMD2	CMD3	CMD1	CMD2	CMD3
Number of installed CMDs (#)	0	0	0	9	11	10	9	11	10
Annual income from BTC mining ($)	0	0	0	19040.5	29009.7	38143.4	19030	29085.8	38039.3
Annual income from selling electricity ($)	1199.7	1050.5	975.5	257.3	79.1	0	250.3	104.9	0
Annual cost of buying electricity ($)	11298.6	9696	9509.8	21451.1	25206.2	29429.2	20106.4	23978.3	28187.2
Annual investment of BESS ($)	0	1292.5	1292.5	0	0	0	1292.5	1292.5	1292.5
Annual investment of CMDs ($)	0	0	0	5830.5	9939	11933.7	5830.5	9939	11933.7
Total annual cost minus income ($)	10098.9	9938	9826.7	7983.8	6056.4	3218.9	7949.1	6019.1	3374
Cost reduction (%)	-	1.6	2.7	20.9	40	68.1	21.3	40.4	66.4
Return on investment (%)	-	12.5	21.3	36.3	40.7	57.7	30.2	36.3	50.8

In scenario II, PV generation parallel with a BESS, the results show that investing in BESS along with the PV generation has reduced the annual cost of the building by 1.6% (considering the investment cost of the BESS) and has an *ROI* of 12%. Such a result was expected due to the special conditions of Finland, and the mismatch between peak solar generation and consumption load. Since BESS is typically used for daily peak shaving due to its limited energy capacity, not seasonal storage, therefore investment in this system is not economical for building owners. For more illustration, Fig. 14 shows the results of scenario II for a summer day in 2022 including economic electrical power dispatch and stored energy in the BESS.

As seen in Figs. 14(a) and (b), both in the early morning and during excess energy generation, the BESS is charged, and when the electricity price is high, it is discharged to reduce the amount of imported power from the main grid. But as mentioned before, the high investment and maintenance cost of BESS does not attract building owners to invest in this scenario. This process (charge/discharge of BESS) has little effect on reducing the cost of the building due to the low PV generation in winter days.

In Scenario III, the findings demonstrate that investing in a BESS and employing a simple DR program for optimal use of excess renewable energy can yield economic feasibility. This approach results in a reduction in the total annual cost of the apartment building and an increase in the *ROI* index by 2.7% and 21.3%, respectively. However, it can be concluded that the implementation of this scenario may not be particularly appealing to apartment building owners because BESSs and demand response programs are usually employed for daily generation and consumption shift or daily peak shaving, rather than addressing seasonal shifts.

The results presented for scenario IV show that investing in cryptocurrency mining facilities for optimal use of excess renewable energy has very high economic feasibility compared to BESS and leads to a significant reduction in a total annual cost of the apartment building and an increase in the *ROI* index. Based on the presented results, Whatsminer M50S is an optimal CMD for these apartment owners, which is superior to other types. Also, the optimized number of CMDs would be 10. By implementing this scenario, the reduction of the building's annual cost and the *ROI* index are calculated as 68.1 and 57.7 percent, respectively. In fact, with this proposed mechanism, in addition to the optimal use of surplus energy, building owners invest in a business that has a reasonable return on investment, which also encourages future investment in rooftop solar PV with BESS systems and mitigate their investment risk.

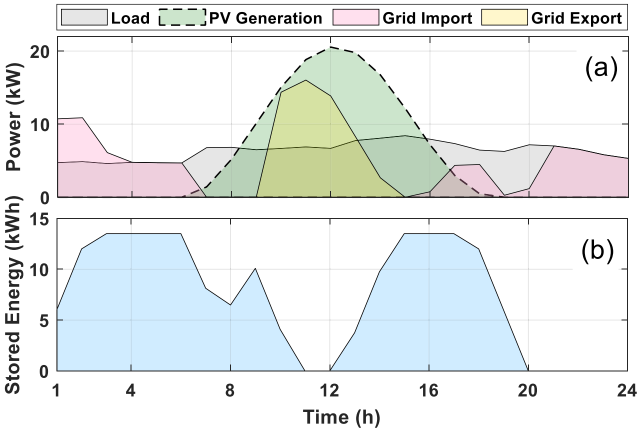

FIGURE 14. The electrical power dispatch of apartment in scenario II on a summer day: (a) Generation and consumption and (b) Stored energy in the BESS.

Figs. 15(a) and (b) depict the economic electrical power dispatch of scenario IV for summer day and winter day in 2022, respectively. As shown in Fig. 15(a), in the summer day, it is economical for building owners to store all excessive renewable energy in value (BTC in this case study) instead of exporting to the main grid. Respectively, even in the early morning or late night when the electricity price is very low, they can import electricity from the main grid to mine cryptocurrency. In the winter day, the results are quite dissimilar to the summer day as shown in Fig. 15(b). Due to the low PV generation, high energy consumption of the building, and high electricity price in the winter day, turning on the CMDs has no economic feasibility. Fig. 15(c) depicts the load profile of the installed CMDs in a summer day and a winter day. As seen in this figure, in a summer day, it is

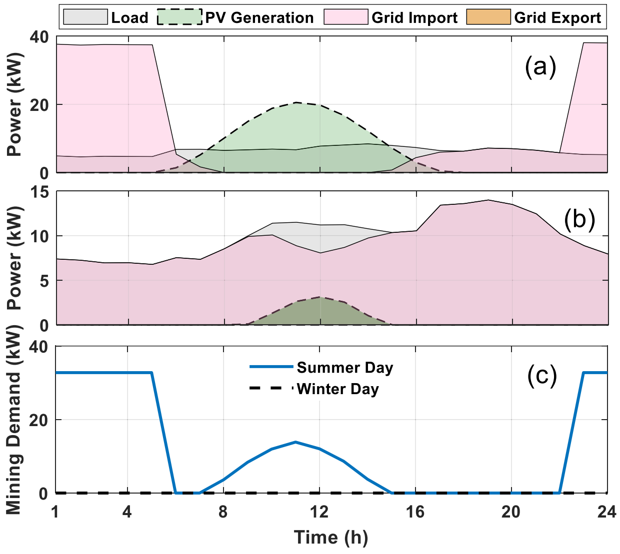

FIGURE 15. Summer day, (b) winter day, and (c) mining demand in summer day and winter day.

economical to mine BTC when there is excess energy or when the price of electricity is low, while it is not economical at any time in the winter day.

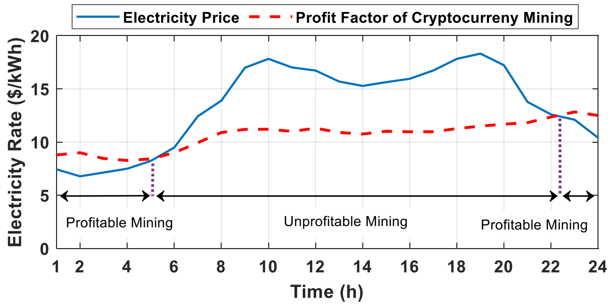

FIGURE 16. Electricity price and profit factor of the CMDs in a summer day.

For additional information, Fig. 16 shows the cost of purchasing electricity from the main grid and the revenue generated by CMDs on a summer day. As can be seen in this figure, CMDs are being utilized during the hours of 1-5 and 22-24 when there is a need to import power from the grid. This is due to the fact that the cost of purchasing electricity from the main grid is lower than the revenue generated from CMDs. It should be noted that this trend applies to many summer days. For example, Fig. 17 depicts the load profile of cryptocurrency mining demand during a summer week. As seen in the figure, it is economically viable to import electricity from the main grid to mine cryptocurrency even during the early morning or late at night when the electricity prices are very low.

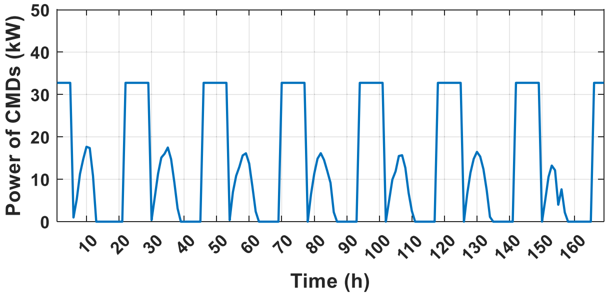

FIGURE 17. Load profile of the mining demand in a summer week.

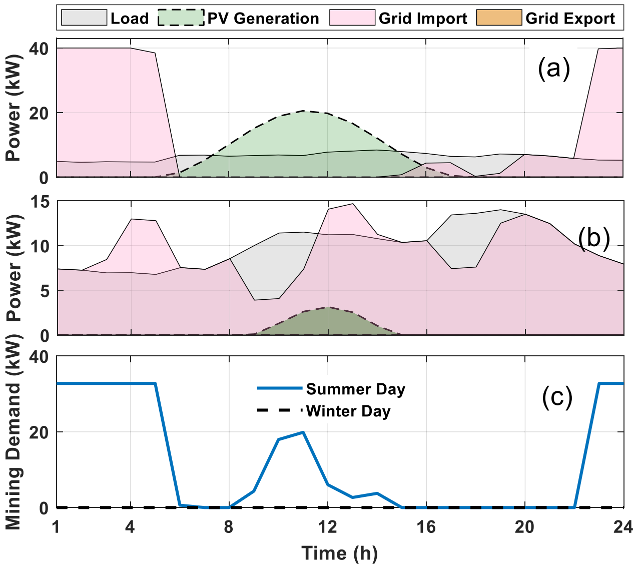

FIGURE 18. The electrical power dispatch of apartment in scenario V: (a) Summer day, (b) winter day, and (c) mining demand in summer day and winter day.

In scenario V, PV generation parallel with BESS and CMDs, the presented results in table 3 show that simultaneous investment in BESS and CMDs for optimal use of surplus energy is not as profitable as the previous scenario, and the reason for this is the high investment cost of BESS. But the implementation of this scenario reduces the annual cost of the apartment building by 66.4% and achieves an *ROI* index of 50.8%. Figs. 18(a) and (b) show the economic electrical power dispatch of scenario V for a summer day and winter day in 2022, respectively. As seen in Fig. 18(a), it is economical to purchase and import electricity from the main grid to charge the BESS in times when the electricity price is low so that more CMDs can be turned on at other times. But in the winter day, as mentioned before, the results are quite dissimilar to the summer day as shown in Fig. 18(b). Fig. 18(c) shows the load profile of cryptocurrency mining load in a summer day and a winter day. As seen in this figure, the mining load is higher compared to scenario VI (PV and CMDs) in some hours in a summer day. However, there is no economic feasibility for mining cryptocurrency on a winter day due to low PV generation and high electricity costs.

For more details, the simulation results indicate that in scenario III, the average and maximum number of running CMDs (for CMD3) are approximately 5 and 10, respectively. In contrast, scenario V yields values of 6 and 10 for the average and maximum number of running CMDs, respectively. Although the use of BESS in scenario V increases the average number of running CMDs, its high investment and maintenance costs result in a lower *ROI* compared to the previous scenario. In the following discussion subsection, the results are presented by changing the capacity of BESS to investigate its impact on this study.

VI. DISCUSSION

A. IMPACT OF BESS CAPACITY

The previous subsection presents the results of the implementation proposed hedging mechanism employing BESS with a capacity of 13.5 kWh. In this subsection, the effect of changing the BESS capacity in scenario IV, PV generation with BESS and CMDs, on the economic energy management of the apartment building is investigated. It is expected the capacity of the BESS affects the profitability of the apartment building due to its high investment and maintenance costs. Therefore, in this subsection, a sensitivity analysis of the BESS capacity is investigated, focusing on the annual cost of the apartment and the profitability of the investment.

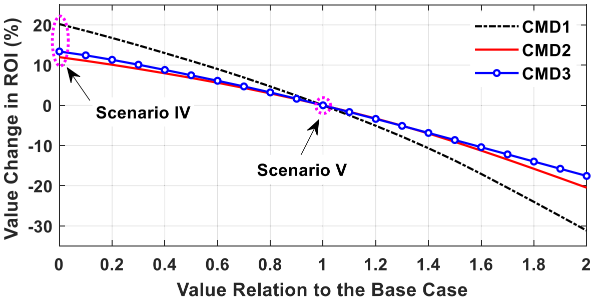

FIGURE 19. Spider diagram of the change of ROI index compared to the base case.

In the base case, as shown in the previous subsection, the capacity and charging/discharging limit of BESS are supposed equal to 13.5 kWh and 6 kW, respectively. These parameters simultaneously change from 0 to 2 times their base value to show the change in the results. Figs. 19 and 20 show the spider diagram to present the trend of the *ROI* index and the annual cost of the apartment building (in percent), respectively, if compared with the base case. As clearly seen in these figures, the capacity of the BESS has a great impact on the profitability of the apartment building; therefore, by increasing its capacity, it results in a significant decrease in *ROI* and an increase in the annual cost of the building. For further discussion, if this system is combined with a high-capacity BESS, it can benefit from the increased storage capacity offered by the BESS. In this case, the BESS's high capacity can allow it to adequately address the seasonal shift caused by the fluctuations in solar PV generation and customers' energy consumption. For example, if the BESS capacity is assumed to be 100 times higher than the standard capacity, it is evident that the rise in BESS investment cost leads to higher building expenses and a decline in the return on grid-connected PV-BESS investment.

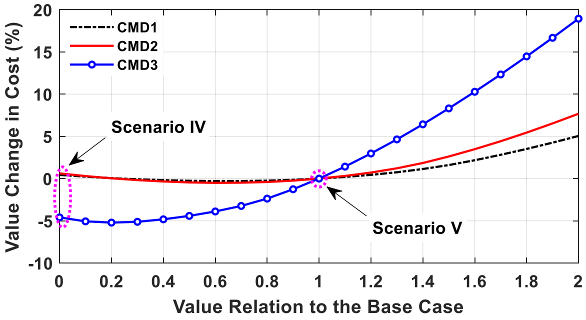

FIGURE 20. Spider diagram of the change of the annual cost of apartment compared to base case.

TABLE 5. The results of proposed uncontrollable and controllable operation for CMD3.

Parameter	Uncontrollable CMDs	Controllable CMDs
Number of installed CMDs (#)	10	10
Annual income from BTC mining ($)	45546.8	38039.3
Annual income from selling electricity ($)	0	0
Annual cost of buying electricity ($)	42870	28187.2
Annual investment of BESS ($)	1292.5	1292.5
Annual investment of CMDs ($)	11933.7	11933.7
Total annual cost minus income ($)	10549.4	3374
Cost reduction (%)	-4.5	66.4
Return on investment (%)	-3.4	50.8

B. IMPACT OF CONTROLLING CRYPTOCURRENCY MINING LOAD

In Scenario V, the system integrates PV systems, a BESS, and controllable CMDs as a dispatchable and profitable load, it is evident that the proposed control framework can manage and coordinate CMDs to adjust their power consumption and start time flexibly. This scenario allows for optimizing the profitability and energy utilization of the CMDs throughout the year. In fact, by incorporating control capabilities, the system can dynamically adjust the power consumption and starting time of the CMDs based on system conditions, energy availability, electricity price, and profitability function. This subsection analyzes the impact of controlling the cryptocurrency mining load within the proposed BEMS. It is assumed that the system consists of PV systems, a BESS, and uncontrollable CMDs that act as a constant common and profitable load during the spring, summer, and autumn seasons.

Table 5 presents the output results of the proposed uncontrollable and controllable operation for CMD3. The results indicate that investing in CMDs without implementing an intelligent controlling algorithm for the optimal utilization of excess renewable energy is economically unfeasible. This approach leads to an increase in the total annual cost of the apartment building by 4.5%. In this case, due to modeling the cryptocurrency mining load as a common and profitable load and not controlling it, the CMDs have been continuously on, which has caused this case to be unprofitable. In fact, these results demonstrate that if the cryptocurrency mining loads are treated as regular loads and do not utilize flexible power and flexible start time in managing them, mining can become unprofitable sometimes and result in a loss. Nevertheless, the results presented for the controlling case indicate that by considering cryptocurrency mining load as a dispatchable load with flexible start time and flexible power and implementing the proposed intelligent control algorithm in BEMS studies based on its profitability function, it can lead to a significant reduction in building costs and increase the profitability of the grid-connected PV project.

Even though this work applies the proposed controlling and hedging mechanism to a residential apartment building in Helsinki of Finland, however, this approach can be easily adapted to other regions and countries in the world, if the investment in RESs has some degree of flexibility.

VII. CONCLUSION AND FUTURE WORKS

A. SUMMARY AND CONCLUSION

The dramatic increase in retail electricity prices over the last months in Finland has made customers increasingly interested in employing small-scale RESs such as rooftop solar PV systems to generate cheap renewable energy and reduce their electricity costs. Due to the maritime and continental climate of Finland, investing in the PV system faces some unique challenges including non-simultaneity of PV generation and energy consumption, increase in the excessive renewable energy, energy curtailment, and profitability reduction. Conventional solutions such as BESS are unable to address the arisen concerns due to the non-simultaneity generation and consumption which resulted from peak power consumption in winter and the peak power generation of solar PV systems in summer.

In this paper, a hedging mechanism is presented to encourage investment in a rooftop solar PV system and by investing in cryptocurrency mining facilities to store excessive renewable energy in cryptocurrency value. This proposed approach allows customers to optimally switch excessive energy between electricity and cryptocurrency value depending on the relative prices of electricity and cryptocurrency. The typical BEMS formulation for a grid-connected apartment building is presented as the benchmark scenario. Then, three operational strategies are presented including BESS and CMDs along with related BEMS frameworks to minimize the annual electricity costs of the apartment building. Using a case study of a residential apartment building in Helsinki, Finland, involving different CMDs, it has been shown that employing the proposed hedging mechanism will result in sufficient encouragement to invest in PV systems and decrease the annual cost of residential apartments.

B. FUTURE WORKS

This paper has demonstrated the feasibility of cryptocurrency mining with renewable energy in apartment buildings and identified several key factors that affect the profitability and sustainability of such operations. However, several areas require further investigation. Future work in this field could include:

- Investigating the potential impact of cryptocurrency mining with renewable energy on the building's electrical infrastructure and identifying strategies to ensure that the building's electrical system can accommodate the energy resources which are required for the mining system operation.
- Exploring the potential for using blockchain technology to enable peer-to-peer energy trading among apartment building tenants with renewable energy systems and investigating the potential benefits and challenges of such an arrangement.
- Investigating the potential impact of government policies and regulations on the adoption of renewable energy-powered cryptocurrency mining in apartment buildings and identifying strategies to promote more widespread adoption.
- Exploring the potential for using artificial intelligence and machine learning algorithms to optimize the energy efficiency and profitability of cryptocurrency mining with RESs in apartment buildings.

Continuing to work on these research directions, it is expected to discover new opportunities and challenges associated with cryptocurrency mining with renewable energy in apartment buildings and to identify new strategies to promote sustainable and profitable cryptocurrency mining operations.

REFERENCES

[1] M. Shafie-khah, *Blockchain-Based Smart Grids*. London, U.K.: Academic Press, 2020, doi: 10.1016/c2018-0-02741-3.

[2] F. Tschorsch and B. Scheuermann, "Bitcoin and beyond: A technical survey on decentralized digital currencies," *IEEE Commun. Surveys Tuts.*, vol. 18, no. 3, pp. 2084–2123, 3rd Quart., 2016, doi: 10.1109/COMST.2016.2535718.

[3] A. Kumari and S. Tanwar, "A reinforcement-learning-based secure demand response scheme for smart grid system," *IEEE Internet Things J.*, vol. 9, no. 3, pp. 2180–2191, Feb. 2022, doi: 10.1109/JIOT.2021.3090305.

[4] A. Kumari and S. Tanwar, "A secure data analytics scheme for multimedia communication in a decentralized smart grid," *Multimedia Tools Appl.*, vol. 81, no. 24, pp. 34797–34822, Oct. 2022, doi: 10.1007/s11042-021-10512-z.

[5] M. Hajiaghapour-Moghimi, K. A. Hosseini, E. Hajipour, and M. Vakilian, "Distribution transformer loss-of-life assessment in the presence of cryptocurrency mining loads," in *Proc. 26th Int. Electr. Power Distribution Conf. (EPDC)*, May 2022, pp. 108–115, doi: 10.1109/EPDC56235.2022.9817210.

[6] M. Hajiaghapour-Moghimi, K. A. Hosseini, E. Hajipour, and M. Vakilian, "An approach to targeting cryptocurrency mining loads for energy efficiency enhancement," *IET Gener., Transmiss. Distrib.*, vol. 16, no. 23, pp. 4775–4790, Dec. 2022, doi: 10.1049/gtd2.12640.

[7] The University of Cambridge. (2021). *Cambridge Bitcoin Electricity Consumption Index (CBECI)*. Accessed: Feb. 1, 2023. [Online]. Available: https://ccaf.io/cbeci/index

[8] Md. S. Alam, F. S. Al-Ismail, A. Salem, and M. A. Abido, "High-level penetration of renewable energy sources into grid utility: Challenges and solutions," *IEEE Access*, vol. 8, pp. 190277–190299, 2020, doi: 10.1109/ACCESS.2020.3031481.

[9] R. Puhakka, "The potential of electricity generation with renewable energy sources in Finland 2030," Åbo Akademi Univ., Turku, Finland, Tech. Rep., 2020.

[10] R. Panigrahi, S. K. Mishra, S. C. Srivastava, A. K. Srivastava, and N. N. Schulz, ''Grid integration of small-scale photovoltaic systems in secondary distribution network—A review,'' *IEEE Trans. Ind. Appl.*, vol. 56, no. 3, pp. 3178–3195, May 2020, doi: 10.1109/TIA.2020.2979789.

[11] G. Strbac, ''Demand side management: Benefits and challenges,'' *Energy Policy*, vol. 36, no. 12, pp. 4419–4426, Dec. 2008, doi: 10.1016/j.enpol.2008.09.030.

[12] R. Daiyan, I. MacGill, and R. Amal, ''Opportunities and challenges for renewable power-to-X,'' *ACS Energy Lett.*, vol. 5, no. 12, pp. 3843–3847, Dec. 2020, doi: 10.1021/acsenergylett.0c02249.

[13] J. Koskela, A. Rautiainen, and P. Järventausta, ''Using electrical energy storage in residential buildings—Sizing of battery and photovoltaic panels based on electricity cost optimization,'' *Appl. Energy*, vol. 239, pp. 1175–1189, Apr. 2019, doi: 10.1016/j.apenergy.2019.02.021.

[14] R. Khezri, A. Mahmoudi, and M. H. Haque, ''Optimal capacity of solar PV and battery storage for Australian grid-connected households,'' *IEEE Trans. Ind. Appl.*, vol. 56, no. 5, pp. 5319–5329, Sep. 2020, doi: 10.1109/TIA.2020.2998668.

[15] A. K. Yadav, H. Malik, S. M. S. Hussain, and T. S. Ustun, ''Case study of grid-connected photovoltaic power system installed at monthly optimum tilt angles for different climatic zones in India,'' *IEEE Access*, vol. 9, pp. 60077–60088, 2021, doi: 10.1109/ACCESS.2021.3073136.

[16] N. Alqahtani and N. Balta-Ozkan, ''Assessment of rooftop solar power generation to meet residential loads in the city of Neom, Saudi Arabia,'' *Energies*, vol. 14, no. 13, p. 3805, Jun. 2021, doi: 10.3390/en14133805.

[17] M. J. Usmani and A. Haque, ''Power management of solar PV systems for PEER load,'' *IEEE Trans. Ind. Appl.*, vol. 57, no. 6, pp. 6327–6338, Nov. 2021, doi: 10.1109/TIA.2021.3100809.

[18] V. Bagalini, B. Y. Zhao, R. Z. Wang, and U. Desideri, ''Solar PV-battery-electric grid-based energy system for residential applications: System configuration and viability,'' *Research*, vol. 2019, Jan. 2019, doi: 10.34133/2019/3838603.

[19] D. Çelik and M. E. Meral, ''Current control based power management strategy for distributed power generation system,'' *Control Eng. Pract.*, vol. 82, pp. 72–85, Jan. 2019, doi: 10.1016/j.conengprac.2018.09.025.

[20] P. Rorich, K. Moloi, T. F. Mazibuko, and I. E. Davidson, ''Cryptocurrency mining powered by renewable energy using a DC–DC connection,'' in *Proc. 31st Southern Afr. Universities Power Eng. Conf. (SAUPEC)*, Jan. 2023, pp. 1–7, doi: 10.1109/SAUPEC57889.2023.10057799.

[21] L. Gundaboina, S. Badotra, T. K. Bhatia, K. Sharma, G. Mehmood, M. Fayaz, and I. U. Khan, ''Mining cryptocurrency-based security using renewable energy as source,'' *Secur. Commun. Netw.*, vol. 2022, pp. 1–13, Jun. 2022, doi: 10.1155/2022/4808703.

[22] M. A. Jirdehi and V. S. Tabar, ''Risk-aware energy management of a microgrid integrated with battery charging and swapping stations in the presence of renewable resources high penetration, crypto-currency miners and responsive loads,'' *Energy*, vol. 263, Jan. 2023, Art. no. 125719, doi: 10.1016/j.energy.2022.125719.

[23] H. Niaz, J. J. Liu, and F. You, ''Can Texas mitigate wind and solar curtailments by leveraging bitcoin mining?'' *J. Cleaner Prod.*, vol. 364, Sep. 2022, Art. no. 132700, doi: 10.1016/j.jclepro.2022.132700.

[24] A. Nikzad and M. Mehregan, ''Techno-economic, and environmental evaluations of a novel cogeneration system based on solar energy and cryptocurrency mining,'' *Sol. Energy*, vol. 232, pp. 409–420, Jan. 2022, doi: 10.1016/j.solener.2022.01.014.

[25] C. L. Bastian-Pinto, F. V. D. S. Araujo, L. E. Brandão, and L. L. Gomes, ''Hedging renewable energy investments with bitcoin mining,'' *Renew. Sustain. Energy Rev.*, vol. 138, Mar. 2021, Art. no. 110520, doi: 10.1016/j.rser.2020.110520.

[26] J. Miettinen, ''Solar potential in Helsinki,'' Aalto Univ., Espoo, Finland, Tech. Rep., 2021.

[27] *Energy Supply and Consumption—Statistics Finland*. Accessed: Feb. 1, 2023. [Online]. Available: https://stat.fi/en/statistics/ehk

[28] *Wind Power Generation*. Fingrid. Accessed: Feb. 1, 2023. [Online]. Available: https://www.fingrid.fi/en/electricity-market-information/wind-power-generation/

[29] *Solar Power*. Fingrid. Accessed: Feb. 1, 2023. [Online]. Available: https://www.fingrid.fi/en/electricity-market-information/solar-power/

[30] *Average Monthly Hours of Sunshine in Helsinki (Southern Finland)*. Accessed: Feb. 1, 2023. [Online]. Available: https://weather-and-climate.com/average-monthly-hours-Sunshine,Helsinki,Finland

[31] R. Usman, P. Mirzania, S. W. Alnaser, P. Hart, and C. Long, ''Systematic review of demand-side management strategies in power systems of developed and developing countries,'' *Energies*, vol. 15, no. 21, p. 7858, Oct. 2022, doi: 10.3390/en15217858.

[32] S. M. Vaziri, B. Rezaee, and M. A. Monirian, ''Utilizing renewable energy sources efficiently in hospitals using demand dispatch,'' *Renew. Energy*, vol. 151, pp. 551–562, May 2020, doi: 10.1016/j.renene.2019.11.053.

[33] N. S. Thomaidis, F. J. Santos-Alamillos, D. Pozo-Vázquez, and J. Usaola-García, ''Optimal management of wind and solar energy resources,'' *Comput. Oper. Res.*, vol. 66, pp. 284–291, Feb. 2016, doi: 10.1016/j.cor.2015.02.016.

[34] Z. Zhao, W. C. Lee, Y. Shin, and K. Song, ''An optimal power scheduling method for demand response in home energy management system,'' *IEEE Trans. Smart Grid*, vol. 4, no. 3, pp. 1391–1400, Sep. 2013, doi: 10.1109/TSG.2013.2251018.

[35] K. Ma, T. Yao, J. Yang, and X. Guan, ''Residential power scheduling for demand response in smart grid,'' *Int. J. Electr. Power Energy Syst.*, vol. 78, pp. 320–325, Jun. 2016, doi: 10.1016/j.ijepes.2015.11.099.

[36] E. Hajipour, F. Khavari, M. Hajiaghapour-Moghimi, K. A. Hosseini, and M. Vakilian, ''An economic evaluation framework for cryptocurrency mining operation in microgrids,'' *Int. J. Electr. Power Energy Syst.*, vol. 142, Nov. 2022, Art. no. 108329, doi: 10.1016/j.ijepes.2022.108329.

[37] M. Hajiaghapour-Moghimi, K. A. Hosseini, E. Hajipour, and M. Vakilian, ''A TOU-IBT pricing strategy to manage the cryptocurrency micro-miners,'' *IEEE Trans. Smart Grid*, vol. 13, no. 3, pp. 1838–1848, May 2022, doi: 10.1109/TSG.2021.3138906.

[38] Y. Kosharnaya, S. Yanchenko, and A. Kulikov, ''Specifics of data mining facilities as energy consumers,'' in *Proc. Dyn. Syst., Mech. Mach.*, Nov. 2018, pp. 1–4, doi: 10.1109/Dynamics.2018.8601462.

[39] A. Ghasemi, M. Banejad, and M. Rahimiyan, ''Integrated energy scheduling under uncertainty in a micro energy grid,'' *IET Gener., Transmiss. Distrib.*, vol. 12, no. 12, pp. 2887–2896, Jul. 2018, doi: 10.1049/iet-gtd.2017.1631.

[40] A. Meriläinen, P. Puranen, A. Kosonen, and J. Ahola, ''Optimization of rooftop photovoltaic installations to maximize revenue in Finland based on customer class load profiles and simulated generation,'' *Sol. Energy*, vol. 240, pp. 422–434, Jul. 2022, doi: 10.1016/j.solener.2022.05.057.

[41] *Market Data*. Nord Pool. Accessed: Feb. 1, 2023. [Online]. Available: https://www.nordpoolgroup.com/en/Market-data1/Dayahead/Area-Prices/FI/Hourly/?view=table

[42] A. Soroudi, *Power System Optimization Modeling in GAMS*. Cham, Switzerland: Springer, 2017, doi: 10.1007/978-3-319-62350-4.

[43] *Realtime Mining Hardware Profitability: ASIC Miner Value*. Accessed: Feb. 1, 2023. [Online]. Available: https://www.asicminervalue.com/

[44] *Powerwall*. Tesla. Accessed: Feb. 1, 2023. [Online]. Available: https://www.tesla.com/powerwall

[45] *Blockchain Charts*, 2023.

[46] *GAMS Platform: General Algebraic Modelling System (GAMS)*.

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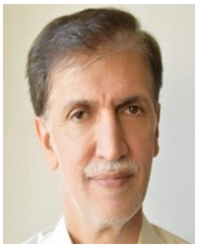

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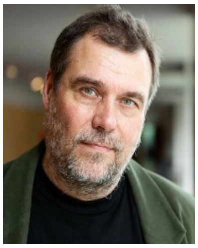

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