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Cryptocurrency mining as a novel virtual energy storage system in islanded and grid-connected microgrids

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ABSTRACT

Renewable electrical energy (such as: solar and wind energies) generation in microgrids (MGs), is gaining attention to reduce greenhouse gas emissions. Microgrid operators (MOs) aim to create self-sufficient, environmentally sustainable grids, increasing the capacity of renewable energy sources (RESs) by up to 100%. Despite of the benefits of this trend, challenges arise from non-controlled characteristics of these power generations and their seasonal variations, causing fluctuations and renewable energy curtailment. Although the technical solutions; such as: the demand response (DR) programs, and the conventional electrical energy storage systems (EESSs) can help, however those may face limitations in countries with high seasonal energy generation and consumption variations. This paper introduces cryptocurrency mining loads (CMLs) as innovative virtual energy storage systems (VESSs), named cryptocurrency energy storage systems (CESSs). It proposes a structure to store excess renewable energy in cryptocurrency units (CCUs) like Bitcoin (BTC). CESSs can be charged during off-peak intervals and, conversely, they discharge during high-demand periods to reduce the overall operational cost of MGs. Furthermore, it presents a new energy management system (EMS) formulation for the optimal operation of MGs in the presence of CESSs, providing an opportunity to generate additional electricity from RESs and to mitigate renewable energy curtailment. This paper explores the optimal operation conditions of both islanded and grid-connected MG with the proposed CESS. Utilizing a dataset from an island in Finland as a practical MG, its effectiveness is demonstrated through several case studies. The results of one case study in this paper demonstrate that the proposed CESS can decrease the operating cost of the MG by about 46.5%. Additionally, it is showed that by application of CESS the renewable energy curtailment is significantly reduced, and approached zero.

1. Introduction

Cryptocurrencies are spreading and arousing the interest of enterprises, start-ups, entrepreneurs, economists, as well as common people rapidly around the world. Its proponents claim, these types of money, due to their robust mathematical backbone based on cryptography, are more secure, reliable, transparence, available, and convertible than traditional money [1]. They assert that cryptocurrencies can play their role superbly in exchange for goods and services on one side and store of value on the other side. They were named digital gold, money 2.0, viable asset class, etc., by some famous financial experts [2]. Therefore, they might have an enormous potential to act as an alternative form of cash shortly [3]. In general, cryptocurrency mining is a process where miners confirm and validate cryptocurrency transactions via solving a computational problem. Miners with their application-specific integrated circuit (ASIC) devices tend to check the dates and validity of every transaction and gain block rewards as motivation. However, there are two critical problems miners face: the high energy consumption of cryptocurrency mining devices (CMDs) and, as a result, environmental pollution indirectly due to these energy-hungry devices [4]. To overcome these problems, miners can utilize renewable energy sources (RESs), such as wind and solar power, as their energy suppliers.

Today, energy systems around the world are transitioning from fossil-based energy systems to low carbon energy systems to realize the

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global targets of mitigating climate change, along with energy efficiency. In order to meet these targets, the role of the RESs in the global power supply will reach significant importance, as wind and solar photovoltaic (PV) are estimated to supply almost 60 % of the annual energy consumption in 2050 [5]. However, with the increasing penetration of the non-dispatchable variable RESs, the power system operators face a challenge in balancing supply and demand of the electricity grid. Balancing the grid becomes more costly as the share of RESs rises and may bring some challenges such as over generation, transmission congestion, renewable energy curtailment, increasing reserve capacity, increasing costs, and reducing environmental benefits of RESs [6]. In order to address the mentioned problems in microgrids (MGs), energy system flexibility solutions including electrical energy storage systems (EESSs) [7], virtual energy storage systems (VESSs) [8], and demand-side flexibility [9] have been presented to mitigate the renewable energy curtailment; however, these solutions will not be enough to cover the increased flexibility needs due to the large-scale deployment of RESs. Therefore, there is an obvious need for flexible and fast-response solutions that can store excessive renewable energy generated during the low-demand period. With this in mind, this paper study the role of cryptocurrency mining loads (CMLs) in the renewable energy transition.

This paper proposes a novel method to store excessive renewable energy (energy surplus) of RESs. Renewable energy producers and owners can consume excessive energy using cryptocurrency mining to save energy in cryptocurrency value with a novel form of VESS; it is defined as cryptocurrency energy storage system (CESS). The contribution of CESSs as VESSs to MGs brings flexible, fast-response characteristics to store excessive renewable energy in cryptocurrency units (CCUs) such as Bitcoin (BTC) in off-peak periods, and conversely, to discharge in high-demand periods to decrease the overall operation cost of the MGs. In the following subsection, the authors delve into related work, setting the context for the study and highlighting the gaps their research aims to fill.

1.1. Literature review

RESs and generation techniques contain solar cells, wind turbines (WTs), biomass, hydroelectric plants, geothermal, and others [10]. The integration of RESs into power generation will reduce fossil fuel dependency, environmental pollutions, and greenhouse gas emissions [11] and it is one of the main drivers for the rapid transition to renewable-based energy power systems. Such a rapid growth brings new challenges associated with the variability and uncertainty of these sources, which have non-controllable and unpredictable output power on an hourly/daily/weekly basis. Although some papers have conducted some research to improve RESs forecasting [12–15], high uncertainty and variability of RESs cause a large amount of excessive energy, which is wasted without usage due to mismatch between renewable generation and demand [16]. EESSs combining with renewable energy production for uncertainty reduction and uncertainty management in power systems would be necessary as well, and they have been the focus from the past until now [17,18]. The primary focus of this section is on the utilization of CMLs as VESSs in MGs. However, for a more comprehensive understanding of EESSs applications within MGs, readers are encouraged that for in-depth insights and analysis of the subject to review these references [19–22].

As mentioned before, the increasing penetration of the RESs, especially the intermittent solar PV and wind farms, causes several challenges for the power systems. VESS is an innovative and effective way to add and control the flexibility provided by various types of flexible demands, so that more RESs can be integrated into energy systems. In fact, flexible loads such as heating, ventilation, and air conditioning (HVAC) systems can be employed to present an EESS-like service to MGs by varying their demand up and down over a baseline. Employing VESSs approach in the energy management system (EMS) of RES-powered MG have been the focus from the past until now. The authors in [23] proposed EESS optimal sizing strategy considering dispatch of air conditioners as VESS in the MG with high solar PV penetration to minimize system cost and mitigate the impact of uncertainties. In [24], the round-trip efficiency of HVAC-based VESSs was analyzed. Building based VESS and dynamic economic dispatch model of MGs presented in [25] by utilizing the heat storage capability of apartment buildings. The benefit of employing VESS formed by refrigerators [26] and HVAC system [27] were studied to provide the frequency response service for power system. In [28], the construction of smart VESSs was presented by aggregating the air conditioners to mitigate the imbalance between supply and demand. Reference [8] introduced a hierarchical framework for optimal scheduling of thermostatically controlled loads (TCLs) as VESSs for optimal operation of the distribution system and providing grid flexibility. Additionally, for a deeper understanding of VESSs applications in MGs, readers are advised to review papers [29,30] for a comprehensive analysis. In the following, the penetration of CMLs in the power grid, along with their associated challenges and benefits, are reviewed.

The rapid growth of the cryptocurrency economy has placing new types of demands on electricity grids known as CMLs. The high penetration of these loads and their intense energy consumption can cause new challenges and opportunities for global energy systems, which have been examined in the literature. In general, the research works in this field can be divided into three main parts: examining the challenges of the penetration of CMLs in the power system, providing approaches to address these challenges, and finally, analyzing the positive opportunities of these loads to accelerate the renewable energy transition. As mentioned, the introduction of CMLs to the power system and the huge energy consumption of CMDs may cause many challenges in the grid. In order to investigate the challenges, the authors in [31] presented quantitative energy consumption and environmental impacts of CMLs. The authors in [32] studied the economic damages of air pollution emissions, associated human mortality, and climate impacts of CMLs in the US and China. In [33], the impact of power factor and harmonic distortion of CMLs on the electricity grid was studied. In [34], the adverse effect of CMLs on the premature aging of distribution was examined. The authors in [35] introduced a methodology for estimating cryptocurrency's electronic waste (e-waste). In order to address the challenges of CMLs in electricity grid, an energy efficiency programs was presented in [36] to decrease the energy consumption of these loads. In [37], a practical electricity pricing strategy was introduced to manage the operation of CMLs appropriately by making the cryptocurrency mining business unprofitable during the on-peak periods.

In other to investigate the positive opportunities of CMLs to accelerate the renewable energy transition, the authors in [38,39] introduced practical hedging mechanisms to encourage investments in wind and solar farms projects by simultaneously investing in cryptocurrency mining facilities, respectively. In line with the findings presented in reference [38], the authors in [40] introduced a method that integrates CMLs with wind power to enhance profitability and expedite investment returns. This approach promotes the growth of RESs, addresses variations in renewable energy generation, and facilitates a transition towards a low-emission energy system. In [41], the impact of CMLs on the interaction between RESs-powered MGs and main grids was investigated by modeling these loads in the energy management studies of MGs. The authors in [42] optimized the energy management of a MG integrated with EESSs and swapping stations in the presence of RESs and CMLs. Reference [43] presented economic and operational evidence regarding applicability of CMLs to mitigate renewable energy curtailments for the energy reliability council of Texas. The authors in [44] presented the optimal day-ahead planning of a renewable multi-carrier system consisting of various RESs, EESSs, multi-level electric vehicle charging station, CMLs and flexible loads. A novel cogeneration system based on solar PV system and CMLs was investigated in [45] considering technical, economic, and environmental analyses.

Reference [46] introduced a novel geothermal system that generated electricity, cooling, and contributed to cryptocurrency mining by integrating steam and carbon dioxide cycles, a liquid gas line, and utilizing liquefied natural gas for power generation. The authors in [47] examined the practicality of utilizing electricity generated from individually optimized PV systems to meet the power requirements of CMLs at both small and commercial scales. The authors in [48] employed the robust optimization with a stochastic approach to choose a cryptocurrency farm location, powered by RESs; while addressing the uncertainties in its positioning. Additionally, for a deeper understanding of the possibilities and challenges involved with integrating RESs into sustainable cryptocurrency mining processes, readers are advised to review the following references [49,50] for a comprehensive analysis of the subject. However, to the best of our knowledge, existing literature largely viewed CMLs as fixed profit-driven entities, neglecting their potential for storing energy in CCUs. This paper fills this gap by proposing a novel model that portrays these loads not just as consumers but also contributors to surplus renewable energy storage as VESSs. This approach aims to enhance sustainability in cryptocurrency mining operations, providing a comprehensive understanding of their role in renewable energy transition. Table 1 illustrates the contribution of the proposed approach versus the data of selected reviewed literatures on utilization of RESs for powering CMLs.

1.2. The main contribution of this work

In order to investigate the effectiveness of the CMLs in the flexibility of MGs, the typical EMS of MGs should be rewritten to consider these loads as storage systems. To the best of the authors' knowledge, so far, there is a lack of a comprehensive study explaining how CMLs contribute to MGs operating objective function as well as how they can be used optimally to store excessive renewable energy of MGs and convert from electrical energy (kWh) to CCUs. This paper is dedicated to fill this gap. CMLs can resemble VESSs because this flexible load can provide functions like charging/discharging EESSs by intelligently managing the power and energy consumption of loads. By well-utilizing the existing network assets, these load can be deployed at scale with many advantages compared to conventional EESSs, will be approved in this paper later, as follows: lower maintenance cost, infinite energy storage capacity, higher power and energy density, zero total capital energy cost, endless life cycle and full charge/discharge times, higher scalability from a tiny residential house to a massive power plant storage, shorter rate of return, zero cost energy stored portability with the concept of VESS. The main contribution of this paper is to introduce CMLs as VESSs, and other contributions can be summarized as follows:

- The profitability of CMLs in both islanded and grid-connected MGs consisting of RESs, conventional EESSs, and loads is investigated in different seasons.
- A new EMS formulation is introduced to model CMLs as VESSs in the optimal operation of both islanded and grid-connected MGs.
- A novel structure is proposed to store excessive renewable energy in CCUs and present the opportunity to generate more electricity from RESs and mitigate the renewable energy curtailment.
- The optimal capacity of the CESSs in both islanded and grid-connected MGs can be evaluated by employing the proposed EMS formulation.

1.3. Paper organization

The next sections of this paper are organized as follows: In section 2, the idea of novel CESS will be discussed in detail. Section 3 compares different types of conventional EESSs with CESS; considering its merits and demerits, thoroughly. The next section prepares a typical MG architecture for our study. Section 5 presents an optimization algorithm and solution for optimized MG operation considering techno-economic constraints. Section 6 represents case studies and simulation results. Section 7 summarizes and concludes.

2. Microgrid and cryptocurrency energy storage system

In this section, the concept of MGs integrated with distributed generations (DGs), EESSs, and their role in the AC network are described. Then cryptocurrency mining in MG is explored standing as a virtual storage element, and the proposed systematic algorithm for CESS contribution to the MG is investigated in the final subsection.

2.1. Microgrid

RESs or renewable DGs are emerging in the distribution grids as clean energy in the world to mitigate environmental pollutions of fossil fuel-dependent power plants. Nevertheless, the intermittent nature of energy generation with this technique results in power generation fluctuations and instability in power systems due to the deviation of power supplied from actual demand. With this in mind, the need for EESSs makes sense more than ever integrated with RESs. Therefore, EESSs and RESs together are prevailing in power systems, especially in distribution systems. DGs combined with storage devices result in loss reduction, reliability enhancement, and diminish of greenhouse gases emission. In such distribution systems, all components of the grid such as: the generation, and the distribution elements are presented. Therefore, they were named MGs, a small or micro-scaled of a network. MG, like the power grid, in order to convey its purpose, energy delivery with a guaranteed level of power quality and reliability, must be operated under the control of a system operator or a microgrid operator (MO). Many MG energy management and control systems (EMCSs) utilize a mix of control components to address various time-based needs.

Table 1
Contribution of the proposed method compared to the other literature reviews.

Ref.	Distributed generations			EESSs	Grid connection		Modeling CMLs		Storing excessive renewable energy in CCUs (CESSs)	Optimization
	Wind	Solar	Others		Connected	Islanded	Fixed loads	Controllable loads		
[38]	✓	×	×	×	✓	×	✓	×	×	×
[39]	×	✓	×	✓	✓	×	×	✓	×	✓
[40]	✓	×	×	×	✓	×	✓	×	×	×
[41]	✓	✓	✓	✓	✓	×	✓	×	×	✓
[42]	✓	✓	×	✓	×	✓	✓	×	×	×
[43]	✓	✓	×	×	✓	×	✓	×	×	✓
[44]	✓	✓	×	×	✓	×	✓	×	×	✓
[45]	×	✓	×	×	✓	×	✓	×	×	×
[46]	×	×	✓	×	×	✓	✓	×	×	×
[47]	×	✓	×	×	×	✓	✓	×	×	×
[48]	✓	✓	×	×	✓	×	✓	×	×	✓
This paper	✓	✓	✓	✓	✓	✓	×	✓	✓	✓

Referred to as hierarchical control, it consists of primary, secondary, and tertiary levels, varying based on operational timeframes. Primary control, operating at the millisecond level, focuses on tasks like voltage, frequency, current regulation, maximum power point tracking (MPPT), and power distribution. This control is often decentralized, implemented within individual DGs by using local controllers as shown in Fig. 1. Secondary control, with timescales spanning from seconds to minutes, handles voltage and frequency reference adjustments, power dispatching, and transition control, typically through centralized or distributed means. Tertiary control operates on timelines ranging from hours to days, involving activities like energy trading, unit commitment, forecasting generation, and load demand [51–53].

MO, by employing its assets properly, DGs and storage devices, running an optimization problem, tries to minimize MG total electricity cost and reduce the dependence on the main grid. This process is named microgrid EMS, as depicted in Fig. 1, shown on the next page. MO after demand, electricity price, and non-dispatchable RESs forecasting, runs a cost-based optimization problem trying to minimize the operating costs. The output of its solution would be the required power of dispatchable RESs, other DGs, and the EESSs charge/discharge states. Nowadays, MGs face a new challenge with respect to the consumption load's patterns, i.e., the pattern of cryptocurrency mining. The advent of CMLs into the power systems cause some challenges to the grid. There are many opponents and critics for this technology around the world. They state that the CMDs tremendous amount of electricity requirement results in a complete loss of value. However, as mentioned in the previous section, its benefits outweigh the disadvantages. The following subsections propose an EESS-based model for this technology that is connected to a MG. It presents CMLs as VESSs, which allows for the storage of electricity in the form of value or money. The concept of CESS in the MG is introduced and scrutinized as well. Therefore, MOs can turn this challenge into an opportunity by adapting this new technology and modifying the optimization problem by considering this technology as an effective remedy for the storage reserve.

2.2. CESS description and mathematical model

Storage elements emerged in distribution systems, especially integrated with DGs, to reduce and manage the uncertain nature of renewable generation. For further illustration, consider a renewable energy producer, for instance, wind or solar power plants. There are three options for scheduling and dispatching the energy produced by this power plant. This energy could be sold to the grid via the wholesale market if the network demands this amount of energy. On the other hand, if the energy produced exceeds the existing demand of the grid, the excessive energy, or energy surplus, could be consumed in two ways: i) stored in EESSs such as batteries, for later usage during grid peak demand, or ii) left idle to be wasted instead of generating energy, which is more cost-effective than storing the energy at the prevailing energy storage prices. However, there is still another way to store excessive energy. Cryptocurrency mining is a way that provides a wonderful chance for grid operators and other players who have CMDs in the MG to save excessive energy as money in the CCU.

This subsection wants to review the concept of how cryptocurrency mining is profitable generally for a company investigating the profitability of cryptocurrency mining business. Then, we narrow our model for doing this business and investigate MOs who can act as miners to store energy in the form of money. In every monetary sector, a predefined specific validation method is needed to ensure correct sequencing of money transactions and prevent any crime. For example, fiat currency, which does not have intrinsic value itself, is declared by governments to be legal tender, and people are engaging in exchange by agreeing on its value. Cryptocurrencies need a consensus mechanism as well. There are numbers of validation methods for cryptocurrencies feasibility determination in the blockchain platform which include: proof of work (PoW), proof of stake (PoS), proof of space, proof of authority, etc. The most popular one is PoW scheme, where many cryptocurrencies like Bitcoin (BTC), Monero (XMR), Dash (DASH), Etherium (ETH), and others are included. In this mechanism, cryptocurrency miners must solve a computational problem (Hash calculation), referred to cryptocurrency mining. When a miner solves this problem makes a new block, contains some validated transactions, in blockchain, and gets the block reward. In PoW system, the more computational power or energy consumption, the more chance for new block creation. Also, miners can participate and join cryptocurrency mining pools together to increase their computational power, and then increase the chance of new block creation and get more block reward.

Cryptocurrency mining in cryptocurrency mining pools besides its advantages such as: i) higher computational power, ii) more block rewards, have some demerits compared to individual cryptocurrency

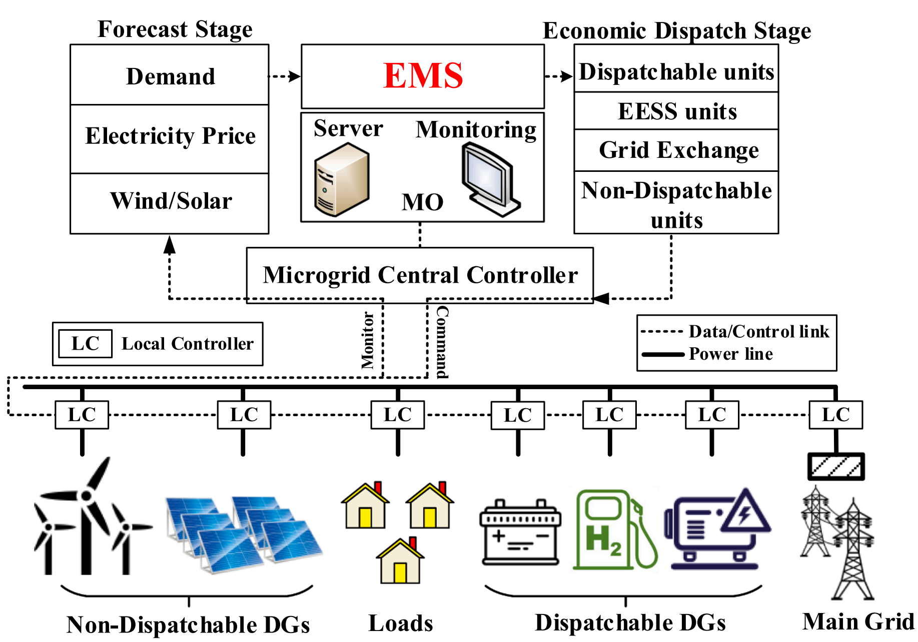

Fig. 1. EMS of a MG including forecast stage, optimization problem, and economic dispatch output.

mining. Cryptocurrency mining pools participants must pay a little bit of cryptocurrency mining fee as their membership fee. They must share their rewards to all other participants proportional to their computational power in PoW based system or proportional to the cryptocurrency they have in PoS based systems. This was the revenue that came from cryptocurrency mining. Miners spend money as their costs of running CMDs by energy consumption. In response, they produce and gain a higher level/class of commodities in CCU. In PoW-based cryptocurrencies, which are more popular and available rather than others, the miners' revenue function is highly dependent on the computational power in the numbers of Hash they can calculate with CMDs. Also, they expend money to purchase the required electricity, which is dependent on electricity price. The interaction of these revenue and cost function is the profit or motivation for doing this business.

Fig. 2 depicts the parameters that affect cryptocurrency mining revenue, cost, and profit function and their satisfactory or adverse effects on profitability in summary. Increasing each parameter may cause more/less profit, as illustrated in Fig. 2. For further illustration, the reader is referred to [1]. With this concept in mind, this work investigates the revenue, cost, and as a result, the profit function of cryptocurrency mining in CESS elements, which consumes energy to mine cryptocurrency. The following paragraph directly presents the CESS main points. Cryptocurrency mining converts electrical energy to the cryptocurrency value. Therefore, the amount of energy, a miner can store, equals to the amount of cryptocurrency gain, in his or her cryptocurrency wallet account. This amount of cryptocurrency could be converted to traditional money in stock markets with every cryptocurrency to every unit of money. For example, in a BTC wallet, the amounts of BTC with the "Bitcoin-dollar index" or $\lambda^{\$}_{BTC}$ can be converted to dollar unit.

In general, $\lambda^{\$}_{crypto}$ symbol can be used for the conversion coefficient. Also, with this converted money, miners can purchase electrical energy from the wholesale market every time needed. Because, as mentioned before, cryptocurrency mining can be done with excessive energy within the MG, which is entirely free of charge, a miner has produced value/profit (stored energy in CCU) without cost expenditure. Wallet balance for cryptocurrency mining, based on PoW system, is modeled as follows:

$$WB_{CESS}(t+\Delta t) = WB_{CESS}(t) + \{R(\Delta t) - Mic(\Delta t)\} - \{PC(\Delta t)\} \tag{1}$$

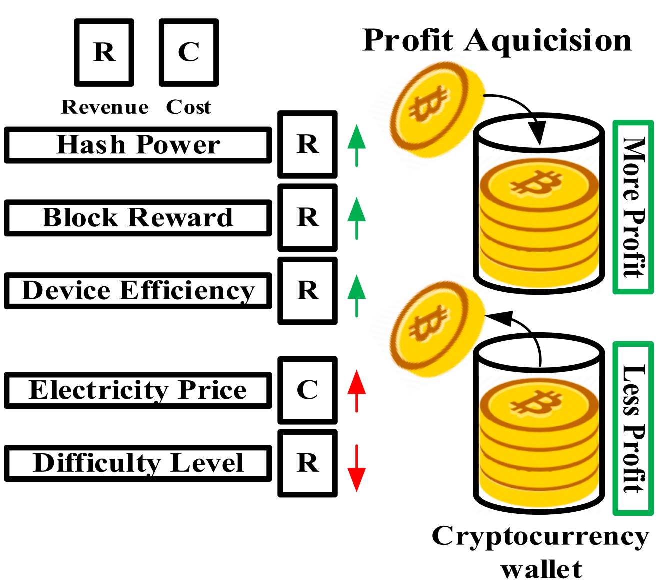

Fig. 2. Parameters that have a significant impact on cryptocurrency mining profitability.

$$R(\Delta t) = \int_{\Delta t} \frac{3600 \times \beta \times \rho(t)}{2^{32} \times \delta(t)} \times I^{ch}_{CESS}(t)dt \tag{2}$$

$$Mic(\Delta t) = \int_{\Delta t} P^{ch}_{CESS}(t) \times \pi^{e}_{Buy}(t) \times \lambda^{crypto}_{\$}(t) \times I^{ch}_{CESS}(t)dt \tag{3}$$

$$PC(\Delta t) = \int_{\Delta t} P^{dch}_{CESS}(t) \times \pi^{e}_{Buy}(t) \times \lambda^{crypto}_{\$}(t) \times I^{dch}_{CESS}(t)dt \tag{4}$$

$$E_{CESS}(t) = \frac{WB_{CESS}(t)}{\pi^{e}_{Buy}(t) \times \lambda^{\$}_{crypto}(t)} \tag{5}$$

$$N^{CMD}_{CESS}(t) = \frac{(1-\gamma^{cooling}) \times P^{ch}_{CESS}(t)}{P^{CMD}_{D}} \times I^{ch}_{CESS}(t) \tag{6}$$

Subject to:

$$0 \leqslant WB_{CESS}(t) \leqslant \infty \tag{7}$$

$$0 \leqslant P^{ch}_{CESS}(t) \leqslant P^{ch,Max}_{CESS} \times I^{ch}_{CESS}(t) \tag{8}$$

$$0 \leqslant P^{dch}_{CESS}(t) \leqslant \infty \tag{9}$$

$$0 \leqslant I^{ch}_{CESS}(t) + I^{dch}_{CESS}(t) \leqslant 2 \tag{10}$$

where, WB_{CESS} in (1) is wallet balance in CCU. In charge mode, the profit gained from cryptocurrency mining is added to wallet balance, and when CESS discharges, the wallet balance decreases for money spent. Two binary variables I^{ch}_{CESS} and I^{dch}_{CESS} show whether the storage device is on charge mode or discharge mode. Eq. (2) formulates revenue function from doing cryptocurrency mining in CCU in the charge interval, when I^{ch}_{CESS} is 1. Revenue function depends on block reward (β in CCU/block), hash power (ρ in THash/s), difficulty level of cryptocurrency mining (δ in THash/block), which is determined or restricted by the system at any time. In Eq. (3), *MiC* is the level cost or electricity cost in CCU. π^{e}_{Buy} is the electricity price when doing cryptocurrency mining. When cryptocurrency mining uses excessive RESs in the MG, this price is approximately zero. Until now, a miner or our storage device has stored electricity in CCU. In another time, this amount of stored money can be used for electricity purchases from the electricity market. By doing so, a MO who employs cryptocurrency mining and acts as miner can achieve two goals at once. On the one hand, a MO uses almost free excessive energy in off-peak periods from distributed generators and stores it in CCU, which is in the more valuable form. On the other hand, that operator can buy more expensive electricity from the electricity market during the on-peak period or price spikes. In (4), P^{dch}_{CESS} (kW) is the purchased demand and *PC* is the purchased energy cost or the cost for buying energy from the main grid in CCU in the discharge interval, when I^{dch}_{CESS} is 1.

In summary, in the charging mode, miner consumes free of charge excessive electricity from RESs, spends *MiC*, approximately zero, and gains (mines) *R* in CCU. In the discharge mode, wallet balance is reduced by *PC*. In (5), the instantaneous value of stored energy or *State of Charge* (SOC) parameter, E_{CESS}, of this storage device can be expressed by converting the wallet balance in CCU to kWh. In this case, dividing wallet balance value to electricity price and cryptocurrency to dollar index results in the total kWh that can be purchased from the main grid. In the charging mode, the total running CMDs (N^{CMD}_{CESS}) and power demand (P^{ch}_{CESS} in kW) for cryptocurrency mining are optimized based on the employed cooling system ($\gamma^{cooling}$), as shown in Eq. (6). CESS charges and discharges based on some constraints (7) to (10). Eq. (7) claims that CESS has infinite energy storage capacity because of the unlimited capacity of cryptocurrency wallets for saving money. In (8), the amount of power at charging mode is limited. Therefore, $P^{ch,Max}_{CESS}$ is the maximum power for charging mode, which is the installed capacity of cryptocurrency mining with the cooling system. According to wallet balance, a certain amount of energy could be purchased, which equals E_{CESS}. However, purchasing power is not limited at all and only dependent on the time for storage discharge, as shown in (9). For instance, lower power for more extended periods, higher power for shorter durations can be purchased. CESS, unlike other storage elements, does not have the limit of simultaneous charging/discharging mode as (10) shows.

2.3. CESS systematic contribution to microgrid

As mentioned earlier, in order to mine cryptocurrency, not only environmental pollution constraint must be met, but cryptocurrency mining must be profitable. For this reason, excessive energy from distributed RESs is the best choice for cryptocurrency mining. This work assumes that marginal cost of excessive energy production is zero in a MG for two reasons: i) there is no demand or load to consume it, and ii) if they are not consumed, they are wasted. The proposed algorithm for CESS contribution to the MG is as follows. When MO checks whether there are some amounts of excess energy, P_{ex}, in the MG, the cryptocurrency mining would be profitable if P_{ex} or P_{Wasted} is positive. Because revenue value (R) exceeds from cost value of cryptocurrency mining (MiC) in a differential of time or an interval, the cryptocurrency mining is profitable, and MO can turn on CMDs by remote control switch (RCSs) with a communication data link. The decision to activate the CMDs is based on the optimization results of energy management, as well as the amount of excessive energy detected. This algorithm must be checked repetitively, and RCSs on/off states be coordinated. By doing so, MO would gain from CESS elements as much as possible. Fig. 3 illustrates this proposed systematic approach.

3. CESS vs. conventional EESSs: Specification and comparison

Conventional EESSs based on employed technologies, configurations, and what energies they store could be classified into six different groups: electrochemical, thermal, mechanical, chemical, electrical, and hybrid storage systems [54]. Fig. 4 illustrates these groups and the proposed one, CESS. Each electrical energy storage technology has unique characteristics in its application. These characteristics are employed to compare the different storage technologies proposed by constructors and to guide the selection of storage technology for a certain application. The main characteristics for comparing energy storage technologies are explained in the following subsections, and the definitions of these main characteristics and the adaption of them to the specific characteristics of the CESS are discussed.

3.1. Power range

The power range of an EESS is the maximum amount of power it can

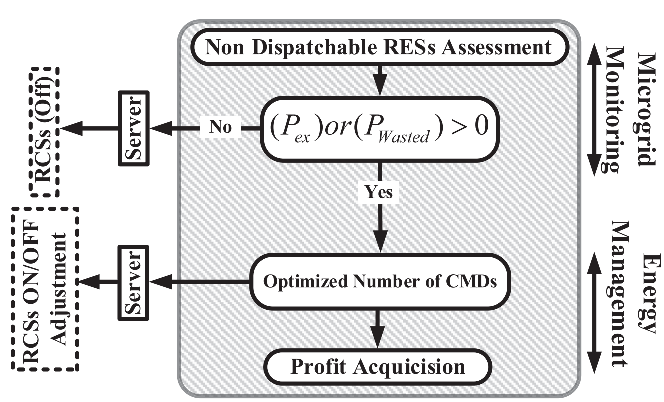

Fig. 3. Real-time systematic algorithm for CESS employment.

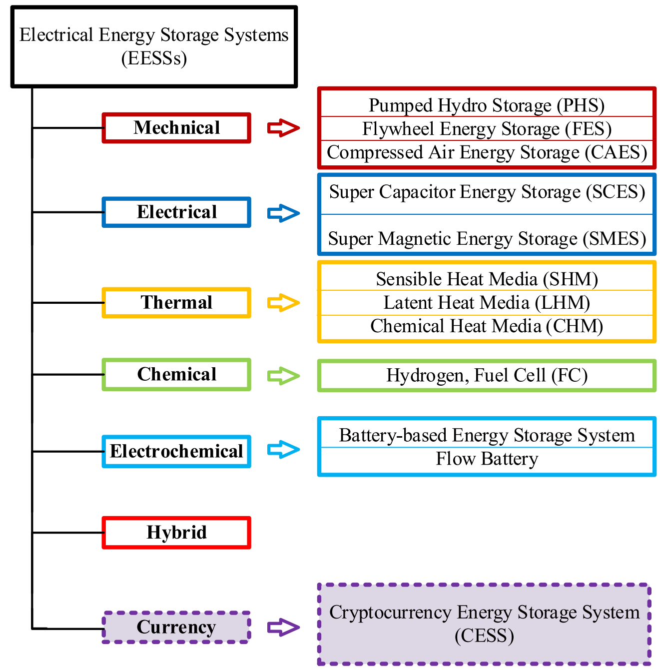

Fig. 4. EESSs with various energy conversion types [14].

be supplied in watt (W) and its multiples. It is generally indicated as an average value, as well as a peak value often used to represent maximum power of charge or discharge under normal operating conditions. It has a powerful impact on dimensioning in EESSs. The size, mass, and cost of an EESS are affected by this parameter. The power range of a CESS depends on the number of installed CMDs, its cooling systems, and temperature regulators [54].

3.2. Discharge time

Discharge time is the amount of time that storage discharges at its rated power to be empty without recharging. In other words, the discharge time is the maximum-power discharge duration. It depends on the depth of discharge, is the amount of storage capacity that is utilized, and the operational conditions of the storage system, constant power delivery, or not [54]. For storage systems in an isolated region depending on volatile renewable energy, discharge time is a crucial attribute. As mentioned before, in the CESS, electrical energy is stored in CCU; therefore, depending on the amount of saved money from cryptocurrency mining in the cryptocurrency value which has not any limit, the amount is spent, the discharge time of this storage can be varied from less than second to more than days. EESSs are classified broadly into long duration (frequent), medium duration (fast response), and short duration (highly frequent) applications depending on their power rating and discharge time. In the long duration category, PHS, CAES, and FC are appropriate for applications in scales above 100 MW with hourly to daily output discharge time. They can be employed for energy management for large-scale generations such as bulk energy storage, peak shaving, load levelling, frequency regulation, spinning reserve, and renewable penetration. Large-scale batteries and flow batteries are suitable for medium-scale energy management with a capacity of 10–100 MW.

In the medium duration category, batteries, flow batteries, and FC not only have a relatively fast response (less than 1 s) but also have comparatively long discharge time (hours); consequently, they are more appropriate for bridging power. The typical power rating for these kinds of applications is about 100 kW–10 MW. In the short duration category, FES, batteries, SCES, and SMES have a fast response (~milliseconds) and, therefore, can be used for transient stability and power quality, such as the instantaneous voltage drop, flicker mitigation, and short duration UPS. The typical power rating for this type of application is less than 1 MW [54]. According to the above classification of energy storage systems and particular characteristics of CESS technology (especially power rating and discharge time), this storage is in the first category (long duration as storage service). In this paper, CESS is employed for renewable penetration as service applications.

3.3. Energy rating

For an EESS, the most fundamental characteristic, in theory, is its Energy rating, usually expressed in watt-hours (Wh) and their multiples. This characteristic presents an estimation of the amount of energy that can be stored [54]. In other words, the energy rating is the measure of how much EESS can deliver power over an hour. In each application of EESSs, depending on storage power rating and its discharge time, the energy rating of storage can be varied from less than 1kWh to more than 1GWh. According to the power range and discharge time of the CESS, its energy rating is unlimited because energy is stored in a cryptocurrency wallet, which is not limited at all.

3.4. Power and energy density

Power density is the amount of power that can be delivered from EESS over its weight or volume in kW/kg or kW/m^3. Similarly, energy density is the amount of energy that can be stored in an EESS divided into its volume or weight in kWh/kg or kWh/m^3. These criteria are significant in conditions where space is worthwhile or limited and/or weight is essential (remarkably for portable EESSs). Depending on the storage technology, space constraints may be a challenge, especially in heavily urbanized regions like residential-based MGs. These characteristics can vary depending on the type of CMDs in the CESS. For example, assume an *Antminer S19j Pro* device with the following two specifications: *i*) weight: 14.2 kg, *ii*) rated power: 2.832 kW. If such devices are used in the CESS, the power density will be 199.4 W/kg, and energy density will be infinite. By comparison the power density of the CESS with other types of EESSs presented in [54], it can be seen that the power density of CESS is in the range of electrochemical EESSs which offers the best performance in this category.

3.5. Response time

Response time is defined as how long it takes for the EESSs to deliver requested stored energy. For example, in the FES system, power can be delivered very quickly, yielding response times in the order of a few milliseconds more or less, depending on the scale of storage. Conversely, a PHS system in power system requires an amount of time ranging from one to several minutes to attain rated power [54]. Converting digital currency to electrical energy is far less time consuming than converting other energies into electrical energy. In other words, by saving excess energy in digital currency, the MO can supply electricity at any time in the electricity market.

3.6. Lifetime and lifecycle

In EESSs, the lifetime is usually determined by the lifetime of the mechanical components. The lifetime of the CMD depends on its ASICs devices, which is expected to operate from 2.5 to 5 years [55]. However, the lifetime of other EESSs varies up to 40 years. Lifecycle of EESSs refers to the number of times the storage system can discharge the energy capacity amount it was designed for after each recharge, indicated as the maximum number of cycles (one cycle conforms to one full charge and one full discharge) [54]. All EESSs depreciate during each charge-discharge cycle. The rate of depreciation depends on the type of energy storage technology, operating conditions, and other variables. This is especially important for electrochemical storage affected significantly by the depth of discharge. CESS, in its lifetime, has an unlimited lifecycle.

3.7. Operating temperature

The performance of the energy storage system is affected by environmental temperature. The optimal operating temperature varies from -200 °C for SMES to 600 °C for FC, depending on the type of EESS [54]. The normal operating temperature for the CMDs is about 0–45 °C, which can vary slightly for different devices [55].

3.8. Nominal voltage

The nominal voltage of the EESS is the voltage to which the storage is discharged. The nominal voltage undeniably affects the amount of capacity that can be carried [54]. If an energy storage system discharges in a lower voltage, it will, of course, give more capacity. Because the CESS stores excess electricity in digital currency, the output voltage level of this storage can be different depending on the owner.

3.9. Capital cost

The investment cost is one of the most critical factors for the technical acceptability of EESSs. Investment cost for a particular system change with many factors. These factors include the size of the EESS, location, market variability, voluntary use of EESS, local climate, environmental considerations, transportation issues, and availability. The total capital cost of an EESS consists of two parts: power cost ($/kW) and energy cost ($/kWh). The power cost of the EESS is generally defined per unit of power capacity. Energy cost contains all the costs undertaken to construct energy storage banks or reservoirs, expressed per unit of stored or delivered energy. Because there is no limitation of energy rating on using CESS, therefore the energy cost of this storage system is zero. The capital power cost of CESS is different depending on the type of CMD and its cooling system. For example, consider an *Antminer S19j Pro* device, if such a device is used to mine cryptocurrency, the capital power cost will be approximately 935.7 $/kW [55], which is in the range of capital power cost of developing/immature storage technologies such as flow battery.

3.10. Self-discharge and round-trip efficiency

In general, EESSs cannot retain stored energy at a permanent level over the storage duration. This is because of self-discharge, depending on internal processes or external factors. These losses are called self-discharge energy losses [54]. For example, in chemical storage, self-discharge is due to a destructive/irreparable chemical reaction that occurs while the energy is stored. This characteristic is particularly vital with short-duration EESSs such as batteries and FES. All energy conversion processes in EESSs have losses. Round-trip efficiency of EESSs demonstrates the amount of energy that comes out of the EESS relative to the amount put into it. Typical values for round-trip efficiency of EESSs range from 30 to 95 percent [54]. As mentioned before, in the CESS, excess electrical energy is stored in CCU, such as BTC. So, at different times depending on the amount of stored digital currency, various amounts of power/energy can be purchased in the electricity market.

Given the unique nature of the CESS, which is made of money, some power/energy, and price-dependent parameters such as round-trip efficiency, self-discharge, and foremost instantaneous energy capacity are not normally defined. According to equation (5) in the previous section, instantaneous energy storage capacity, E_{CESS}, is a function of electricity price (π^{e}_{Buy}) with reverse relation and crypto-dollar index ($\lambda^{\$}_{crypto}$) with direct relation. It means that an increase in cryptocurrency price will increase the amount of energy that can be purchased from the grid. With the constant market electricity price, crypto-dollar index fluctuation may change the energy stored that can be extracted from the CESS device. For more illustration, assume 850 kWh has been consumed extracted from free of charge renewable energy surplus by cryptocurrency mining within a week to store that energy in CCU and gain one BTC, and the electricity price is 10 cents/kWh. Fig. 5 illustrates bitcoin-dollar index fluctuation in a day (February 28, 2023 [56]) and energy stored in the CESS that can be purchased from the market at that time. With this in mind, the round-trip efficiency parameter (extractable energy to consumed energy) goes up and declines with the crypto-dollar index.

4. Microgrid model and description

In this section, a typical MG is reviewed, and a mathematical model of such system and its components, include DGs, EESSs, loads, and AC grid, are formulated. In order to complete the discussion for a typical MG, the mathematical model of PV panels and WTs as non-dispatchable DGs, microturbines (MTs) as dispatchable DGs, and battery energy storage systems (BESSs) as a conventional method for energy storage in MGs are studied in the following paragraphs.

4.1. PV generation model

Intermittent nature of solar radiation causes uncertainty in the power generation output of solar power plants. In a certain level of solar radiation, ambient temperature, and wind speed, predicted output power of this type of plant has been calculated as follows [57]:

$$P_{PV}(t) = A_{PV} \times I_r(t) \times [1 + \mu(T_c(t) - T_s)] \tag{11}$$

where, P_{PV} is the output power (kW), A_{PV} is the total surface area of solar arrays (m^2), I_r is solar irradiance (kW/m^2), μ is temperature coefficient, T_c is the ambient temperature, T_s is a constant, stands for standard test temperature. Solar irradiance is an uncertain variable and highly depends on atmospheric conditions, seasons, radiance angle, *etc*. Historical data for solar irradiance for a particular region can be employed for output power estimation. In this paper, the operating cost of this plant is assumed zero.

4.2. Wind generation model

The power generated by a wind power plant, P_W (kW), is dependent on wind speed. Equation (12) shows the output power in every wind speed [58].

$$P_W(t) = \begin{cases} 0 & S(t) \leqslant S_{ci}, S(t) \geqslant S_{co} \\ P_r \times \dfrac{S(t) - S_{ci}}{S_r - S_{ci}} & S_{ci} \leqslant S(t) \leqslant S_r \\ P_r & S_r \leqslant S(t) \leqslant S_{co} \end{cases} \tag{12}$$

where, P_W is the output power of wind power plant, P_r is the rated output power of the WT generator, S is wind speed variable (m/s), S_{ci} is the cut-in speed where wind speed is so low that generation is ceased. S_{co} is the cut-out speed where wind high speed is destructive for mechanical components, and S_r is the rated or nominal speed.

4.3. Micro turbine model

MTs are small gas turbines with a power generation range of 1 kW to 1 MW. MTs burn a variety of gaseous and liquid fuels to produce fast turning that rotates an electrical generator. The operation cost of an MT ($cost_{MT}$) in time interval t is modelled by piece-wise linearization of the quadratic cost function as follows [58]:

$$cost_{MT}(t) = c \times I_{MT}(t) + \sum_{m \in M} c_m \times P^m_{MT}(t) \tag{13}$$

$$0 \leqslant P^m_{MT}(t) \leqslant P^{m,Max}_{MT} \tag{14}$$

$$P_{MT}(t) = P^{Min}_{MT} \times I_{MT}(t) + \sum_{m \in M} P^m_{MT}(t) \tag{15}$$

$$P^{Min}_{MT} \times I_{MT}(t) \leqslant P_{MT}(t) \leqslant P^{Max}_{MT} \times I_{MT}(t) \tag{16}$$

where, P_{MT} is the active power output of MT in time interval t, c is fixed cost for running MT at its minimum power, P^m_{MT} is generation level of the MT in segment m, and M is set of MT cost segments. $P^{Min}_{MT}/P^{Max}_{MT}$ is minimum/maximum dispatch level of the MT, and I_{MT} is condition indicator of a MT where 1 means ON and 0 means OFF.

4.4. BESS model

One of the most common storage elements in MGs is BESS. They are commercially successful in distribution systems and MGs applications because of their portability and availability in various sizes. Energy stored in these types of storage can be modelled simply in the following equations [41]:

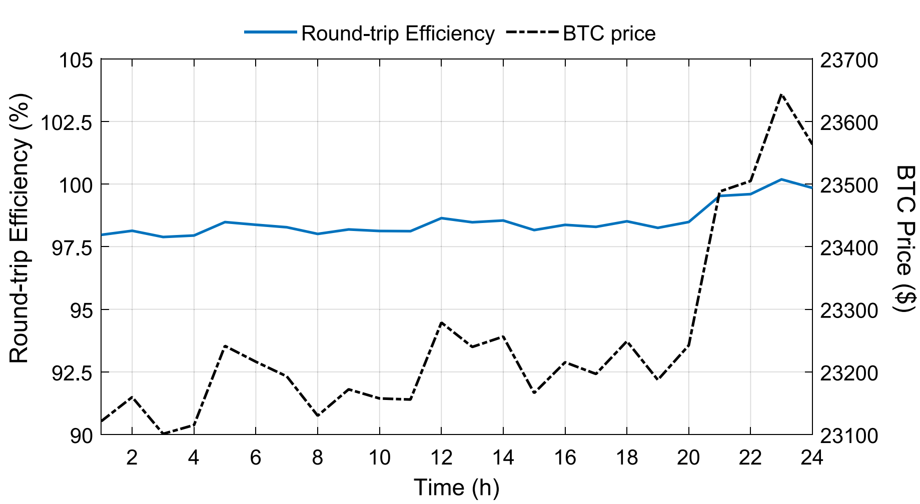

Fig. 5. Round trip efficiency of a CESS during a 24-hour period.

$$E_{BESS}(t+\Delta t) = E_{BESS}(t) + I^{ch}_{BESS}(t) \times \int_{\Delta t} \eta^{ch}_{BESS} \times P^{ch}_{BESS}(t)dt - I^{dch}_{BESS}(t) \times \int_{\Delta t} \frac{P^{dch}_{BESS}(t)}{\eta^{dch}_{BESS}} dt \tag{17}$$

$$0 \leqslant E_{BESS}(t) \leqslant E^{Max}_{BESS} \tag{18}$$

$$0 \leqslant P^{ch}_{BESS}(t) \leqslant I^{ch}_{BESS}(t) \times P^{ch,Max}_{BESS} \tag{19}$$

$$0 \leqslant P^{dch}_{BESS}(t) \leqslant I^{dch}_{BESS}(t) \times P^{dch,Max}_{BESS} \tag{20}$$

$$0 \leqslant I^{ch}_{BESS}(t) + I^{dch}_{BESS}(t) \leqslant 1 \tag{21}$$

where, E_{BESS} is the cumulative stored energy (kWh), η^{ch}_{BESS}, η^{dch}_{BESS}, P^{ch}_{BESS}, P^{dch}_{BESS} are the charging/discharging efficiency (%) and charging/discharging power rate (kW), respectively. Constraint (18) shows the minimum and maximum energy capacity of the storage. In constraints (19) and (20), $P^{ch,Max}_{BESS}$ and $P^{dch,Max}_{BESS}$ are the maximum charging/discharging power that can be injected to or extracted from the BESSs. The last equation explains a physical limitation of BESSs, which simultaneous charge and discharge is not possible. BESS operating costs include maintenance cost in charging/discharging mode connecting to the MG.

4.5. Integration of all microgrid components

Fig. 6 depicts a complete system architecture of a typical MG connected to the main grid including lumped model of RESs, MT, loads, BESSs, CESS with their ancillary components. This sample system will be used as optimization problem input.

5. The proposed energy management system optimization solution

5.1. Optimization solution

In this section, an optimal operation model for a MG within the next 24 h is presented in the presence of CESS as a VESS. The problem of energy/power management in a MG is defined as the problem of the optimal allocation of DGs, RESs and EESSs as well as their appropriate on/off conditions. This energy/power management is done to minimize the MG operating costs and meet the equality and inequality operation constraints. The objective function, considered in this section, is the total operating costs of MG, including operating costs of dispatchable DGs (such as MT), operating costs of BESSs, CESS, and the costs of power exchange between the MG and main grid. In this paper, operating cost for non-dispatchable DGs (wind and solar generators) are considered zero. This objective function is expressed as follows:

$$OF = Min \sum_{t=1}^{T} \{ \text{cost}_{MT}(t) + \text{cost}_{BESS}(t) + \text{cost}_{CESS}(t) + \text{cost}_{Grid}(t) \} \tag{22}$$

$$\text{cost}_{MT}(t) = \sum_{g=1}^{N_{MT}} \text{cost}_{MT_g}(t) \times I_{MT_g}(t) \tag{23}$$

$$\text{cost}_{BESS}(t) = \sum_{k=1}^{N_{BESS}} \left\{ I^{ch}_{BESS_k}(t) + I^{dch}_{BESS_k}(t) \right\} \times \left\{ P^{ch}_{BESS_k}(t) + P^{dch}_{BESS_k}(t) \right\} \times B_{BESS_k} \tag{24}$$

$$\text{cost}_{CESS}(t) = \sum_{l=1}^{N_{CESS}} \left\{ I^{ch}_{CESS_l}(t) \times P^{ch}_{CESS_l}(t) \times B_{CESS_l} - I^{ch}_{CESS_l}(t) \times R_l(t) \times I^{\$}_{crypto}(t) + DC_{CESS_l}(t) \right\} \tag{25}$$

$$DC_{CESS}(t) = \frac{N^{CMD}_{CESS}(t) \times Price^{CMD}_{CESS}}{UL_{Year} \times 8760} \tag{26}$$

$$\text{cost}_{Grid}(t) = \left\{ P_{Buy}(t) \times \pi^{e}_{Buy}(t) - P_{Sell}(t) \times \pi^{e}_{Sell}(t) \right\} \tag{27}$$

where, N_{MT} (indexed by g), N_{BESS} (indexed by k), and N_{CESS} (indexed by l) are set of MT, BESS, and CESS units, respectively. P is the real power (kW) stands for DG output power, EESS and CESS charging/discharging power, bought/sold electricity from/to the grid in time t. Binary variables, I, show whether BESS and CESS are charging/discharging mode, electricity is buying or selling from/to the main grid or not, and MT is turn on or off. Constant parameters, B in \$/kWh, are operating or maintenance costs for each element. DC_{CESS} is the hourly depreciation cost of the CESS paid by owner of the MG. $Price^{CMD}_{CESS}$ is the purchase price of a CMD (in \$) and UL_{Year} is its useful life (in year). Finally, P_{Buy}/P_{Sell} and $\pi^{e}_{Buy}/\pi^{e}_{Sell}$ are the imported/exported power and electricity price for buying/selling electricity from/to the main grid, respectively. The constraints of the objective function include load balance, DGs power generation limits, and EESSs requirement. Equation (28) describes the load balance within the MG:

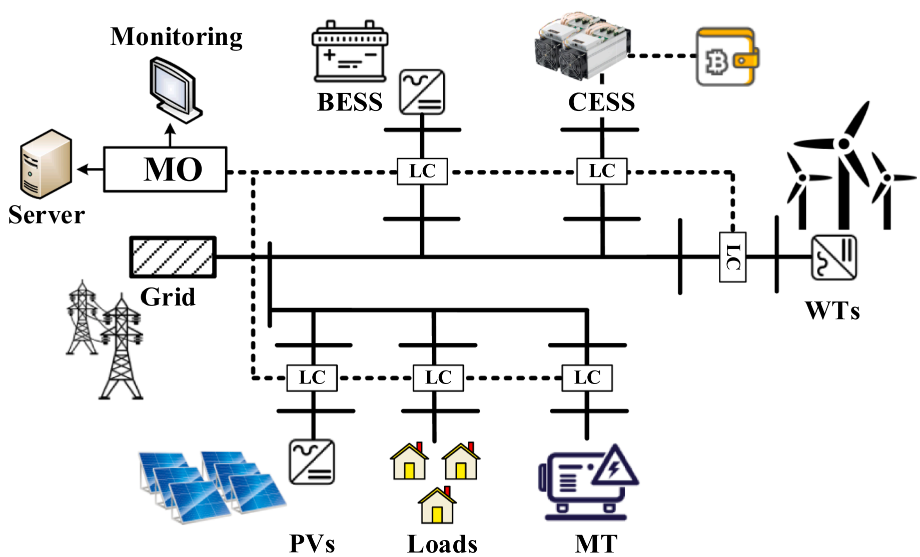

Fig. 6. Proposed microgrid network integrated with RESs, EESS, dispatchable DG, and CESS.

$$\sum_{g=1}^{N_{MT}} P_{MT_g}(t) + \sum_{k=1}^{N_{BESS}} P_{BESS_k}^{dch}(t) \times I_{BESS_k}^{dch}(t) + \{P_{Buy}(t) - P_{Sell}(t)\} = P_L(t) \quad (28)$$

Also, equation (29) shows total load in the MG (P_L) include the demand of customers (P_{Demand}), required power for BESSs, and CESS in their charging mode.

$$P_L(t) = P_{Demand}(t) + \sum_{k=1}^{N_{BESS}} P_{BESS_k}^{ch}(t) \times I_{BESS_k}^{ch}(t) + \sum_{l=1}^{N_{CESS}} P_{CESS_l}^{ch}(t) \times I_{CESS_l}^{ch}(t) \quad (29)$$

Other constraints have already been explained in previous sections. The diagram and problem-solving method for short-term MG operation are shown in Fig. 7. As mentioned in the previous sections, the optimization results include the generation of DGs for the next 24 h and the amount of stored power in the EESSs such that the constraints of the problem are satisfied, and the objective function is minimized. In this algorithm, it is assumed that energy is supplied within 24 h by the power generation/storage resources, including the main grid, PVs, WTs, MTs, BESSs, and CESSs.

The proposed EMS in MGs in the presence of CESS includes the following functions. The first step of the proposed EMS is input data acquisition. The inputs of the optimization model used in this algorithm contain forecasting the power required for loads, information about RESs from historical data, real-time electricity price, SOC of BESS, operation cost of MT, BTC network parameters, and characteristics of CMDs. In the second step, by comprehensively considering load demand, electricity prices, and special needs from the main grid side if grid-connected, the EMS optimizes the capacity of CESS and its scheduling, the power allocation of each DG, and the power exchanged with the main grid. Finally, the optimized power allocations are dispatched to the CESS and controllable DGs, eventually achieving the effective and economic operation of the MG.

5.2. Proposed approach implementation

The developed optimization model for the CESS presented in this paper considers the dynamic nature of MG operations, enabling real-time adjustments in energy dispatch and storage in response to grid conditions and demand fluctuations. The resemblance of CESS to conventional storage elements and the adaptability inherent in our proposed methodology align closely with the flexibility requirements highlighted in IEEE 2030.7. This ensures the seamless interfacing of our approach with MG tertiary control systems. This method can be implemented by using open and standardized communication interfaces, as specified in IEEE 2030.7, facilitating the exchange of data and control signals with the tertiary control system. The following section presents a practical case study to demonstrate the effectiveness of the proposed CESS as a VESS in more details.

6. Case study

In order to verify the effectiveness of the proposed optimization model for energy management of a MG in the presence of the CESS, this paper takes a practical test system of an island in Finland for case study. Finland is one of the world leaders in the use of RESs. Fig. 8 shows the total solar and wind electricity generation capacity in this country from 2016 to 2022 [59,60]. As can be seen in this figure, the capacity of solar and wind generation has increased rapidly in recent years.

Finland has many islands that are transitioning to 100 % renewable energy supply; however, MOs in these islands face high seasonal variation in renewable generation and energy consumption due to the maritime and continental climate of these regions, which has led to some challenges such as excessive renewable energy and energy curtailment. The real-world network data for one of these islands are considered as a case study for this paper. The tested MG system is shown in Fig. 6. This case study includes three subsections as follow: optimization parameters, optimization results, and discussion. The following subsection presents the simulation parameters, and the later one discusses the results.

6.1. Optimization parameters

The simulated MG under study consists of 50 households which are supplied by generating units (solar, wind, and MT) and the main grid, as shown in Fig. 6 [58]. The general parameters of the MT, WT, PV, and BESS are presented in Table 2 and Table 3. Furthermore, the characteristics of these units are also provided in [58].

The upper limit for electricity exchange between the main grid and the island is 100 MW [58]. The maximum power demand of the island is

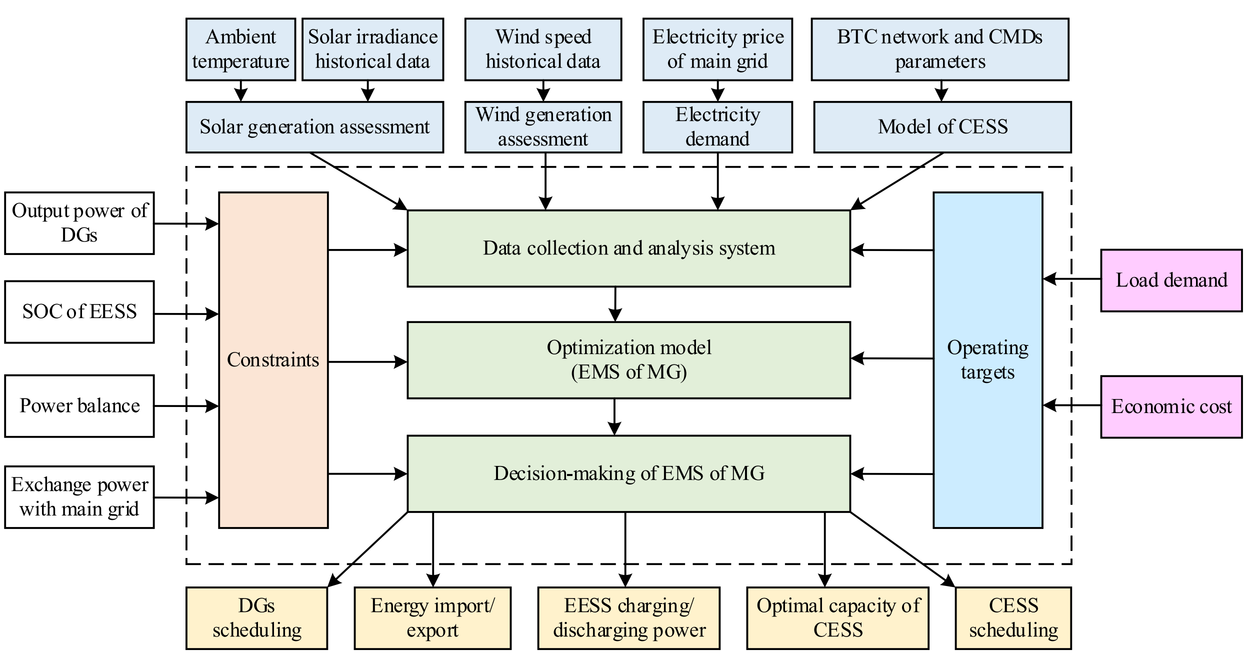

Fig. 7. Diagram of architecture of EMS in MG including CESS.

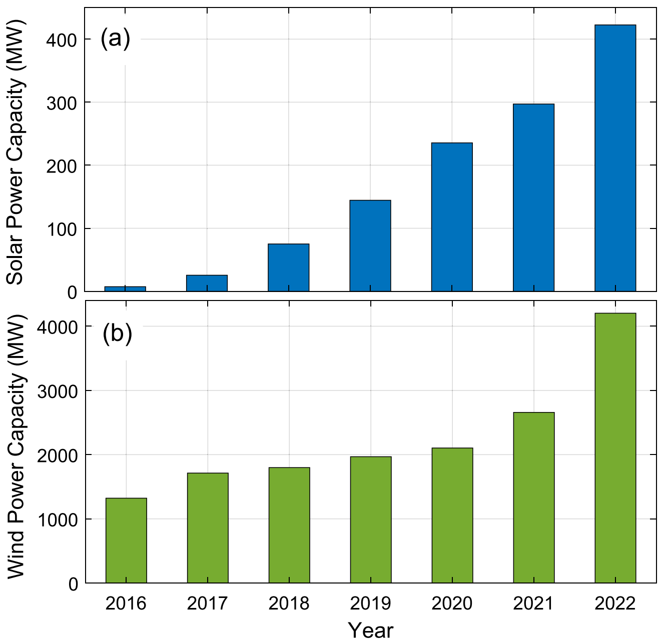

Fig. 8. Finland's renewable energy resources: a) solar generation, and b) wind generation [39,40].

Table 2
Parameters of MT, WT, and PV used in the case study.

Type	Cost coefficient ($/h)	Minimum – Maximum output power (kW)
MT	6	15–150
WT	0	0–400
PV	0	0–400

Table 3
Parameters of BESS used in the case study.

Type	Energy capacity (kWh)	Maximum charging/discharging rate (kW)	Efficiency (%)
BESS	200	60	90

375 MW, as stated in [58]. In this paper, the actual historical data including wind speed, solar radiation, energy consumption, and electricity price from January 2020 to December 2022 have been employed to evaluate the average corresponding parameters during different seasons of a year [59–63]. Figs. 9-11 show the normalized load profiles, electricity pricing patterns, and RESs generation for different seasons of the year, respectively. In Finland, in a typical case, the selling price of

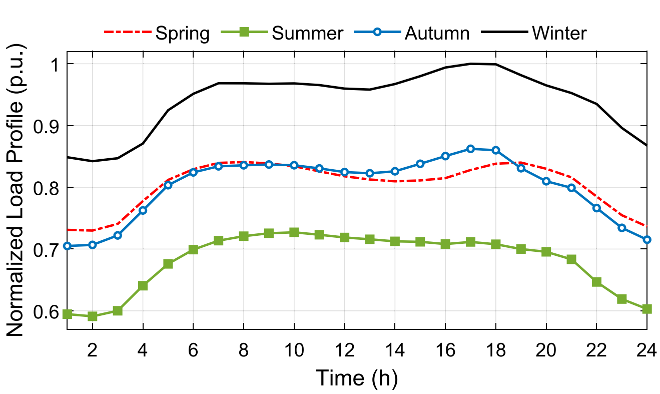

Fig. 9. 24-hour normalized load profile for different seasons of a year.

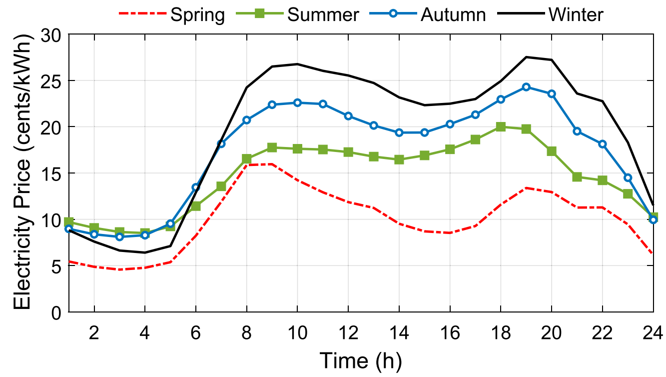

Fig. 10. Hourly electricity price for different seasons of a year.

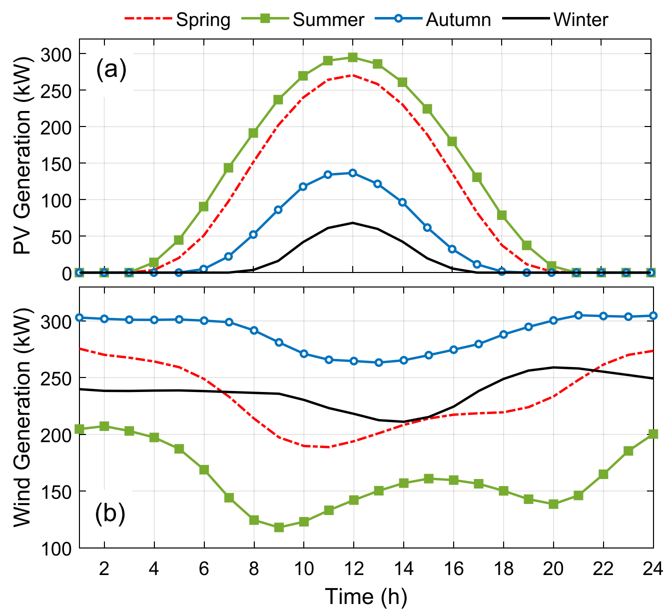

Fig. 11. Hourly RESs generation for different seasons of a year: a) PV output, and b) WT output.

electricity to the main grid is assumed to be one-third of the purchase price of electricity from it [64]. In this paper, *Antminer S19j* miner has been selected for the case study. The hash rate, power consumption, efficiency, purchase price, and the useful life of this CMD, at the time of this study, are 40 THash/s, 2.832 kW, 94 %, 2650 $, and 3 years, respectively [55]. In this paper, it is assumed that the depreciation cost of the CESS can be linearly divided over its useful life. The difficulty level, BTC price, and block reward are obtained from [56] over one year to calculate the average parameters of BTC network. Finally, according to the climate of Finland, the cooling factor of the CESS is assumed to be zero.

Based on the above data, the presented MILP optimization model for the MG is solved by Branch and Bound method to get the optimal scheduling results. The solving process is implemented with generalized algebraic modeling system (GAMS) software [65] installed on a computer of which the master frequency of CPU is 2.8 GHz and memory is 32 GB.

6.2. Optimization results

In order to validate the effectiveness of the optimal scheduling model for the MG considering the proposed CESS, the study conducts simulations for both islanded and grid-connected operations. These simulations explore scenarios with and without the integration of CESS, providing a comprehensive analysis of the system's performance under varying conditions. A specific case study presented in reference [58] serves as a benchmark for comparison, allowing for an evaluation of our proposed method against existing approaches. This comparative study aims to highlight the distinctive features and advantages of the proposed optimal scheduling model in enhancing MG operations with CESS as detailed below:

- Case I: the optimal scheduling of the islanded MG without considering the CESSs – case study from reference [58] (benchmark in islanded mode).
- Case II: the optimal scheduling of the grid-connected without considering the CESSs – case study from reference [58] (benchmark in grid-connected mode).
- Case III: the optimal scheduling of the islanded MG with considering the CESSs;
- Case VI: the optimal scheduling of the grid-connected MG with considering the CESSs.

In each case, according to the structure of the MG, some terms in the objective function and constraints are ignored. Then, simulations are performed in different seasons to obtain the optimal scheduling strategy. The above-mentioned cases are optimized for candidate days in the spring, summer, autumn, and winter. In order to calculate the annual values of the decision variables, the summation of their daily values over these candidate days are considered. Fig. 12 depicts the optimal scheduling results of case I (islanded MG without CESS) for different seasons.

As seen in this figure, in some hours (between 8 AM and 7 PM) in spring, summer and autumn, the power from the RESs is more than the demand. Therefore, after charging the BESS, the MO must curtail the excessive renewable energy. During the night hours in spring and summer, RESs do not provide power for the system and the DG is turned on. However, in the autumn, RESs can supply 100 % of the power demand, as shown in Fig. 12(c). In fact, the strategy of 100 % self-sufficient renewable energy for this island is established in the autumn season. But the winter power dispatch is quite dissimilar to the autumn, as shown in Fig. 12(d). For more details, Table 4 presents the numerical results of the MG optimal operation in this case for different seasons.

In this table, it is evident that the total annual curtailed renewable energy amounts to 190.8 MWh when the CESS is not considered. The MO can utilize CESSs to store this surplus energy in the CCU, subsequently employing it to offset the costs associated with energy production by the DGs during other periods. This concept will be further explored in cases where CESSs are available. Fig. 13 illustrates the optimal scheduling results for Case II, representing a grid-connected MG without CESS, across different seasons. As can be seen in this figure, in this case, the excessive renewable energy is exported to the main grid and the required energy is supplied from RESs and if not the main grid or DG provide the power. For more details, Table 5 shows the numerical results of the optimal operation of the MG.

Table 4
Numerical results of the proposed EMS in case I for different seasons.

Decision variable	Case I (islanded MG without CESS)			
	Spring	Summer	Autumn	Winter
DG generation (MWh)	20.0	37.8	0.0	220.9
Curtailment (MWh)	69.1	78.9	42.8	0
Annual curtailment (MWh)	190.8			

As shown in this table, the total annual curtailed renewable energy in a year is reduced from 190.8 in Case I to 10.3 MWh in Case II. In the following, the results of the optimal operation of the MG in the presence of the CESS are presented in two islanded and grid-connected cases. Fig. 14 shows the optimal scheduling results of case III (islanded MG with CESS) for different seasons.

As seen in this figure, during the hours in spring, summer, and autumn when excessive renewable energy is available, after charging the BESS, the rest of the surplus energy is stored by CESS in the CCU. In fact, at these periods, the CESS is in charging mode. Depending on the amount of the excessive energy, the capacity of the CESS can be optimized. In the rest of the times, when the demand is more than the generation of RESs, the CESS is discharged so that the MO can draw the required power from the main grid or DG. For more details, Table 6 presents the numerical results of the islanded MG optimal operation in the presence of the CESS for different seasons.

As seen in this table, the potential capacity of the CESS in the autumn season is higher than the other seasons due to the availability of excessive renewable energy, while the CESS does not charge or discharge in the winter season. The use of the CESS in this case has caused the curtailment of excessive energy to be reduced to 0.14 MWh. Fig. 15 shows the charging/discharging of the CESS and its state of charge. As can be seen in this figure, between 6 AM and 5 PM and 5 AM and 5 PM in spring and summer, the CESS is charging, and the SOC of this virtual storage is increasing, while the rest is discharging, and wallet

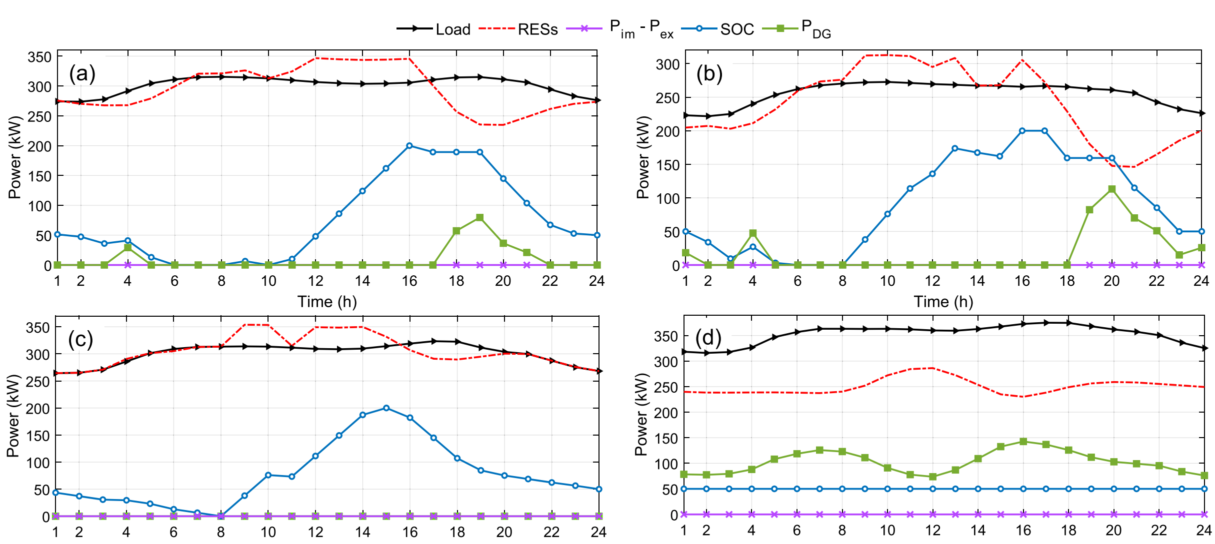

Fig. 12. Profile of power disspatch of the MG for different seasons in case I: a) spring, b) summer, c) autumn, and d) winter.

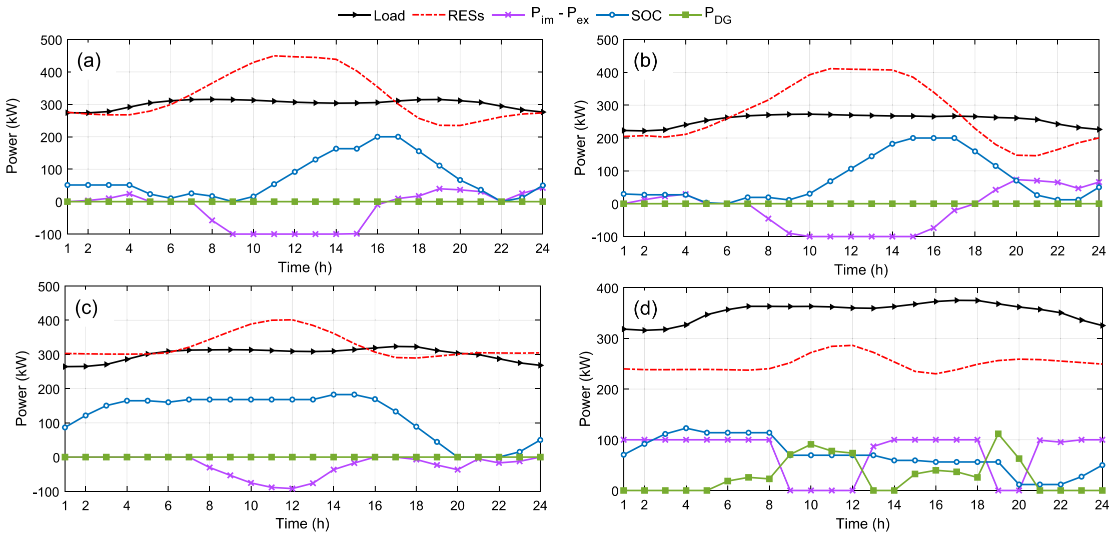

Fig. 13. The electrical power dispatch of the MG for different seasons in case II: a) spring, b) summer, c) autumn, and d) winter.

Table 5
Numerical results of the proposed EMS in case II for different seasons.

Decision variable	Case II (grid-connected MG without CESS)			
	Spring	Summer	Autumn	Winter
Imports (MWh)	21.6	38.4	0.0	160.3
Exports (MWh)	69.0	74.7	51.4	0.0
DG generation (MWh)	0.0	0	0.0	62.1
Curtailment (MWh)	3.2	7.1	0.0	0.0
Annual curtailment (MWh)	10.3			

balance is decreasing to import electricity from the main grid or generate energy from DG. This process is different in autumn and winter seasons. In autumn, the CESS is constantly in charging mode, but in winter, the CESS is not charging at all due to the decrease in electricity generation by the RESs and not having energy surplus.

Fig. 16 depicts the optimal scheduling results of case IV (grid-connected MG with CESS) for different seasons. As seen in this figure, it is economical for MO to store excessive renewable energy in CCU instead of selling it to the main grid and when the electricity price is very low, they can import electricity from the main grid to charge the CESS. This opportunity increases the CESS capacity in this case compared to case III.

For more details, Table 7 presents the numerical results of the optimal operation of the grid-connected MG in the presence of the CESS. As shown in this table, the CESS potential capacity increases in spring and autumn, but remains constant in autumn. The reason for this is that in the autumn season, more surplus renewable energy is expected than in the rest of the seasons. Also, using the CESS in this case has caused the curtailment of excessive renewable energy to be reduced to zero.

As shown in this table, the CESS potential capacity increases in spring and autumn, but remains constant in autumn. The reason for this is that in the autumn season, more surplus renewable energy is expected than in the rest of the seasons. Also, using the CESS in this case has caused the curtailment of excessive renewable energy to be reduced to zero. Table 8 summarizes the annual numerical results of the MG obtained for different proposed cases by introducing an annual cost/income analysis.

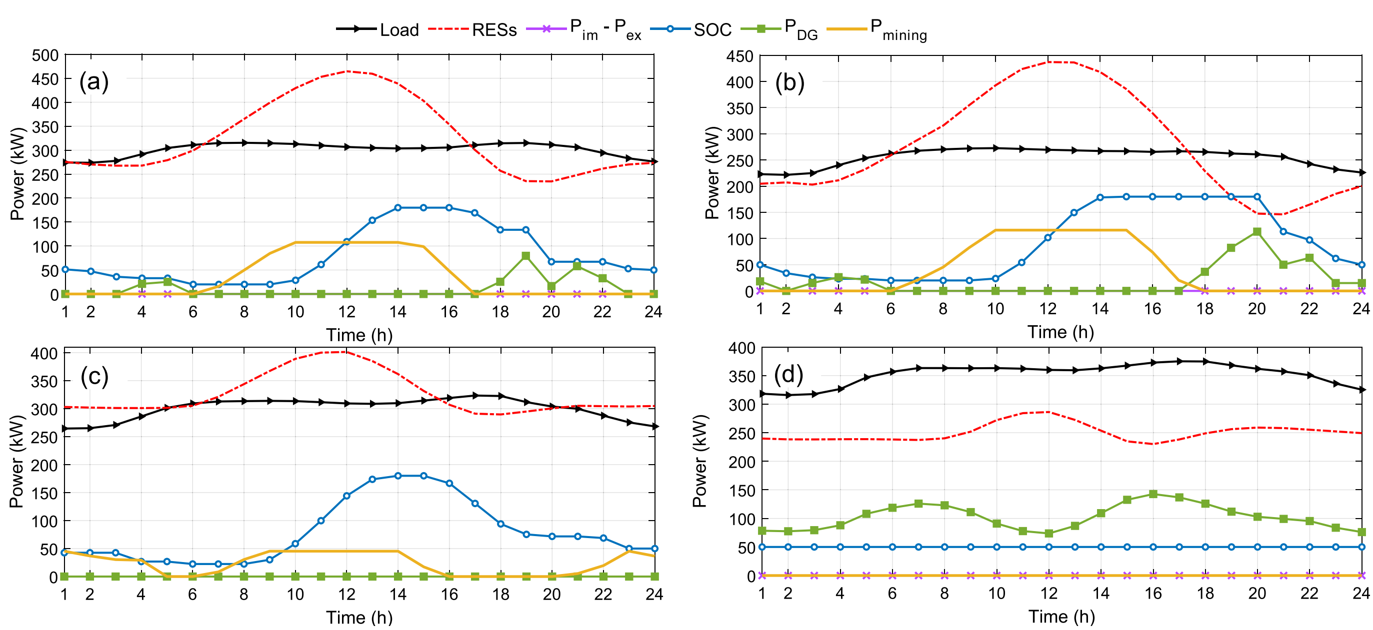

Fig. 14. The electrical power dispatch of the MG for different seasons in case III: a) spring, b) summer, c) autumn, and d) winter.

Table 6
Numerical results of the proposed EMS in case III for different seasons.

Decision variable	Case III (islanded MG with CESS)			
	Spring	Summer	Autumn	Winter
DG generation (MWh)	20.2	37.8	0.0	220.9
Curtailment (kWh)	137.7	0.0	0.0	0.0
Number of CMDs (#)	35.0	39	13	0.0
Investment of CMDs ($)	7623.0	8496.0	2835.0	0.0
CESS charging ($)	13725.0	15633.0	9792.0	0.0
CESS discharging ($)	5049.0	9468.0	0	0.0
Annual curtailment (MWh)	0.14			

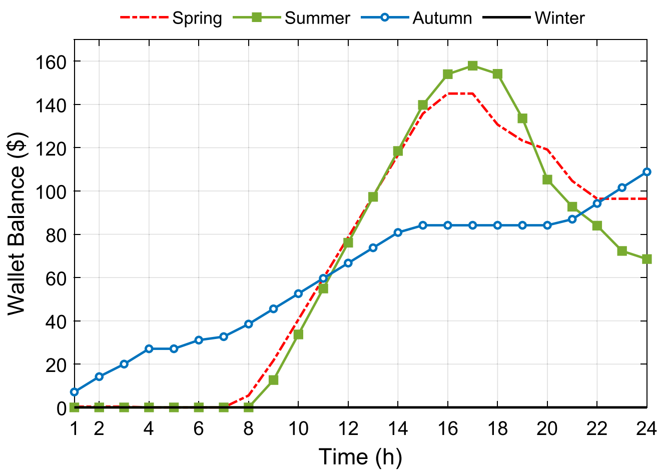

Fig. 15. Wallet balance of the CESS for different seasons in case III: a) spring, b) summer, c) autumn, and d) winter.

In this table, the first two rows present the annual investment cost and income of the CESS due to its optimal capacity for each case, respectively. The next two rows are related to the annual total cost and income of the MG. The sixth row of the table presents the annual total cost of the MG minus its income. Finally, the last row reports the economic index of return on investment (ROI) as a popular profitability metric to evaluate how well the CESS investment has performed. In this paper, the ROI index is defined by dividing the total benefit gained from employing CESSs by their initial investment. It should be noted that in order to compare the operating costs of the MG, two cases with and without considering the CESS should be considered for the same network mode (islanded or grid-connected). By doing so it can be observed that the CESS can reduce the operating cost of the MG in both islanded and grid-connected cases. From the MO's perspective, case III yields 7.4 % cost savings compared to case I. Similarity, case IV awards 46.5 % cost savings compared to case II. As shown in this table, by employing CESS in the operation of the islanded and grid-connected MG, the ROI indices for this CESS are calculated as 44.2 and 51.6, respectively. In fact, with considering this VESS in the energy management of

Table 7
Numerical results of the proposed EMS in case IV for different seasons.

Decision variable	Case IV (grid-connected MG with CESS)			
	Spring	Summer	Autumn	Winter
Imports (MWh)	158.9	134.4	73.2	160.3
Exports (kWh)	0.0	348.3	0.0	0.0
DG generation (MWh)	0.0	0.0	0.0	62.2
Curtailment (kWh)	0.0	0.0	0.0	0.0
Number of CMDs (#)	41	39	27	0.0
Investment of CMDs ($)	8928.0	8496.0	5886.0	0.0
CESS charging ($)	40662.0	34290.0	24012.0	0.0
CESS discharging ($)	14445.0	17370.0	8541.0	0.0
Annual curtailment (MWh)	0			

Table 8
Comparison of results for different cases.

Expected decision variable	Case I	Case II	Case III	Case IV
Annual investment of CESS ($)	0.0	0.0	34450.0	36217.0
Annual revenue of CESS ($)	0.0	0.0	39698.0	100340.0
Annual cost of MG ($)	70692.0	51018.0	95168.0	121850.0
Annual income of MG ($)	0.0	10821.0	39698.0	100340.0
Total Annual cost minus income ($)	70692.0	40197.0	65470.0	21510.0
Return on investment (%)	–	–	44.2	51.6

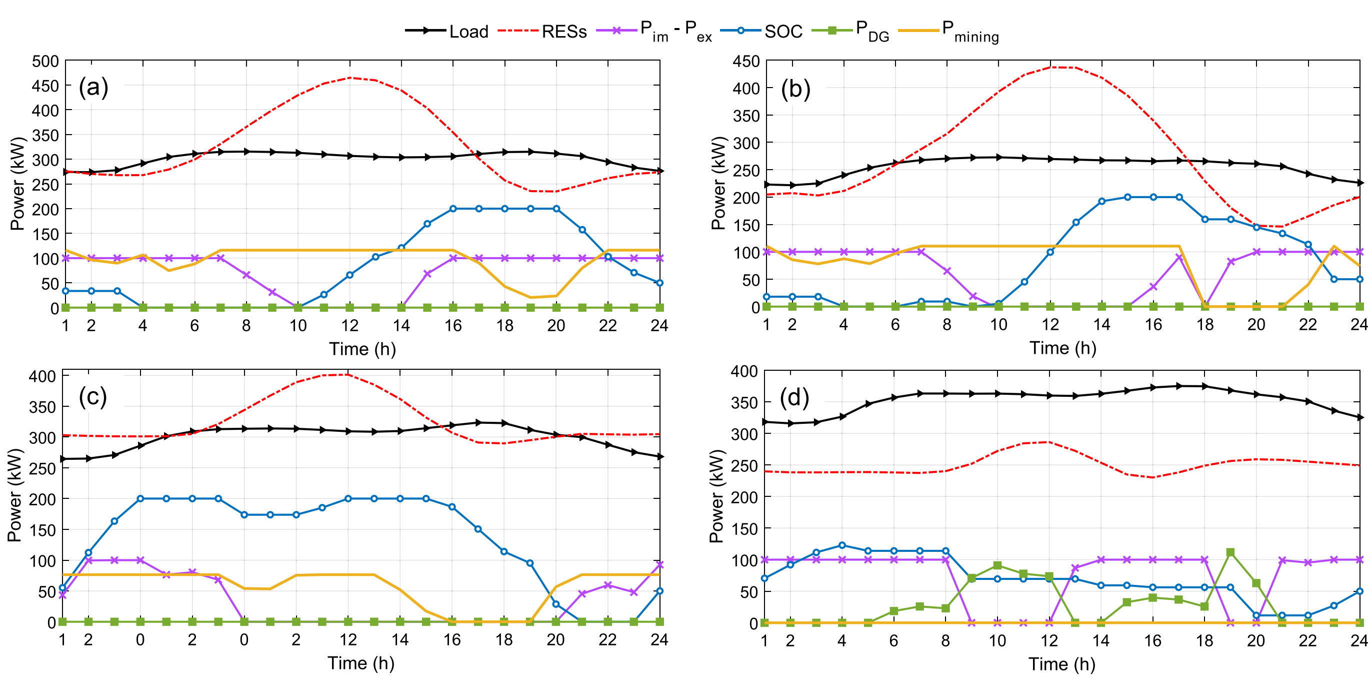

Fig. 16. The electrical power dispatch of the MG for different seasons in case IV: a) spring, b) summer, c) autumn, and d) winter.

the MGs, in addition to a decrease in the operating cost and renewable energy curtailment, MOs' investment in business can have a shortened payback period.

6.3. Discussion

The correlation between excessive renewable energy and the power of CMLs is an integral to the comprehension of the potential of CESSs. In Fig. 17(a), monthly variations in the excessive renewable energy within the MG, often generated during peak renewable production periods are evident. This surplus energy, challenging for conventional EESSs and daily peak shaving systems, plays a role in the monthly energy consumption patterns of CMLs, as depicted in Fig. 17(b).

The symbiotic relationship between cryptocurrency mining and excessive renewable energy lays the groundwork for the unique capabilities of CESS. Unlike the traditional EESSs which are optimized for short-term use, CESS efficiently harnesses and stores energy over extended periods, presenting an innovative solution for long-term energy storage needs. To expand the importance of these capabilities, a discussion is presented on the effectiveness of monthly peak shaving. A comparative analysis using a cumulative cost scenario over a year reveals intriguing insights, as shown in Fig. 18.

In Case II, where the grid-connected MG operates without CMLs as VESSs, the cost steadily increases over time. However, in Case IV, leveraging the proposed CESS, the cumulative cost trajectory takes a different path. The CESS strategically stores or charges excessive renewable energy in cryptocurrency values during high-generation months (such as summer and autumn) and subsequently discharges it in other months, acting as a long-duration discharge solution. This dynamic approach leads to a substantial reduction in the overall cost of the MG, marking a significant departure from conventional cost trends. The prolonged discharge time of the CESS proves instrumental in optimizing RESs utilization and economically benefiting the MG throughout the year. The CESS effectively manages the non-simultaneity between renewable energy generation and demand consumption, even during monthly/seasonal variations. Its capability to store excess renewable energy as the developed cryptocurrency for consumption in another period underscores its potential as an efficient and cost-effective solution for energy management within the MG, particularly in the presence of high penetration of RESs. In fact, the CESS's ability to facilitate monthly/seasonal generation and consumption shifts, or monthly/seasonal peak shaving, not only results in economic savings but also will be align with the broader goals of sustainable energy practices, promoting a more resilient and adaptive energy infrastructure. This innovative approach toward energy storage and energy management has the potential to reshape the dynamics of MG operations and pave the way for more efficient and environmentally conscious energy utilization on a broader scale.

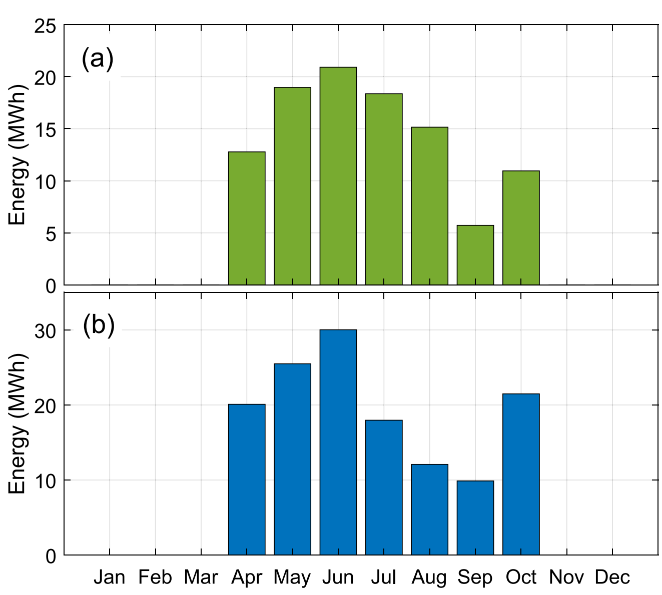

Fig. 17. Monthy energy: a) monthly excessive renewable energy in the MG, and b) monthly energy consumption of the CML.

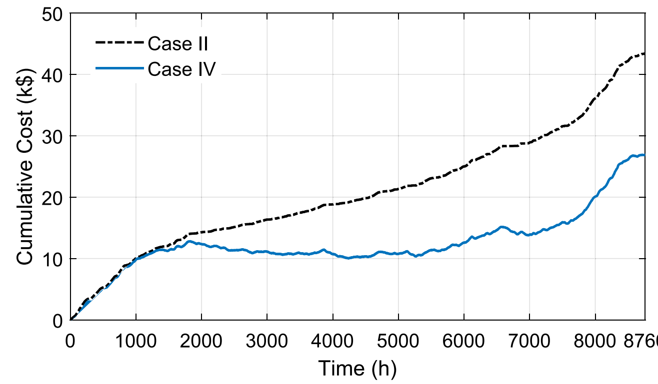

Fig. 18. The cumulative cost of the MG over a year in Cases II and IV.

One crucial distinction between CESS and conventional EESSs is the significant difference in discharge times. Conventional EESSs are typically optimized for short-term use, enabling quick releases of stored energy for daily peak shaving. These systems excel in addressing immediate energy demands but may struggle to provide sustained power over extended periods. On the other hand, CESS stands out due to its long-duration discharge capability, making it well-suited for meeting long-term energy needs and providing a flexible and adaptive solution for optimizing energy utilization within MGs. This adaptability feature, makes CESS as a valuable asset in the process of transition towards sustainable and economically viable energy systems.

7. Summary and conclusion

The global efforts to reduce the climate change negative effects have caused the shift of power generation to low-carbon RESs such as wind and solar energy in the planning and operation of the power systems. Transitioning to such variable RESs brings economic and technical challenges such as high investment cost and curtailment of the excessive renewable energy. These challenges can be addressed by employing flexible load and conventional EESSs such as BESSs; however, the values of these solutions are limited in some countries due to the high seasonal variation of energy consumption and generation. In this paper, an energy management framework of the MG by introducing cryptocurrency mining as novel VESSs to present the opportunity to reduce the renewable energy curtailment and minimize the operating cost of the MG, has been investigated. This concept allows MOs to store excessive renewable energy by CESSs in CCUs in off-peak times, and conversely, to discharge in the high-demand period. Using both islanded and grid-connected MG as practical case studies in Finland, it has been demonstrated that employing the VESSs in the operation of the islanded and grid-connected MG will result in sufficient decrease in the operating cost of the MG: i.e., about 7.4 % and 46.5 %, respectively.

CRediT authorship contribution statement

Mehran Hajiaghapour-Moghimi: Conceptualization, Methodology, Software, Visualization, Writing – original draft. **Ehsan Hajipour:** Conceptualization, Methodology, Software, Visualization, Writing – review & editing. **Kamyar Azimi Hosseini:** Conceptualization, Methodology, Writing – review & editing. **Mehdi Vakilian:** Methodology, Project administration, Supervision, Writing – review & editing. **Matti Lehtonen:** Methodology, Project administration, Supervision, Writing – review & editing.

Declaration of competing interest

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

Data availability

Data will be made available on request.

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