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Analysing the Sustainability Effects of Using Energy Storage Solutions at Eco-industrial Parks

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The importance of energy storage is increasing to enhance the efficiency of energy grids and integrate renewable energy sources. This is particularly relevant for micro-communities that rely on decentralized energy sources and grids for part of their energy supply. Examples of such communities include internally settled electricity communities (ECs) and eco-industrial parks (EIPs). EIPs are industrial sites that operate according to the principles of industrial symbiosis (IS), prioritizing resource management and environmental stewardship by optimizing material and energy exchange networks.
Industrial parks structured along the principles of industrial symbiosis often depend on renewable energy sources. Energy storage stabilizes renewable energy production and ensures the flexibility of energy supply. Energy storage enables ECs and EIPs to operate more energy-efficiently, facilitates the asynchronous mitigation of demand and capacity, reduces peak-period consumption and can also serve as a backup power source during emergencies.
The aim of this article is to present an overview of the role and significance of energy storage in energy-communities and EIPs, underscore the potential for self-consumption of locally generated renewable energy, optimize the utilization of exchange connections, and provide an analysis of international research and industrial practices in this field. The literature review in this paper shows that energy storage and battery management play a key role in the optimal operation of ECs and in maximizing self-consumption, i.e. minimizing the load on the grid, and therefore minimizing the grid-wide sustainability effects.

1. Introduction

Many nations have established ambitious goals to boost the proportion of renewable energy in their power mix. These targets aim to cut greenhouse gas emissions, enhance energy security, and decrease dependency on external energy sources. The European Commission's 2050 Roadmap (2011) outlines a vision for a sustainable future, achievable through the adoption of renewable energy and the gradual electrification of various services. However, this vision presents significant challenges for current electricity grids, which are traditionally designed to maintain a constant balance between supply and demand.
Traditionally, the balance in electricity grids has been maintained by centralized, quick-start power plants capable of scaling up and regulating output as needed. However, the unpredictable nature of intermittent renewable energy sources, combined with rising peak loads due to the electrification of services, places significant strain on the grid. This situation necessitates greater power reserves to swiftly respond to dynamic fluctuations in demand (Bartolini et al., 2020).
An MIT study (Comodi and Rossi, 2016), based on data from 2005-2009, shows that peak power plants are no longer a sustainable solution. The study shows that in New England and Washington states, national energy demand exceeded 70 % of its peak for only about 1,000 h/y, leaving more than 30 % of installed capacity in use less than 12 % of the time. Apart from environmental considerations, this trend is also making peak power plants less and less attractive from an economic point of view. The smart grid paradigm suggests that this problem should be addressed by increasing the flexibility of the power grid, using data and information technology and

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remote coordination of distributed generation and storage technologies (decentralised supply, energy communities, eco-industrial parks) so that they can actively respond to changing grid conditions.
Especially the so-called multi-energy districts, as eco-industrial parks can be understood, which leverage advanced integration of energy storage technologies and polygeneration systems, are currently garnering significant interest from both research and industrial sectors. By utilizing these technologies, smart districts aim to better manage fluctuations in local energy demand, enhance service reliability, and optimize the use of local renewable energy sources.
The role of energy storage in local communities and micro-grids has been extensively studied. For instance, Wang et al. (2018) explored the impact of heat storage and intelligent asset management within a community energy system. Hafiz et al. (2019) used stochastic programming to determine the optimal size of a community-serving storage system, considering various management strategies and uncertainty assessments. Additionally, Barbour et al. (2018) discovered that installing batteries in areas with high PV penetration is more efficient at the community level compared to individual consumers.
All these scientific efforts and their results can be put to excellent use in the design and optimal operation of internal electricity transmission and accounting systems in eco-industrial parks.
The aim of this review article is to assess the impact of various energy storage solutions on energy community systems and eco-industrial parks. This review is necessary because there is currently no comprehensive model for the optimal integration of energy storage solutions into the grid. The findings from this review will serve as input parameters for a complex optimization method with multiple objective functions in the next phase of the research.

2. The role of energy-communities in the energy policy of the European Union

The energy community is a legislative and policy tool designed to empower EU citizens to actively engage in the clean energy transition, as endorsed by the Clean Energy Package (CEP) (Nouicer et al., 2020). The CEP comprises eight regulations and directives aimed at shaping EU energy policy, with overarching goals of reducing greenhouse gas emissions by 40 % by 2030, improving energy efficiency by 32.5 %, and ensuring that 32 % of electricity consumption comes from renewable energy sources (RES) within the same timeframe.
The recently adopted "Fit for 55" package of legislative proposals (European Commission, 2021) and the EU Green Deal package (European Commission, 2019) aim to further develop these allocations by increasing the RED II (European Parliament Directive, 2018) 2030 renewable energy target from 32 % to 40 % of the EU's energy mix, roughly doubling the level of 19.7 % in 2019. As regards energy demand in buildings, the Commission proposes an indicative target of at least 49 % coming from renewable energy sources by 2030; To achieve this goal, the use of renewable electricity, heat pumps, solar heat and district heating needs to be sharply increased. More specifically, Directive 2019/944 (European Parliament Directive, 2019) contains common rules for the internal electricity market that make it easier for citizens to actively interact with the fork energy system and improve the inclusion of energy communities. Such market participation may relate to the generation, consumption, sharing or sale of electricity and to the provision of flexibility services through demand response and storage.

3. The role of energy storage in ECs and EIPs

The rise of decentralised energy production is creating a new energy ecosystem that poses a tangible threat to the grid, relying on it as a virtually cheap storage mechanism. One emerging framework that tries to address this problem is energy sharing in community microgrids, such as ECs and EIPs. In this framework, facilities make more efficient use of energy resources through complementary demand profiles and shared energy storage, reducing the number of grid interactions.
In a study, Vindel et al. (2019) present a one-year discrete-time simulation model of 40 residential and non-residential buildings and investigate the impact of community energy exchanges and shared storage on grid interactions. Their results show that when sharing is allowed, buildings with energy storage achieve a 9.5 % reduction in grid interactions. In addition, month-to-month analysis shows that annual patterns in generation dramatically affect the benefits of energy sharing. The reduction in grid utilisation ranged from 20 % during periods of high energy surplus (e.g. summer) to 5 % during periods of low generation (e.g. winter).
Battery Energy Storage System (BESS) within the Renewable Energy Community (REC) requires specific control and optimisation algorithms. This is particularly true for RECs that include source-side photovoltaic generation, electrochemical storage, and non-constrained loads. Talluri et al. (2021) propose a BESS control strategy to solve this problem, which consists of three different modules:

1. A machine learning-based forecasting algorithm that generates a one-day forecast for microgrid loads and PV generation using historical data and weather forecasts,

2. A Mixed-integer Linear Programming (MILP) algorithm that optimizes the scheduling of BESS for minimum REC operating costs, taking into account electricity prices, variable feed-in tariffs for PV generators, BESS costs and maximizing self-consumption,
3. Decision tree algorithm that works on an hourly, one-minute time step and real load and PV generation measurements and adjusts the BESS schedule in real time.

3.1 Machine learning for battery energy storage systems

BESS often requires an algorithmic approach both for accurate modelling and for optimal management of the modes. As far as modelling is concerned, although there are several equivalent circuit models available in the literature (Corti et al., 2021), practical applications are often faced with the task of accurately estimating the state of charge and state of health of the battery. Indeed, the whole system is highly nonlinear and affected by losses that have to be taken into account at all stages of the energy conversion.

Henri and Lu (2019) propose a comparison of different techniques (neural network, support vector machine, logistic regression and random forest algorithms) for optimal scheduling of BESS in real-time, usually coupled with higher level network optimization).

Management systems are based on knowledge of a wide range of electrical, environmental and economic parameters. The knowledge of these quantities is often limited to historical values, which is why Machine Learning (ML) based forecasting techniques are often proposed in the literature. Sheha and Powell (2019) propose proactive forecasting of the energy demand of an entire city, to be incorporated into an intelligent management system for energy storage and flexible loads.

3.2 Managing community energy storage using MILP techniques

From a technical point of view, ECs, RECs and EIPs can be considered as real or virtual microgrids consisting of controllable and non-controllable consumers, renewable energy sources and possibly energy storage facilities, including BESSs, connected to the main grid. A proper power and energy management system is essential to optimise the use of community assets and is the subject of significant ongoing research.

Malysz et al. (2014) proposed an optimal control method based on MILP optimization for operating a BESS in a grid-connected electric microgrid, aiming at minimizing the operating cost and shaping the demand profile. Elkazaz et al. (2018) investigate the optimization of BESS scheduling using MILP technique to increase the self-consumption of renewable energy sources, while the main objectives of the multi-objective optimization performed by Jung et al. were cost and emission reduction (Jung et al., 2020).

Talluri et al. (2021) considered a small REC consisting of five households, a PV system and a BESS, modelled as non-regulated consumers. The PV system and the BESS were modelled as a single integrated system, owned by one of the five households, thus configured as a prosumer, while the other four are simple consumers. The BESS can only be charged with the energy produced by the PV system, while can be discharged both by the consumers and the grid. The discharge to the grid is only allowed if the load of the consumers is already covered, either by the PV system or by the BESS. These restrictions reflect the existing legal framework for the use of BESS in grid-connected applications (d'Halluin et al., 2020).

To evaluate the performance of the proposed REC management algorithms, the results were compared with those obtained in two other different scenarios: (a) a "baseline" scenario, representing a REC without BESS and no management, and (b) a "BESS without MILP" scenario, where battery storage is installed in the REC but neither generation and load forecasting nor battery management is applied; only basic occasional charging is enabled.

The Table 1 shows the average of the main results, in terms of energy exchanges within the REC and with the grid, total BESS consumption and finally the revenues distributed among REC participants.

On average, the availability of a 1 kWh/0.5 kW BESS REC as a device increases residential self-consumption by 18%, and the optimal scheduling method results in an increase of 21.4 %. Overall, the average energy exchange within the REC and with the grid is not significantly affected by the installation of a BESS. In any case, the optimal scheduling allows such exchanges to be better distributed throughout the day, synchronizing them with the electricity price trends predicted for the day in the market. This in turn results in a 45-47 % revenue increase for REC customers; for consumers, the revenue increase is 10% without optimization and 17.8 % with MILP-based optimization.

These different behaviours are related to the fact that on the customer side, revenues are based only on the amount of energy shared and the fixed incentive. Instead, prosumer revenues also take into account PV electricity sales in the market, which are naturally influenced by the timing of grid feed-in and avoided purchase costs associated with self-consumption (Talluri et al., 2021).

Table 1: Main techno-economic results of the analysis

	Baseline	BESS-NO MILP	BESS-MILP
Total REC demand (MWh)		13.03	
Prosumer demand (MWh)		2.606 (1.296-5.323)	
Other REC members demand (MWh)		10.424 (7.707-11.734)	
PV generation (MWh)		6.744	
Prosumer self-consumption (MWh)	1.157 (0.628-2.293)	1.367 (0.78-2.613)	1.405 (0.749-2.605)
Shared energy within REC (MWh)	3.211 (2.074-3.738)	3.35 (2.15-4.05)	3.29 (2.074-3.922)
Exports to grid (MWh)	2.376	2.41	2.37
Imports from grid (MWh)	8.662	8.43	8.412
Total BESS use-capacity: 1 kWh, power 0.5 kW	-	0,772 (0.714-0.836)	0.496 (0.242-0.625)
REC yearly revenues (€/y)	733 (595-819)	806 (733-884)	859 (671-947)
Prosumer revenues (€/y)	574 (493-636)	576 (564-625)	627 (495-687)
Other REC members tot. rev. (€/y)	158 (102-184)	230 (169-259)	232 (176-260)

3.3 Hierarchical governance approach

Nagpal et al. (2022) propose a hierarchical approach to optimise the operation of Local Energy Communities (LECs) that integrate energy storage. In their work, they present a two-stage hierarchical energy management framework for LECs, guided by the minimisation of end-user costs in the first stage and the maximisation of LEC self-supply and self-consumption in the second stage.

The following figure shows the scheme of the modelled LEC and its components. The buildings are connected to a common energy storage system, namely the CES, and to the main energy grid via AC transmission lines.

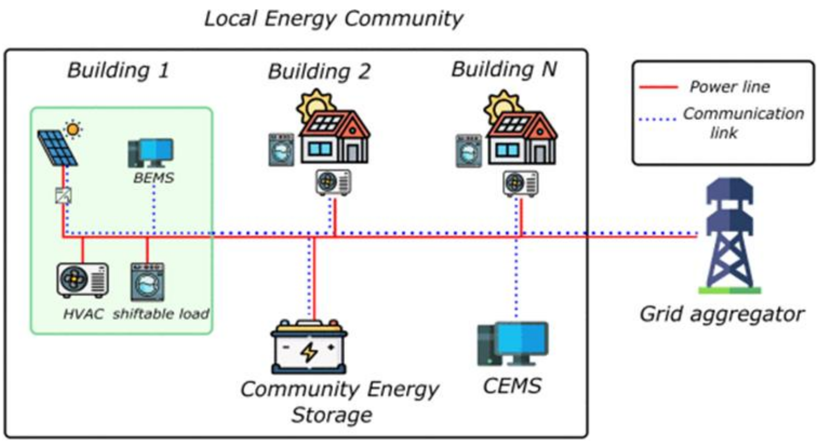

Figure 1: Structure of the modelled local energy community (Nagpal et al., 2022)

The performance of the two-step hierarchical strategy used was found to be consistent and effectively independent of the number of buildings in the LEC, paving the way for large-scale extension to real-world cases, e.g. eco-industrial parks. The technique to quantify the available resilience of buildings has proven remarkably easy to use and provides the network aggregator with a practical tool to manage and maintain resilience in real time. This has provided significant monetary benefits to end-users, either by directly providing load resilience or by sharing a corresponding share of storage capacity (Nagpal et al., 2022).

4. The importance of hydrogen in ECs and EIPs

A number of local systems have been analysed in the literature, but little effort has been made to investigate the role that hydrogen, in particular low-temperature water electrolysis and power-to-gas (P2G), can play in facilitating the large-scale deployment of renewable energy sources.

Several models have been developed for power-to-gas analysis, and here we present the results of an analysis based on an open dataset of consumption data from a micro-community in Austin, USA (Bartolini et al., 2020). The scenarios analysed aim to explore the technological options that would allow an eco-industrial park to meet the objective of accommodating a large share of non-regulated renewable electricity generation through distributed energy systems with less burden on the local distribution infrastructure. The two scenarios considered are:

- Scenario 1: availability of several decentralised conversion (e.g. natural gas CHP, heat pumps, fuel cells) and storage (electric, thermal, hydrogen) technologies. This scenario also takes into account the possibility of feeding a mixture of natural gas and hydrogen into the gas engine, with a limitation on the maximum hydrogen content of the mixture (15 V%).
- Scenario 2: The only available technology to address the surplus of renewable energy generation is lithium-ion battery electricity storage systems, which is the technology generally proposed to address the high share of renewable electricity at the micro-community level. The purpose of this is to compare the costs of the approach to surplus energy systems from Scenario 1.

The results of the model run for the two scenarios led to the following conclusions (Bartolini et al., 2020):

1. P2G (power-to-gas) combined with polygeneration is a viable solution for renewable energy storage.
2. The cost-effective optimal solution consists of cogeneration, electrochemical electricity and hydrogen storage.
3. Using only batteries is currently too costly to store excess renewable energy in a micro-community.
4. The batteries are more efficient than the P2G solution due to significantly higher overall system efficiency: electrochemical storage: 90 %, P2G storage: 23 %.
5. Synergies between central energy networks and decentralised energy production can reduce the power ramp.

5. Conclusion

This article aims to highlight the importance of energy storage in energy communities and eco-industrial parks. It analyses international research and practices in this field and provides insights into the growing acceptance of energy storage in European energy communities. Energy storage is crucial for enhancing energy grid efficiency and integrating renewable sources, especially in decentralised systems like eco-industrial parks that prioritise resource management and environmental sustainability. Energy storage stabilises production and provides flexibility, reducing supply fluctuations and balancing demand in EIPs. As a consequence, industrial parks can lower energy costs and improve competitiveness by operating more efficiently and reducing peak consumption. Storage systems also serve as backups during emergencies, enhancing reliability. Shared energy storage facilitates efficient resource use and reduces grid interactions in EIPs, leading to significant reductions in energy costs and, for EIPs integrating renewable energy sources, their environmental footprint. Due to these features, energy storage plays a crucial role in enhancing the sustainability of energy communities and facilitating the green transition of the energy sector. Improved efficiency and the establishment of optimal operating conditions also help in minimising the environmental impact.

A selection of key sources supporting the analysis is provided, emphasising the importance of advanced algorithms in controlling modern energy systems. The literature reviewed in this paper shows that energy storage modelling and battery management play a key role in the optimal operation of ECs and in maximising self-consumption, i.e. minimising the load on the grid, and minimising the grid-wide sustainability effects.

For EIPs, however, it is recommended to develop optimisation for multiple objective functions and to include more energy types besides electricity in the internal energy exchange system to enforce principles of industrial symbiosis, significantly reducing resource use, waste generation, waste energy flows and, through this, better integrating the energy efficiency and renewable energy related activities into the whole system design supporting the reduction of the environmental impact of industrial parks. This review clarifies the impact of energy storage options in eco-industrial parks. The findings from this research can be effectively used in subsequent research phases to model and optimise energy use in these parks.

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