LAPPEENRANTA-LAHTI UNIVERSITY OF TECHNOLOGY LUT

Mikko Nykyri

PROMOTING LOCAL RENEWABLE ENERGY PRODUCTION WITH ENERGY COMMUNITIES AND SERIOUS GAMES

ACTA UNIVERSITATIS LAPPEENRANTAENSIS 1125

Mikko Nykyri

PROMOTING LOCAL RENEWABLE ENERGY PRODUCTION WITH ENERGY COMMUNITIES AND SERIOUS GAMES

Dissertation for the degree of Doctor of Science (Technology) to be presented with due permission for public examination and criticism in the Auditorium 1318 at Lappeenranta–Lahti University of Technology LUT, Lappeenranta, Finland on the 26th of January, 2024, at noon.

Acta Universitatis
Lappeenrantaensis 1125

Supervisors Professor Pertti Silventoinen
LUT School of Energy Systems
Lappeenranta–Lahti University of Technology LUT
Finland

Dr. Salla Annala
LUT School of Energy Systems
Lappeenranta–Lahti University of Technology LUT
Finland

Reviewers Professor Pertti Järventausta
Faculty of Information Technology and Communication Sciences
Electrical Engineering
Tampere University
Finland

Dr. Antonio Bucchiarone
Motivational Digital Systems
Fondazione Bruno Kessler
Italy

Opponent Professor Matti Lehtonen
Department of Electrical Engineering and Automation
Aalto University
Finland

ISBN 978-952-412-051-7
ISBN 978-952-412-052-4 (PDF)
ISSN 1456-4491 (Print)
ISSN 2814-5518 (Online)

Lappeenranta–Lahti University of Technology LUT
LUT University Press 2024

Abstract

Mikko Nykyri
Promoting Local Renewable Energy Production With Energy Communities and Serious Games
Lappeenranta 2024
76 pages
Acta Universitatis Lappeenrantaensis 1125
Diss. Lappeenranta–Lahti University of Technology LUT
ISBN 978-952-412-051-7, ISBN 978-952-412-052-4 (PDF), ISSN 1456-4491 (Print), ISSN 2814-5518 (Online)

Local, small-scale energy production with renewable energy like solar energy is becoming more and more commonplace as people seek methods to reduce their reliance on grid energy. Besides individual households investing in a solar installation, co-owned installations are also raising interest. They can provide locally produced affordable energy for multiple households while allowing the initial investment to be shared, which reduces the financial burden.

However, implementing shared installations imposes a unique set of problems to be solved in order to use them efficiently. The current energy distribution infrastructure may cause a situation where it is not economically viable to provide the produced energy directly for the installation owners but only to power any common property they own. Solutions for this exist, but they are not ideal as in many cases they require the implementation of an energy aggregator to govern this energy allocation, which may lead the installation owners to lose their place in the open retail electricity market. In some solutions, the allocation is based on active participation in, e.g., energy auctioning, which can be considered troublesome since many laypeople find concepts regarding energy and electricity difficult to grasp.

This dissertation presents a solution for energy allocation that is based on formation of an energy community and utilization of a blockchain-based balance settlement ledger. The blockchain allows for a secure and immutable data storage system that can be used to store the energy consumption and production data of the energy community. A blockchain is also able to automatically perform the energy allocation by using smart contracts. This makes it possible to remove the energy aggregator altogether, resulting in the installation owners maintaining their position in the open retail electricity market.

Although the blockchain-based balance settlement and energy allocation are effortless for residents to take part in, people need to understand how the electrical system works and what affects their energy consumption, allocated amount of energy, and the cost of the energy used. For this, serious gaming is proposed as a means to teach people how the system works. With a serious game, the players can experiment on how their actions change the outcome of the system, which can be a viable way to promote demand response. For this purpose, a prototype serious game is developed and its design process is discussed.

To promote the rollout of local renewable production, the threshold of making the decision to invest in the system has to be minimized. This requires solutions that can be implemented without major infrastructural changes in the distribution system. The arrangements should be as easy to understand as possible to make them appealing to the people.

Keywords: solar energy, energy community, demand response, serious games, gamification, blockchain

Acknowledgments

The research work of this dissertation was carried out at the LUT School of Energy Systems at Lappeenranta–Lahti University of Technology LUT, Finland, between 2019 and 2023. As a junior researcher with the Laboratory of Applied Electronics, my research activities eventually focused on energy communities and serious games and gamification.

I would like to express my sincere thanks to my supervisors Prof. Pertti Silventoinen and Dr. Salla Annala for your support. You have played a crucial role as a “catalyst” in the research by providing me with guidance and encouragement. I am also grateful to Prof. Pertti Järventausta and Dr. Antonio Bucchiarone for reviewing this work and giving valuable comments and suggestions to improve this dissertation.

A thank you to Lappeenrannan Energia Oy for providing the energy consumption data, which have been invaluable for the research of this dissertation. The financial support of the Walter Ahlström Foundation is also gratefully acknowledged.

I express my gratitude to Dr. Tommi Kärkkäinen for his contribution in the articles of this dissertation: working in your task force has been a delight. I would also like to extend my appreciation to all the other contributors of the articles presented in this dissertation: Prof. Samuli Honkapuro, Dr. Saku Levikari, and Dr. Johanna Naukkarinen: your support has been very valuable. In addition, I would like to thank all the other past or present merrymakers of Room 6405: Mr. Juuso Rautio, Mr. Janne Jäppinen, Ms. Katriina Korpinen, Dr. Juhamatti Korhonen, Dr. Heikki Järvisalo, and Mr. Lauri Tuimala. The working environment of this “pretty normal room” has provided an excellent counterbalance to the research work. Further, special thanks to Dr. Hanna Niemelä; your support in proofreading this dissertation and help in transforming it into proper English is highly appreciated.

Lastly, my thanks go to my family and friends for their support and interest in my studies and dissertation work. My special thanks are reserved for Linda for always encouraging me and making me to believe in myself.

Mikko Nykyri
December 2023
Lappeenranta, Finland

Contents

Abstract

Acknowledgments

Contents

List of publications 9

Nomenclature 11

1 Introduction 13
- 1.1 Prosumer electricity market 13
- 1.2 Serious games and gamification 16
- 1.3 Objective and research questions 17
- 1.4 Scientific contributions 17
- 1.5 Outline of the dissertation 18

2 Shared energy resources and energy communities 21
- 2.1 Energy communities 22
- 2.2 Blockchain-based balance settlement 24
  - 2.2.1 Energy allocation 28
  - 2.2.2 Blockchain 29
- 2.3 Application scenarios 34
- 2.4 Simulations of energy sharing 35
  - 2.4.1 Self-sufficiency of a multifamily residential building 36
  - 2.4.2 Intracommunal network service pricing 38

3 Serious gaming and gamification 43
- 3.1 Serious games as educational tools 43
- 3.2 Serious game design 44
- 3.3 Serious games in energy 46
- 3.4 Prototype serious game 51

4 Results and discussion 61
- 4.1 Energy sharing methods 61
- 4.2 Prosumer energy comprehension 62

5 Conclusions 65
- 5.1 Further work 66

References 67

Publications

List of publications

This dissertation is based on the following papers. The rights have been granted by the publishers to include the papers in the dissertation. The same entries will also appear in the References in a standard format.

I. M. Nykyri, T. J. Kärkkäinen, S. Levikari, S. Honkapuro, S. Annala, and P. Silventoinen (2022). Blockchain-based balance settlement ledger for energy communities in open electricity markets. *Energy* 253, p. 124180. DOI: https://doi.org/10.1016/j.energy.2022.124180

II. M. Nykyri, T. J. Kärkkäinen, S. Annala, and P. Silventoinen (2022). Review of Demand Response and Energy Communities in Serious Games. *IEEE Access* 10, pp. 91018–91026. DOI: https://doi.org/10.1109/ACCESS.2022.3202013

III. M. Nykyri, T. J. Kärkkäinen, S. Levikari, S. Honkapuro, S. Annala, and P. Silventoinen (2023). The impact of intracommunal network service pricing on the economic feasibility of an energy community. In: *2023 19th International Conference on the European Energy Market (EEM)*, pp. 1–6. DOI: https://doi.org/10.1109/EEM58374.2023.10161928

IV. M. Nykyri, T. J. Kärkkäinen, S. Annala, J. Naukkarinen, and P. Silventoinen (2023). Tutorial Serious Game for Demonstrating Demand Response in an Energy Community. In: *2023 IEEE PES Innovative Smart Grid Technologies Conference Europe (ISGT-Europe) (In press)*

Author's contribution

The author of this doctoral dissertation is the principal author and investigator in all of the publications. In **Publication I**, the author conducted the literature study, simulations, and data analyses. Dr. Kärkkäinen assisted the author in planning the experimental work and performing the analyses. Prof. Honkapuro and Dr. Annala assisted the author by participating in the literature survey. The work was later continued in **Publication III**. In **Publication II**, the author conducted the systematic literature review and received assistance in its planning from Prof. Silventoinen and Dr. Annala. In **Publication IV**, the author was responsible for the development of the presented game, which is based on the work of **Publications I–II**.

Nomenclature

In the present work, variables and constants are denoted using *slanted style* and abbreviations are denoted using regular style.

Latin alphabet

C	Energy cost	€
E	Energy	kWh
N	Game avatar need	
P	Score	
R_{PV}	Photovoltaic energy ratio	
S_{PV}	Self-sufficiency rate	
T	Energy tariff	€/kWh

Subscripts

A	Apartment- or residence-specific
B	Billed
C	Common property
D	Deficit
E	Excess
i	Indexing variable

Abbreviations

BESS	Battery energy storage system
DLT	Distributed ledger technology
DSO	Distribution system operator
EU	European Union
PV	Photovoltaic
HTTP	Hypertext transfer protocol
IP	Internet protocol

1 Introduction

The ongoing energy transition and efforts toward carbon neutrality have raised public interest in photovoltaic (PV) installations. Locally produced solar energy is often seen as an opportunity for gaining economic benefit by reducing the installation owner's reliance on grid energy. The cost of PV panels has gradually decreased (Pillai, 2015), which has further incentivized homeowners and real estate developers to invest in local PV energy production. This changes the energy market in a fundamental way, as more and more energy consumers become producer–consumers, also known as "prosumers" (Sioshansi, 2019), meaning that people are producing and consuming energy instead of only consuming it. However, plain installation of PV energy does not guarantee that the most value out of the system is obtained. Various challenges, like handling a production–consumption mismatch and controlling how PV production can be shared to multiple prosumers, must be overcome to make the most of the systems and to accelerate the rollout of renewable energy solutions.

1.1 Prosumer electricity market

Locally produced PV energy is a source of low-cost electricity for the installation owners, and therefore, it could be argued that people should aim to install as much PV energy as possible. However, larger PV installations become an issue when there is an imbalance between the consumed and the produced energy. In particular, situations where more energy is being produced than what can be used locally can be problematic. The excess energy has to be directed somewhere, and in most cases, the energy can be sold to the grid. However, this is often considered not profitable if feed-in tariffs are waived, and therefore, PV installations tend to be dimensioned so that as little energy as possible is sent back to the grid (Simola et al., 2018; Muenzel et al., 2015). Thus, instead of targeting the maximum PV capacity, the installed capacity tends to be as small as possible. This is caused by unsymmetrical pricing of sold and purchased energy. For example, in the Finnish open retail electricity market, when a prosumer or a regular consumer purchases energy from the grid, they are obliged to pay the energy price, the network service fee, and taxes. On the other hand, when they sell energy to the grid, they are only compensated for the energy price. In many open retail electricity markets, the energy price changes once in every balancing period (e.g., once in every hour). The problem of the production–consumption mismatch is emphasized in situations where there is a large surplus of PV energy and the current cost of grid energy is low. This can happen, e.g., during midday, when the solar irradiance and thus the PV installation production are at their highest, but the demand for (domestic) energy is rather low.

Besides the grid energy selling being inefficient, depending on the situation or location, the local grid may not be able to accept all the surplus local energy production. Grid integration of PV resources presents technical challenges (Shafiullah, Ahmed, and Al-Sulaiman, 2022), and, e.g., in Germany, strict requirements are in place to avoid voltage fluctuations in the low-voltage distribution network. This issue is addressed, e.g., by Moshövel et al. (2015), who point out that there are situations where the local network gets overloaded during high solar irradiance. Instead of selling the energy to the grid, alternative solutions have been studied. For example, battery energy storage systems (BESSs) are sometimes proposed as a means to store the energy produced during times when the production exceeds the consumption (Muenzel et al., 2015; Gul et al., 2022). Using a BESS to store the excess energy can be beneficial, because the energy stored in the battery can be retrieved if the energy needs must be fulfilled when the local production is low, or when the cost of grid energy is very high. The problem with BESS implementations is the high cost of viable systems mainly due to the batteries being expensive, which may lead to the investment in a BESS not being economically viable (Puranen, Kosonen, and Ahola, 2021; Mao, Jafari, and Botterud, 2022). Still, energy storage systems like BESSs, hot water storages, and electric vehicles are seen as possible incentivizing or motivating factors to increase the installed PV capacity (Nyholm et al., 2016; Parra, Walker, and Gillott, 2016; Khaboot et al., 2019; Puranen, Kosonen, and Ahola, 2021). However, even if the PV installations themselves are becoming less expensive, adding energy storages to counter the production–consumption mismatch increases the initial investment cost of the system, and therefore, it can be argued that energy storages may not always be a viable option. For example, not everyone needs or wants to own an electric car even if it could be used as a means of mobility and energy storage. Instead of attempting to store the energy to be used later (i.e., shift the production), an alternative way to increase the efficiency of local energy production is to try to shift the consumption of energy to times when the production is available. This is called *demand response*, and it can be very effective in countering the problems caused by the production–consumption mismatch. However, engaging in demand response requires knowledge (Yang et al., 2018) and active participation from the energy user, which may not always be possible. For example, if the PV installation produces a high output during midday and everyone at the PV-supplied house is at work or school, there is nobody home to use the energy. Not all activities that require energy can be shifted.

In many countries, a considerable amount of PV energy has been installed by households. Much of this capacity is located in single-family (detached) homes (Jäger-Waldau et al., 2020). However, not everyone lives in a single-family home, and multifamily residential buildings are a common form of residence. Large numbers of multifamily residential buildings mean that there is a lot of rooftop area available for potential PV installations, which has a significant potential for energy production. In Finland alone there is potential for 1.3 GW of PV production in multifamily residential buildings (Pöyry Management Consulting Oy, 2017). However, this potential is mostly left unused because of the aforementioned dimensioning trends favoring smaller PV installations. In addition, installations on multifamily residential building rooftops face other kinds of unique challenges and obstacles, e.g., regulatory challenges (Roberts, Bruce, and MacGill, 2019). Still, a considerable proportion of the potential PV installation space is left unutilized because of unsolved difficulties.

Because the rooftop of a multifamily residential building is not allocated to any specific residence(s), it would make sense that if there is a PV installation on the building, the PV installation would be co-owned by the residences of the building. Then, the energy that is produced in the building's PV installation could be shared between the residences that own a share of the PV installation. A common arrangement in a multifamily residential housing is sharing the ownership of the entire building between the residences. This means that the residents are together responsible for the maintenance of the building and make decisions on, e.g., renovations and janitor work. In Finland, these arrangements are called *housing cooperatives*, but similar housing solutions are also found elsewhere. Housing cooperatives can consist of one or multiple buildings, which are usually multifamily buildings. Maintaining conditions suitable for housing consumes energy not only in the residences themselves but also in the *common property* of the building(s), e.g., in hallway lighting and ventilation. This energy consumption is paid together by the cooperative residents in the form of (monthly) maintenance charges. This gives the housing cooperative residents as individuals an incentive to invest in shared local energy production, because the energy consumption of the common property has to be paid by the residents together anyway. Using a co-owned PV installation to supply the energy needs of the common property is possible without major challenges.

Although being a simple solution to improve the energy self-sufficiency of a building or a housing cooperative, investing in a PV installation that provides energy only for the common property affects the maintenance charges only and does not contribute to the reduction of reliance on grid energy of the residences themselves. In order to capitalize on the potential of low-cost PV energy for the residences of the housing cooperative, new procedures for energy sharing are needed. Questions are raised on how the energy produced should be shared, and the rules of fair energy distribution have to be ensured because of the possible lack of trust between the residents. There is no consensus on who or what controls or governs the energy sharing and distribution, and whether infrastructure changes are needed.

The shareholders of the housing cooperative make the decisions on whether to invest in local energy production or not, and making these kinds of decisions can be difficult. Ready-made solutions for sharing co-owned PV production are not available, and many people can find concepts regarding electricity and energy difficult to grasp (van den Broek, 2019; Herrmann, Brumby, and Oreszczyn, 2018). For example, the difference between kilowatt and kilowatt-hour may not be straightforward for everyone (Nilsson et al., 2018), and dynamic energy pricing can be seen as complex (Layer, Feurer, and Jochem, 2017). Combining these problems with the inefficiency of selling excess energy to the grid during a production–consumption mismatch presents a situation where a lot of uncertainties remain, and novel techniques for energy sharing and prosumer energy awareness are needed. People should know, e.g., when and how to engage in demand response. Smart metering is becoming more and more common, and arguments about its suitability for raising energy awareness could be made. However, counterarguments are also made that the plain visualization of data does not provide sufficient incentive for people to change their energy consumption habits (Fraternali et al., 2017). This makes sense, because observing the energy consumption readings going up and down can be pointless if the person making the observations does not know what the values mean and what causes them to change.

Energy conservation is a hot topic worldwide, and any tools and methods to help conserve energy and reduce carbon emissions are welcomed by many. For example, the European Union (EU) is targeting to reach net zero greenhouse gas emissions by 2050. The goal can be considered ambitious, and reaching it requires that people understand where energy is consumed and what they can do to conserve it. As more and more complex systems, such as local shared energy production, are being introduced, the problem of difficult-to-grasp concepts becomes even more imminent and can be argued to be a barrier holding up the rollout of local renewable energy production.

1.2 Serious games and gamification

Video games have become very common, and playing various digital games is now more popular than ever. This trend has been going on ever since home computers became affordable, and over the past decade the prevalence of video games has been accelerated by the emergence of smartphones as suddenly many people own a pocket-sized computer capable of running video games. Especially casual, low-threshold gaming has gained ground in recent years. These kinds of games are usually free-to-play mobile games designed to be easy to play. A somewhat related and prospective type of video games, *serious games*, are designed for educating people by playing a game. Their intention is to both entertain the player of the game and also simultaneously pursue to achieve at least one additional goal like learning or health (Dörner et al., 2016). Another term usually discussed in similar contexts is *gamification*, which means adding game elements to something that is originally not a game (Dörner et al., 2016). Gamification can be seen in many places; e.g., language learning through gamified applications like Duolingo are popular (Huynh, Zuo, and Iida, 2016). Gamification does not necessarily require a digital aspect: e.g., one could consider that rewarding oneself with a piece of chocolate after each 15 min spent on a repetitive task is an example of gamification of a boring chore.

Serious games are claimed to have the potential in teaching their players different things, including concepts of energy and electricity. Numerous studies on the effectiveness of serious games to teach concepts of energy have been made (e.g., Wu, Liu, and Shukla, 2020; Casals et al., 2020; Mulcahy et al., 2021). Serious gaming has been effective as a method for influencing the players' domestic energy consumption (Johnson et al., 2017; Casals et al., 2020). Furthermore, Schweiger et al. (2020) conclude that serious games have the potential to make smart energy tools more effective, but the gamification and game design elements are left underutilized in real-world applications. Wu, Liu, and Shukla (2020) show similar results and state that serious games in energy have not reached their full potential because of the underutilization of indirect learning from effects that reflect from the game to real life. In addition, serious games can be seen as a viable medium to reach young adults who can be difficult to reach with traditional media (Mulcahy et al., 2021).

1.3 Objective and research questions

The objective of this doctoral dissertation is to investigate how local co-owned energy production can be shared to its owners efficiently while focusing on how the problems caused by the difficult-to-grasp concepts of energy, electricity, and sharing local co-owned PV production could be overcome. The problem of prosumer energy comprehension is approached with a study on the applicability of serious gaming and gamification of people's everyday energy use experience as a method for raising energy awareness.

This dissertation answers the following research questions:

- How can co-owned PV installations be utilized efficiently in a way that promotes both fair sharing of the produced energy and easy understandability of the system?
- How serious gaming and gamification can be used to promote efficient use of energy resources?

1.4 Scientific contributions

The main scientific contributions of this doctoral dissertation are the introduction of a novel way to arrange the sharing of energy produced in a co-owned PV installation and the proposition to further utilize serious games and gamification in everyday life to raise awareness about concepts of energy and electricity. Earlier implementations of PV installations within a multifamily residential building tend to use the locally produced PV energy only in the common property of the building, or either have a centralized energy aggregator that governs the energy balancing in the building. This kind of arrangement prevents the residents from taking part in the open retail electricity market, which results in the residents not being able to select the supplier of their electrical energy. This dissertation presents an arrangement where these restrictions can be overcome and discusses how the rollout of efficient energy use techniques, such as demand response and energy communities, can be supported with serious games that can be used to teach people the concepts of energy, which can be difficult to grasp.

This doctoral dissertation consists of four publications, which are listed in a chronological order. The first and third publications consider the energy sharing infrastructure and applicability of a blockchain-based energy balance settlement ledger in different energy communities. The second and fourth publications focus on serious games in energy.

Publication I introduces an arrangement for sharing the energy produced with a co-owned PV installation of a multifamily residential building arranged as a housing cooperative. The system is based on formation of an energy community and utilization of a blockchain-based balance settlement ledger, which allows logging, storage, and processing of the apartments' energy consumption data in a way that is secure due to the immutability of the blockchain. The proposed arrangement allows the members of the energy community to remain in the open retail electricity market, which has not been possible in earlier implementations of such arrangements. In the publication, simulations are presented to show that the proposed system has an economic advantage when compared with a more common PV arrangement where all the locally produced energy is either used in the common property of the building or sold to the grid.

Publication II provides a systematic literature review of the state of the art of serious games considering energy and/or electricity. Special attention is paid to games that contain features of demand response or shared energy resources. The review was conducted using the PRISMA method and 34 games were identified in total, four of which had aspects regarding demand response, and five of which had aspects of shared energy resources or energy communities. No games were identified with features of both demand response and shared energy resources while having a link to real-life events, which emphasizes that the concepts are new, and a serious game covering those aspects could be introduced.

Publication III discusses how the blockchain-based ledger and formation of an energy community where the members remain in the open retail electricity market can be applied also to more suburban or rural settings where the energy community members consist of detached households instead of apartments in a multifamily residential building. In the publication, the effect of intracommunal network service pricing on the economic viability of detached household energy communities is studied using a simulation based on the same sharing methodology as presented in **Publication I**.

Publication IV presents the design process of a serious game that could be used to raise awareness of efficient energy use. Factors that motivate players to keep playing a serious game and features that promote learning through playing a game are discussed. The identified motivational factors and crucial features are applied to a prototype serious game that takes place in an apartment within an energy community in a multifamily residential building.

1.5 Outline of the dissertation

This doctoral dissertation can be divided into two main parts: a study of a blockchain-enabled energy sharing infrastructure solution and a study on how serious gaming can be used to promote efficient use of energy resources.

Chapter 2 discusses energy communities and factors that enable and promote them. The chapter also addresses the utilization of co-owned PV installations and how the produced energy can be shared efficiently. The problem of fairness and clarity of the sharing logic is also approached.

Chapter 3 focuses on the state of the art of serious games in energy. Further, the design process of a tutorial serious game for energy community members is addressed.

Chapter 4 studies how the findings presented in Chapters 2 and 3 can be deployed together.

Chapter 5 concludes the research by presenting a summary of the main results and discusses avenues for further research.

2 Shared energy resources and energy communities

The conventional electrical system architecture is based on centralized energy production and decentralized energy consumption. In an open retail electricity market, the consumer purchases their electrical energy from an energy supplier, and the purchased energy is transferred to the consumption location using the network of the distribution system operator (DSO). The DSO is usually a local company, which is in a state of monopoly in its operating area (Saplacan, 2008; Newbery, 1999), unless parallel grids exist. Building parallel networks is inefficient, and thus, the customers in those cases have no choice over the power distributor. This is also the case in Finland, where the distribution service provider is always the local DSO, but the consumers have the right to select the retailer (aka supplier) of the actual energy. The freedom to select the energy supplier is also backed with legislation under Directive (EU) 2019/944, Article 4, and the Finnish Electricity Market Act §72 (Sähkömarkkinalaki 9.8.2013/588).

The implementation of local energy production in a single-family home means that a single household becomes a prosumer. This changes the energy consumption structure so that the location that previously only consumed energy now also supplies it in situations when there is a production–consumption mismatch and the DSO network is willing and capable of receiving this produced energy. An individual prosumer household has a single connection point to the DSO network, and when a single-family home invests in energy production to become a prosumer, the energy generation (e.g., with a PV installation) takes place behind the DSO network connection and metering point. Things get more complicated when residents in a multifamily residential building pursue to become prosumers. A multifamily residential building consists of multiple residences, all of which are metered individually even if the building's internal wiring has a single physical connection to the DSO network. The residences are connected to this internal wiring. This means that the residences are all customers of the DSO, and depending on the country, the energy meters of the residences are owned by the DSO (Saplacan, 2008), even if the intrabuilding wiring is not, and is instead the property of, e.g., a housing cooperative.

Implementing a PV installation behind a residence-specific metering point is not a viable option in multifamily residential buildings, especially when the target of the installation is to share the produced energy and/or supply the building's common property with it. A shared installation is likely to be connected to the same building's internal wiring as the residences are. This causes a significant problem when considering the option of using a shared PV installation to provide energy for the residences in addition to the common property of a multifamily residential building. Because the metering is DSO owned, the DSO is entitled to impose a network service fee on distribution of energy that is transmitted from the shared (rooftop) PV installation to the residences in the same building, even if the energy never leaves the building or uses the DSO network. The DSO pricing should be cost-reflective so that the payments charged from the prosumer are based on the costs that they actually cause to the distribution system. The end users are charged for energy distribution within the building when the DSO network is not used, which reduces the incentive for increasing energy self-sufficiency as it may not be economically viable. This leads to a situation where co-owned PV installations are used only to provide energy for the common property of the building (Fig. 2.1).

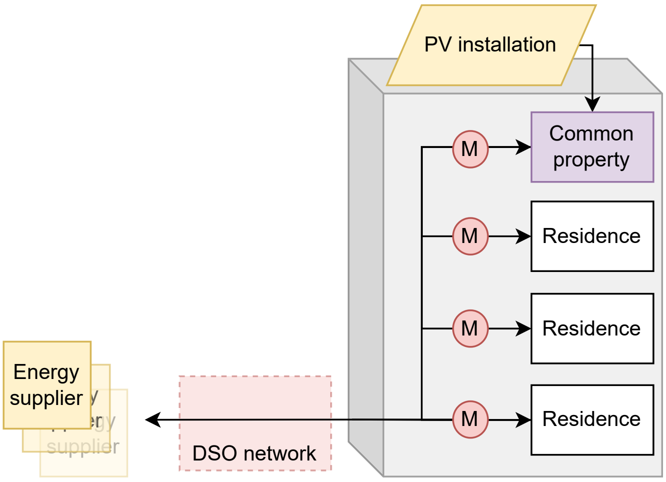


Figure 2.1: Conventional PV installation on a multifamily residential building. The co-owned production is used only to supply energy to the common property of the building (**Publication I**).

2.1 Energy communities

Because the present-day infrastructure is not directly viable for providing low-cost PV energy for the residents of a multifamily residential building, new kinds of arrangements or infrastructural changes are studied. A prospective arrangement for energy sharing between individuals is called *an energy community*. Directive (EU) 2019/944 states that citizen energy communities are legal entities based on voluntary and open participation, and they are controlled by natural persons, local authorities (including municipalities), or small enterprises. Instead of generating profit, an energy community's primary purpose is to provide economic, environmental, or social community benefits for its members or shareholders, or the area it operates in. Energy communities may engage in consumption, production, distribution, supply, aggregation, or storage of energy for their members or shareholders. In addition, they may feature other energy efficiency services or, e.g., promote electric vehicle charging. (Directive (EU) 2019/944) In addition to the above-mentioned directive, the European Parliament also defines a renewable energy community, which has similar features to a citizen energy community, but the members should be located in proximity to a renewable energy project that is owned and developed by the energy community (Directive (EU) 2018/2001). In Finland, the above-mentioned directives are interpreted so that the prosumers should, regardless of being a part of an energy community or not, be able to select the supplier of their electrical energy (Pahkala, Uimonen, and Väre, 2018).

Energy communities have been a topic of academic interest lately, and they have often been proposed as a solution to the problems associated with inefficient or obscure sharing principles of co-owned PV installation energy. Examples of the state-of-the-art energy community pilots include the Brooklyn Microgrid (Mengelkamp et al., 2018), the peer-to-peer energy trading innovation trial in western Australia (Wilkinson et al., 2020), and the peer-to-peer microgrid pilot in Switzerland (Wörner et al., 2019). These solutions allow the energy community members to get a share of the locally produced energy for consumption in their residences, which makes the arrangements superior to the conventional setups that only supply energy to the common property. However, Roberts, Bruce, and MacGill (2019) argue that the design of a tariff for intrabuilding energy sharing is not straightforward when cost recovery, efficiency, and consumer acceptance are considered. The state-of-the-art energy sharing solutions also tend to rely on active participation methods, such as peer-to-peer trading, some with active energy auctioning and bidding on shares of the produced energy (Liu, Wu, and Li, 2019; Han et al., 2020; Sun et al., 2021). This can prove problematic because gaining benefit from the system will require being active, and may be difficult for those unfamiliar with the technology and energy terminology.

Energy communities sometimes feature an intermediate between the community and the energy supplier called an *energy aggregator* (Di Somma, Graditi, and Siano, 2019). The energy aggregator works as the manager of energy resources (Correa-Florez, Michiorri, and Kariniotakis, 2020; Li et al., 2015), and is responsible for the distribution of energy within the community (Favuzza et al., 2015) and buying the energy from the grid for the community, e.g., when there is a deficit (Iria, Scott, and Attarha, 2020). In an energy community with an energy aggregator where the community members are not participating in the open retail electricity market, the energy aggregator is responsible for purchasing any deficit energy from the market without community member participation or input. The energy can be bought from a single source with which the aggregator has made an agreement, such as a local energy company. The energy aggregator is usually independent, and can, e.g., participate in active energy bidding in order to pursue economic benefit (Wang et al., 2020; Qi et al., 2017).

When considering the problem of difficult energy concepts and the requirement of active prosumer behavior, shifting the requirement of activity from the prosumer to the aggregator is a step in the right direction. This changes the energy distribution infrastructure from the conventional PV setup (Fig. 2.1) to a less constrained one where the energy is free to move within the energy community, although the residences lose their place in the open retail electricity market (Fig. 2.2). In this kind of arrangement, the intracommunal metering may be still owned by the DSO, but the DSO no longer has billing rights to the intracommunal energy transmission because the residents are no longer directly the DSO's customers. Instead, the energy aggregator is responsible for the energy billing and collects all the fees associated with it (energy cost, network service fee, and taxes). This kind of arrangement is not without problems, because the residences lose their participation in the open retail electricity market and any possible benefits (e.g., personal preferences for the energy source or cost structure) with it. Research is needed to promote ways for energy community members to participate in open retail electricity markets (Sousa et al., 2019).

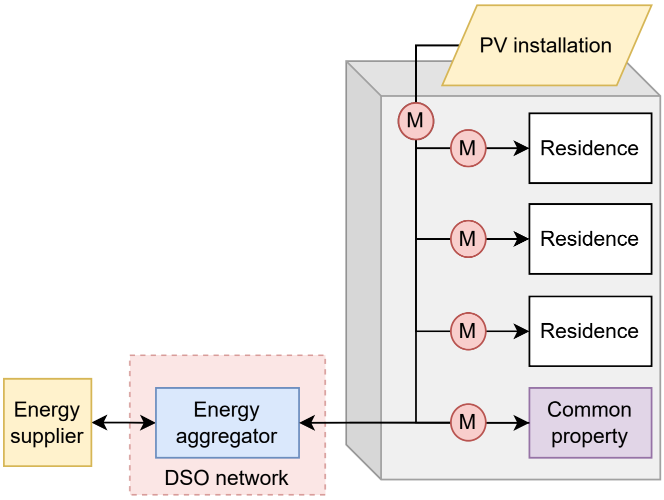


Figure 2.2: State-of-the-art energy sharing infrastructure in a multifamily residential building where the energy balance settlement is done by the energy aggregator (**Publication I**).

2.2 Blockchain-based balance settlement

Allowing energy community members to remain in the open retail electricity market requires that instead of an energy aggregator being the energy community's centralized energy manager with which every residence is in a customer relationship, the aggregator has to be either removed altogether or it has to act as a virtual metering entry point only. The aggregator removal, however, will again result in the intracommunal energy distribution being under the DSO's billing area, unless the network service charges can be waived with another arrangement. If the DSO only imposes network service charges on the network services outside of the community, i.e., the energy transmission between the energy supplier and the energy consumption location, a prosumer of the energy community will be in a customer relationship with the energy community itself, the energy supplier, and the DSO (Fig. 2.3).

However, if the energy community itself is in charge of the energy sharing, problems may arise because fair energy transfer has to be ensured somehow between the community members. The community consists of the individuals who live in the premises, and if

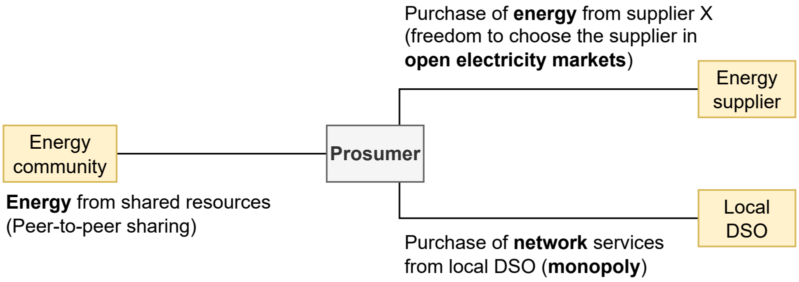


Figure 2.3: Prosumer within an energy community has customer relations to three different actors in the electricity market: the energy community, the energy supplier, and the DSO (**Publication I**).

the energy sharing is done without a governing body, such as an energy aggregator, the community members have to trust each other enough so that fair PV resource sharing can be achieved between them. This requires sharing each member's energy consumption data to others, and a tamperproof and secure method for this has to be implemented.

One possible method for data sharing is utilization of a centralized data exchange system. These systems, like the DataHub of the Finnish transmission system operator Fingrid (Fingrid DataHub Oy, 2021), allow collection of data automatically from consumption locations. In the case of the Finnish DataHub, the system was introduced in the legislation with the amendment to the Electricity Market Act (Laki sähkömarkkinalain muuttamisesta 108/2019), which allows the energy consumption data of consumption locations to be stored in the system by the DSO. The data stored in the system can be used, e.g., to arrange information exchange in the contexts of agreement processes, metering data, and connection/disconnection of services (Fingrid DataHub Oy, 2021). Furthermore, according to the government decree on balance settlement and measurement (Valtioneuvoston asetus sähköntoimitusten selvityksestä ja mittauksesta 767/2021) the data stored in the centralized data exchange system have to be stored so that they can be utilized for balance settlement (e.g., within an energy community). However, such systems may not exist in all energy markets, and it is possible that a centralized data exchange system will again result in relying on a central authority. If a less centralized system is desired or a centralized data exchange system is not available, distributed ledger technologies (DLT), such as *blockchain*, could also be considered a solution. Siano et al. (2019) even deem them necessary.

A blockchain (Fig. 2.4) is a distributed database where pieces of data are stored in interchained containers or *blocks* (Aitzhan and Svetinovic, 2018; Fernández-Caramés and Fraga-Lamas, 2018). The blocks contain data in the form of *transactions*, which can include various types of information. In addition to the transactions, each block also contains a hash of the previous block in the chain. The hash is a fixed-width string constructed of the transaction data in the block, which works as a validation token for the data. The hashes and the interchained structure of the blockchain make the chain secure and immutable by nature, because even the tiniest change in the data within any of the transactions in any of the blocks will result in the rest of the chain being invalid as the hashes are no longer valid. This makes even small tampering attempts on the data easily detectable and ensures immutability of the data. Because of this, blockchains can be used as secure transaction ledgers. Notable examples of blockchain-based ledgers include cryptocurrency ledgers like Bitcoin and Ethereum. Although usually associated with cryptocurrencies, blockchains are not restricted to cryptocurrency only and can be used to store also other data. Because the data are stored in transactions, the transaction data can contain, e.g., information about movement of funds, energy, or other goods. For instance, a transaction can contain a specification of energy consumption of a consumption location (e.g., a residence) for a given time span. In addition, transactions can contain information about the energy cost of a specific time, and thus, transactions can be expressed both in currency or in kilowatt-hours.

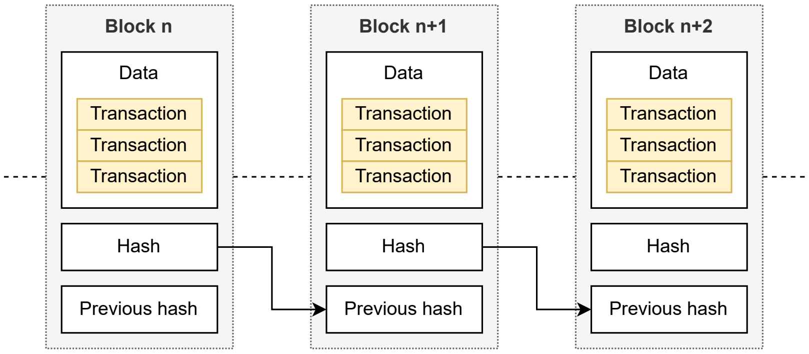


Figure 2.4: Blockchain is a database where the data (transactions) are placed in interchained blocks. Each block contains a hash of the current block that is calculated from the data that the block contains, and the hash of the previous block.

The versatility of blockchains has raised interest among academics to study the opportunity of applying them into use in the energy sector. Contributions have been made on the utilization of blockchain in peer-to-peer energy trading by using a blockchain to enable peer-to-peer energy bidding and offering among peer prosumers (AlAshery et al., 2021; Han et al., 2020). Combining blockchain technology with smart metering is discussed by AlAshery et al. (2021) and Zia et al. (2020), who deem blockchains viable as a data storage of smart meter data. The rollout of smart energy meters is mandated in the EU legislation (Annex I of Directive 2009/72/EC), and they are becoming increasingly common in the EU: e.g., in the Nordic countries and in Estonia, the rollout rate is almost 100% (the European Union Agency for the Cooperation of Energy Regulators and the Council of European Energy Regulators, 2022). Smart meters allow remote access to the energy consumption data, which makes automatic data processing with *smart contracts* possible.

Smart contracts are a key part of blockchain technology. They are instructions or pieces of code that can be automatically executed to perform operations on the data stored in the blockchain. The contracts can be utilized in, e.g., demand management (Afzal et al., 2020).

Based on the facts that blockchains are secure and they can be fitted with smart contracts using automatized code execution, a blockchain-based energy balance settlement ledger could be built to control the energy flows and allocation within an energy community. This solution will mitigate the need for an energy aggregator as an independent entity that manages the energy resources. If the blockchain system is responsible for the energy balancing, the blockchain is the energy aggregator of the energy community. However, the blockchain is only a ledger for the energy balancing, and the members of the energy community still remain as participants in an open retail electricity market (Fig. 2.5). The intracommunal energy transmission remains a concern, but if the energy data are collected by the energy community itself in the form of a blockchain-based balance settlement ledger, there is reason for a contract to be negotiated with the DSO so that the intracommunal network service fees could be waived. In countries where modern smart meters are common (e.g., in Finland), this kind of arrangement does not require additional infrastructure investments in energy metering.

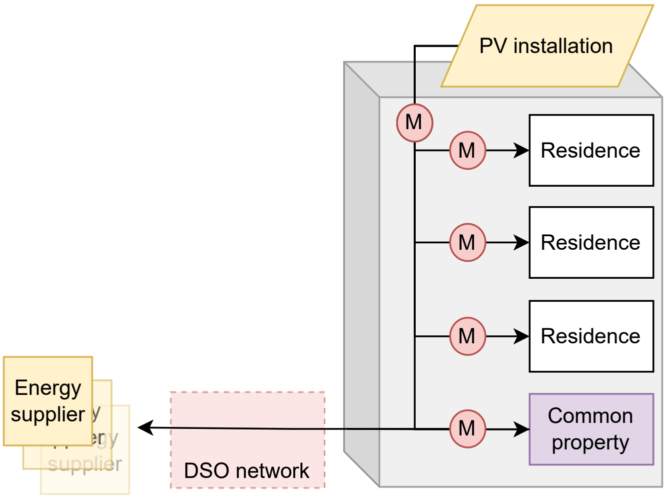


Figure 2.5: When the energy aggregator is removed, the residences can remain in the open retail electricity market (**Publication I**).

Blockchain is a technology suitable for multiple use cases, and it has flexibility to work in different situations ranging from cryptocurrency to energy markets and smart grid solutions. Ghorbanian et al. (2020) also discuss how to combine them in a case where cryptocurrency is used in an intracommunal energy market. Hamouda, Nassar, and Salama (2021) study the implementation of a peer-to-system-to-peer arrangement of an intracommunal energy market where the participants store energy consumption data in a blockchain. They suggest that the system itself is a participant of the ledger. This can be thought as if the energy resources that the energy community has form a common energy pool, where the energy is either brought to, or taken from. When smart contracts are introduced to the setup, automatic energy allocation based on immutable and trusted energy consumption and cost data can be achieved.

2.2.1 Energy allocation

In a multifamily residential building, the energy is consumed in the residences (apartments) and in the common property. The sources of energy are the grid and the co-owned PV installation. As discussed above, the common property is owned together by all the building shareholders (the residents), and maintaining the common property requires energy. Therefore, supplying the common property with the produced PV energy is justified, because supplying the common property with energy will have to be paid by the residents together anyway.

During times when the PV production exceeds the consumption of the common property, instead of selling it inefficiently to the grid (if possible, to the local distribution grid) and being compensated only for the energy price and not for the network services and taxes, the remaining energy can be allocated to the residences. How the allocation is carried out has to be agreed upon beforehand, with specific rules defined for the allocation. These rules can be explained in, e.g., the lease contract of the apartment, or in the board meetings of the housing cooperative. It is crucial that the rules for sharing the available energy are understandable, transparent, and fair. However, what is fair and what is not is not straightforward to determine. There is no correct answer to this, and fairness can depend on the building. That being said, because the way how the electrical system works is not evident to many people, it can be argued that the methods and rules for how the energy is shared should not be complicated, perhaps even promoting simpleness to ensure that everyone understands how the allocation works. Therefore, as an example, each residence could be allocated with an equal ratio of PV energy into their use. This PV ratio R_{PV} is calculated by

$$R_{\mathrm{PV}} = \frac{E_{\mathrm{PV}} - E_{\mathrm{C}}}{\sum E_{\mathrm{A}_i}}, \tag{2.1}$$

where E_{PV} is the PV energy production of the PV installation, E_{C} is the energy consumption of the building's common property, and $\sum E_{\mathrm{A}_i}$ is the combined energy consumption of all the apartments in the energy community. The values used in all the calculations represent values over a fixed-length time interval, i.e., the balancing period in the electricity market. In this dissertation, the balancing period is one hour. The amount of energy that each individual apartment is allocated, $E_{\mathrm{PV,A}_i}$, is then obtained by

$$E_{\mathrm{PV,A}_i} = E_{\mathrm{A}_i} R_{\mathrm{PV}_i}, \tag{2.2}$$

where E_{A_i} is the energy consumption of the individual apartment (over the balancing period). Then, the billed cost of energy for each specific apartment over the balancing period C_{B_i} can be calculated by

$$C_{\mathrm{B}_i} = T_{\mathrm{E}}(E_{\mathrm{A}} - E_{\mathrm{PV,A}_i}), \tag{2.3}$$

where T_{E} is the energy tariff (i.e., the cost of energy per kilowatt-hour). This cost can, depending on the scenario, be a fixed cost or a dynamic tariff that changes once every balancing period, and it can be different with each member of the energy community, because they remain as independent entities in the open retail electricity market. From the residents' perspective, depending on the current energy consumption (the common property and the residences) and the PV installation output, the system can have two main operating states: excess and deficit. These will be further divided into full and partial excess and deficit. The system is in the excess state if $E_{\mathrm{PV}} \geq E_{\mathrm{C}}$, and otherwise it is in the deficit state. In the deficit state, the PV production is not enough to fulfill the total energy consumption of the common property of the building ($E_{\mathrm{PV}} < E_{\mathrm{C}}$). The common property is partially powered with PV energy if $E_{\mathrm{PV}} > 0$. The remaining energy needs of the energy community E_{D} have to be bought from the grid, and the amount is calculated by

$$E_{\mathrm{D}} = \sum E_{\mathrm{A}_i} + E_{\mathrm{C}} - E_{\mathrm{PV}}. \tag{2.4}$$

The state of full deficit is reached when $E_{\mathrm{PV}} = 0$. During this, all energy must be bought from the grid. When the system is in excess, there is energy for the residences to use, meaning that $E_{\mathrm{PV}} > E_{\mathrm{C}}$. If the system is in full excess, meaning $E_{\mathrm{PV}} > E_{\mathrm{C}} + \sum E_{\mathrm{A}_i}$. In such a case, the building's energy needs are completely fulfilled with PV production, and the remaining excess energy E_{E} is then sold to the grid. The excess to be sold to the grid is calculated by

$$E_{\mathrm{E}} = E_{\mathrm{PV}} - \sum E_{\mathrm{A}_i} - E_{\mathrm{C}}. \tag{2.5}$$

These, or any other energy allocation calculations, can be done in the blockchain ledger nodes so that the balance settlement algorithm (Fig. 2.6) can be executed in real time once in every balancing period. is The data are stored in transactions in the blockchain blocks.

2.2.2 Blockchain

The blockchain-based balance settlement ledger is built on interchained data containing blocks, and the data immutability is based on the hashes in the blocks. A common type of blockchain is called a proof-of-work blockchain, where the integrity of the data is guaranteed by the difficulty of creating new blocks. The hashes are complex, and solving them requires significant computational power. This process of calculating the hashes to form a new block is often referred to as *mining*. The complexity and requirement for effort is designed on purpose so that it requires a lot of effort to create new blocks on the chain, which could potentially contain false data. Furthermore, because tampering a piece of data in the existing chain requires all the hashes to be recalculated to make the chain valid

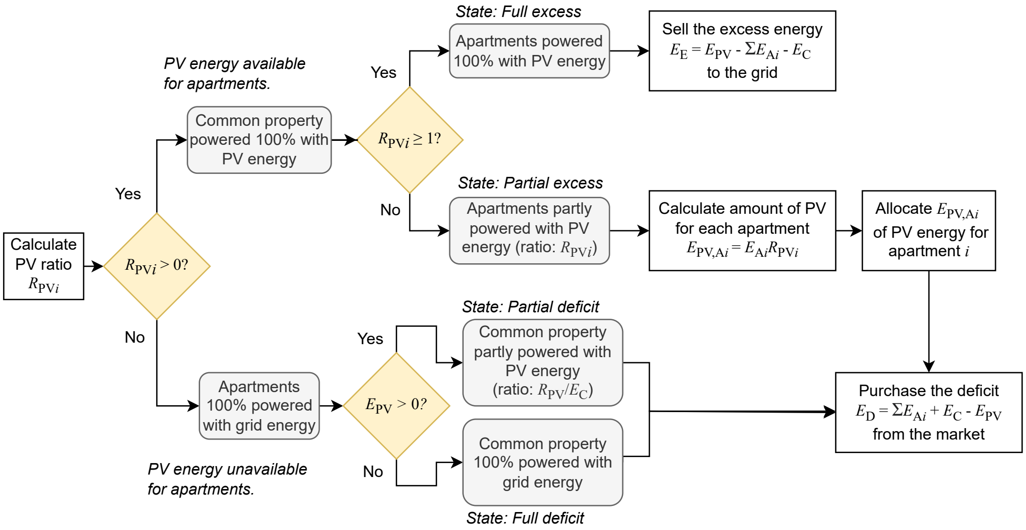


Figure 2.6: Flowchart of the hourly energy allocation principles of the blockchain system. The PV ratio (R_{PV_i}) and the amount of PV energy each apartment gets (E_{PV,A_i}) depend on the amount of produced PV (E_{PV}) and the usage of the common property (E_C). After the sharing, any excess energy (E_E) is sold to the grid, or the deficit energy (E_D) is purchased from the grid (**Publication I**).

again, it is not a trivial task to alter any data in the blockchain. Proof-of-work technology is widely adopted in cryptocurrency blockchains, and therefore, it can be argued that it meets the security and immutability requirements for a energy balance settlement ledger also.

A blockchain can be run in various environments ranging from regular computers to a cloud environment. The system requirements for a blockchain-capable device depend on the difficulty of the hash calculation and the scale of the system. The blockchain itself along with the smart contracts can be made, e.g., in Python like in the tutorial by Flymen (2017). The tutorial shows that a simple blockchain can be built with Python and its libraries Flask, jsonify, and request, and can be controlled completely with Hypertext Transfer Protocol (HTTP) requests (POST and GET). The blockchain system is presented in full detail in **Publication I**. In short, the system can consist of one or more nodes, and each of the nodes (Fig. 2.7) has six main components: a list of nodes, a list of transactions, a smart contract, a miner, a blockchain, and a consensus algorithm:

- **List of nodes** contains the list of all nodes in the system. The list stores the Internet Protocol (IP) addresses of all the nodes in the system. Whenever a new node joins the system, it announces its IP address using an HTTP request (POST).

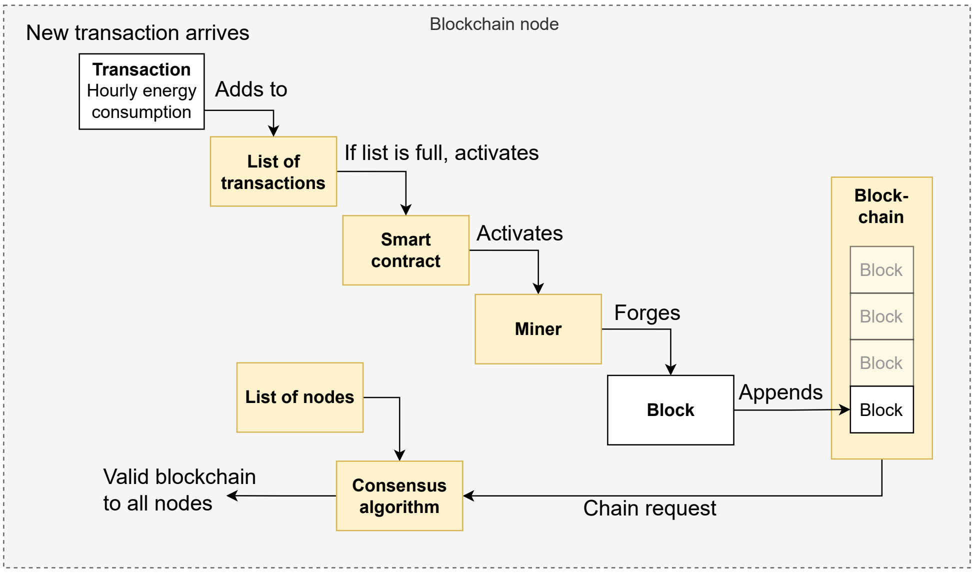


Figure 2.7: Each of the blockchain nodes has six main components (indicated by yellow color): the list of transaction, the smart contract, the miner, the blockchain, the consensus algorithm, and the list of nodes.

- **List of transactions** contains transactions that are not yet stored in a block. These transactions are pieces of energy information, such as energy consumption, energy production of a PV installation, or additional data like the energy cost over the balancing period of the energy system. Each energy transaction contains information about where the energy is from, where it is going to, when the transaction took place, and how much energy was transferred. The energy flow data inside the transactions originate from the smart meters within the energy community.

- **Smart contract** contains the program code that can be executed when all the required information regarding a balancing period has been received. This means the energy consumption data of all consumption locations, including the common property, and the PV production amount and the grid energy cost. When the data are available, energy balancing can be carried out using Eqs. (2.1) and (2.2) (Fig. 2.6). After the balancing, information about the allocated PV energy can be stored in a list of transactions, the list can be deemed ready, and the miner can be started.

- **Miner** is a program that stores the transactions of the list of transactions into a new block on the blockchain. After the data are stored in the block, the data become immutable. When the miner is finished, the list of transactions is cleared, and it is then ready to receive the data from the next balancing period.

- **Blockchain** contains all the blocks and the data stored in them. The chain can be retrieved with a chain request using HTTP (GET).

- **Consensus algorithm** is a component of a blockchain that ensures that all the nodes of the system have the same blockchain if there are multiple nodes in the system. The algorithm can be called by any of the nodes, and it checks that all the hashes in each block's blockchain are valid. Invalid chains are disregarded, and if there are multiple valid chains, the longest is selected as the valid one and others are disregarded. If the chains are of equal length, the most recent one is selected as the official blockchain.

A principal concept of the system, besides the data being logged into a blockchain, is that all the consumption locations are drawing energy from a virtual energy source called *community pool*. This community pool can be considered an energy "container", into which energy is either brought into or taken from. Energy can be brought from a PV installation or from energy supplier companies through the DSO network, and it is taken by consumption locations, i.e., residences and the common property. The purpose of the community pool is to make the energy accounting effortless and easy to grasp, because in every balancing period, the energy input to the community pool equals the energy output from the community pool. The transactions in the blockchain follow this scheme, and all the energy transactions either originate from or terminate to the community pool. The transactions in the blockchain are in the text form, and can look, e.g., like:

```
2023-02-21T14:00 COMMUNITY-POOL COMMON-PROPERTY 1.50-kWh
```

The example transaction shows that on February 21, 2023 during the balancing period that started at 14:00 hrs, 1.50 kWh of energy was transmitted from the community pool to the common property. The hourly energy balancing using a simplified example with only three participating residences in an energy community is shown in Tables 2.1–2.3. The tables present the energy balancing using Eqs. 2.1 and 2.2. For easier comparison, the energy consumption or all the residences and the common property is kept constant, and the consumptions as well as the PV installation production amount are presented as round figures. In reality, the values would vary depending on the residents' activities. The monetary values are calculated using a constant energy cost of 0.2134 €/kWh (including taxes and network service pricing), which is the average cost of electricity for household customers in the European Union (second half, 2020) (Eurostat, 2020).

The first scenario in Table 2.1 represents a situation where the PV installation output is low. Over the balancing period (one hour), some energy is produced (1.30 kWh), but it is not enough to fully supply the common property (2.00 kWh) with PV energy. In this case, the residences receive no direct cost reduction in their electricity bills, because all the PV energy is used to partially power the common property.

Table 2.1: Energy balancing during low PV production (1.3 kWh)

Energy source	Energy recipient	Actual [kWh]	Billed [kWh]	Billed [€]
Community pool	Residence 1	1.50	1.50	0.3201
Community pool	Residence 2	1.00	1.00	0.2134
Community pool	Residence 3	0.50	0.50	0.1067
Community pool	Common property	2.00	0.70	0.1494
Solar installation	Community pool	1.30	–	–
Bought from market	Community pool	3.70	–	–

Table 2.2: Energy balancing during medium PV production (3.5 kWh)

Energy source	Energy recipient	Actual [kWh]	Billed [kWh]	Billed [€]
Community pool	Residence 1	1.50	0.75	0.1601
Community pool	Residence 2	1.00	0.50	0.1067
Community pool	Residence 3	0.50	0.25	0.0534
Community pool	Common property	2.00	0	0
Solar installation	Community pool	3.50	–	–
Bought from market	Community pool	1.50	–	–

Table 2.3: Energy balancing during high PV production (8.5 kWh)

Energy source	Energy recipient	Actual [kWh]	Billed [kWh]	Billed [€]
Community pool	Residence 1	1.50	0	0
Community pool	Residence 2	1.00	0	0
Community pool	Residence 3	0.50	0	0
Community pool	Common property	2.00	0	-0.2490[a]
Solar installation	Community pool	8.50	–	–
Community pool	Sold on the market	3.50	–	0.2490[a]

[a] If one-third of the consumer purchase price of energy is compensated when sold to the grid

Table 2.2 shows a situation where the PV installation production over the hour has risen to 3.50 kWh. In this case, the PV production exceeds the energy consumption of the common property, and the residences will receive the surplus PV energy (1.50 kWh) to be shared among the residences, resulting in partially fulfilling their energy needs. The rest (1.50 kWh) is bought from the market. Finally, in Table 2.3, a situation is presented where the PV output is high (8.50 kWh) and enough to completely fulfill the needs of all the residences and the common property. There is even a surplus of 3.50 kWh that is sold to the market, generating income for the energy community (i.e., reducing the long-time electricity bill for the energy of the common property that is paid together by the community members). An assumption was made that for the sold energy, one-third of the consumer purchase price is compensated for the energy sold to the grid based on an estimation that the energy purchase price consists roughly of three equal-sized components of energy cost, network services, and taxes.

2.3 Application scenarios

So far in this dissertation, multifamily residential buildings have been used as an example of an energy community with a shared PV installation. However, energy communities are not constrained to consist of one multifamily building only. An energy community can be formed from multiple buildings, including (detached) single-family homes. In such a case, instead of the shareholders of the housing cooperative, individual houses have a share of a separate PV installation located typically within proximity of the houses. This can be done in either a rural setting where, e.g., farms share a larger PV installation, or in a suburban environment where, e.g., families living on the same street or cul-de-sac together own a PV installation in either someone's property or in a co-owned space.

Whether the energy community is formed in a multifamily residential building or a group of single-family homes, the principles considering the energy allocation are the same, and thus, a blockchain-based energy balancing ledger can be applied to both use cases. The energy allocation in a single-family home energy community is carried out like in the scenario in the multifamily residential building example. However, single-family home energy communities do not have any common property that needs energy. Furthermore, because of the larger distance between the prosumers, the reliance on the DSO grid is higher, and the DSO waiving intracommunal transmission fees completely may not be justified. Building parallel networks especially in rural areas where the distances are longer is not viable to avoid DSO network service fees. Still, it can be argued that differentiating the intracommunal and extracommunal network services (Fig. 2.8) is reasonable, and some kind of arrangement with the DSO should be negotiated. For example, a discount (e.g., 50% price reduction) on the network service fee for the intracommunal transmission of energy could be negotiated for the PV installation energy especially if there are some benefits also for the DSO. This would be more cost-reflective than the intracommunal transmission being as costly to the prosumer as the transmission of energy from the energy supplier using a much larger proportion of the DSO grid. However, the economic benefit from a shared PV installation in a single-family home energy community is promoted, compared with one in a multifamily residential building, by the lack of common property requiring energy, even if the DSO places a fee on the intracommunal network use.

Despite the fact that the differentiation of network service pricing of intracommunal and extracommunal energy transfer can be prospectively justified, the current electricity market legislation, at least in Finland, does not allow this kind of tariff structure. The net-

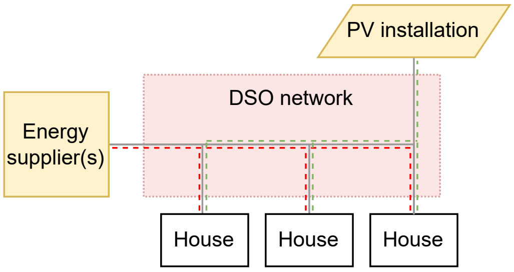


Figure 2.8: Intra- and extracommunal energy transfer could be differentiated, even if they both utilize the DSO network (**Publication III**).

work service pricing of the DSO has to follow certain limitations that are enforced by EU and national legislation. EU legislation mandates that the network service pricing is cost-reflective, transparent, and nondiscriminatory. For example, in Finland, the Finnish Electricity Market Act §55 (Sähkömarkkinalaki 9.8.2013/588) mandates that distance is not allowed to be used as a basis of network service pricing, and it is not allowed to offer different pricing models to a certain group of a DSO's customers within the same customer segment (e.g., among household customers). This means that at least within the boundaries of the current legislation, the considerations presented in this dissertation for network service pricing are not possible. That being said, consideration and implementation of new tariff structures are allowed within the current electricity market legislation, but the tariff structure has to meet the constraints of the legislation. The considerations of this dissertation can, however, be regarded as a conceptual work when assessing the economic viability of energy communities.

2.4 Simulations of energy sharing

To test the viability of the blockchain-based energy balance settlement ledger and the proposed energy allocation principles, simulations were run using real-life energy consumption data. The target of the simulations was to find out how well the system suits different use case scenarios. This was tested with a simulation experiment to study the energy self-sufficiency rate of a multifamily residential building with a PV installation where the energy allocation is done using the presented methods and compare it with a conventional PV setup where the PV energy is used only to supply energy to the common property. In addition, the effect of intracommunal network service pricing on the economic viability of an energy community in a single-family home energy community was studied with a simulation.

The energy consumption data used for the simulations are real energy consumption data from single-family homes from Lappeenranta, Finland. The dataset contained hourly energy consumption data from different consumption locations for the year 2014. The data were annotated to include information of whether the location, besides an electrical services connection, had also a district heating connection. In addition to the energy consumption data, PV production data from the same year were collected from the flatroof PV installation of LUT University. These PV production data, when scaled down, can be used to emulate different PV installations in energy communities.

2.4.1 Self-sufficiency of a multifamily residential building

To determine the energy self-sufficiency rate S_{PV} of an energy community within a multifamily residential building, a simulation for one full year was run for an imaginary energy community consisting of 39 apartments. Each of the apartments was entitled to an equal proportion of the produced PV energy during a state of excess ($R_{\mathrm{PV}} \geq 0$). As the energy consumption data used for the simulations originate from single-family homes, the annual energy consumption of the houses is too large to represent apartments. Therefore, the consumption values were scaled down to better represent apartments in a multifamily residential building. The typical energy need of a Finnish apartment is approx. 1500–2500 kWh/a, and thus, the energy consumption data of the homes were scaled down with a factor of 2.5. Despite this approximation, the energy consumption values can be considered to match the energy needs of a typical Finnish apartment, especially since the houses selected were heated with district heating, which is a common way to heat Finnish/North European multifamily residential buildings, and which reduces the seasonal energy consumption caused by heating. The apartments in the final test dataset had an annual energy consumption ranging between 921 kWh/a and 5284 kWh/a, the average and median being 2423 kWh/a and 2217 kWh/a, respectively. The PV production data were scaled down to match a 15 kW installation. The PV self-sufficiency rate S_{PV} is calculated by

$$S_{\mathrm{PV}} = 1 - \frac{\sum E_{\mathrm{D}}}{\sum E_{\mathrm{A}_i} + \sum E_{\mathrm{C}}}, \tag{2.6}$$

where $\sum E_{\mathrm{D}}$ is the *annual* energy deficit (Eq. 2.4), and $\sum E_{\mathrm{A_i}}$ and $\sum E_{\mathrm{C}}$ are the annual energy consumption of the apartments and the common property.

If the energy is allocated within the energy community using the methods described in Section 2.2.1, in terms of self-sufficiency, the proposed system outperforms a conventional PV setup where the PV energy is used only in the common property. The energy self-sufficiency rate for the proposed system in the test conditions is 9.61%, and for the conventional system with a similarly sized PV installation it is only 4.03% (Fig. 2.9). Table 2.4 shows the detailed energy production values including expenditures and income from energy sold to the market. It is noteworthy that in a conventional PV setup the income from sold energy is much higher than in the proposed system. However, this is not enough to offset the monetary benefit from the residents being able to directly use the energy in their apartments (Fig. 2.10). The cost of energy in this simulation is set at a fixed rate of 0.2134 €/kWh, including taxes and network service fees. For the energy sold back to the market, an approximation is made that one-third of this rate is compensated. The intracommunal network service charges are waived.

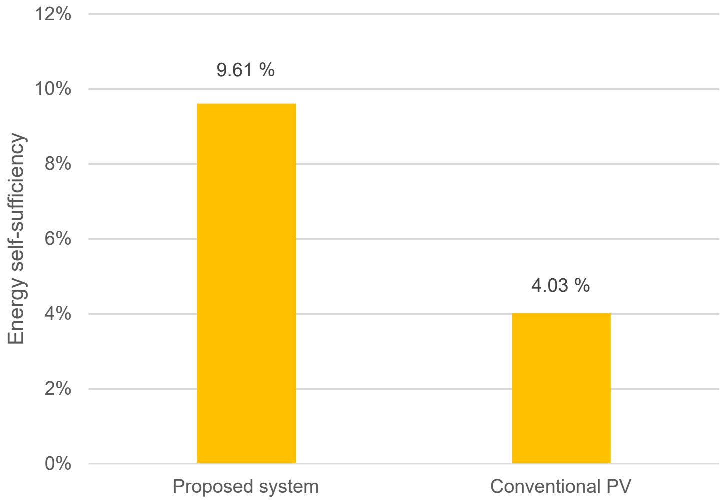


Figure 2.9: Simulated energy self-sufficiency in the proposed system (9.61%) is higher than one in a conventional PV arrangement (4.03%) (**Publication I**).

Table 2.4: Comparison of the proposed system with a conventional PV system where the PV energy is only used in the common property and with a similar building with no PV at all

	Proposed system	Conventional PV	No PV
Energy consumption ($\sum E_{\mathrm{A}_i} + \sum E_{\mathrm{C}}$) [kWh]	120 008.84		
PV production [kWh]	11 750.72		0
Energy bought ($\sum E_{\mathrm{D}}$) [kWh]	108 539.74	115 242.56	120 084.15
Expenditure [€]	23 162.38	24 592.76	25 625.96
Energy sold [kWh]	206.31	6909.13	0
Income[a] [€]	14.68	491.47	0
Total energy expense [€]	23 147.70	24 101.29	25 625.96
Self-sufficiency (S_{PV})	9.61%	4.03%	0%
Monetary benefit[b]	2566.31	1524.67	0

[a] If one-third of the consumer purchase price of energy is compensated when sold to the grid

[b] When compared with not having any PV system installed

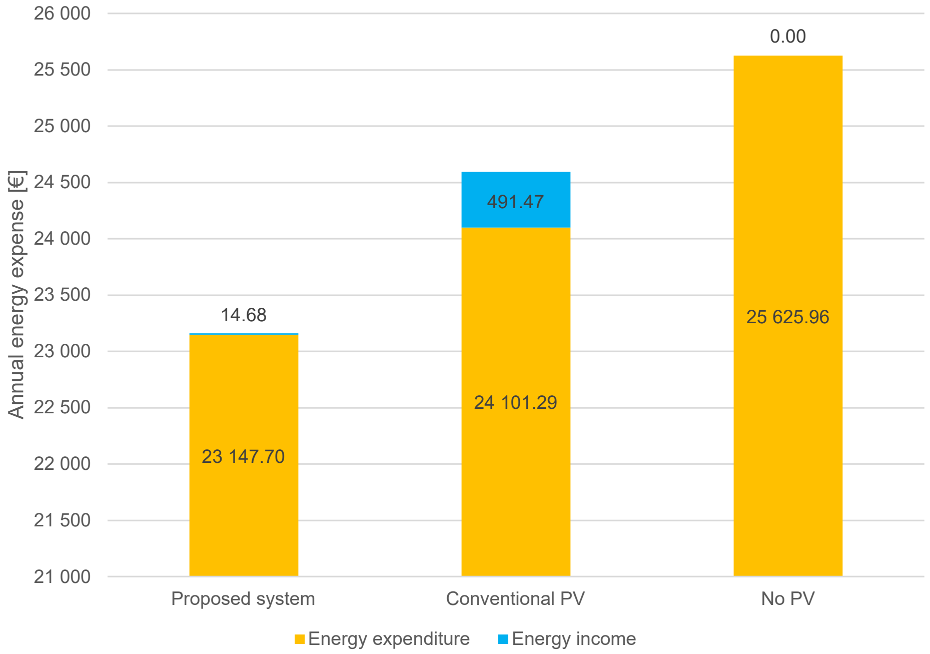


Figure 2.10: Simulated annual expenses on energy in a 39-apartment multifamily residential building using the proposed arrangement, a conventional PV system and one without any PV. The conventional arrangement produces more income than the proposed one, but the total expenses are lower (**Publication I**).

2.4.2 Intracommunal network service pricing

As discussed above, energy communities can come in multiple forms, and they are not limited to multifamily residential buildings. An energy community can also be formed from single-family homes. A single-family home energy community is likely to rely on the DSO network for intracommunal energy distribution. Therefore, a simulation was performed to test how much this intracommunal network service pricing affects the economic viability of a single-family home energy community in a rural or a suburban environment. The simulation uses the same dataset for the source of energy consumption data, but for the members of the simulated energy community, six houses were selected that did not feature a district heating connection. The energy consumption of the houses varied between 12 099.7 kWh/a and 20 148.59 kWh/a, the average and median consumptions being 14 316.75 kWh/a and 13 499.41 kWh/a, respectively. This rather high annual energy consumption combined with the fact that the selected houses did not have a district heating connection suggests that the houses were mainly electrically heated, which is common for single-family homes in Finland.

For the simulation, the households were all assumed to have a dynamic pricing model for their electrical energy. The hourly energy cost data were retrieved from NordPool, which is a pan-European power exchange representing the transmission system operators of the Nordic and Baltic countries. From NordPool, the history data for the hourly energy cost were used, but to make the scenario more up-to-date, the hourly prices were scaled up with a factor of 4.28, because the dataset featured data from the year 2014. This increased the average energy cost (from 0.036 €/kWh) to match the average cost of Finnish NordPool spot energy in 2022 (0.154 €/kWh). The cost of network service was 0.0465 €/kWh as per the pricing of the local DSO in the Lappeenranta region. The simulation was performed to cover one full year with different scenarios where the six-household energy community shares a 5, 10, or 15 kW PV installation while the intracommunal network service pricing is at 0% (free intracommunal network services), 50% or 100% of the standard DSO network service pricing. For a situation where the PV production exceeds the energy consumption of the whole community, the remaining energy is sold to the market, and the same assumption is made as in Section 2.4.1 that the energy sold to the market yields one-third of the energy retail price.

In a scenario where there is no PV present, the annual expenditure on energy for the whole community is €17 517.69 (Table 2.5). This sum also contains the extracommunal network service charges for energy distribution from the energy suppliers to the houses. Adding a PV installation reduces this cost annually between €503.22 and €1655.71, depending on the PV installation capacity and the intracommunal network service pricing (Fig. 2.11). The savings are calculated by subtracting each cost from the cost of energy when there are no PV installations present. The revenue from sold excess PV energy is added to this value. This revenue is only dependent on the installed PV capacity and not on the intracommunal network service pricing as the network services for this energy transmission are extracommunal.

Table 2.5: Combined total annual energy costs of the energy community with different intracommunal network service pricings and PV capacities (rounded to the nearest full euro)

	Intracommunal network service pricing		
PV capacity	Free intracommunal network services (0%)	50% pricing reduction	Full price (100%)
No PV	€17 518		
5 kW	€16 839	€16 927	€17 014
10 kW	€16 292	€16 444	€16 596
15 kW	€15 862	€16 057	€16 251

The revenue generated by increasing the installed PV capacity is not as significant as the savings made from being able to use the PV energy directly in the community. Further, the savings potential of possible intracommunal pricing reductions are also greater than the profit from selling energy to the market (Fig. 2.11). The results suggest that even a rather small 5 kW shared PV installation can generate monetary benefit for an energy community without any prosumer input. Increasing the installation capacity and reducing the intracommunal network service pricing will both increase the monetary benefit.

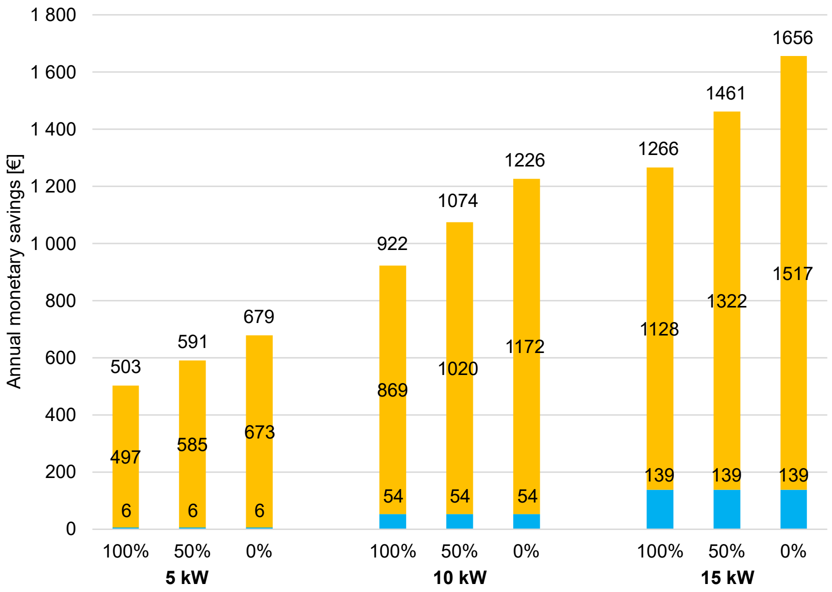


Figure 2.11: Annual monetary savings in € for the whole community with PV installation capacities of 5, 10, and 15 kW when the intracommunal network service pricing is 0%, 50%, and 100% of the standard DSO network service pricing. The savings consist mainly of the benefit from the price reduction (yellow), but also slightly of the income from the sold energy (blue) (**Publication III**).

The effect of the variables can be seen when assessing the scenarios featuring different installation capacities individually (5, 10, and 15 kW) and comparing the monetary savings with a scenario with no PV installed. With a 5 kW installation, halving the intracommunal network service pricing to 50% will increase the monetary savings by 17.45%. With 10 and 15 kW installations, the figures are 16.4% and 15.37%, respectively. When assessing the increase in savings when the network service fees are waived completely (from 100% to 0%), the figures are 34.91%, 36.16%, and 30.74%. The savings percentage is thus not dependent on the installation capacity, but rather on the reduction in the intracommunal network service pricing. This is because the PV installation will generate economic benefit even if full pricing is imposed on the intracommunal network services.

Regardless of which kind of energy community is formed and what kinds of energy allocation rules are agreed upon, the prosumers have to understand how the electrical system works and what it means to co-own a PV installation. Even with the simplest and most straightforward PV sharing sharing methods, additional motivation is needed to engage the prosumers to get the most out of the local PV installation. Making the prosumers actively participate in energy auctioning may not be meaningful—efficient use of the available energy resources (e.g., demand response) can be argued to be a more effective and rewarding way to optimize energy usage. For raising awareness about this, serious games and gamification can be seen as a prospective method.

3 Serious gaming and gamification

Video games are sometimes considered related to television, a next step from (educational) television programs. They are more interactive than television, and allow introduction to new concepts, event recreation, and motivation to learn without being aware of it (Schwarzwalder, 2008). In addition, video games can have educational aspects even if they are not made specifically for educational purposes. Schwarzwalder (2008) mentions *Cooking Mama* as an example of such a game. In the game, the player prepares food, but the motivation for playing the game can come from entertainment rather than from the desire to learn how to cook. This is in line with the definition of a serious game presented by Dörner et al. (2016). The same observation on simultaneous entertainment and education can be made about educational television programs also (e.g., cooking shows), but serious games can provide more interaction and feedback to support learning.

3.1 Serious games as educational tools

Serious games promote learning in a few different ways. According to Mitgutsch (2011), learning takes place both in-game when the player gathers information and reacts to stimuli, and also in real life when making decisions and relating to the data they have gathered by playing the game. This educational content has to be somehow included in the game, which is not necessarily a straightforward task to accomplish. Embedding educational content in the game can be considered one of the major design choices and challenges when designing a serious game. An arguably low-effort method for including educational content is *extrinsic design*, where the main game content is occasionally interrupted with a learning task (Dörner et al., 2016), or a gameplay element is a reward for succeeding in an educational challenge (Marfisi-Schottman, 2020). Extrinsic design means that the main gameplay element can be completely separated from the educational content of the game. An example of such a design would be a character-based action game where the play session is periodically halted with a quiz session. This kind of content can be seen as annoying since it blocks the main gameplay element. Therefore, *intrinsic design* is preferred, which means that the gameplay itself is educational like in simulator games (Dörner et al., 2016; Marfisi-Schottman, 2020). Sometimes this kind of design is referred to as *stealth learning*, which means that the educational content is hidden in the main gameplay content (Dörner et al., 2016). Breuer and Bente (2010) claim that players dislike or even reject games because they are labelled as educational. Therefore, it can be argued that stealth learning and intrinsic design are features that are desirable in a serious game.

Serious games are also recognized in the field of education, and using them in educational institutes like schools and in higher education seems promising. Gamification is argued by Fernandez-Antolin, Río, and Gonzales-Lezcano (2021) to make the experience of learning more enjoyable and resulting in a better reception of the taught knowledge. Learning happens in different ways, and one method for learning is learning through experiences.

Experiences can come from real life or from the digital world, such as educational simulations or even serious games. However, it is important to differentiate plain simulations from serious games. Although they can cover same topics, not all simulations can be considered a game if they lack game elements like being able to win or compare how well a player has played (Imlig-Iten and Petko, 2018).

One could argue that educational institutes should adapt to the present world and seek methods to improve learning results by exploring options of how the teaching is conducted. People who are currently in school have lived their lives in the digital age. Sánchez-Mena and Martí-Parreño (2017) argue that serious games can be used to enhance the motivation for learning for people who are digital natives and feel that traditional learning methods are demotivating, or have grown up in the age of games. However, active learning methods like gamification are not yet widely adopted in higher education (Murillo-Zamorano et al., 2021). Reasons for this underutilization include the requirement of a lot of skills to develop a serious game, from deep understanding of the material, instructional design, game design, and learning theory to digital game programming skills (Dimitriadou et al., 2021). Thus, making a game, e.g., for a single course in a university, is a considerable task. Furthermore, making a serious game usually ends up as a team effort because one person is unlikely to have all the required skills to make the game. Team work, on the other hand, requires more time, money, and resources, which may not be available (Dimitriadou et al., 2021). Marfisi-Schottman (2020) suggests that the use of professional game developers would be ideal, but is often too costly, and therefore, instead of programming a game from scratch, teachers should consider premade game development tools, which allow game development without programming. Despite the above-mentioned barriers that prevent the rollout of serious games and gamification in education, one could argue that the advantages that serious games present as an educational tool should encourage people in education to consider looking into serious game utilization and/or development. That being said, a serious game may be likely to fail in its (educational) target if the game is not designed well.

3.2 Serious game design

Serious games can take various forms, and the type of game depends on the game audience and the topic that the game aims to teach the player. The development of digital games can roughly be categorized into three parts: conception, design, and production (Freyermuth, 2015). Out of these three, the importance of design can be emphasized. For example, Paciarotti, Bertozzi, and Sillaots (2021) state that the design phase of a serious game is important because the players of the game are the recipients of the game and the success of reaching the educational target relies on the quality of the experience.

The gameplay elements are what make the player of the game interested in the game and also what keep the player motivated to continue playing. Video games keep the player motivated to continue playing by showing that the player actions contribute to making progress, and by giving the player rewards for successful play. When the game gives a feeling that progress is being made, it reduces the chances of the game feeling boring, and the player is less likely to abandon the game. This is also true for serious games, and in order for the serious game to be effective, it must be enjoyable to play regardless of the educational outcome. Here, serious games have an advantage over their nonserious counterparts in that they can also provide rewards in real life and not only in game. This can take place, e.g., by learning to communicate by using a foreign language or to cook a previously unknown dish, or by gaining knowledge on how to engage in demand response in one's home. However, this indirect feedback alone can be too delayed to provide enough incentive for the player to keep playing the game. Therefore, also in-game rewards are required, and the players have to be engaged in the same way as players of nonserious games.

Keeping the player engaged in the game requires that the player is motivated to keep playing. Different game elements can be used to accomplish this. The effectiveness of these elements depends on the player, and Reyssier et al. (2022) suggest that the elements are selected for each game to best suit the target audience of the game. Common examples of motivational game elements include virtual collectibles like achievements, trophies, and badges, and they are said to have a greater educational impact than, e.g., educational messages (Mulcahy et al., 2021). Thus, educational messages can be identified as a valid form of instant positive feedback (Wang and Sun, 2012). The difficulty of the game can also work as a way to engage players and make them go into a state of “flow” (Laffan et al., 2016). This can take place, e.g., by introducing penalties for poor performance, like making the player to retry a level in the game. This kind of game design used to be popular in arcade and early console games, but it can appear intimidating, and thus, punishing mechanics are less common in casual gaming where the target is to make the threshold of play as low as possible. A classic way to keep players engaged in the game and motivated to improve their performance is utilization of a scoring system. Games that keep score are everywhere from sports to arcade games, and the desire to beat your friend's high score either in bowling or in *Tetris* can be something that motivates the player to continue playing. Wang and Sun (2012) discuss categorization of different forms of reward, and mention that scoring systems are often categorized as glory rewards. Nebel et al. (2016), in turn, state that leaderboards are impactful since they both induce competitiveness and and give praise for performing well. However, not all players are competitive, and if the game feels like a competition, it can be intimidating for certain players that prefer to play and enjoy the game without their performance being compared with others. Therefore, implementing multiple distinct elements of game engagement can be argued to be reasonable. Other identified engagement methods include plot animations (i.e., rewarding the player by showing how the game story progresses), feature unlocking, and experience points (Wang and Sun, 2012).

Considering that a serious game has a target or accomplishing something other than just plain entertainment, the selection of gameplay elements is crucial so that they support learning and keep the player interested in the game. Johnson (2012) states that it is important to distinguish the theme and the meaning of a game, and that the game meaning should emerge from the mechanics of the game rather than from the game's theme. A serious game should then ideally be based on intrinsic design so that the rewarding game mechanics incentivize the player to both keep playing and to make the player make better choices in real life. Punishing and rewarding game mechanics guide the way the player plays the game and show the player what the game is about (Johnson, 2012). In the case of serious games, these mechanics will also guide how to act outside the game.

To make the player learn through playing a serious game and not just during playing it, the game world should be as relatable as possible. When considering a serious game that teaches, e.g., optimizing one's energy consumption habits, the game world should reflect the players' actual real-life surroundings as well as possible. The player should not need to interact in-game with appliances and things that are completely unfamiliar and meaningless to them. As an example, Wu, Liu, and Shukla (2020) state that simulation-type games are easy for the player to identify with.

3.3 Serious games in energy

Various serious games considering energy aspects have been made, and they have been studied widely and shown effective in teaching things about energy. Demand response and shared energy resources (energy communities) are powerful methods for promoting efficient use of energy resources. Engaging in demand response requires active involvement from the prosumer and may also need a behavioral change. Gamification and serious games have been proposed as tools for promoting demand response in (Behi et al., 2020; Zehir et al., 2019). According to Makris et al. (2018), serious games contribute, in addition to demand response, to creation, adaptation, and management of energy communities.

A systematic literature review (**Publication II**) reveals that although serious games considering electricity or energy are numerous, only a handful of games have aspects regarding shared energy resources (e.g., energy communities) or demand response. The target of the review was to investigate which kinds of serious games in energy and electricity there are, while paying extra attention to detecting games with features on the aforementioned topic. The literature review was conducted using the PRISMA principle (Page et al., 2021), which is usually intended for medical research but now used widely also in other fields of study. Research databases *IEEE Xplore* and *Scopus* were selected as the sources of records, and the search terms were selected so that records containing serious gaming and electricity and/or energy were included. The search was done using the following query:

```
"serious game*" AND (energy OR electricity)
```

The search was carried out in March 28, 2022. The query resulted in 77 hits in IEEE

Xplore and 257 hits in Scopus. After removal of duplicate records, 284 unique records were identified. The index terms of the query were selected to be broad so that they will cover the majority of viable studies, and any viable studies are unlikely to be left out. On the other hand, wide index terms resulted in a lot of records being included that are out of the scope of the review, e.g., records that discuss other forms of energy than electrical energy.

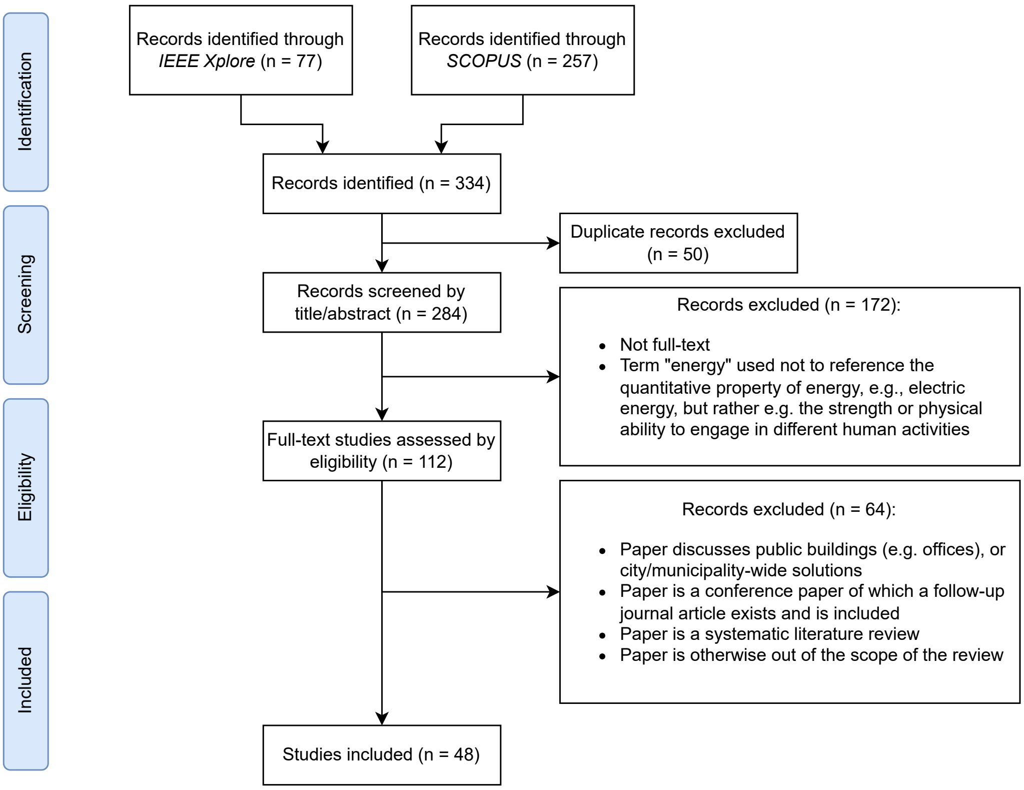


Figure 3.1: PRISMA flowchart of the systematic literature review (**Publication II**).

Following the PRISMA principle (Fig. 3.1), the records were first screened by title and abstract. A large proportion of the records (n = 172) were excluded for either being index lists of conference proceedings, abstract-only papers, or completely outside of the scope of the review. A common reason for exclusion based on being outside of the scope was that the term energy was used to refer to something other than electrical energy, e.g., as the property of having strength or ability to engage in physical activities. This review thus incorporates only records that use the term energy to discuss electricity consumed in buildings, which may be complemented with district heating or heating fuels. The remaining full-text records (n = 112) were accessed for eligibility, out of which a number of articles (n = 64) were excluded. The eligibility assessment revealed whether the records are within or outside the scope of the study. Many records were excluded for being focused on public buildings (e.g., offices) or city/municipality-wide energy solutions instead of a single building or energy community. Additionally, conference papers having/with a follow-up journal article were excluded from the records. In this case, the conference paper was excluded, and the journal paper was included if it was within the scope of this study. Further, other systematic literature reviews and papers that were otherwise outside the scope were excluded, e.g., papers that focus mainly on the Internet of Things, energy production, or augmented reality technologies.

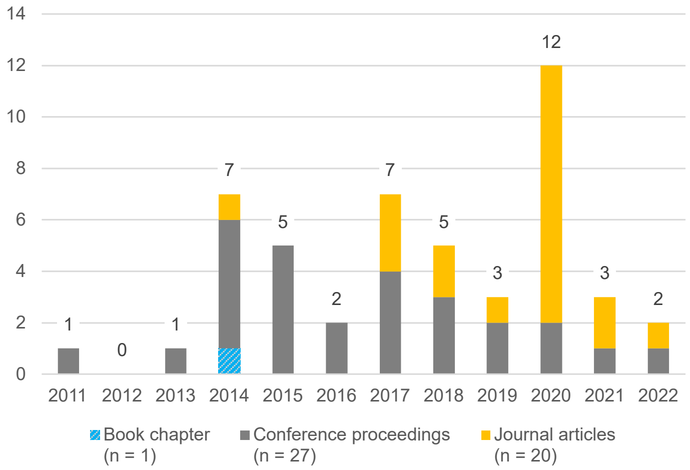


Figure 3.2: Distribution of years of publication and types of publication. The publication year of the records ranged between 2011 and 2022. The most common year of publication in the records is 2020 (n = 12) (**Publication II**).

In total, 48 records were included in the final review. The records contain journal articles (n = 20), conference proceedings (n = 27), and a book chapter (n = 1). The records were published between the years 2011–2022, the most common year of publication being 2020 (n = 12) (Fig. 3.2). The year range shows that the field is emerging and the popularity of the subject is rising, despite the years 2021 and 2022 having a low number of conference proceedings included in the review. The included records were reviewed to determine what games were discussed in them. From each game, the following core elements were identified:

- The **name** of the game;
- The main target **audience** of the game;
- The **availability** of the game (whether the game was effortlessly available/downloadable for everyone in April–May 2022, when the review was conducted);

- The main **educational target** of the game;
- The main **gameplay element** of the game.

In addition to the core features, special attention was paid to investigate the state of the art of serious games that focus especially on shared energy resources, energy communities, and domestic demand response. For this, the following aspects were documented for each game identified in the records:

- **Prizes:** Are there any rewards or prizes (other than in-game awards like badges) awarded to the players of the game if they succeed and play well?
- **Demand response:** Does the game feature demand response in domestic environments as a core game mechanic?
- **Energy communities:** Does the game have aspects about energy communities as a core game mechanic, such as shared energy resources or shared local energy production?
- **Link to real-life events:** Does the game have feature a link to real life, e.g., is the real-life energy consumption, local energy production, energy cost, or the current weather presented in the game and affecting its outcome?

The review resulted in mentions and information about 31 different serious games in energy in domestic environments. Although the term serious games usually refers to digital games, a board game (*Changing the Game – Neighbourhood*) was identified in the review, and it was decided to be included as it otherwise fits well in the scope of the study. The games that were identified varied considerably in complexity and their target audiences; both simple games for children and more intricate games for more grown-up audiences were found. The games intended for children included games that focus more on exploration and teaching the main concepts of energy usage. These kinds of games range from simple quiz games to platformer games, e.g., *Power Pets* (Bayley et al., 2020), where the player controls their virtual pet and learns about concepts of energy. These kinds of exploration games can also utilize the real world like in *The Ghost Hunter* (Wu, Liu, and Shukla, 2020), where the player attaches an electromagnetic field detection device in their smartphone and uses it to find energy-consuming devices in their home. In *ecoGator* (Casals et al., 2017), the players also use their smartphones and scan energy labels of appliances. On the other hand, games for more mature audiences include, e.g., *Social Power Game* (Behi et al., 2020), where the players enter an energy saving contest, and *Energy Cat* (Hafner et al., 2020), which despite its juvenile name, is a living simulator. A common theme among the games in general was the reduction of energy usage, and in many of the records, the viability of a serious game to reach this target was studied. A detailed list of games identified in the survey is presented in full in **Publication II**.

Six games were identified that either contained features regarding demand response or energy communities (Table 3.1):

1. **Social Mpower** (Bourazeri and Pitt, 2014) is a game where multiple players interact in a 3D world, where their target is to ensure that every player's house gets enough electrical energy. The players share a common energy pool, from which only a limited amout of power can be drawn at any moment. The players need to co-operate and coordinate that the power limit is not exceeded.

2. **Sharebuddy** (Brewer et al., 2015) is a casual mobile game that is based on tracking the player's real-life electricity and water consumption. The game presents a timeline showing when it would be the optimal time to use electricity.

3. **DLT Energy Game** (Veeningen and Szirbik, 2018) is a game that focuses on teaching the player about DLT like peer-to-peer trading of electricity by using a cryptocurrency. The emphasis is on displaying of energy transactions and building trust to a blockchain.

4. **Changing the game – Neighbourhood** (Lanezki, Siemer, and Wehkamp, 2020) is a board game where the players cooperate in an imaginary neighborhood in arranging their energy supply while minimizing their CO_2 emissions.

5. **Social Power Game** (Behi et al., 2020) is a mobile serious game where the players enter an energy saving contest. The players are divided into teams of their own neighborhoods, which each have a shared energy resource. The players pursue to use their energy resources in as efficient way as possible, and everyone's consumption history is recorded.

6. **Electric City** (Singh et al., 2015) is a resource management game where the players are placed on an virtual neighborhood on a virtual island. The players have to ensure their house's survival by obtaining energy either by own production or by purchasing it from peer-to-peer market.

The number of games with features of demand response and energy communities can be considered rather low. Possible reasons for this can be that dynamic energy spot pricing is not common in many countries, and therefore, participating in demand response is an unfamiliar concept to make a game about, as there is no direct incentive for the players. Shared energy resources as a trend are even more novel than demand response, and thus, developers of serious games have not yet seen an audience for games featuring them. It is worth noticing that none of the six games had a link to real-life events while also containing features of *both* demand response and energy communities. None of the games had real-life prizes for successful gameplay either. The only exception is *Sharebuddy*, among the players of which people were randomly selected to receive a gift card.

Table 3.1: Games identified with features concerning demand response and energy communities

Game	Demand response	Energy communities	Audience	Target
Social MPower	Yes	Yes	Energy community members	Raising energy usage awareness
Sharebuddy	Yes	No	Students	Showing how demand response works
DLT Energy Game	Yes	Yes	Energy community members	Understanding of DLT
Changing the Game – Neighbourhood	Yes	Yes	Adults	CO_2 reduction
Social Power Game	No	Yes	Households	Behavioral change
Electric City	No	Yes	Unspecified	Energy sharing

A noteworthy finding in the review is that the vast majority of the games identified are not anymore available to effortlessly download and/or play. Only four games out of the 31 identified were accessible, and only *Changing the Game – Neighbourhood* was available in May 2022, but out of stock, because it is a physical board game. This may be due to many of the games being only offered to a small limited audience, among which the effectiveness of the serious game was studied with pregame and postgame surveys. Many studies conclude that serious games are viable tools to raise awareness on, e.g., energy consumption habits. However, one could say that the viability of the tool can be considered reduced if the tools are not available for everyone. Games made for everyone to play regardless of whether the associated research or game development project has ended are not commonplace. This was a motivating factor to develop a novel serious game that has an emphasis on demand response in an energy community. This kind of game, if made available for a wide audience, would be a prospective tool for teaching people about difficult-to-grasp concepts of energy and electricity.

3.4 Prototype serious game

As discussed above, serious games seem to be promising in teaching people many kinds of things, energy among them. However, based on the results of **Publication II**, thus far, no serious game has been developed where the players of the game can practice optimizing their energy consumption and engagement in demand response in which the actions of their home are reflected in the game. This kind of game could be useful to people, but problems arise when the number of real-life elements affecting the game increases. This will increase complexity and limit the audience so that the game can be played only by a group of people who are the providers of real-life event data. Therefore, it would be justified that instead of mandating a real-time link to real-life events, history data and/or simulations could be employed as an alternative when real-time data are not available. In this way, the game can reach a larger audience. Based on these findings, the prototype development started with the following specifications:

1. The game is based on an energy community with shared PV resources.
2. The game rewards the player for good demand response actions.
3. There is an option between a real-life source of data and a simulation.

Meeting these criteria would introduce a novel serious game to the field of energy, which could present itself as a prospective tool for raising awareness of shared energy resources, energy communities, demand response, and of course, the basic concepts regarding energy.

For a serious game to be effective, it must be as relatable as possible for the player and be focused on intrinsic design. A noteworthy example of intrinsically designed games are simulator games. This is because a simulator game tries to replicate the real world as much as possible and allows the player to see what consequences there are for each of their action. The game world should reflect the real world in order to be effective in reaching its educational goals. In a case where the target of a serious game is to promote efficient use of energy in people's homes, it is reasonable for the game to also take place in the player's home.

Based on this foundation, a *life simulator* like the popular *The Sims* franchise was chosen as the genre for the serious game. Alternatively, a real-time energy usage tracker app was also considered, but a more "video-game-like" solution was preferred over a tracker app. Realization of a tracker app would also have to be tailored to a specific player location to retrieve the energy consumption and production data. A tracker app would be essentially a data visualization app with some gamification elements, which is not as engaging as an actual video game, and arguably, may also not provide a significant incentive to induce a potential behavioral change.

The target of the game is to teach the player of the game how to engage in demand response when living in a multifamily residential building with a shared PV installation. In the game, the player controls *an avatar* who lives in an energy community within a multifamily residential building, where the residents share an equal proportion of a rooftop PV installation. The apartment is entitled to free PV energy if there is enough PV production for the energy community to reach the state of excess ($R_{\mathrm{PV}} \geq 0$). The energy consumption that is not covered by the PV installation is bought from the open retail electricity market using a dynamic tariff where the pricing changes once in an hour. Despite the game scenario seeming quite complex, anyone living in a multifamily residential building could be considered a potential audience of the game even if they do not themselves have all the features (e.g., dynamic energy pricing or a PV installation) of the game in their own homes. This is so although it was stated above that it is reasonable for a serious game to replicate the real world as much as possible to be the most effective in reaching its educational goal. However, making an exact copy of the player's apartment in the game would not be sensible because it would require tailoring the game to each player separately. Thus, making the game world to match a typical Finnish/Northern European apartment can be justified, because making the game world not an exact copy but a relatable one is a valuable trade-off. It can be reasoned that the game world is relatable enough to reach the educational target if the appliances in the apartment are the same kinds of appliances that the player would most likely interact with in their daily lives (e.g., kitchen appliances, a television, or a shower).

In order to help a serious game to reach its educational targets, a design framework can be used to guide the design process of the gamified experience. There are various different frameworks; one of such frameworks, GamiDOC (Bassanelli and Bucchiarone, 2022), is an online tool for designing, developing, and evaluating gamified solutions. The tool can be used online to create design documents, and it allows peer review of the documents to evaluate the designs of the proposed gamified experiences and/or serious games. GamiDOC is based on a model that categorizes the game design into five main components and their subcomponents: context, technology, modality, core, and game aesthetics. The *context* component defines the game's *domain* (using taxonomy by Koivisto and Hamari, 2019), *target user(s)*, *aim* (using the taxonomy by Tondello, Premsukh, and Nacke, 2018), and *encouraged behaviors*. The *technology* component tells what is needed to play the game or gain the gamified experience, and the *modality* component classifies how the game is played (individually, cooperatively, competitively, or cooperative-competitively (Morschheuser, Maedche, and Walter, 2017)). The *core* component defines the game's *feedback* method, *game behavior*, *gamification elements* (using the taxonomy by Toda, Klock, et al. (2019) and Toda, Oliveira, et al. (2019)), and *personalization* elements. Finally, the *game aesthetics* component considers the graphical assets of the game (Bassanelli and Bucchiarone, 2022). As GamiDOC relies on scientific publications for the taxonomy of the components, it can be considered a viable tool for designing gamified experiences, including serious games. A GamiDOC-based gamification model of the prototype game is presented in Table 3.2.

The prototype serious game titled *EcoDream* was developed for computers with a Windows operation system using the *GameMaker* game engine. The core target of the game is to take care of the player avatar, who lives in a single-bedroom apartment while using as little money on energy as possible. The avatar has six different *needs* that have to be catered for: *food, endurance, fun, hygiene, comfort,* and *social interaction.* The level of needs will deplete slowly over time, and if any of the needs runs out completely, the game is over. A few exceptions are that when asleep, the endurance level rises instead of decreasing, and an apartment temperature greater than 22°C causes a fast decrease in comfort. In addition, the hygiene deterioration rate is proportional to the dirtiness of the

Table 3.2: GamiDOC-based gamification model of the prototype game, EcoDream

Component	Description
Domain	Education/Learning (Koivisto and Hamari, 2019)
Target users	People who live in a multifamily residential building with a shared PV installation
Aim	Performance (Tondello, Premsukh, and Nacke, 2018)
Encouraged behaviors	The game encourages the players to study how domestic appliances consume electrical energy and how they can optimize their energy consumption based on what is happening in the game world. The players are discouraged to live in a way that is unlikely in real life (e.g., inverting the day–night activity cycle in order to benefit from lower energy prices or wasting energy to maximize avatar well-being).
Technology	Computer/laptop
Modality	Single player, competitive (Morschheuser, Maedche, and Walter, 2017)
Game behavior	The player controls an avatar inside a virtual apartment in a multifamily residential building. The target of the player is to use as little money on electricity as possible, while also catering for the needs of the player avatar. If the needs are ignored, the game ends in a failure. The player is given points based on their performance.
Feedback	Explanatory immediate feedback (Bassanelli and Bucchiarone, 2022) when the game is over
Gamification elements	Points, stats, time pressure, and competition (Toda, Klock, et al., 2019; Toda, Oliveira, et al., 2019)
Personalization	The standard mode is similar for all players. The custom mode allows personalization of the game experience.
Game aesthetics	Prototype game graphics are pixel art influenced by games from early home video game consoles. The artwork is simple in order to promote understandability.

apartment. The player has to engage in activities to cater for the needs of the avatar, and most of them require energy. Performing the activities is optional, but failing to cater for the needs of the avatar will result in the game ending. The player has no restrictions on when each action can be performed, although the avatar has to go to work every weekday (i.e., not Saturday nor Sunday) between 8:00 and 9:00 hrs in the morning.

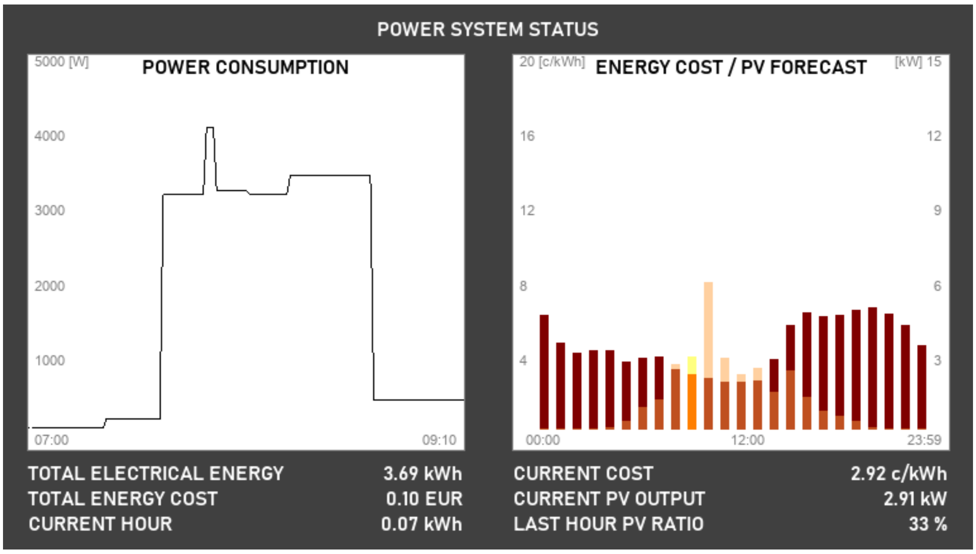
The game window (Fig. 3.3) features the play area of the game. The player avatar is controlled with the keyboard of the computer, and the avatar can interact with the appliances and objects of their home. The avatar's apartment consists of a bedroom, a living room with a kitchenette, and a bathroom. The user interface features the avatar needs as bar graphs on the upper-left corner on the screen. Other important information on the user interface includes current in-game time, date and weather/indoor climate information, current power consumption, and the current PV installation production. Furthermore, the game occasionally displays a list of tasks that the player should complete. These tasks can range from hints to cater for the needs of the avatar (e.g., "Eat something"), or reminding

Figure 3.3: Screenshot of the prototype game, EcoDream, where you can see 1) the player needs, 2) the current in-game time and score, 3) the current in-game date, temperature and tasks, 4) the player avatar, 5) the current power, and 6) the total PV installation production (**Publication IV**).

that the avatar has to go to work.

To increase the authenticity of the game, the game uses real-life data. As the sources of data for the game, the historical PV production data from the PV installation at LUT University and the same household dataset as described in Section 2.4 are used. The PV production data are presented to the player as PV production forecasts. For the energy consumption data, the same downscaling as in Section 2.4.1 is used with a constant value of 2.5 to make the data from detached households to better represent apartments in a multifamily residential building. These data are used to simulate the neighbor apartments in the game. The source for the weather information (i.e., the outside air temperature) is from the open data archives of the Finnish Meteorological Institute. The temperature readings were obtained from the historic data from the weather station of Lappeenranta Airport.

The activities in which the player engages consume different amounts of energy and have different magnitudes of effect on the avatar needs (Table 3.3). The player has to decide when and how to use energy to cater for the avatar's needs. In the game, the apartment energy pricing is based on a dynamic tariff, and the cost of electrical energy changes once every hour. The PV installation provides a constant power output that changes every hour based on the PV production forecast presented to the player. The player can observe these values by bringing up the power system status screen (Fig. 3.4), where they can assess what to do in which situation in order to take advantage of the PV installation and the free energy it provides by engaging in demand response. This can be done, e.g., by moving energy-intensive tasks (if possible) to a time when the PV production is forecasted high or when the energy cost is low.



TOTAL ELECTRICAL ENERGY 3.69 kWh
TOTAL ENERGY COST 0.10 EUR
CURRENT HOUR 0.07 kWh

CURRENT COST 2.92 c/kWh
CURRENT PV OUTPUT 2.91 kW
LAST HOUR PV RATIO 33 %

Figure 3.4: Holding down the control key brings up the power system status screen, where the player can observe the power consumption in their apartment (left) and the energy cost and PV production forecasts (right). (Screenshot zoomed in and cropped for better viewing) (**Publication IV**).

Besides demand response, the player can assess how they use the appliances they have. Some of the appliances have multiple functions. For example, the refrigerator can be used to cook a small snack, a medium-sized meal, or a large feast (Fig. 3.5). Preparing a snack requires less energy than the larger meals, but they improve the avatar needs more. The player must also assess when it is clever to use appliances like the washing machine or the dishwasher. They can be used no matter how full they are, but will always consume the same amount of energy.

Table 3.3: Interactive objects and their effects in the game. The avatar needs that are affected are *italicized*.

Action	Effect	Power [W]	Notes
Bed	+ *Endurance*, + *Comfort*; Halt *Food* & *Fun* depletion	0	Available only if dark and *Endurance* $<$ 50%
Alarm clock	Wakes up the avatar at a selected time	1	
Computer	+ *Fun* (Internet) or + *Fun*, + *Social interaction* (Game)	100[a]/400[b]	[a] Internet, [b] Gaming
Television	++ *Fun*	125	Requires sitting on the sofa
Sofa	+ *Comfort*	0	
Stove & oven	+/++/+++ *Food*	1000–3000	Power use and *Food* increase depend on meal
Refrigerator	Allows selection of the meal to be cooked	20	Requires clean dishes
Dishwasher	Washes dishes	850[a]/50[b]	When [a] washing, [b] keeping dishes warm
Coffee maker	+ *Endurance*	900[a]/50[b]	When [a] brewing, [b] keeping the pot warm
Washing machine	Washes clothes	250	Available if there is laundry in the basket
Shower	+ *Hygiene*	0	Available if the laundry basket is not full
Air conditioner	Reduces the apartment temperature	1300	If the room temperature is above a set point
Lights	Illuminates the room if dark	10–30[a]	[a] 10 W per room
Vacuum cleaner	Cleans dust	900	
Door	+ *Social interaction* (Friend); + *Fun*, – *Hygiene*, – *Endurance* (Exercise); – *Fun*, – *Comfort* (Work)	0	On weekdays, the avatar has to work

The standard game session consists of seven in-game days, which each last 24 min in real time. Thus, each in-game hour lasts 1 min in real time. The game can be sped up when the player desires to do so in order to skip boring parts (e.g., when the avatar is at work or asleep). The player is given a score based on how well they manage the monetary expenses on energy and how well the avatar needs are catered for. After each in-game hour, the player score is increased by P, which is calculated by

$$P = \frac{\min(N_i)}{C_{\mathrm{B}_i} + 0.1}, \tag{3.1}$$

Figure 3.5: Some appliances (e.g., the refrigerator) in the game have multiple functions to choose from. (Screenshot zoomed in and cropped for better viewing) (**Publication IV**).

where $\min(N_i)$ is the minimum value of all the avatar needs during the end of the hour, and C_{B_i} is the billed expense on energy (in euros) over the past hour calculated using Eqs. (2.1), (2.2), and (2.3). The constant value of 0.1 is present in the equation to avoid division by zero error and an excessively high number of points when the billed energy is very low.

The scoring system works as the main engagement factor of the game by providing the player an incentive to play well, because the player is given a score based on their performance. This promotes efficient use of energy resources instead of just plain “survival” of the game. The scoring system is complemented with a leaderboard, which works as the main method of player engagement. Players that have managed to play through the full seven days of gameplay can enter their name on the leaderboard. The leaderboard position will tell the player how well they managed to play when compared with others. If at any moment any of the needs are completely depleted, or the player neglects going to work on a weekday, the game is over and the player is not eligible for the leaderboard.

Besides the leaderboard, additional engagement features should also be considered to make the game more interesting by providing additional goals to pursue and by presenting other kinds of engagement methods to players that may find the leaderboard unappealing. Not all people like competitive games, and the presence of a leaderboard can be intimidating if the player feels unsafe and is afraid to fail. For this, as supplementary engagement content, reward badges can be introduced for playing well or achieving a specific goal. These goals can include, e.g., using $\geq X$ kWh of energy in an hour for free ($R_{\mathrm{PV}_i} \geq 1$), catering all the needs of the avatar over $Y\%$ for a whole day, or spending less than €Z in a day for energy, where X, Y and Z are predetermined values. In addition, the leaderboard itself can be complemented with special mentions for players who have either used the least amount of energy or the least amount of money (i.e., ignoring the main scoring system of the game). These metrics are not suitable as the primary game performance metric, because it can be argued that not many people would like to make their lives miserable to reach extreme monetary and/or energy savings in real life, as there is no leaderboard for such things in real life.

A game like this presents a wide array of opportunities and points that could be developed further. A feature identified in this context is the inclusion of a custom mode in addition to the standard game mode, where the players could change the parameters of the game. These parameters include the length of the play sequence, the number of apartments, the installed PV capacity, the heating method, and the appliances that are present in the apartment (Table 3.4). In this way, the player is able to make the apartment to better match their actual living arrangement. Even the dataset used for the energy consumption of the neighbors, the weather data, and the PV production (forecasts) can be altered or replaced, if an alternative source of data is desired.

Table 3.4: Different game modes and their differences

Mode	Standard	Custom
Duration	7 days[a]	1–30 days[a]
Number of apartments	16	1–39[b]
Dataset	Standard	Standard or custom
Leaderboard	Yes	No
PV capacity	15 kW	0–99 kW
Heating	District	District or electric
Appliances	All listed on Table 3.3	Custom
Game over if needs or work are neglected	Yes	Optional

[a] In-game time
[b] Maximum of 39 apartments in the default dataset

Changing any of the parameters will, however, present challenges to the engagement and the gamification content of the game. If the parameters change, the leaderboard is not usable, because the scores given are not comparable with each other. Still, the custom mode could work as a complementary “playground” to test how different things affect the gameplay and the energy usage in the game.

4 Results and discussion

Organizing the sharing of the production of a co-owned PV installation is a complex task that falls into the hands of ordinary people. Even if implementation of local PV production or arrangements like energy communities may seem irrelevant for many laypeople at the moment, various kinds of efforts are required for the transition to carbon-free energy and to combat climate change. Therefore, as smart energy solutions can be argued to be crucial, the systems should be as easy to understand as possible, yet containing all the necessary features to make the systems viable.

4.1 Energy sharing methods

The simulations for use cases in energy communities formed from a multifamily residential building (Section 2.4.1) and single-family homes (Section 2.4.2) show that a blockchain-based energy balance settlement can be utilized, and it allows the energy community members to effortlessly gain monetary benefit from a shared PV installation. The novelty of the proposed arrangement is in the fact that the energy community members are able to both directly use the co-owned energy in their homes and maintain their position in the open retail electricity market. This differentiates the arrangement from the state-of-the-art energy communities like the Brooklyn Microgrid, and also from conventional PV setups where the PV energy is used only in the common property (Table 4.1).

Table 4.1: Comparison between different methods of sharing co-owned PV production

	Proposed system	State-of-the-art energy community[a]	Conventional PV	No PV
Residents in the open retail electricity market	Yes	No	Yes	Yes
PV energy for the common property	Yes	Yes	Yes	No
PV energy for the residents	Yes	Yes	No	No
Data architecture	Distributed[b]	Centralized or distributed[b]	Centralized	n/a
Self-sufficiency potential	High	High	Low	None
Energy sharing complexity	Low	High	Low	n/a
Authority	Community[c]	Aggregator or community[c]	Aggregator	n/a

[a] e.g., the Brooklyn Microgrid
[b] e.g., a blockchain-based ledger
[c] Data integrity and immutability assured, e.g., with a blockchain-based ledger

The proposed solution promotes, above all, simplicity and comprehensibility. It could be argued that distributing the ledger and using a solution like blockchain is counterintuitive, and it makes the arrangement more complex than having a centralized authority to govern the energy allocation and intracommunal distribution. However, implementing the system without this central governing agent (i.e., an energy aggregator) allows the residents to effortlessly remain in the open retail electricity market without additional costs that would likely be imposed by the governing agent. The blockchain is arguably quite complex, but the inner workings of it do not directly concern the end users, because the system is only responsible for the secure data storage. On the other hand, the energy allocation scheme that is executed by the blockchain is simple, and it can be argued that it is easy to understand, or at least easier than requiring the energy community members to actively participate in, e.g., energy auctioning. However, active participation in some form is necessary to gain the most out of the shared PV system. Instead of managing the energy allocation, the prosumers can manage their energy usage with demand response to maximize their gains from the PV system. Still, because the system consists of multiple components working together, efforts are needed to enhance the prosumer energy comprehension.

4.2 Prosumer energy comprehension

Promotion of smart grids and prosumer-based energy solutions can be difficult. Even if people want to contribute to the rollout of renewable energy and small-scale distributed production, it may require some effort. Not knowing what the systems do manifests as a barrier that must be overcome, because if the solutions seem intimidating because of a lack of understanding, the willingness to invest in, e.g., a shared PV installation can be low. Thus, it can be argued that an effective way to increase the prosumer energy comprehension is needed before large-scale deployment can be considered possible.

Serious gaming is an emerging trend, which has shown potential as a method of an alternative way to teach people about various topics. One of the major advantages of serious games is that they are, if successfully developed, both enjoyable to play and educational. It could be argued that if a game does not meet both of these criteria, its design has failed to some degree. Determining whether a game is enjoyable or not is not an easy task, and varying answers will likely be obtained when this is asked from the people who play the specific game. Furthermore, whether a game is educational or not depends on how this is defined. The game may pursue to be educational, but one could say that a game is only educational if it is successful in delivering the educational message. Serious games come in various forms, and the method by which they aim to reach the additional goal besides entertainment (e.g., learning) among the players varies significantly. Educational games that are designed to be played by elementary school children in school are completely different from, e.g., simulator games that people of any ages play in their free time for fun. In the latter, the educational content is more intrinsically designed, and one could say that it is hidden in plain sight. It is also worth noticing that if serious games are defined like Dörner et al. (2016) do, educational computer applications that do not contain any entertainment value are not serious games, even though they may be referred to as “learning games” or “educational games” in layman’s terms.

The literature review on the state of the art of serious games on energy and electricity shows that the field is relatively new, and most of the games are simple. First of all, almost all the games identified are no longer available. If the target is to promote prosumer energy comprehension by using serious games, the games should not be strictly for a limited audience but rather playable for everyone interested. Limiting the audience to a test group of, e.g., a case study does not significantly enhance the energy comprehension of the general public. Although the game described in this dissertation does not feature direct real-time data from anywhere, it supports external data sources, and the data with which the simulations are run are authentic. Thus, the game can be played by anyone, and it is not limited to a specific audience but it has an opportunity to be upgraded by switching the data source into something more real-time, e.g,. by using PV production forecasts, intraday electricity spot pricing, and weather information.

In addition to individuals seeking to reduce their energy expenses, also energy companies and DSOs are interested in energy saving technologies. Although this may considered counterintuitive, energy management techniques like demand response are beneficial also for the DSOs, because periods of high peak demand cause stress for the distribution infrastructure. Energy suppliers and consumers both benefit from a low peak demand, because it ensures that there is enough reasonably priced energy available, e.g., in the form of the energy supplier's own production or quotas of purchased low-cost energy.

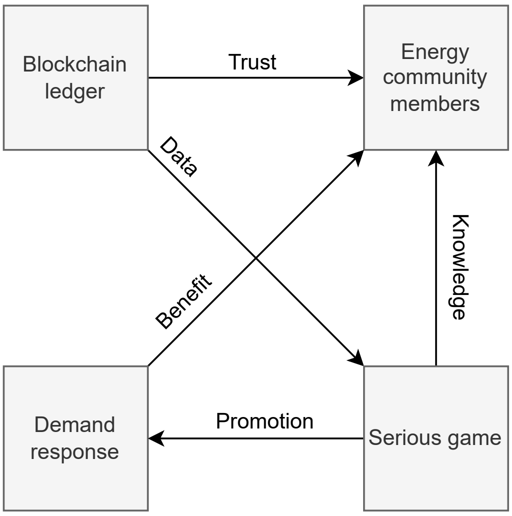


Figure 4.1: Blockchain-based balance settlement ledger, demand response, and serious games are concepts that complement each other to deliver benefit to the energy community members.

When combined, the proposed blockchain-based energy balance settlement ledger and the serious game support and complement each other. Together, they can be used to deliver economic benefit to the energy community members (Fig. 4.1). During the writing of this dissertation, the cost of energy is high in many parts of the world, and especially in the EU. The topics of energy conservation and consumer energy comprehension are very current, and many people seek methods for reducing their energy expenses. A serious game is not a panacea for the problem, but it can be a viable tool among other instruments to enhance laypeople's comprehension on energy. The changes in the power distribution system with a rising emphasis on renewable energy along with dynamic energy pricing, energy communities, and demand response have made the topic perhaps more important than ever. In addition, inclusion of a power component, i.e., network service pricing depending on the (peak) power demand rather than on the quantity of transferred energy, is sometimes proposed as a viable pricing model to promote demand response (Lummi et al., 2017) and to affect the distribution service costs (Pahkala, Uimonen, and Väre, 2018).

In order to better promote these changes in the energy system, it is reasonable that the system is made keeping the laypeople's comprehension in mind. If exaggerated somewhat, it seems like engineers sometimes tend to design things that can only be understood by other engineers in the same field. These kinds of solutions present themselves to the general public as a black box that "does something", which may not make these new innovations as compelling. When designing an energy sharing infrastructure, this issue can be avoided when the emphasis is placed on simple and effortless energy sharing that is complemented by a serious game that can show people how the system works.

5 Conclusions

Implementing increasing amounts of renewable energy is crucial to reach the net carbon neutrality target of the EU by 2050. These renewable energy solutions range from large power plants to smaller systems like PV installations owned by individual households. Between these two are PV installations that are owned by multiple houses or apartments. In this way, people can share the initial financial burden of investing in a PV installation but gain the benefit from affordable PV energy. Furthermore, the initial investment per residence can be lower, because only one inverter is needed instead of multiple ones, even though more money is needed for solar panels (if the capacity is higher than in an installation that would be installed in a single home). These installations, however, are not without problems. Challenges arise in the distribution arrangement of the co-owned PV energy. The intracommunal energy distribution may be subject to the network service charges by the local distribution system operator even if the intracommunal energy distribution does not use the DSO network. In addition, in many cases, the installation shareholders tend to lose their place in the open retail electricity market when they pursue to share locally produced energy in the community with the help of an energy aggregator. Furthermore, many of the proposed energy sharing methods are complex and may seem intimidatingly difficult to laypeople who may find even basic concepts of energy and electricity difficult to comprehend.

This doctoral dissertation studied a solution for energy sharing between energy communities using a blockchain-based energy balance settlement ledger. State-of-the-art energy community energy sharing systems rely on using a centralized energy aggregator, which governs the energy allocation and balance settlement, but result in the energy community members not being individual entities in the open retail electricity market. This dissertation presented a system that allows the energy aggregator to be replaced with a blockchain-based system, which provides, because of the nature of a blockchain, an immutable and secure data storage system. The blockchain removes the need for an aggregator that the community members in state-of-the-art systems use to ensure trust. The blockchain also enables all the energy balancing to be made automatically with any rules desired. If the rules are such that they emphasize simplicity to make them easy to understand, the system can be both economically viable and nonintimidating.

Still, despite underlining simplicity in the design process of the energy sharing rules, understanding the concepts can be challenging because shared PV installations are new. The system is complex and consists of multiple parts, and therefore, to further increase system understandability, this dissertation also studied the viability of using serious games as a method for teaching people about the key concepts of energy in their homes. Serious games are shown to be viable tools for teaching people about various topics, energy among them. This dissertation described the design process of a novel serious game that has an emphasis on more advanced energy management techniques like demand response.

Based on the findings of this dissertation, an energy community with a blockchain-based energy balance settlement ledger is a viable way to arrange co-owned energy sharing. The system should promote low-threshold participation, which can be reached by making the energy allocation system as visible and effortless to grasp as possible. This can be further advanced by educating the (potential) energy community members with a serious game where they can see how their actions affect the energy usage in their virtual apartment. Through the game, people can learn the best practices that they can later implement in real life.

5.1 Further work

Serious games are widely studied, and they have been shown to be effective in teaching various topics. Although the game whose design process was discussed in this dissertation is promising because the design choices are based on solutions that are considered suitable in the literature, empirical data by field testing the presented serious game could be gathered to investigate how much this particular game would induce behavioral change. This would allow for tweaking the game to be more effective in reaching its educational goals.

The blockchain-based energy balance settlement ledger could next be implemented in a pilot building where the presented system could be tested in practice. The pilot building could also be used in the serious game, because it could provide more real-time data sources for the game.

References

Afzal, M., Huang, Q., Amin, W., Umer, K., Raza, A., and Naeem, M. (2020). Blockchain Enabled Distributed Demand Side Management in Community Energy System With Smart Homes. *IEEE Access* 8, pp. 37428–37439. DOI: https://doi.org/10.1109/ACCESS.2020.2975233.

Aitzhan, N. Z. and Svetinovic, D. (2018). Security and Privacy in Decentralized Energy Trading Through Multi-Signatures, Blockchain and Anonymous Messaging Streams. *IEEE Transactions on Dependable and Secure Computing* 15(5), pp. 840–852. DOI: https://doi.org/10.1109/TDSC.2016.2616861.

AlAshery, M. K., Yi, Z., Shi, D., Lu, X., Xu, C., Wang, Z., and Qiao, W. (2021). A Blockchain-Enabled Multi-Settlement Quasi-Ideal Peer-to-Peer Trading Framework. *IEEE Transactions on Smart Grid* 12(1), pp. 885–896. DOI: https://doi.org/10.1109/TSG.2020.3022601.

Bassanelli, S. and Bucchiarone, A. (2022). GamiDOC: A Tool for Designing and Evaluating Gamified Solutions. In: *Extended Abstracts of the 2022 Annual Symposium on Computer-Human Interaction in Play*. CHI PLAY '22. Bremen, Germany: Association for Computing Machinery, pp. 203–208. ISBN: 9781450392112. DOI: https://doi.org/10.1145/3505270.3558345.

Bayley, M., Snow, S., Weigel, J., and Horrocks, N. (2020). Serious Game Design to Promote Energy Literacy among Younger Children. In: *ACM International Conference Proceeding Series*. DOI: https://doi.org/10.1145/3441000.3441047.

Behi, B., Arefi, A., Jennings, P., Pivrikas, A., Gorjy, A., and Catalao, J. P. S. (2020). Consumer Engagement in Virtual Power Plants through Gamification. In: *2020 5th International Conference on Power and Renewable Energy, ICPRE 2020*, pp. 131–137. DOI: https://doi.org/10.1109/ICPRE51194.2020.9233110.

Bourazeri, A. and Pitt, J. (2014). Social Mpower: A Serious Game for Self-Organisation in Socio-technical Systems. In: *2014 IEEE Eighth International Conference on Self-Adaptive and Self-Organizing Systems*, pp. 199–200. DOI: https://doi.org/10.1109/SASO.2014.43.

Breuer, J. and Bente, G. (2010). Why so serious? On the Relation of Serious Games and Learning. *Journal for Computer Game Culture* 4, pp. 7–24.

Brewer, R. S., Verdezoto, N., Holst, T., and Rasmussen, M. K. (2015). Tough shift: Exploring the complexities of shifting residential electricity use through a casual mobile game. In: *CHI PLAY 2015 - Proceedings of the 2015 Annual Symposium on Computer-Human Interaction in Play*, pp. 307–318. DOI: https://doi.org/10.1145/2793107.2793108.

Casals, M., Gangolells, M., Macarulla, M., Forcada, N., Fuertes, A., and Jones, R. (2020). Assessing the effectiveness of gamification in reducing domestic energy consumption: Lessons learned from the EnerGAware project. *Energy and Buildings* 210. DOI: https://doi.org/10.1016/j.enbuild.2019.109753.

Casals, M., Gangolells, M., Macarulla, M., Fuertes, A., Vimont, V., and Pinho, L. M. (2017). A serious game enhancing social tenants' behavioral change towards energy efficiency. In: *2017 Global Internet of Things Summit (GIoTS)*, pp. 1–6. DOI: https://doi.org/10.1109/GIOTS.2017.8016257.

Correa-Florez, C. A., Michiorri, A., and Kariniotakis, G. (2020). Optimal Participation of Residential Aggregators in Energy and Local Flexibility Markets. *IEEE Transactions on Smart Grid* 11(2), pp. 1644–1656. DOI: https://doi.org/10.1109/TSG.2019.2941687.

Di Somma, M., Graditi, G., and Siano, P. (2019). Optimal Bidding Strategy for a DER Aggregator in the Day-Ahead Market in the Presence of Demand Flexibility. *IEEE Transactions on Industrial Electronics* 66(2), pp. 1509–1519. DOI: https://doi.org/10.1109/TIE.2018.2829677.

Dimitriadou, A., Djafarova, N., Turetken, O., Verkuyl, M., and Ferworn, A. (2021). Challenges in Serious Game Design and Development: Educators' Experiences. *Simulation & Gaming* 52(2), pp. 132–152. DOI: https://doi.org/10.1177/1046878120944197.

Directive (EU) 2009/72/EC of the European Parliament and of the Council of 13 July 2009 concerning common rules for the internal market in electricity and repealing Directive 2003/54/EC (Text with EEA relevance) (2009). URL: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:32009L0072.

Directive (EU) 2018/2001 of the European Parliament and of the Council of 11 December 2018 on the promotion of the use of energy from renewable sources (recast) (Text with EEA relevance.) (2018). URL: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:32018L2001.

Directive (EU) 2019/944 of the European Parliament and of the Council of 5 June 2019 on common rules for the internal market for electricity and amending Directive 2012/27/EU (recast) (Text with EEA relevance.) (2019). URL: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:32019L0944.

Dörner, R., Göbel, S., Effelsberg, W., and Wiemeyer, J., eds. (2016). *Serious games: Foundations, concepts and practice*. Springer. DOI: https://doi.org/10.1007/978-3-319-40612-1.

Eurostat (2020). Electricity prices (including taxes) for household customers, second half 2020.

Favuzza, S., Galioto, G., Ippolito, M., Massaro, F., Milazzo, F., Pecoraro, G., Riva Sanseverino, E., and Telaretti, E. (2015). Real-time pricing for aggregates energy resources in the Italian energy market. *Energy* 87, pp. 251–258. ISSN: 0360-5442. DOI: https://doi.org/10.1016/j.energy.2015.04.105.

Fernandez-Antolin, M.-M., Río, J. M. del, and Gonzales-Lezcano, R.-A. (2021). The use of gamification in higher technical education: perception of university students on innovative teaching materials. *International Journal of Technology and Design Education* 31, pp. 1019–1038. DOI: https://doi.org/10.1007/s10798-020-09583-0.

Fernández-Caramés, T. M. and Fraga-Lamas, P. (2018). A Review on the Use of Blockchain for the Internet of Things. *IEEE Access* 6, pp. 32979–33001. DOI: https://doi.org/10.1109/ACCESS.2018.2842685.

Fingrid DataHub Oy (2021). *Electricity retail market business processes in Datahub 6.7.2023*. URL: https://palvelut.datahub.fi/api/documents/file/0-232454-1-294929.

Flymen, D. van (2017). *Learn Blockchains by Building One*. [Online]. Available: https://hackernoon.com/learn-blockchains-by-building-one-117428612f46. [Accessed: 21-May-2021].

Fraternali, P., Herrera, S., Novak, J., Melenhorst, M., Tzovaras, D., Krinidis, S., Rizzoli, A. E., Rottondi, C., and Cellina, F. (2017). EnCOMPASS - An integrative approach to behavioural change for energy saving. In: *GIoTS 2017 - Global Internet of Things Summit, Proceedings*. DOI: https://doi.org/10.1109/GIOTS.2017.8016256.

Freyermuth, G. S. (2015). *Games | Game Design | Game Studies : An Introduction*. transcript Verlag, Bielefeld. Chap. 5, p. 171. ISBN: 978-3-8394-2983-9.

Ghorbanian, M., Dolatabadi, S. H., Siano, P., Kouveliotis-Lysikatos, I., and Hatziargyriou, N. D. (2020). Methods for Flexible Management of Blockchain-Based Cryptocurrencies in Electricity Markets and Smart Grids. *IEEE Transactions on Smart Grid* 11(5), pp. 4227–4235. DOI: https://doi.org/10.1109/TSG.2020.2990624.

Gul, E., Baldinelli, G., Bartocci, P., Bianchi, F., Domenghini, P., Cotana, F., and Wang, J. (2022). A techno-economic analysis of a solar PV and DC battery storage system for a community energy sharing. *Energy* 244, p. 123191. ISSN: 0360-5442. DOI: https://doi.org/10.1016/j.energy.2022.123191.

Hafner, R. J., Fuertes, A., Pahl, S., Boomsma, C., Jones, R. V., Casals, M., and Gangolells, M. (2020). Results and insight gained from applying the energycat energy-saving serious game in UK social housing. *International Journal of Serious Games* 7(2), pp. 27–48.

Hamouda, M. R., Nassar, M. E., and Salama, M. M. A. (2021). A Novel Energy Trading Framework Using Adapted Blockchain Technology. *IEEE Transactions on Smart Grid* 12(3), pp. 2165–2175. DOI: https://doi.org/10.1109/TSG.2020.3045662.

Han, D., Zhang, C., Ping, J., and Yan, Z. (2020). Smart contract architecture for decentralized energy trading and management based on blockchains. *Energy* 199, p. 117417. ISSN: 0360-5442. DOI: https://doi.org/10.1016/j.energy.2020.117417.

Herrmann, M. R., Brumby, D. P., and Oreszczyn, T. (2018). Watts your usage? A field study of householders' literacy for residential electricity data. *Energy Efficiency* 11, pp. 1703–1719. ISSN: 1570-6478. DOI: https://doi.org/10.1007/s12053-017-9555-y.

Huynh, D., Zuo, L., and Iida, H. (2016). Analyzing Gamification of "Duolingo" with Focus on Its Course Structure. In: pp. 268–277. ISBN: 978-3-319-50181-9. DOI: https://doi.org/10.1007/978-3-319-50182-6_24.

Imlig-Iten, N. and Petko, D. (2018). Comparing Serious Games and Educational Simulations: Effects on Enjoyment, Deep Thinking, Interest and Cognitive Learning Gains. *Simulation & Gaming* 49(4), pp. 401–422. DOI: https://doi.org/10.1177/1046878118779088.

Iria, J., Scott, P., and Attarha, A. (2020). Network-constrained bidding optimization strategy for aggregators of prosumers. *Energy* 207, p. 118266. ISSN: 0360-5442. DOI: https://doi.org/10.1016/j.energy.2020.118266.

Jäger-Waldau, A., Adinolfi, G., Batlle, A., Braun, M., Bucher, C., Detollenaere, A., Frederiksen, K. H., Graditi, G., Lemus, R. G., Lindahl, J., Heilscher, G., Kraiczy, M., Masson, G., Mather, B., Mayr, C., Moneta, D., Mugnier, D., Nikoletatos, J., Neubourg, G., Platt, G., Reinders, A., Roberts, M. B., and Ueda, Y. (2020). Self-consumption of electricity produced with photovoltaic systems in apartment buildings - Update of the situation in various IEA PVPS countries. In: *2020 47th IEEE Photovoltaic Specialists Conference (PVSC)*, pp. 0938–0950. DOI: https://doi.org/10.1109/PVSC45281.2020.9300442.

Johnson, D., Horton, E., Mulcahy, R., and Foth, M. (2017). Gamification and serious games within the domain of domestic energy consumption: A systematic review. *Renewable and Sustainable Energy Reviews* 73, pp. 249–264. ISSN: 1364-0321. DOI: https://doi.org/10.1016/j.rser.2017.01.134.

Johnson, S. (2012). Theme Is Not Meaning: Who Decides What a Game Is About? In: *Games, Learning, and Society: Learning and Meaning in the Digital Age*. Ed. by S. A. Barab, K. Squire, and C. Steinkuehler. Cambridge University Press, New York. Chap. 1.3, p. 33. ISBN: 9780521196239.

Khaboot, N., Chatthaworn, R., Siritaratiwat, A., Surawanitkun, C., Khunkitti, P., and Meng, W. (2019). Increasing PV penetration level in low voltage distribution system using optimal installation and operation of battery energy storage. *Cogent Engineering* 6(1), p. 1641911. DOI: https://doi.org/10.1080/23311916.2019.1641911.

Koivisto, J. and Hamari, J. (2019). The rise of motivational information systems: A review of gamification research. *International Journal of Information Management* 45, pp. 191–210. ISSN: 0268-4012. DOI: https://doi.org/10.1016/j.ijinfomgt.2018.10.013.

Laffan, D. A., Greaney, J., Barton, H., and Kaye, L. K. (2016). The relationships between the structural video game characteristics, video game engagement and happiness among individuals who play video games. *Computers in Human Behavior* 65, pp. 544–549. ISSN: 0747-5632. DOI: https://doi.org/10.1016/j.chb.2016.09.004.

Laki sähkömarkkinalain muuttamisesta 108/2019. [Amendment to the Electricity Market Act] (2019). URL: https://www.finlex.fi/fi/laki/alkup/2019/20190108.

Lanezki, M., Siemer, C., and Wehkamp, S. (2020). “Changing the game—Neighbourhood”: An energy transition board game, developed in a co-design process: A case study. *Sustainability (Switzerland)* 12(24), pp. 1–18.

Layer, P., Feurer, S., and Jochem, P. (2017). Perceived price complexity of dynamic energy tariffs: An investigation of antecedents and consequences. *Energy Policy* 106, pp. 244–254. ISSN: 0301-4215. DOI: https://doi.org/10.1016/j.enpol.2017.02.051.

Li, J., Wu, Z., Zhou, S., Fu, H., and Zhang, X. (2015). Aggregator service for PV and battery energy storage systems of residential building. *CSEE Journal of Power and Energy Systems* 1(4), pp. 3–11. DOI: https://doi.org/10.17775/CSEEJPES.2015.00042.

Liu, Y., Wu, L., and Li, J. (2019). Peer-to-peer (P2P) electricity trading in distribution systems of the future. *The Electricity Journal* 32(4). Special Issue on Strategies for a sustainable, reliable and resilient grid, pp. 2–6. ISSN: 1040-6190. DOI: https://doi.org/10.1016/j.tej.2019.03.002.

Lummi, K., Rautiainen, A., Järventausta, P., Heine, P., Lehtinen, J., Apponen, R., and Hyvärinen, M. (2017). Analysis of transition steps towards power-based distribution tariff of small customers. English. *CIRED - Open Access Proceedings Journal* 2017 (1), 2611–2614(3). DOI: https://doi.org/10.1049/oap-cired.2017.0908.

Makris, P., Efthymiopoulos, N., Vergados, D. J., Varvarigos, E., Nikolopoulos, V., Papagiannis, J., Pomazanskyi, A., Irmscher, B., Stefanov, K., Pancheva, K., and Georgiev, A. (2018). SOCIALENERGY: A gaming and social network platform for evolving energy markets' operation and educating virtual energy communities. In: *2018 IEEE International Energy Conference, ENERGYCON 2018*, pp. 1–6. DOI: https://doi.org/10.1109/ENERGYCON.2018.8398797.

Mao, J., Jafari, M., and Botterud, A. (2022). Planning low-carbon distributed power systems: Evaluating the role of energy storage. *Energy* 238, p. 121668. ISSN: 0360-5442. DOI: https://doi.org/10.1016/j.energy.2021.121668.

Marfisi-Schottman, I. (2020). Games in Higher Education. In: *Encyclopedia of Education and Information Technologies*. Ed. by A. Tatnall. Cham: Springer International Publishing, pp. 799–807. ISBN: 978-3-030-10576-1. DOI: https://doi.org/10.1007/978-3-030-10576-1_35.

Mengelkamp, E., Gärttner, J., Rock, K., Kessler, S., Orsini, L., and Weinhardt, C. (2018). Designing microgrid energy markets: A case study: The Brooklyn Microgrid. *Applied Energy* 210, pp. 870–880. DOI: https://doi.org/10.1016/j.apenergy.2017.06.054.

Mitgutsch, K. (2011). Serious Learning in Serious Games; Learning In, Through, and Beyond Serious Games. In: *Serious Games and Edutainment Applications*. Ed. by M. Ma, A. Oikonomou, and C. J. Lakhmi. Springer London, pp. 55–56. ISBN: 978-1-4471-2160-2.

Morschheuser, B., Maedche, A., and Walter, D. (2017). Designing Cooperative Gamification: Conceptualization and Prototypical Implementation. In: *Proceedings of the 2017 ACM Conference on Computer Supported Cooperative Work and Social Computing*. CSCW '17. Portland, Oregon, USA: Association for Computing Machinery, pp. 2410–2421. ISBN: 9781450343350. DOI: https://doi.org/10.1145/2998181.2998272.

Moshövel, J., Kairies, K.-P., Magnor, D., Leuthold, M., Bost, M., Gährs, S., Szczechowicz, E., Cramer, M., and Sauer, D. U. (2015). Analysis of the maximal possible grid relief from PV-peak-power impacts by using storage systems for increased self-consumption. *Applied Energy* 137, pp. 567–575. ISSN: 0306-2619. DOI: https://doi.org/10.1016/j.apenergy.2014.07.021.

Muenzel, V., Mareels, I., de Hoog, J., Vishwanath, A., Kalyanaraman, S., and Gort, A. (2015). PV generation and demand mismatch: Evaluating the potential of residential storage. In: *2015 IEEE Power Energy Society Innovative Smart Grid Technologies Conference (ISGT)*, pp. 1–5. DOI: 10.1109/ISGT.2015.7131849.

Mulcahy, R. F., McAndrew, R., Russell-Bennett, R., and Iacobucci, D. (2021). "Game on!" Pushing consumer buttons to change sustainable behavior: a gamification field study. *European Journal of Marketing* 55(10), pp. 2593–2619.

Murillo-Zamorano, L., Ángel, L. S. J., Godoy-Caballero, A., and Carmen, B. M. (2021). Gamification and active learning in higher education: is it possible to match digital society, academia and students' interests?: Revista de Universidad y Sociedad del

Conocimiento. English. *International Journal of Educational Technology in Higher Education* 18(1). DOI: https://doi.org/10.1186/s41239-021-00249-y.

Nebel, S., Beege, M., Schneider, S., and Rey, G. D. (2016). The higher the score, the higher the learning outcome? Heterogeneous impacts of leaderboards and choice within educational videogames. *Computers in Human Behavior* 65, pp. 391–401. ISSN: 0747-5632. DOI: https://doi.org/10.1016/j.chb.2016.08.042.

Newbery, D. M. G. (1999). *Privatization, restructuring, and regulation of network utilities*. MIT Press.

Nilsson, A., Wester, M., Lazarevic, D., and Brandt, N. (2018). Smart homes, home energy management systems and real-time feedback: Lessons for influencing household energy consumption from a Swedish field study. *Energy and Buildings* 179, pp. 15–25. ISSN: 0378-7788. DOI: https://doi.org/10.1016/j.enbuild.2018.08.026.

Nyholm, E., Goop, J., Odenberger, M., and Johnsson, F. (2016). Solar photovoltaic-battery systems in Swedish households – Self-consumption and self-sufficiency. *Applied Energy* 183, pp. 148–159. ISSN: 0306-2619. DOI: https://doi.org/10.1016/j.apenergy.2016.08.172.

Nykyri, M., Kärkkäinen, T. J., Annala, S., Naukkarinen, J., and Silventoinen, P. (2023). Tutorial Serious Game for Demonstrating Demand Response in an Energy Community. In: *2023 IEEE PES Innovative Smart Grid Technologies Conference Europe (ISGT-Europe) (In press)*.

Nykyri, M., Kärkkäinen, T. J., Annala, S., and Silventoinen, P. (2022). Review of Demand Response and Energy Communities in Serious Games. *IEEE Access* 10, pp. 91018–91026. DOI: https://doi.org/10.1109/ACCESS.2022.3202013.

Nykyri, M., Kärkkäinen, T. J., Levikari, S., Honkapuro, S., Annala, S., and Silventoinen, P. (2022). Blockchain-based balance settlement ledger for energy communities in open electricity markets. *Energy* 253, p. 124180. DOI: https://doi.org/10.1016/j.energy.2022.124180.

Nykyri, M., Kärkkäinen, T. J., Levikari, S., Honkapuro, S., Annala, S., and Silventoinen, P. (2023). The impact of intracommunal network service pricing on the economic feasibility of an energy community. In: *2023 19th International Conference on the European Energy Market (EEM)*, pp. 1–6. DOI: https://doi.org/10.1109/EEM58374.2023.10161928.

Paciarotti, C., Bertozzi, G., and Sillaots, M. (2021). A new approach to Gamification in engineering education: the Learner-Designer Approach to Serious Games. *European Journal of Engineering Education* 46(6), pp. 1092–1116. DOI: https://doi.org/10.1080/03043797.2021.1997922.

Page, M. J., McKenzie, J. E., Bossuyt, P. M., Boutron, I., Hoffmann, T. C., Mulrow, C. D., Shamseer, L., Tetzlaff, J. M., Akl, E. A., Brennan, S. E., Chou, R., Glanville, J., Grimshaw, J. M., Hróbjartsson, A., Lalu, M. M., Li, T., Loder, E. W., Mayo-Wilson, E., McDonald, S., McGuinness, L. A., Stewart, L. A., Thomas, J., Tricco, A. C., Welch, V. A., Whiting, P., and Moher, D. (2021). The PRISMA 2020 statement: an updated guideline for reporting systematic reviews. *BMJ* 372. DOI: https://doi.org/10.1136/bmj.n71.

Pahkala, T., Uimonen, H., and Väre, V. (2018). Flexible and customer-centred electricity system Final report of the Smart Grid Working Group. *Publications of the Ministry of Economic Affairs and Employment 39/2018*.

Parra, D., Walker, G. S., and Gillott, M. (2016). Are batteries the optimum PV-coupled energy storage for dwellings? Techno-economic comparison with hot water tanks in the UK. *Energy and Buildings* 116, pp. 614–621. ISSN: 0378-7788. DOI: https://doi.org/10.1016/j.enbuild.2016.01.039.

Pillai, U. (2015). Drivers of cost reduction in solar photovoltaics. *Energy Economics* 50, pp. 286–293. ISSN: 0140-9883. DOI: https://doi.org/10.1016/j.eneco.2015.05.015.

Pöyry Management Consulting Oy (2017). *Hajautetun uusiutuvan energiantuotannon potentiaali, kannattavuus ja tulevaisuuden näkymät Suomessa. Valtioneuvoston selvitys- ja tutkimustoiminnanjulkaisusarja 5/2017*.

Puranen, P., Kosonen, A., and Ahola, J. (2021). Techno-economic viability of energy storage concepts combined with a residential solar photovoltaic system: A case study from Finland. *Applied Energy* 298, p. 117199. ISSN: 0306-2619. DOI: https://doi.org/10.1016/j.apenergy.2021.117199.

Qi, W., Shen, B., Zhang, H., and Shen, Z.-J. M. (2017). Sharing demand-side energy resources - A conceptual design. *Energy* 135, pp. 455–465. ISSN: 0360-5442. DOI: https://doi.org/10.1016/j.energy.2017.06.144.

Reyssier, S., Hallifax, S., Serna, A., Marty, J.-C., Simonian, S., and Lavoué, E. (2022). The Impact of Game Elements on Learner Motivation: Influence of Initial Motivation and Player Profile. *IEEE Transactions on Learning Technologies* 15(1), pp. 42–54. ISSN: 1939-1382. DOI: https://doi.org/10.1109/TLT.2022.3153239.

Roberts, M., Bruce, A., and MacGill, I. (2019). Opportunities and barriers for photovoltaics on multi-unit residential buildings: Reviewing the Australian experience. *Renewable and Sustainable Energy Reviews* 104, pp. 95–110. ISSN: 1364-0321. DOI: https://doi.org/10.1016/j.rser.2018.12.013.

Sähkömarkkinalaki 9.8.2013/588. [Finnish Electricity Market Act] (2013). URL: https://www.finlex.fi/fi/laki/ajantasa/2013/20130588.

Sánchez-Mena, A. and Martí-Parreño, J. (2017). Drivers and Barriers to Adopting Gamification: Teachers' Perspectives. *The Electronic Journal of e-Learning* 15(5), pp. 434–443.

Saplacan, R. (2008). Competition in electricity distribution. *Utilities Policy* 16(4). European Regulatory Perspectives, pp. 231–237. ISSN: 0957-1787. DOI: https://doi.org/10.1016/j.jup.2008.03.004.

Schwarzwalder, J. (2008). Edutainment Before Second Life. In: *Virtual Worlds, Real Libraries : Librarians and Educators in Second Life and Other Multi-user Virtual Environments*. Ed. by R. B. Trueman and L. Bell. Medford: Information Today, Inc. Chap. 4, p. 33. ISBN: 9781573873611.

Schweiger, G., Eckerstorfer, L. V., Hafner, I., Fleischhacker, A., Radl, J., Glock, B., Wastian, M., Rößler, M., Lettner, G., Popper, N., and Corcoran, K. (2020). Active consumer participation in smart energy systems. *Energy and Buildings* 227, p. 110359. ISSN: 0378-7788. DOI: https://doi.org/10.1016/j.enbuild.2020.110359.

Shafiullah, M., Ahmed, S. D., and Al-Sulaiman, F. A. (2022). Grid Integration Challenges and Solution Strategies for Solar PV Systems: A Review. *IEEE Access* 10, pp. 52233–52257. ISSN: 2169-3536. DOI: https://doi.org/10.1109/ACCESS.2022.3174555.

Siano, P., De Marco, G., Rolán, A., and Loia, V. (2019). A Survey and Evaluation of the Potentials of Distributed Ledger Technology for Peer-to-Peer Transactive Energy Exchanges in Local Energy Markets. *IEEE Systems Journal* 13(3), pp. 3454–3466. DOI: https://doi.org/10.1109/JSYST.2019.2903172.

Simola, A., Kosonen, A., Ahonen, T., Ahola, J., Korhonen, M., and Hannula, T. (2018). Optimal dimensioning of a solar PV plant with measured electrical load curves in Finland. *Solar Energy* 170, pp. 113–123. ISSN: 0038-092X. DOI: https://doi.org/10.1016/j.solener.2018.05.058.

Singh, A., Van Dijk, H. W., Wartena, B. O., Herrera, N. R., and Keyson, D. (2015). 'Electric city': Uncovering social dimensions and values of sharing renewable energy through gaming. In: *Conference on Human Factors in Computing Systems - Proceedings*. Vol. 18, pp. 1519–1524. DOI: https://doi.org/10.1145/2702613.2732929.

Sioshansi, F., ed. (2019). *Consumer, Prosumer, Prosumager - How Service Innovations Will Disrupt the Utility Business Model*. ISBN: 978-0-12-816835-6.

Sousa, T., Soares, T., Pinson, P., Moret, F., Baroche, T., and Sorin, E. (2019). Peer-to-peer and community-based markets: A comprehensive review. *Renewable and Sustainable Energy Reviews* 104, pp. 367–378. ISSN: 1364-0321. DOI: https://doi.org/10.1016/j.rser.2019.01.036.

Sun, L., Qiu, J., Han, X., and Dong, Z. Y. (2021). Energy sharing platform based on call auction method with the maximum transaction volume. *Energy* 225, p. 120237. ISSN: 0360-5442. DOI: https://doi.org/10.1016/j.energy.2021.120237.

the European Union Agency for the Cooperation of Energy Regulators and the Council of European Energy Regulators (2022). *Annual Report on the Results of Monitoring the Internal Electricity and Natural Gas Markets in 2021*.

Toda, A. M., Klock, A. C. T., Oliveira, W., Palomino, P. T., Rodrigues, L., Shi, L., Bittencourt, I., Gasparini, I., Isotani, S., and Cristea, A. I. (2019). Analysing gamification elements in educational environments using an existing Gamification taxonomy. *Smart Learning Environments* 6(1), pp. 1–14. DOI: https://doi.org/10.1186/s40561-019-0106-1.

Toda, A. M., Oliveira, W., Klock, A. C., Palomino, P. T., Pimenta, M., Gasparini, I., Shi, L., Bittencourt, I., Isotani, S., and Cristea, A. I. (2019). A Taxonomy of Game Elements for Gamification in Educational Contexts: Proposal and Evaluation. In: *2019 IEEE 19th International Conference on Advanced Learning Technologies (ICALT)*. Vol. 2161-377X, pp. 84–88. DOI: https://doi.org/10.1109/ICALT.2019.00028.

Tondello, G. F., Premsukh, H., and Nacke, L. E. (2018). A Theory of Gamification Principles Through Goal-Setting Theory. In: *Hawaii International Conference on System Sciences*, pp. 1118–1127. ISBN: 978-0-9981331-1-9.

Valtioneuvoston asetus sähköntoimitusten selvityksestä ja mittauksesta 767/2021. [Government decree on balance settlement and measurement] (2021). URL: https://finlex.fi/fi/laki/alkup/2021/20210767.

van den Broek, K. L. (2019). Household energy literacy: A critical review and a conceptual typology. *Energy Research & Social Science* 57, p. 101256. ISSN: 2214-6296. DOI: https://doi.org/10.1016/j.erss.2019.101256.

Veeningen, J. W. and Szirbik, N. B. (2018). *Using serious gaming to discover and understand distributed ledger technology in distributed energy systems*. Vol. 535. IFIP Advances in Information and Communication Technology.

Wang, F., Ge, X., Yang, P., Li, K., Mi, Z., Siano, P., and Duić, N. (2020). Day-ahead optimal bidding and scheduling strategies for DER aggregator considering responsive uncertainty under real-time pricing. *Energy* 213, p. 118765. ISSN: 0360-5442. DOI: https://doi.org/10.1016/j.energy.2020.118765.

Wang, H. and Sun, C.-T. (2012). Game Reward Systems: Gaming Experiences and Social Meanings. In: *Proceedings of DiGRA 2011 Conference: Think Design Play*.

Wilkinson, S., Hojckova, K., Eon, C., Morrison, G., and Sandén, B. (2020). Is peer-to-peer electricity trading empowering users? Evidence on motivations and roles in a prosumer business model trial in Australia. *Energy Research and Social Science* 66. DOI: https://doi.org/10.1016/j.erss.2020.101500.

Wörner, A., Ableitner, L., Meeuw, A., Wortmann, F., and Tiefenbeck, V. (2019). Peer-to-Peer Energy Trading in the Real World: Market Design and Evaluation of the User Value Proposition. *4th International Conference on Information Systems. (ICIS 2019)*.

Wu, X., Liu, S., and Shukla, A. (2020). Serious games as an engaging medium on building energy consumption: A review of trends, categories and approaches. *Sustainability (Switzerland)* 12(20), pp. 1–16.

Yang, Y., Wang, M., Liu, Y., and Zhang, L. (2018). Peak-off-peak load shifting: Are public willing to accept the peak and off-peak time of use electricity price? *Journal of Cleaner Production* 199, pp. 1066–1071. ISSN: 0959-6526. DOI: https://doi.org/10.1016/j.jclepro.2018.06.181.

Zehir, M. A., Ortac, K. B., Gul, H., Batman, A., Aydin, Z., Portela, J. C., Soares, F. J., Bagriyanik, M., Kucuk, U., and Ozdemir, A. (2019). Development and Field Demonstration of a Gamified Residential Demand Management Platform Compatible with Smart Meters and Building Automation Systems. *Energies* 12(5). ISSN: 1996-1073. DOI: https://doi.org/10.3390/en12050913.

Zia, M. F., Benbouzid, M., Elbouchikhi, E., Muyeen, S. M., Techato, K., and Guerrero, J. M. (2020). Microgrid Transactive Energy: Review, Architectures, Distributed Ledger Technologies, and Market Analysis. *IEEE Access* 8, pp. 19410–19432. DOI: https://doi.org/10.1109/ACCESS.2020.2968402.

Publication I

Nykyri, M., Kärkkäinen, T.J., Levikari, S., Honkapuro, S., Annala, S., and
Silventoinen, P.

Blockchain-based balance settlement ledger for energy communities in open electricity markets

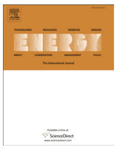
Reprinted under Creative Commons (CC BY 4.0) from
Energy
Vol. 253, p. 124180, 2022

Energy 253 (2022) 124180

Contents lists available at ScienceDirect

Energy

journal homepage: www.elsevier.com/locate/energy



Blockchain-based balance settlement ledger for energy communities in open electricity markets

Mikko Nykyri*, Tommi J. Kärkkäinen, Saku Levikari, Samuli Honkapuro, Salla Annala, Pertti Silventoinen

LUT University, LUT School of Energy Systems, Yliopistonkatu 35, Lappeenranta, Finland

ARTICLE INFO

Article history:
Received 4 November 2021
Received in revised form
12 March 2022
Accepted 1 May 2022
Available online 5 May 2022

Keywords:
Blockchain
Energy community
Smart grid
PV
Solar energy

ABSTRACT

Sharing local co-owned photovoltaic (PV) energy in multifamily residential buildings is inefficient. Energy produced and consumed within the same building may be considered purchased energy, of which the customer must pay the purchase price, the network service fee, and taxes. As PV typically does not allow self-sufficiency in the Nordic countries, a distribution system operator is needed to provide the grid connection. Earlier solutions to this problem are focused on energy communities where an energy aggregator is responsible for the energy balance settlement. However, this does not allow the energy community members to remain in the open electricity market. This paper introduces a blockchain-based balance settlement ledger and a set of rules for energy sharing in energy communities where members participate in the open electricity market while supplied with local low-cost PV energy. This, to the authors' knowledge, has not been previously implemented. The blockchain mitigates the need for any central entity for balance settlement and ensures fair sharing of PV energy. The existing smart meters can be used so no investments are required. The system performance is tested with simulations which show potential for increase in profitability. The self-sufficiency rate increases in our test scenario from 4.03% to 9.61%.

1. Introduction

Energy markets worldwide are going through a major change as small-scale photovoltaic (PV) system installations are becoming increasingly common. The cost of solar panels has gradually decreased [1], which increases interest among consumers and real estate developers to invest in PV systems. As they do so, the energy consumers become producer–consumers—"prosumers", which changes the way electric power is generated, transmitted, and consumed in the grid in a fundamental way [2].

Locally produced PV power is low-cost energy for the installation owners, and therefore, efforts are made to maximize the amount of installed local PV capacity. However, a large amount of installed PV becomes an issue when there is a local imbalance between the produced and consumed energy, especially in situations where more energy is produced than can be used locally. The excess energy can, in most situations, be sold to the grid, but it is usually not profitable when feed-in tariffs are being waived. Thus, PV installation capacities tend to be dimensioned so that as little power is sold to the grid as possible [3,4]. This is because of the unsymmetrical pricing of sold and purchased energy; when taking energy from the grid, the customer pays the energy price, the grid fee, and taxes, while for sales, only the energy price is compensated for the prosumer. Alternative uses for this surplus energy are currently being studied, and, e.g., energy storage systems are often proposed [4,5]. The storage of surplus energy in, e.g., electric vehicles, batteries, or a hot water storage is also deemed a possible incentive and motivation to increase installed PV capacity [6–9].

While in many countries a considerable amount of solar PV has been installed by households, much of this capacity is located on rooftops of single-family homes [10]. This is even if multifamily residential buildings are common and the rooftop areas of these buildings have a significant potential for PV energy (e.g. up to 1.3 GW in Finland) [11]. This potential is however not utilized because of the dimensioning trends favoring small-sized PV installations in multifamily residential buildings. In addition, multifamily residential buildings with shared PV installations face their set of unique challenges and obstacles, requiring coordination and

---

* Corresponding author.
E-mail address: mikko.nykyri@lut.fi (M. Nykyri).

https://doi.org/10.1016/j.energy.2022.124180

agreements between the residents of the building and other entities in the electricity market [12].

At least in Finland, it is common that a multifamily residential building is arranged as a *housing cooperative*. In such an arrangement, each owner of an apartment or a residence in a building owns a share of the cooperative, and the shareholders together are responsible for the maintenance of the building. The cooperative shareholders thus own a small part of the whole building, and the owners together make decisions on, e.g., renovations and janitor work. In a typical Finnish housing cooperative, the local distribution system operator (DSO) owns the energy meters of the apartments, i.e., meters within the apartment building. Any energy flowing through the meter is considered to have flowed through the DSO's grid. Therefore, a distribution fee and taxes are charged even for power distribution from the PV installation to the apartments.

The present-day infrastructure reduces the economic benefits of the local PV energy, as the residents will not be able to use the energy directly in their own apartments. In order to better exploit this potential low-cost energy for the residents or the housing cooperative, new procedures for energy sharing are needed. However, if changes are made to the procedures, the integrity of the energy consumption data and the rules of fair energy distribution have to be ensured as there may be a lack of trust between the residents. In addition, any investments in e.g. metering equipment that have to be made will decrease the profitability of the PV installation. Therefore, a straightforward but robust and secure technical solution based on existing infrastructure is needed. Based on [13], distributed ledger technologies (such as blockchain) are usually necessary in a peer-to-peer energy market.

Recently, energy communities have been the interest of academic research and the utilization of them is proposed to counter the aforementioned problems. However, typically, projects have focused on regions without open retail electricity markets, such as Brooklyn Microgrid [14], the peer-to-peer electricity trading innovation trial in western Australia [15], or the peer-to-peer microgrid pilot in Switzerland [16]. In Ref. [17] it is concluded that research is needed to promote the ways for energy community members to participate in open wholesale and retail electricity markets. To the authors' best knowledge, this kind of research has not been previously carried out.

Common methods among state-of-the art smart grid distribution systems focus on peer-to-peer trading, some with active bidding among peers [18–20]. However, this may prove to be problematic, because many people tend to understand the concepts of energy rather poorly [21,22]. Therefore, it would be reasonable if the energy sharing methodology, logic and rules were as straightforward, clear and transparent as possible to maximize fairness. However, sharing the locally produced PV energy has certain challenges; in Ref. [23] it is argued that the design of a tariff for intrabuilding energy sharing is not simple when it comes to cost-recovery, efficiency, and consumer acceptance. Especially because of the challenges related to acceptance and defining what is considered fair, the target of this study is to promote a simple and effortlessly understandable solution suitable for rapid deployment of PV production.

The novelty of the present study compared with the above-mentioned examples is a fair methodology, which is not dependent on active participation of end-users, does not require new hardware investments, and is interoperable with the present energy market processes. The technical concept presented in this paper promotes effortless (e.g. no active bidding and offering of PV energy) PV energy sharing within a multifamily residential building to, e.g., enhance the energy self-sufficiency of the existing PV system of the building. This paper presents a solution where the produced PV energy is shared fairly between the residents of the housing cooperative. Formation of an *energy community* and a *blockchain-based balance settlement ledger* is presented as a possible solution to this to ensure fair and tamper-proof energy consumption data transfer and storage, without the need for the residents to trust each other. In terms of this paper, *balance* means the matching of the financial transaction to the actual energy consumption so that the prosumers are only charged for the cost of the energy deficit. The concept allows the energy community residents the benefits of local PV energy while still participating in an open electricity market. The solution is in line with the definitions of a citizen energy community (as presented in The European Union (EU) Directive 2019/944 [24]) and a renewable energy community (as presented in EU Directive 2018/2001 [25]). Although this paper studies energy sharing and related issues taking Finnish housing as a case, but the results can also be adopted in other arrangements in other parts of the world.

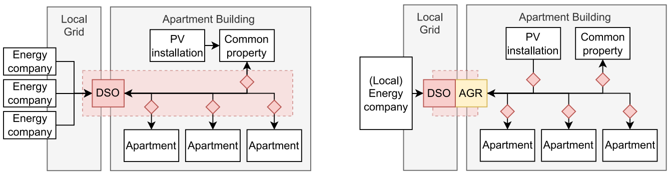
In Section 2, the legal and technical background of energy communities in general and energy communities in an open retail electricity market are reviewed. Section 3 presents the proposed energy sharing solution, the blockchain energy balance settlement ledger, and the energy allocation principles. The viability of blockchain as an energy balance settlement ledger is tested by building a rudimentary proof-of-concept demo platform. Sections 4 provides the results of the study and discussion about the benefits and challenges of an open retail electricity market energy community, along with objectives for future research. Section 5 concludes the paper.

2. Legal and technical framework

The conventional infrastructure of power distribution is based on centralized energy production. Although generation and sales of energy are opened up for competition in many countries, network operations, i.e., transmission and distribution, remain in a monopoly position because of the inefficiency of building parallel networks. In many countries, the infrastructure is optimized for one-directional power flow. The local DSO has a monopoly on power distribution in an area [26,27]. This is also the case in Finland: when it comes to the delivery of electric power, the residents have no choice about the power distributor. However, they do have the possibility to select the *retailer* (aka *supplier*) of the energy itself, and the freedom of being able to do this is backed with legislation [28].

The distribution architecture varies around the world, and depending on the country, the local DSO may, in addition to the power grid in the district, own the actual energy meters [26] and/or also the intrabuilding wiring. However, the main issue of the present-day infrastructure is not necessarily the ownership but the location of the meters. In an apartment building, the transmission infrastructure used to transmit any energy is considered to use the DSO-owned grid, even if this is not the case. Thus, the present-day infrastructure resembles the one pictured in Fig. 1a. In such a case, the DSO is charging not only for the energy transmitted from the grid to the apartment but also for the energy transmitted within the building.

Many people live in apartment buildings where the housing infrastructure outside the apartments itself is shared between the residents. In Finland, such apartment buildings are usually arranged as housing cooperatives. A single housing cooperative contains multiple residences, and if a PV plant is installed on the building, no individual resident alone owns the installation. Therefore, it is justified that the produced energy should be fairly shared and distributed between all of the households of the building, which can be difficult. To avoid the issue of setting the



(a)
(b)

Fig. 1. Conventional (a) and the state-of-the-art energy community (b) infrastructure of power distribution in an apartment building with a PV plant installed. The area controlled by the DSO is presented in red color, and transmission fees are charged whenever power is transmitted through this area. In (b), the DSO's control only reaches up to the energy aggregator (AGR), which acts as the entry point for the community. The meters (aka submetering, indicated by diamonds), even though still owned by the DSO, are left outside the DSO's area.

rules for fair energy sharing, PV installations in housing cooperative buildings today mostly use the locally produced energy only in the common property of the building, for instance, for hallway lighting, ventilation, and other utilities. However, this often leads to the installation of only a small PV system. There would be a significantly higher potential for PV, if the generated energy was shared among the apartments, in addition to the use in the common property.

2.1. Energy communities in the EU and Finnish legislation

Energy communities are new entities in energy markets. According to the definition of the European Parliament (Directive 2019/944 [24]), a citizen energy community is a legal entity that is based on voluntary and open participation and is effectively controlled by members or shareholders that are natural persons, local authorities, including municipalities, or small enterprises. Its primary purpose is to provide environmental, economic, or social community benefits to its members or shareholders or to the local areas where it operates rather than to generate financial profits, and it may engage in generation, including from renewable sources, distribution, supply, consumption, aggregation, energy storage, energy efficiency services, or charging services for electric vehicles or provide other energy services to its members or shareholders [24].

According to the above-mentioned directive, an enabling regulatory framework for citizen energy communities is to be provided by the EU Member States. The participation in a citizen energy community must be open and voluntary, and the members have to be entitled to leave the community. Further, the members or shareholders must not lose their rights and obligations as household customers [24]. In addition to the citizen energy community, Directive 2018/2001 [25] defines a renewable energy community, which has quite similar properties to the citizen energy community, added with the definition that the shareholders or members should be located in the proximity of the renewable energy projects that are owned and developed by the energy community.

The EU Member States adopt the directives to their national legislation. In Finland, rules related to energy communities are defined in the Decree of the Council of State concerning balance settlement and measurement (767/2021) [29]. In the Decree, it is stated that the DSO is responsible for metering of the electricity consumption of the members of the energy community, and the community has to inform the DSO about the local generation sharing principles within the community. Based on the measurements and the information related to the sharing principles, the DSO can calculate the internal balance settlement for the energy community. Based on that, local generation within the energy community will be shared to each member of the community, and the remaining part of the consumption will be the amount that is purchased from a retailer. Such an approach promotes the fair sharing of local generation within an energy community (benefits of local renewable generation for the community) while ensuring that each community member maintains their own electricity purchase contract with the electricity retailer (members do not lose their rights as household customers).

2.2. Energy communities and free choice of supplier

A common intermediate between an energy community and an open energy market is called *an energy aggregator* [30–33] or an energy community service provider, and the application of such an arrangement results in a change in the distribution infrastructure (Fig. 1b). The aggregator is responsible for the distribution of energy within the community [33] and purchasing of energy for the community and its members [34]. In an energy community without prosumer participation in an open retail electricity market, any deficit in PV production is covered by the aggregator without a prosumer input (e.g., from a single source, such as the local energy company). Aggregators usually act independently and can actively bid on energy in order to gain economic benefit [35,36]. The seller of the electricity can take up the role of the energy aggregator, or it can be a third party other than the DSO or the energy supplier.

An open retail electricity market means that each consumer is entitled to choose where they purchase their electric power from. For an energy community to remain in such a market, the participants of the community must maintain this right. This allows the energy community participants to, e.g., negotiate cost profiles that fit their needs, select the source of electric energy to their liking (e.g. fossil, renewables, nuclear) and choose the energy company with which they want to start a customer relationship. Remaining in an open electricity market is also in line with the Finnish and European Union electricity market legislation [28]. Therefore, when participating in an open retail electricity market, the energy aggregator and the community rules cannot state where the electric power to cover the deficit from the PV installation is purchased from. In such a case, the community participants are not in a customer relationship with the energy aggregator when it comes to purchasing the energy itself. This kind of arrangement maintains the present-day system where each apartment forms a contract with a retailer of their choice. Thus, the members of the community, the prosumers, have customer relations to the energy community itself, the energy supplier, and the local DSO (Fig. 2). If an energy aggregator is present, the role of the aggregator in this kind of arrangement would be to act as the link between the apartments and the grid.

Remaining in the open electricity market changes the state-of-the-art prosumer energy community infrastructure (Fig. 1b) so

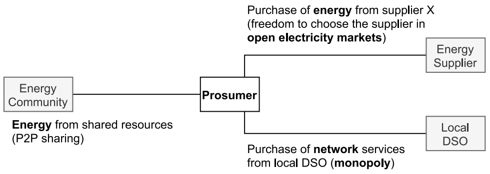


Fig. 2. Prosumer has customer relations to three different actors in the presented electricity market: the energy community, the energy supplier, and the local DSO.

that the number of electricity providers can increase. As each prosumer retains its status as a customer to an electricity provider, the necessity of an energy aggregator is mitigated (Fig. 3). However, this requires a method for ensuring that the rules agreed upon PV energy sharing are followed and secure sharing of the consumption data, e.g., a blockchain-based energy balance settlement ledger is ensured.

3. Proposed energy sharing solution

3.1. Blockchain as an energy ledger

Blockchain is a distributed database, where the pieces of data are stored into interchained containers called *blocks* [37,38]. These blocks contain data as *transactions*, which can hold various forms of information. Each block also contains the *hash* of the previous block, which is a fixed-length string constructed using the transaction data. The hash is the key factor for the security of a blockchain: if data are altered in any block, the hashes are no longer valid and the data can be deemed invalid [37]. Even the tiniest modification causes the hash to change, which makes any data tampering immediately detectable, and thereby ensures immutability of data. This allows blockchain to be used as a secure transaction ledger. Notable examples of such ledgers are Bitcoin and Ethereum.

Blockchain transactions are not limited to cryptocurrency use, and they can also be used for other data. For example, a transaction can contain specifications of a transfer of energy, like the energy consumption data of a residence for a given time span. Therefore, the use of blockchains in the energy market has attracted interest in the research community. Contributions have also been made to peer-to-peer trading of PV energy by using blockchain as a platform for bidding and offering between peer prosumers [19,39]. Blockchain has been deemed a useful tool for energy consumption data storage when combined with smart metering [39,40]. *Smart contracts* are a key part in blockchain technology. They allow automated processing of data based on transactions on the blockchain in the form of a self-executing code. The contract processes data according to predetermined rules that are distributed along the blockchain. Smart contracts have been used, e.g., in demand management [41] and can be used in the energy flow control between nontrusted parties.

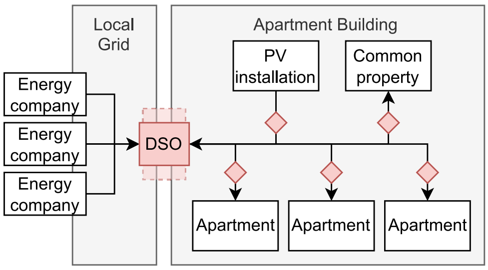


Fig. 3. Power distribution infrastructure in an apartment building managed by a housing cooperative where the residents are members of an energy community. Each resident is an individual customer in the open retail electricity market, and the need for a separate energy aggregator is mitigated. Also in this scenario, the local power distribution company does not control the intrabuilding metering (although still owning the meters), but no transmission fee is charged for power transmitted from the PV installation to the apartments.

Although the use of cryptocurrencies is not needed when a blockchain-based ledger is used, the use of a cryptocurrency in the energy market within energy communities has also been proposed [42]. This shows that blockchain is a technology with multiple use cases, and it is flexible to be used in different kinds of applications, like different energy markets. The viability of a peer-to-system-to-peer-based system in the energy market is studied in Ref. [43], which describes how energy community participants can store their energy consumption data on a blockchain where the system itself is one participant of the ledger. The distribution system presented in this paper features a similar kind of distribution system where the DSO takes part in the ledger but introduces a novel solution for automated energy distribution within an energy community with PV installations and multiple participants.

3.2. Energy allocation principles

The energy consumption of an apartment building consists of the energy usage of the residents and the energy used in the common property. The PV installation is wired to supply energy to the common amenities first and the excess energy is then available to be used elsewhere. Because the PV system is mutually owned and the amenities are required by everyone, there is no real incentive to change this. The possible excess energy is to be shared between the residents in a manner specified in an agreement between each resident and the housing cooperative, e.g., a lease contract or a share agreement by the housing cooperative. Below, an example set of rules is proposed, which could be used for local PV energy sharing in case the energy produced in the housing cooperative is not enough to fulfill the needs of the whole building. The presented rules are based on the logic that each resident receives the same percentage of one's energy consumption as local PV energy, if all the residences own an equal share of the installation.

In an apartment building owned by a housing cooperative, the sources of electric power are *the local grid* and *the PV installation.* In the housing cooperative, energy is consumed in *the apartments, the common property*, and, if present, *electric vehicle charging*. The common property includes elements such as hallway lighting, heating, and air conditioning of the building.

The ratio of the PV energy to the total energy R_{PV_i} is

$$R_{\mathrm{PV}_i} = \frac{E_{\mathrm{PV}} - E_{\mathrm{C}}}{\sum E_{\mathrm{A}_i}} \tag{1}$$

where E_{PV} is the produced PV energy of the building, E_{C} is the energy consumption of the common property of the building, and $\sum E_{\mathrm{A}_i}$ is the combined energy consumption of all the apartments of the building. The values used in calculation are values over a fixed time interval (aka balancing period in the electricity market), which in our example is 1 h.

The amount of PV energy of each apartment $E_{\mathrm{PV,A}_i}$ can then be calculated with

$$E_{\mathrm{PV,A}_i} = E_{\mathrm{A}_i} R_{\mathrm{PV}_i} \tag{2}$$

where E_{A_i} is the total energy consumption of the apartment.

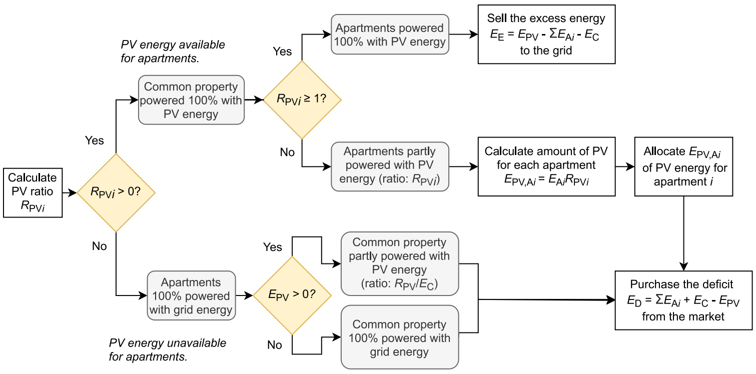


Fig. 4. A flowchart of the hourly energy balancing and allocation principles. The PV ratio (R_{PV_i}) and the amount of PV energy each apartment gets (E_{PV,A_i}) depends on the amount of produced PV (E_{PV}) and the usage of the common property (E_C). After the sharing, any excess energy (E_E) is sold to the grid. In case of a energy deficit, the needed energy (E_D) is purchased from the grid. All the energy amounts represent the energy sums of the last passed balancing period (1 h).

Therefore, each residence will need to purchase E_{PV,A_i} less power from the grid, thus making savings.

Whether and how much the apartments get PV energy is therefore dependant on the hourly PV production and the power needs of the common property. (Fig. 4). A situation may arise that there is excess PV energy production if all the apartments, the common property, and possible electric vehicles are fully powered with local PV energy. In such a case, the excess energy E_E will be sold to the grid, generating income for the energy community. When the local PV production is not enough to fulfill the needs of the whole building, the deficit energy E_D has to be bought from the grid. The amount of sold and bought energy can be calculated using Eqs. (3) and (4).

$$E_E = E_{PV} - \sum E_{A_i} - E_C \tag{3}$$

$$E_D = \sum E_{A_i} + E_C - E_{PV} \tag{4}$$

If electric vehicles are present in the housing cooperative and they are charging, the produced PV energy can also be used to power them. In the example use case, charging of individual vehicles is a low-priority task when it comes to the sharing of PV energy. Therefore, PV energy is supplied to the vehicles if there is excess energy after all the apartments and the common property are fully supplied with power. The amount of local PV energy for each electric vehicle can be calculated in a similar manner as with the apartments.

The energy consumption data (the consumptions of each apartment, the common property, and the calculated shares of local PV energy) are stored in the blockchain-based ledger as transactions. These transactions specify the hourly energy consumption balance throughout the energy community, and the data are stored securely for later use. When the participants of the energy community remain in the open electricity market, the ledger itself can take the role of the energy aggregator.

3.3. Proof-of-concept demo

To test the viability of blockchain as an energy balance settlement ledger, a demonstration platform was built. The platform was designed to receive energy meter data at regular intervals and to store them into a blockchain. The system simulated a real environment where data are gathered from energy meters in a housing cooperative and stored into a blockchain to be used for energy balancing purposes and co-owned PV energy sharing.

In a proof-of-work blockchain, the integrity of the data is guaranteed by the difficulty of creating new blocks. In order to create new blocks in a proof-of-work blockchain, a complex mathematical problem has to be solved, which requires significant computational power. This is usually done by multiple hash calculations. The purpose of this complexity is that it requires a significant amount of work to create new blocks, which makes it difficult to create blocks with potentially false data, thereby altering the chain. Thus, any alteration would result in a need to calculate all the hashes again, which in a proof-of-work blockchain is a very troublesome task. The technology is widely adopted in cryptocurrency blockchain networks, and therefore, a proof-of-work blockchain is suitable also for an energy balance settlement ledger.

The proof-of-concept blockchain platform was programmed in Python using HTTP libraries *Flask*, *jsonify*, and *request*. The control of the blockchain system is based entirely on HTTP, including the communication between the meters and the blockchain, anyone wishing to retrieve data from the blockchain, and between the nodes of the blockchain (Fig. 5.). When in action, the system consists of at least one blockchain node, but can be scaled to multiple nodes (Fig. 6). Each of the nodes contains the following components:

1. **List of nodes:** Each node of the blockchain contains a list of nodes in the system. Whenever a new node joins the system, the new node announces itself to other nodes by using HTTP POST. The other nodes log the IP address of the newly joined node into their list of nodes, and they return the old list of nodes to the newly joined node, resulting in a synchronized list of nodes. The new node also calls for the *consensus algorithm* to validate the chain and retrieve the full and valid blockchain.
2. **Transaction list:** Whenever a transaction arrives via an HTTP POST request, it is placed on a temporary *transaction list* stored on the blockchain node. In our demonstration platform, a single transaction describes the energy consumption of 1 h in one metering location. These data would arrive once per hour from each location (e.g., apartment, PV installation, EV charger)

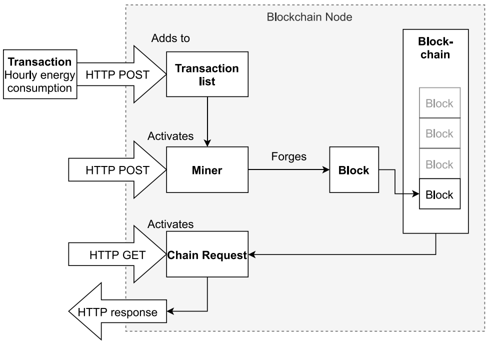


Fig. 5. Flow of data in the blockchain node. The system works on HTTP requests, which move data to and from the node, between nodes, and also to other services, e.g., for billing purposes.

specific meter. This energy transaction contains information about where the energy is coming from, where it is going to, how much energy is transferred, and what was the time window when the energy transaction happened. The transaction list is also used to store the hourly-specific energy cost.

3. **Compensation smart contract:** Each time a transaction is appended to the list of transactions, the status of the transaction list is checked. If all the metering locations, i.e., participating residences and the PV installation, have submitted their hourly energy consumption data, the list is deemed ready. When the list is ready, the shares of PV power can be calculated for the past hour. The calculations are based on the rules presented in Section 3.2. The contract prioritizes the PV energy to the common property, and if there is energy left after powering those premises, a compensation is calculated for each residence, and the adjusted power consumption values are added to the list of transactions. The adjusted consumption values are also converted into cost figures if the current electricity market price is known.
If electric vehicles are charging and there is excess PV energy after supplying the residences with it, these electric vehicles are provided with PV energy by using the same ratio calculation method as with the residences. The remaining energy, if present, is sold to the grid. After the transactions have been processed, the transaction list can be mined into a block and the *miner* is activated.
4. **Miner:** When the miner is activated, the energy consumption data listed on the *transaction list* are forged into a block. A hash is calculated, and the block is placed in the *blockchain*. After the mining, the energy consumption data are “locked” and they can no longer be altered. The resulting block contains all the energy metering data for 1 h from the complete energy community, and the energy balancing for the hour is ready and calculated.
5. **Blockchain:** All the energy consumption data of the energy community are stored in the blockchain. The chain starts from a genesis block, which contains no information, and the last block

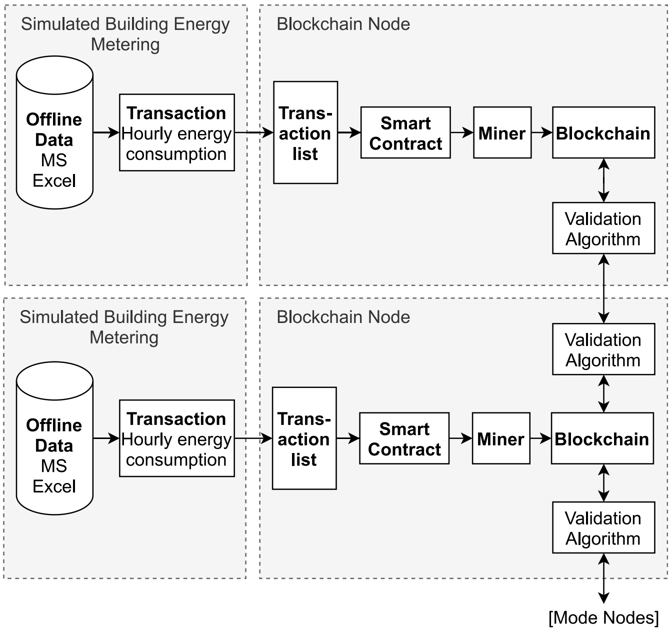


Fig. 6. Architecture of the demonstration system. Test data are stored in an Excel worksheet, which is read at a fixed interval, simulating an hour passing by. The energy consumption data are stored in a list of transactions, which is later processed in a smart contract and mined into a block placed in the blockchain. The system is scalable for multiple nodes.

of the chain is always the block that was mined last. The blockchain nodes can use an HTTP GET request to call for the contents of the blockchain. This will return the whole chain, which can then be used, e.g., to retrieve data for billing purposes. The chain retrieval can also be used to validate the chain.

6. **Consensus algorithm:** If there are multiple nodes in the system, a node can call all the other nodes in the system with an HTTP GET request to receive their *blockchains.* Then, the chains are checked on whether their hashes are valid. If the chains are deemed valid, the length of the chains is compared. The longest of the valid chains is selected as the official chain and the others are discarded. The newly selected valid chain is then sent to all nodes to replace their chains. If the chains are of equal length, the most recent chain is selected as the new chain.

3.4. Simulation

To study the viability and find out whether the proposed system presents concrete real-world advantages, simulations were run. The target of the simulations is to find out the energy self-sufficiency rate of the proposed system and compare it to a more traditional PV setup. In addition, the simulations allow for more detailed inspection of the hourly energy balancing taking place.

The system was tested using a simulated multifamily residential building with 39 apartments, each taking part in the energy community with an equal entitlement to the produced PV energy. The simulation was carried out with a program reading energy consumption values from an Excel worksheet containing real hourly energy consumption data from an apartment building. The same worksheet also contains the amount of PV production from a PV installation at the authors' university from the same date and time as the energy consumption data. The apartment energy consumption data is real data from real detached households. The detached households were selected as data sources for the simulation instead of apartments because hourly energy consumption data from individual apartments was not available. The households are all heated with district heating, which is common for multifamily residential buildings in Finland. Therefore the energy consumption profile is similar to the profile of an apartment as no electric energy is used in direct heating. However, the annual energy consumption of a detached house even when it is heated using district heating is too large compared to usual energy need of a typical Finnish apartment (approx. 1500–2500 kWh/a) of a multifamily residential building. Therefore, the values were scaled with a factor of 2.5, to better represent a smaller place of residence. Despite this approximation, the energy use profile can be considered similar to one in an apartment and as long as the annual energy needs match the typical energy consumption of an apartment, the data can be used in this simulation purposes. The test data set apartments had annual energy consumption ranging between 921 kWh/a and 5284 kWh/a, the average and median being 2423 kWh/a and 2217 kWh/a, respectively.

The simulation program reads the data and parses them into JSON-formatted transactions, which are sent to the blockchain node, which was running on a virtual Linux environment. This kind of arrangement represents the data flows from existing smart, remotely readable meters.

Each transaction contains the time stamp of the transaction, the source of the energy, the recipient of the energy, and the amount or cost of the consumed energy. A special energy source or recipient in the system is called a *community pool*, which represents a virtual energy pool and a balancing account where energy is brought either from the local gird or from the PV installation. In return, the energy used by the apartments, the common property, or anything else is marked to originate from the pool. An example of a transaction list in a blockchain node could have the following format:

If the PV energy is shared according to the rules of fair PV energy sharing presented in Section 3.2, the participants of the energy community are able to use PV energy produced in the housing cooperative itself. Table 1 presents the outcome of the multifamily residential building simulation. Compared to a traditional PV setup where the locally produced energy is either sold or used to supply energy only to the common property, the proposed energy balancing system allows higher self-sufficiency rate of 9.61% compared to 4.03% (Fig. 7). The self-sufficiency SSR_{PV} is calculated using

$$SSR_{\mathrm{PV}} = 1 - \frac{\sum E_{\mathrm{D}}}{\sum E_{\mathrm{A_i}} + \sum E_{\mathrm{C}}} \tag{5}$$

where $\sum E_{\mathrm{D}}$ is the *annual* energy deficit and $\sum E_{\mathrm{A_i}}$ and $\sum E_{\mathrm{C}}$ are the annual energy consumption of the apartments and the common property. It is worth noticing that traditional setup features more energy sold to the grid and thus more income to the community, but this is not desirable as the compensation for sold energy does not make up for the higher amount of bought energy (Fig. 8). The monetary values of the energy is calculated using an energy cost of 0.2134 €/kWh (including taxes and transfer fees), which is the average cost of electricity for household customers in the European Union (second half, 2020) [44]. In reality, the cost of the energy would naturally vary depending on the contract between the prosumer and the energy provider that has been agreed upon in the open retail electricity market.

3.4.1. Detailed energy balancing scenarios

To inspect the hourly energy balancing in detail, a simplified example balancing is presented in Tables 2–4. The tables present the energy flows in an energy community with just three (3) apartments participating in the energy community in three

Table 1
Comparison of the proposed solution to a conventional PV arrangement where PV energy is used only in the common property and a building with no PV at all.

	Proposed	Conventional	No PV
Energy consumption [kWh] ($\sum E_{\mathrm{A_i}} + \sum E_{\mathrm{C}}$)	120084.15		
PV production [kWh]	11750.72		0
Energy bought [kWh] ($\sum E_{\mathrm{D}}$)	108539.74	115242.56	120084.15
Expenditure [€]	23162.38	24592.76	25625.96
Energy sold [kWh]	206.31	6909.13	0
Income[a] [€]	14.68	491.47	0
Total energy expense [€]	23147.70	24101.29	25625.96
Self-sufficiency (SSR_{PV})	9.61%	4.03%	0%
Monetary benefit[b] [€]	2566.31	1524.67	0

[a] If one-third of the consumer purchase price of energy is compensated when sold to the grid.
[b] When compared to not having any PV system installed.

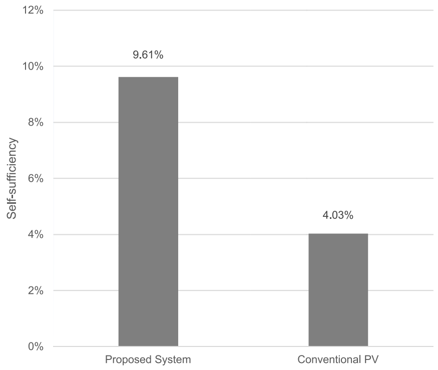


Fig. 7. The simulated energy self-sufficiency of the proposed system (9.61%) and a conventional PV system (4.03%).

Table 2
Energy flows in the community, low PV output (1.3 kWh).

Energy source	Energy recipient	Consumption [kWh]		Billed [€]
		Actual	Billable	
Community Pool	Residence 1	1.50	1.50	0.3201
Community Pool	Residence 2	1.00	1.00	0.2134
Community Pool	Residence 3	0.50	0.50	0.1067
Community Pool	Common Property	2.00	0.70	–
Solar Installation	Community Pool	1.30	–	–
Community Pool	Electric Vehicle	1.84	1.84	0.3927
Bought from Market	Community Pool	5.54	–	–

Table 3
Energy flows in the community, medium PV output (3.5 kWh).

Energy source	Energy recipient	Consumption [kWh]		Billed [€]
		Actual	Billable	
Community Pool	Residence 1	1.50	0.75	0.1601
Community Pool	Residence 2	1.00	0.50	0.1067
Community Pool	Residence 3	0.50	0.25	0.0534
Community Pool	Common Property	2.00	0	–
Solar Installation	Community Pool	3.50	–	–
Community Pool	Electric Vehicle	1.84	1.84	0.3927
Bought from Market	Community Pool	3.34	–	–

example cases with different PV production amounts. The PV energy shares are determined according to Eqs. (1) and (2). For an easier comparison of the presented situations, the energy consumption of all the residences and the common property is kept constant and presented as round figures. In reality, the values would vary depending on the residents' activities.

Table 2 presents a situation where the production of the PV installation is low. During the hour, some energy is produced (1.30 kWh), but it is not enough to fully supply the common property (2.00 kWh). In this case, all the residences (1–3) receive no direct cost reduction in their electricity bills, but they nevertheless benefit from the common property being (partly) powered with locally produced energy, since the residents will in any case pay for the common energy consumption. The electric vehicle present is also charged with grid power, and the bill is directed to the owner of the vehicle.

The second scenario is presented in Table 3. In this scenario, there is medium PV production (3.50 kWh), and it exceeds the consumption of the common property (2.00 kWh). There is thus a surplus of 1.50 kWh of energy to be shared to all the residences, and they will be billed only based on the adjusted consumption figures. However, the PV production is not high enough for all the residences to be fully powered with PV energy, and thus, there is a need for grid power (3.34 kWh), and the electric vehicle is also charged with grid power.

The third scenario (Table 4) presents a case in which the PV production is high (8.5 kWh). This is enough to power the common property, all of the residences, and also the electric vehicle. The residents will not be billed at all. Even after all consumption there is a surplus of 1.66 kWh, which is sold to the grid. The monetary income from the local distribution company to the energy community is approximated as one-third of the total consumer energy purchase price. In reality, the exact compensation would be negotiated with the local grid company. The income from this can be shared to the participants of the energy community or stored as funds for the community: in the table, this is shown as negative billing in the common property (row 4). Thus, if the PV installation

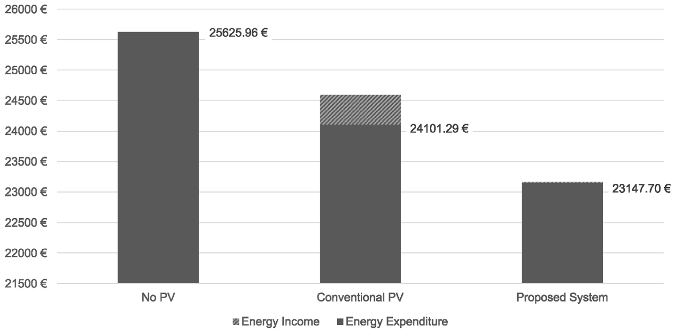


Fig. 8. The simulated annual cost of electrical energy in a 39-apartment housing cooperative with no PV installed and a 15 kW PV installation with conventional and presented energy sharing concepts. The conventional system features more energy income, but it does not compensate the higher expenditures when compared to the presented system. The expenditures of the PV system implementation are not present in the calculations, and the y-axis does not begin from zero.

Table 4
Energy flows in the community, high PV output (8.5 kWh).

Energy source	Energy recipient	Consumption [kWh]		Billed [€]
		Actual	Billable	
Community Pool	Residence 1	1.50	0	0
Community Pool	Residence 2	1.00	0	0
Community Pool	Residence 3	0.50	0	0
Community Pool	Common Property	2.00	0	−0.1181[a]
Solar Installation	Community Pool	8.50	–	–
Community Pool	Electric Vehicle	1.84	0	0
Community Pool	Sold in Market	1.66	–	0.1181[a]

[a] If one-third of the consumer purchase price of energy is compensated when sold to the grid.

is large enough, the bill for the common property can be negative, which reduces the total costs of the housing cooperative common property maintenance and use.

4. Results and discussion

The simulations show that there is a potential for energy and money savings for the participants of the energy community if a blockchain-based energy balancing ledger and the presented energy sharing scheme are utilized. The system enables higher energy self-sufficiency. Thus, while lowering the need for grid-purchased energy, the electricity bill of each resident also decreases without the need for active participation in the energy balancing by, e.g., active bidding of energy. With the presented technical concept using simple rules for PV energy sharing and a blockchain-based balance settlement ledger, the participants can effortlessly enjoy the benefits of low-cost local PV energy. The described system can be applied in various kinds of energy communities, and one of its main benefits is its low need for attention and ease of use, as everything happens automatically. The presented system allows more efficient utilization of co-owned PV installations, because the excess energy left after supplying the building's common property power needs can be shared between the residents, instead of inefficiently selling it to the grid. There have been pilots on energy sharing within energy communities [14–16,23] and the use of blockchain for such a purpose [19,39], but the pilots have not participated in an open electricity market yet.

Earlier adaptations of shared PV energy tend to rely on an energy aggregator responsible for the internal and external energy balancing in an energy community with co-owned PV resources. Introduction of a blockchain-based ledger mitigates the need for the separate energy aggregator and allows the members of the energy community to remain in an open retail electricity market. Instead of the energy aggregator purchasing the deficit energy from the grid, the aggregator, if present at all, will act as an entry point to the community. The deficit energy itself is purchased from the open market by the prosumer, and the balancing and sharing of locally produced PV energy will be handled by the blockchain-based balance settlement ledger.

A key benefit is also that the proposed system does not require additional investments in metering equipment if smart/remote meters are already installed in the energy community. In addition, the local PV energy is green energy, and adoption of the systems presented in this paper could thus prove useful in the fight against climate change.

Utilization of blockchain technology in energy consumption transactions is not a novel concept; however, the arrangement proposed in this paper introduces a potential viable solution for effortless local PV energy sharing. Table 5 compares the presented system to earlier adaptations for local PV energy sharing and a scenario with no PV system at all. When compared to a conventional PV setup where the PV energy is used only in the common property, the state-of-the art methods (such as the Brooklyn Microgrid) and the implementation presented in this paper feature higher potential for energy self-sufficiency. The state-of-the art solutions have this at the cost of participation to the open retail energy market and system complexity. The proposed system counters these disadvantages.

This paper focused mainly on a PV energy sharing solution for a housing cooperative in a multifamily residential building located in Finland. However, despite the focus being on a Finnish setting, the legislation considering energy communities is the same throughout the European Union. Therefore, the findings presented in this paper can be generalized to be valid also in other European Union Member States. In addition, the concept is not restricted to multifamily residential buildings, as it could also be applied in different kinds of energy communities. For example, rural areas with detached households could have a shared PV installation. With agreements concerning network usage for energy sharing within an energy community, the same blockchain-based system could also be applied to this use case. Thus, the consumption locations do not necessarily have to be in the immediate vicinity of each other. However, the present regulation does not recognize such a distributed energy community, and hence, adoption of the concept would require further policy development and supporting research. Furthermore, in this kind of a scenario, the transfer fees are unable to be vacated, since the DSO's grid is likely to be used for energy transfer from the PV installation to the households.

As mentioned above, there are a few major challenges for the implementation of the presented method of shared PV energy. Wide-scale deployment of the proposed arrangement requires cooperation between all the different actors in the electricity market. The present-day energy distribution arrangements and infrastructure can be considered somewhat outdated, inflexible, and unsuited for future smart grid solutions, which are needed to achieve carbon neutrality. For instance, the proposed approach requires deployment of smart meters, which is not yet achieved in

Table 5
A comparison between different methods of co-owned PV sharing.

	No PV	Conventional PV system	State of the art energy community[a]	Proposed system
Residents in open electricity market	Yes	Yes	No	Yes
PV energy for the common property	No	Yes	Yes	Yes
PV energy for the residents	No	No	Yes	Yes
Data architecture	n/a	Centralized	Centralized or Distributed[b]	Distributed[b]
Self-sufficiency potential	None	Low	High	High
Energy sharing complexity	n/a	Low	High	Low
Authority	n/a	Aggregator	Aggregator or Community[c]	Community[c]

[a] e.g. The Brooklyn Microgrid.
[b] e.g. a blockchain-based ledger.
[c] Data integrity and immutability achieved with e.g. a blockchain-based ledger.

every country [45]. Whether the proposed rules for PV energy sharing within the energy community are considered fair or not is difficult to determine, but a key aspect for an energy community like the one presented in this paper is that the rules are agreed between the participants and they are the same for all. The sharing rules can therefore vary from an energy community to another, but it is essential that the participants are aware of the rules and have agreed upon them.

The results show that there is potential for PV system profitability increase without any investments in metering equipment or energy storage systems. Further supporting research on e.g. electricity price forecasting using data analytics and prediction algorithms combined with the work presented in this paper could raise the profitability and self-sufficiency of shared PV systems even more, if, e.g., more efficient PV production sharing methods and taking advantage of energy storages and smart charging of electric vehicles are introduced.

5. Conclusion

This paper presented a novel technical concept for energy balance settlement in a multifamily residential building with a shared PV installation. A blockchain-based ledger for energy balance settlement and billing was presented with an example set of rules for local PV sharing in a housing cooperative where no single residence or resident alone owns the PV installation. The challenges of efficient sharing of co-owned local PV energy within a housing cooperative can be solved with a blockchain-based balance settlement ledger and formation of an energy community where the energy sharing rules are mutually agreed upon. This kind of arrangement is a novel approach for local energy sharing as it also mitigates the need for a separate energy aggregator, and allows the prosumers to remain as participants in an open retail electricity market. Based on the authors' knowledge, research on this kind of shared PV arrangements have not been carried out earlier. The possible lack of trust between the participants of the energy community caused by the removal of a governing party, such as an energy aggregator, is be neglected with the blockchain-based ledger, as it makes the energy consumption data secure and immutable and therefore a valid method as a technical concept to be applied to internal and external energy balance management of an energy community operating in open electricity markets. Remaining in an open electricity market allows the participants of the energy community to choose where they purchase their energy and e.g. how it is produced.

Our findings indicate that the presented system allows for more optimized use of co-owned PV installations in a housing cooperative. Instead of inefficiently selling the excess energy to the grid after powering the common property of the housing cooperative, the surplus could be supplied to the residents. The proposed system was tested with a simulated multifamily residential building, where the PV installation profitability was increased and energy self-sufficiency rate grew from 4.03% to 9.61% compared to a conventional PV system where local energy is used only to power the common property. The system performance is tested with a simulation, and our findings indicate that the system could be deployed into use with low effort. The next step in the deployment process is a proof-of-concept testing in a real-world multifamily residential building. Furthermore, there is more potential for additional increase in self-sufficiency if, e.g., energy storages with smart charge-discharge systems are introduced. Further study is required to determine the best implementation practices of such systems deployed into energy communities.

Credit author statement

Mikko Nykyri: Conceptualization, Methodology, Software, Investigation, Writing - Original Draft; Tommi J. Kärkkäinen: Conceptualization, Resources, Writing - Review & Editing, Supervision; Saku Levikari: Methodology, Writing - Review & Editing; Samuli Honkapuro: Conceptualization, Investigation, Writing - Original Draft; Salla Annala: Conceptualization, Investigation, Writing - Review & Editing; Pertti Silventoinen: Conceptualization, Writing - Review & Editing, Project administration, Funding acquisition

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.

Acknowledgments

The blockchain implementation was partly based on Daniel van Flymen's tutorial [46]. We thank Lappeenrannan Energiaverkot Oy for providing the energy consumption data for this research. This research has received funding from Business Finland research funding agency. We would like to thank the financial support received to make the study possible.

References

[1] Pillai U. Drivers of cost reduction in solar photovoltaics. Energy Econ 2015;50:286–93. https://doi.org/10.1016/j.eneco.2015.05.015. URL, http://www.sciencedirect.com/science/article/pii/S014098831500167X.

[2] Cosumer, Prosumer Sioshansi F. Prosumager - how service innovations will disrupt the utility business model. (Ed.) 2019.

[3] Simola A, Kosonen A, Ahonen T, Ahola J, Korhonen M, Hannula T. Optimal dimensioning of a solar pv plant with measured electrical load curves in Finland. Sol Energy 2018;170:113–23. https://doi.org/10.1016/j.solener.2018.05.058. URL, http://www.sciencedirect.com/science/article/pii/S0038092X18304912.

[4] Muenzel V, Mareels I, de Hoog J, Vishwanath A, Kalyanaraman S, Gort A. Pv generation and demand mismatch: evaluating the potential of residential storage. In: 2015 IEEE power energy society innovative smart grid technologies conference (ISGT); 2015. p. 1–5. https://doi.org/10.1109/ISGT.2015.7131849.

[5] Gul E, Baldinelli G, Bartocci P, Bianchi F, Domenghini P, Cotana F, Wang J. A techno-economic analysis of a solar pv and dc battery storage system for a community energy sharing. Energy 2022;244:123191. https://doi.org/10.1016/j.energy.2022.123191. URL, https://www.sciencedirect.com/science/article/pii/S0360544222000949.

[6] Nyholm E, Goop J, Odenberger M, Johnsson F. Solar photovoltaic-battery systems in Swedish households – self-consumption and self-sufficiency. Appl Energy 2016;183:148–59. https://doi.org/10.1016/j.apenergy.2016.08.172. URL, https://www.sciencedirect.com/science/article/pii/S0306261916312806.

[7] Parra D, Walker GS, Gillott M. Are batteries the optimum pv-coupled energy storage for dwellings? techno-economic comparison with hot water tanks in the UK. Energy Build 2016;116:614–21. https://doi.org/10.1016/j.enbuild.2016.01.039. URL, https://www.sciencedirect.com/science/article/pii/S037877881630038X.

[8] Khaboot N, Chatthaworn R, Siritaratiwat A, Surawanitkun C, Khunkitti P, Meng W. Increasing pv penetration level in low voltage distribution system using optimal installation and operation of battery energy storage. Cogent Eng. 2019;6(1):1641911. https://doi.org/10.1080/23311916.2019.1641911.

[9] Puranen P, Kosonen A, Ahola J. Techno-economic viability of energy storage concepts combined with a residential solar photovoltaic system: a case study from Finland. Appl Energy 2021;298:117199. https://doi.org/10.1016/j.apenergy.2021.117199. URL, https://www.sciencedirect.com/science/article/pii/S0306261921006231.

[10] Jäger-Waldau A, Adinolfi G, Batlle A, Braun M, Bucher C, Detollenaere A, Frederiksen KH, Graditi G, Lemus RG, Lindahl J, Heilscher G, Kraiczy M, Masson G, Mather B, Mayr C, Moneta D, Mugnier D, Nikoletatos J, Neubourg G, Platt G, Reinders A, Roberts MB, Ueda Y. Self-consumption of electricity produced with photovoltaic systems in apartment buildings - update of the situation in various iea pvps countries. In: 2020 47th IEEE photovoltaic

specialists conference (PVSC); 2020. https://doi.org/10.1109/PVSC45281.2020.9300442. 0938–0950.

[11] Pöyry Management Consulting Oy. Hajautetun uusiutuvan energiantuotannon potentiaali, kannattavuus ja tulevaisuuden näkymät Suomessa [The potential of distributed energy production in Finland]. Valtioneuvoston selvitys- ja tutkimustoiminnanjulkaisusarja 2017;5:10–1.

[12] Roberts M, Bruce A, MacGill I. Opportunities and barriers for photovoltaics on multi-unit residential buildings: reviewing the australian experience. Renew Sustain Energy Rev 2019;104:95–110. https://doi.org/10.1016/j.rser.2018.12.013. URL, https://www.sciencedirect.com/science/article/pii/S1364032118308086.

[13] Siano P, De Marco G, Rolán A, Loia V. A survey and evaluation of the potentials of distributed ledger technology for peer-to-peer transactive energy exchanges in local energy markets. IEEE Syst J 2019;13(3):3454–66. https://doi.org/10.1109/JSYST.2019.2903172.

[14] Mengelkamp E, Gärttner J, Rock K, Kessler S, Orsini L, Weinhardt C. Designing microgrid energy markets: a case study: the brooklyn microgrid. Appl Energy 2018;210:870–80.

[15] S. Wilkinson, K. Hojckova, C. Eon, G. Morrison, B. Sandén, Is peer-to-peer electricity trading empowering users? evidence on motivations and roles in a prosumer business model trial in Australia, Energy Res Social Sci 66.

[16] Wörner A, Ableitner L, Meeuw A, Wortmann F, Tiefenbeck V. Peer-to-peer energy trading in the real world: market design and evaluation of the user value proposition. In: 4th international conference on information systems. (ICIS; 2019.

[17] Sousa T, Soares T, Pinson P, Moret F, Baroche T, Sorin E. Peer-to-peer and community-based markets: a comprehensive review. Renew Sustain Energy Rev 2019;104:367–78. https://doi.org/10.1016/j.rser.2019.01.036. URL, https://www.sciencedirect.com/science/article/pii/S1364032119300462.

[18] Liu Y, Wu L, Li J. Peer-to-peer (p2p) electricity trading in distribution systems of the future. Electr J 2019;32(4):2–6. special Issue on Strategies for a sustainable, reliable and resilient grid. doi:https://doi.org/10.1016/j.tej.2019.03.002. URL https://www.sciencedirect.com/science/article/pii/S1040619019300284.

[19] Han D, Zhang C, Ping J, Yan Z. Smart contract architecture for decentralized energy trading and management based on blockchains. Energy 2020;199:117417. https://doi.org/10.1016/j.energy.2020.117417. URL, https://www.sciencedirect.com/science/article/pii/S0360544220305247.

[20] Sun L, Qiu J, Han X, Dong ZY. Energy sharing platform based on call auction method with the maximum transaction volume. Energy 2021;225:120237. https://doi.org/10.1016/j.energy.2021.120237. URL, https://www.sciencedirect.com/science/article/pii/S0360544221004862.

[21] van den Broek KL. Household energy literacy: a critical review and a conceptual typology. Energy Res Social Sci 2019;57:101256. https://doi.org/10.1016/j.erss.2019.101256. RL, https://www.sciencedirect.com/science/article/pii/S2214629619303330.

[22] Herrmann MR, Brumby DP, Oreszczyn T. Watts your usage? a field study of householders' literacy for residential electricity data. Energy Effic 2018;11:1703–19. https://doi.org/10.1007/s12053-017-9555-y. URL, https://link.springer.com/article/10.1007/s12053-017-9555-y.

[23] Roberts MB, Sharma A, MacGill I. Efficient, effective and fair allocation of costs and benefits in residential energy communities deploying shared photovoltaics. Appl Energy 2022;305:117935. https://doi.org/10.1016/j.apenergy.2021.117935. URL, https://www.sciencedirect.com/science/article/pii/S0306261921012460.

[24] DIRECTIVE (EU) 2019/944. OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 5 June 2019 on common rules for the internal market for electricity and amending Directive 2012/27/EU. 2019.

[25] DIRECTIVE (EU) 2018/2001. OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 11 December 2018 on the promotion of the use of energy from renewable sources. 2018.

[26] Saplacan R. Competition in electricity distribution. https://doi.org/10.1016/j.jup.2008.03.004. URL Util Pol 2008;16(4):231–7. european Regulatory Perspectives, http://www.sciencedirect.com/science/article/pii/S0957178708000374.

[27] Newbery DMG. Privatization, restructuring, and regulation of network utilities. MIT Press; 1999.

[28] 9.8.2013/588 Sähkömarkkinalaki 72 [Finnish electricity market act]. 2013.

[29] Valtioneuvoston asetus sähköntoimitusten selvityksestä ja mittauksesta 767/2021 [Decree of the Council of State concerning balance settlement and measurement]. 2021.

[30] Li J, Wu Z, Zhou S, Fu H, Zhang X. Aggregator service for pv and battery energy storage systems of residential building. CSEE J Power Energy Syst 2015;1(4):3–11. https://doi.org/10.17775/CSEEJPES.2015.00042.

[31] Di Somma M, Graditi G, Siano P. Optimal bidding strategy for a der aggregator in the day-ahead market in the presence of demand flexibility. IEEE Trans Ind Electron 2019;66(2):1509–19. https://doi.org/10.1109/TIE.2018.2829677.

[32] Correa-Florez CA, Michiorri A, Kariniotakis G. Optimal participation of residential aggregators in energy and local flexibility markets. IEEE Trans Smart Grid 2020;11(2):1644–56. https://doi.org/10.1109/TSG.2019.2941687.

[33] Favuzza S, Galioto G, Ippolito M, Massaro F, Milazzo F, Pecoraro G, Riva Sanseverino E, Telaretti E. Real-time pricing for aggregates energy resources in the Italian energy market. Energy 2015;87:251–8. https://doi.org/10.1016/j.energy.2015.04.105. URL, https://www.sciencedirect.com/science/article/pii/S0360544215005939.

[34] Iria J, Scott P, Attarha A. Network-constrained bidding optimization strategy for aggregators of prosumers. Energy 2020;207:118266. https://doi.org/10.1016/j.energy.2020.118266. URL https://www.sciencedirect.com/science/article/pii/S0360544220313736.

[35] Wang F, Ge X, Yang P, Li K, Mi Z, Siano P, Duić N. Day-ahead optimal bidding and scheduling strategies for der aggregator considering responsive uncertainty under real-time pricing. Energy 2020;213:118765. https://doi.org/10.1016/j.energy.2020.118765. URL, https://www.sciencedirect.com/science/article/pii/S0360544220318727.

[36] Qi W, Shen B, Zhang H, Shen Z-JM. Sharing demand-side energy resources - a conceptual design. Energy 2017;135:455–65. https://doi.org/10.1016/j.energy.2017.06.144. URL, https://www.sciencedirect.com/science/article/pii/S036054421731143X.

[37] Aitzhan NZ, Svetinovic D. Security and privacy in decentralized energy trading through multi-signatures, blockchain and anonymous messaging streams. IEEE Trans Dependable Secure Comput 2018;15(5):840–52. https://doi.org/10.1109/TDSC.2016.2616861.

[38] Fernández-Caramés TM, Fraga-Lamas P. A review on the use of blockchain for the internet of things. IEEE Access 2018;6:32979–3001. https://doi.org/10.1109/ACCESS.2018.2842685.

[39] AlAshery MK, Yi Z, Shi D, Lu X, Xu C, Wang Z, Qiao W. A blockchain-enabled multi-settlement quasi-ideal peer-to-peer trading framework. IEEE Trans Smart Grid 2021;12(1):885–96. https://doi.org/10.1109/TSG.2020.3022601.

[40] Zia MF, Benbouzid M, Elbouchikhi E, Muyeen SM, Techato K, Guerrero JM. Microgrid transactive energy: review, architectures, distributed ledger technologies, and market analysis. IEEE Access 2020;8:19410–32. https://doi.org/10.1109/ACCESS.2020.2968402.

[41] Afzal M, Huang Q, Amin W, Umer K, Raza A, Naeem M. Blockchain enabled distributed demand side management in community energy system with smart homes. IEEE Access 2020;8:37428–39. https://doi.org/10.1109/ACCESS.2020.2975233.

[42] Ghorbanian M, Dolatabadi SH, Siano P, Kouveliotis-Lysikatos I, Hatziargyriou ND. Methods for flexible management of blockchain-based cryptocurrencies in electricity markets and smart grids. IEEE Trans Smart Grid 2020;11(5):4227–35. https://doi.org/10.1109/TSG.2020.2990624.

[43] Hamouda MR, Nassar ME, Salama MMA. A novel energy trading framework using adapted blockchain technology. IEEE Trans Smart Grid 2021;12(3):2165–75. https://doi.org/10.1109/TSG.2020.3045662.

[44] Eurostat. Electricity prices (including taxes) for household customers, second half. 2020.

[45] Eurelectric. Distribution grids in europe – facts and figures. 2020.

[46] van Flymen D. Learn blockchains by building one [Online]. Available: https://hackernoon.com/learn-blockchains-by-building-one-117428612f46. [Accessed 21 May 2021].

Publication II

Nykyri, M., Kärkkäinen, T.J., Annala, S., and Silventoinen, P.
Review of Demand Response and Energy Communities in Serious Games

Reprinted under Creative Commons (CC BY 4.0) from
IEEE Access
Vol. 10, pp. 91018–91026, 2022

IEEE Access
Multidisciplinary ⋮ Rapid Review ⋮ Open Access Journal

Received 12 August 2022, accepted 20 August 2022, date of publication 26 August 2022, date of current version 2 September 2022.

Digital Object Identifier 10.1109/ACCESS.2022.3202013

TOPICAL REVIEW

Review of Demand Response and Energy Communities in Serious Games

MIKKO NYKYRI, (Member, IEEE), TOMMI J. KÄRKKÄINEN, (Member, IEEE),
SALLA ANNALA, AND PERTTI SILVENTOINEN, (Member, IEEE)
School of Energy Systems, Lappeenranta University of Technology (LUT), 53850 Lappeenranta, Finland
Corresponding author: Mikko Nykyri (mikko.nykyri@lut.fi)

This work was supported in part by the Finnish National Research Funding Organization Business Finland through the Project SolarX.

ABSTRACT Shared energy resources and energy communities are being widely studied and pilots are being implemented in various locations around the world. However, laypeople may find the concepts regarding energy and electricity in general difficult to grasp, and the issue is made more complex by introducing new aspects like demand response and shared photovoltaic (PV) installations. Serious games are proposed as a tool for raising awareness, and this paper presents a systematic literature review on serious games featuring energy and electricity aspects while giving extra attention to whether a serious game has features considering demand response or energy communities. The results are used to determine whether research gaps exist, and if a serious game featuring energy communities and demand response would be meaningful to develop. In total, 34 games were identified, four of which had demand response aspects and five of which had aspects considering energy communities or shared energy resources. None of the games featured both aspects while having a link to real-life events by, e.g., making the energy consumption of the player's home affect the outcome of the game. This emphasizes the fact that the concepts are new, and a serious game covering them could be implemented.

INDEX TERMS Demand response, energy community, energy resources, serious games, solar energy.

I. INTRODUCTION

Energy communities and local energy production are gaining interest worldwide as the demand for fossil-free energy increases and advancements in photovoltaic (PV) technologies make PV installations more efficient [1]. Local energy production, such as different kinds of PV installation implementations are being widely studied to find the most feasible PV arrangements around the world. These include various systems, such as small-scale PV systems in detached households and shared larger installations in, e.g., multifamily residential buildings. However, a major problem with local PV installations is that they produce energy only during high solar irradiance, which happens often during midday when the demand for domestic energy is usually low. In such situations there may be an oversupply of PV production, which will end up being sold to the grid. This is inefficient because of the imbalance of the pricing of bought and sold energy. For instance in the Nordic countries, selling energy to the grid yields approx. one-third of the cost of buying the same amount of energy. To minimize the negative effects of this imbalance, PV installations tend to be dimensioned to be of a low capacity to reduce both the initial investment and the amount of "wasted" energy being sold to the grid [2]. To counter this problem, the excess energy from a PV installation would have to be either stored or shared, or the consumption habits would have to be altered with demand response so that more energy is used when more PV energy is available.

As a solution, energy communities have been proposed as a viable technical framework for situations where PV energy is to be shared from a co-owned source. The concept of an energy community is backed by the legislation of the European Union (EU), but energy communities are not yet common due to their novelty; the EU Directives (which are to be implemented in the national legislation of

The associate editor coordinating the review of this manuscript and approving it for publication was Z. G. Zang.

the EU Member States) considering energy communities are from 2018 and 2019 [3], [4]. An energy community allows an energy resource, such as a PV installation, to be shared between people living in different residences. An energy community could be set up, e.g., in a multifamily residential building or other kind of shared housing solution where the locally produced energy is not fully owned by a single residence. Research is also being made on different methods to store the excess energy, but current battery energy storage systems are not always economically viable solutions [5], [6]. Therefore, it can be argued that the easiest way to increase the efficiency of the usage of locally produced solar energy is to maximize self-consumption by engaging in demand response, within or without an energy community.

Despite the improvements in infrastructure and the emergence of new concepts, the technical solutions of how any energy produced by a co-owned PV installation is shared between the residents of the community can be, depending on the situation, rather complex. Many people tend to feel the concepts of energy and electricity difficult to understand properly [7], [8]. Therefore, if people find the concepts complicated in conventional living arrangements where there are no complex or sophisticated energy sharing systems in place, questions are raised of how well the members of energy communities would understand any PV energy sharing and allocation principles. The same goes for demand response: it may prove to be complicated for the residents to understand what demand response is, how it can be performed, and why it is beneficial. People may need to be advised about these subjects to best utilize any shared PV system they have access to. Despite these challenges, consumers are expected to adopt a larger role in the energy system (see, e.g., [9]). Thus, there is a need to increase consumers' awareness of energy issues, and demand response and energy communities in particular.

A. SERIOUS GAMES IN ENERGY

Video games are very popular, and playing digital games has become more and more common ever since home computers became affordable. Over the past decade, the emergence of smartphones has accelerated the demand for video games, as suddenly many people own a gaming-capable personal device. Especially casual, low-threshold mobile gaming has gained immense popularity in recent years. One subtype of video games is *serious games*, which are a prospective and increasingly popular platform for educating people. A serious game is defined in [10] as *"a digital game created with the intention to entertain and to achieve at least one additional goal (e.g., learning or health)."* Another often used term when discussing serious games is *gamification*, which means adding game elements to something that originally is not a game [10]. Gamification is a popular trend and can be seen, e.g., in the language learning platform Duolingo [11]. Serious games that gamify real-life phenomena can be used to teach or coach people, e.g., in their energy consumption habits, and they can be instructed to act in a certain manner while simultaneously being entertained by the digital game. The player could then be rewarded either in real life by a benefit, such as affordable PV energy and a decrease in the electric bill, or in-game while simultaneously teaching the player optimal energy consumption habits to be later adopted in real life, thus indirectly rewarding the player for good choices and playing well.

Serious games in the field of energy are not new, and numerous studies on their effectiveness have been made (e.g. [12], [13], [14]). In [15] it is said that serious games have a great potential to make smart energy tools more effective, but gamification and game design elements are underutilized in real world applications. Furthermore, more specific aspects of electrical energy usage and distribution, such as energy communities and demand response, are more recent and have not reached their full deployment among the general public. As performing demand response and optimizing the value out of an energy community participation requires active involvement and usually requires behavioral change, gamification and serious games are suggested as tools for promoting demand response [16], [17], [18], [19] and energy communities [17]. Because these concepts can be difficult to understand, the motivation for this study is to find out what kind of a serious game for raising awareness of demand response and utilization of shared PV resources in an energy community could be developed. A player of a serious game could, e.g., learn to optimize their energy consumption to happen during the most suitable time of the day, understand better the energy allocation and sharing logic of a shared PV system, and become acquainted with the modern smart grid and distributed energy production infrastructure.

This paper presents a systematic literature review on serious games for demand response and energy communities. The target of the research is to survey the state of the art on the subject, identify and present research gaps in the literature, and conclude what kinds of aspects a serious game covering any possible research gaps should contain and whether it would be meaningful to develop the game or not.

II. METHODS

The review was conducted as a systematic literature review, following the principles of PRISMA described in [20]. A systematic review is performed by systematically identifying records from a database or databases and assessing the records retrieved until relevant studies remain. Although originally developed for medical research, PRISMA is regarded as a valid tool for systematic literature reviews also in other fields of study [20].

For the sources for the records, *IEEE Xplore* and *Scopus* databases were selected. Serious games are a wide field, and thus, in order to retrieve records of studies on serious games and energy or electricity, the search terms were set so that only articles that match both criteria were selected. The database search was performed using the following

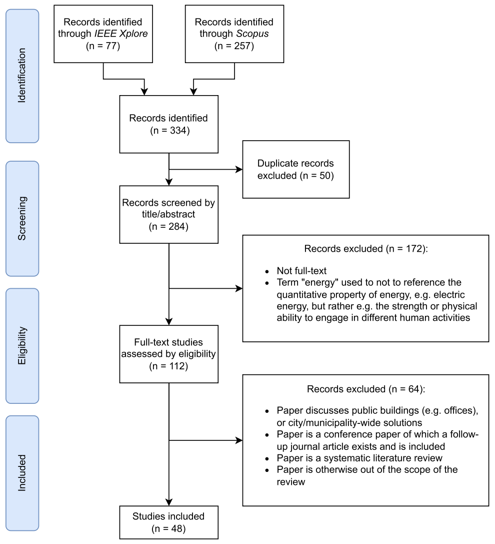


FIGURE 1. **PRISMA flowchart of the systematic review.**

query to include results with both *serious game* and *serious games*, and either with mentions on *energy* or *electricity*, or both:

```
``serious game*'' AND (energy OR electricity)
```

The search was performed on March 28, 2022, and it resulted in 77 hits in IEEE Xplore and 257 hits in Scopus. After removing duplicate records, 284 unique ones were obtained. The search terms were selected so that they will most likely result in the major proportion of articles within the scope of this review and viable studies will unlikely be left out. On the other hand, as the search terms are broad, the query will likely result in some records that are outside the scope of this review (e.g., considering other forms of energy than electrical energy). These are, however, easy to exclude manually.

The obtained records were screened by title and abstract, and a number of records were excluded (n = 172) on the basis of either being outside the scope of this review or being not full-text papers, such as being index listings of conference proceedings or abstracts only. A common reason for exclusion in this step was that the search term ''energy'' is also used to refer to a property of something, e.g., strength or ability to engage in various physical activities. Within the scope of this paper, ''energy'' includes electricity consumed in homes and apartment buildings, which may be complemented by district heating or heating fuels. After this first screening, the remaining articles (n = 112) were assessed for eligibility. Out of these records, a number of articles (n = 64) were excluded, although considering energy and/or electricity and serious games, for being not within the scope of this study. Many excluded papers considered serious games for city- or municipality-wide energy planning including power plant utilization and environmental aspects, such as recycling, and are therefore not within the scope of domestic energy consumption planning. Other reasons for exclusion include the record being a systematic literature review or a follow-up paper from a conference paper, in which case the conference paper was excluded and the journal article was included. In addition, records were also excluded for being otherwise outside the scope, such as focusing more on augmented reality, energy production, and the Internet of Things. The PRISMA flowchart of the record inclusion and exclusion process is presented in Fig. 1.

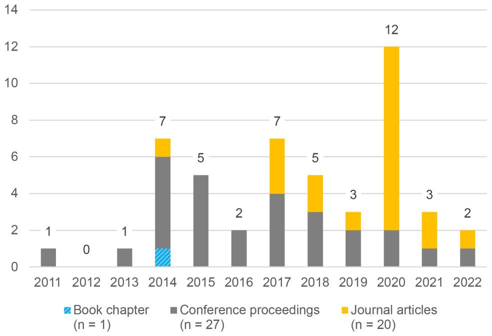


FIGURE 2. **Distribution of years of publication and types of publication. The publication year of the records ranged between 2011 and 2022. Most of the records were published in 2020 (n = 12).**

In total, 48 records were included in the final review. The records consist of journal articles (n = 20), conference proceedings (n = 27), and a book chapter (n = 1). The record years of the papers are distributed between 2011 and 2022, the most common year of publication being 2020 (n = 12). (Fig. 2)

The records were studied for presentations on serious games concerning energy and/or electricity use in domestic environments. Despite [10] defining serious games as digital games, any serious games based on physical media (such as board or card games) that otherwise match the scope of this paper were included. In addition to the records retrieved by the systematic search, some additional references that were used in the included records were employed when studying the presented serious games. The following core aspects were identified for each game:

- The name of the game;
- The main target audience of the game;
- Availability of the game: Is the game effortlessly available for anyone to download and play at the moment of writing of this paper (April–May 2022)?
- The educational target of the game;
- The main gameplay element of the game.

In addition to the core features and specifications, in order to study the state of the art of serious games for domestic demand response and/or energy communities, special attention was paid to detect whether:

- There are any rewards or prizes for playing well in the game, other than in-game awards such as badges;
- The game has any aspects regarding demand response in domestic environments;
- The game features an energy community or any aspects regarding energy communities, such as shared energy resources or shared local energy production;
- The game has a link to real-life events, e.g., real-life energy consumption is presented in the game, and it affects the outcome of the game.

The results of the study are assessed and a conclusion is made as to whether serious games have been used to educate people on demand response and energy communities. The study results are also used to decide on if and what kind of a serious game would be meaningful to develop.

III. RESULTS & DISCUSSION

In total, the records contained mentions of 34 serious games about energy in domestic environments. However, some of the mentioned games ($n = 3$) were excluded from the final listing (Table 1) because of the lack of information available. The included games varied from simple quiz games to more complex living simulation games, and the target audiences ranged from children to homeowners. A common theme among the records was energy saving or reduction in energy usage, and a serious game was proposed as a viable tool for such a purpose. To promote energy savings, awareness of the subject has to be raised in order for people to understand where energy is being used in their homes, and how each person could reduce their energy consumption. Despite people having a positive attitude to energy conservation and fighting climate change, it can be difficult for many people to identify where electric energy is consumed in their homes [34]. Present-day smart metering is becoming more and more common, but visual presentation of sensor data alone is said not to be enough of an incentive for people to make changes in their consumption [58]. For example, in [59] it is noted that many people find units such as kilowatt and kilowatt-hour difficult to interpret and relate to. Smart metering is said to be a powerful enabler to facilitate behavioral change, but more direct and specifically-timed feedback on user actions are needed to make the use of smart metering more viable [58]. Therefore, instead of plain displays of current energy consumption, more engaging methods are required, and serious games are presented as a possible method for that.

A. CORE FEATURES & GENERAL FINDINGS

The identified games varied considerably in their content and gameplay, and thus, some of the games had a specific target audience and some of the games did not. Notable audiences for games were homeowners, teenagers, and children. The target audience was reflected by the difficulty and depth of the game; more complex games were designed for older audiences, whereas easy, learning-focused games were designed for younger children. The games for children included more exploratory games, where the players learn the general concepts of energy usage. A notable example of such a game is *The Ghost Hunter* [12], where the player attaches an electromagnetic field detection device to their smartphone and uses it to locate energy-consuming appliances in their home. Another game clearly designed for children is *Power Pets* [47], a 2D platformer game, where the player learns the concepts of energy while tending their virtual pet. On the other hand, games designed for more mature audiences include games such as *Social Power Game* [16], a game which is played as an energy saving contest, and *Energy Cat* [12], [13], [26], [27], [28], [29], [30], [31], a life simulator similar to *The Sims* franchise where the player controls how their avatar or avatars called *sims* live and manage their daily lives.

To give an incentive to play well in the game and thus encourage the player to change their behavior in real life, all of the presented games featured some kinds of in-game rewards to give the player a sensation of achievement and progress. These kinds of rewards, such as badges or other virtual collectibles, are said to have a bigger educational impact than educational messages, such as energy saving tips, which were present in some of the games [42]. Games with a direct link to real-life events, such as the current energy consumption of the player's residence, can easily gamify any energy savings made with, e.g., in-game badges and trophies of achievement. Not all the games noted in the study contained this link, and rely on indirect rewarding of the player by providing the player with guidance on how to save energy and thus money. However, some games offer concrete rewards and prizes for the best players. For example, in *ecoGator*, the players are allowed to enter a prize contest after beating a level in the game [16].

A link to real-life events, meaning that the gameplay is affected somehow by the real-life surroundings of the player, was found in 18 of the games. The link in the games usually consisted of energy consumption measurements from the player's place of residence. This data link provides a direct feedback on their actions to the player, and instead of the players only controlling a virtual avatar in the game, the gameplay elements included, e.g., energy-saving activity reporting and energy-saving hints and tips. Games like the above-mentioned *The Ghost Hunter* and *ecoGator* contain exploration of the real world. For example in *ecoGator*, the gameplay is based on scanning of the energy labels on appliances with the player's smartphone camera to find the least energy intensive products. On the other hand, the games that did not feature the link to real-life events had the possibility of more creativity. For example, the players could build their own home and try to be as energy efficient as possible like in *Energy Cat*. The games without a real-life link can also

TABLE 1. Identified serious games concerning energy in a domestic environment.

Game/Framework	Audience	Av.[a]	Target	Prize[b]	DR[c]	EC[d]	RL[e]	Gameplay
Social Mpower [21]–[25]	EC Members	No	Raising awareness	No	Yes	Yes	No	Energy sharing simulator
Energy Cat [12], [13], [26]–[31]	Households	No	Energy saving	No	No	No	No	The Sims-like life simulator
Energy Piggy Bank [12], [32]	Anyone	No	Sustainable energy use	No	No	No	Yes	Activity reporting
Power Agent [12], [29], [33], [34]	Teenagers	No	Energy saving	No	No	No	Yes	Energy saving missions
Power House [12], [16], [25], [33]	Adults	No	Efficient energy use	No	No	No	Yes	Real-life and in-game missions
EnergyLife [12], [33], [35]	Households	No	Raising energy awareness	No	No	No	Yes	Quizzes and eco-feedback
Joulebug [33]	Adults	Yes	Energy saving	No	No	No	Yes	Activity reporting
Power Explorer [12], [29], [33], [36]	Teenagers	No	Behavioral change	No	No	No	Yes	Minigame duels
EcoIsland [12], [33], [37]	Households	No	CO_2 reduction	No	No	No	Yes	Acitivity reporting
The Power Saver [33]	Households	No	Energy saving	No	No	No	Yes	Quizzes
The Ghost Hunter [12]	Children	No	Raising awareness	No	No	No	Yes	Scanning EMFs
Ringorang/Energy Games [12], [38]	Unspecified	No	Raising awareness	Yes[1]	No	No	No	Quizzes
Smarter households [12]	Unspecified	No	Energy monitoring	No	No	No	Yes	Energy tips in 3D home
ecoGator [16], [29]	Consumers	No	Energy saving	Yes	No	No	Yes	Scanning energy labels
Social Power Game [16]	Households	No	Behavioral change	No	No	Yes	Yes	Energy saving contest
ECO ECO [39]	Children	No	Energy saving	No	No	No	Yes	Farmville-like
Dungeon of Conquest [40]	Unspecified	No	Raising awareness	No	No	No	No	Quizzes and puzzles
Green Gang vs Cpt. Carbon [41]	Households	No	Energy saving	No	No	No	No	Quizzes
Reduce Your Juice [14], [42]–[45]	Households	Yes[2]	Energy saving	Yes	No	No	No	Minigames and collecting badges
GAIA Challenge [46]	Students	Yes	Energy saving	No	No	No	No	Quizzes and puzzles
Power Pets [47]	Children	No	Understanding energy	No	No	No	No	2D platformer
Changing the Game – Nbhd. [48]	Adults	Yes[3]	CO_2 reduction	No	Yes	Yes	No	Board Game
Eco Ego [49]	Unspecified	Yes[4]	Efficient energy use	No	No	No	No	Energy usage optimization
Electric City [50]	Unspecified	No	Energy sharing	No	No	Yes	No	Resource management
Apolis Planeta [51]	Unspecified	No	Energy saving	No	No	No	Yes	Energy usage feedback
FunergyAR [16], [52]	Children	Yes	Efficient energy use	No	No	No	Yes	Quizzes (Smartphone camera)
DLT Energy Game [53]	EC Members	No	Understanding of DLT	No	Yes	Yes	No	Peer-to-peer energy trading
NRG Game [54]	Homeowners	No	Rebound effect study	No	No	No	No	The Sims-like life simulator
Sharebuddy [55]	Students	No	Demand response	Yes[5]	Yes	No	Yes	Minigames with demand response
Green my place [56]	Unspecified	No	Energy awareness	No	No	No	Yes	MMO Minigames
Less Energy Empowers You [16], [57]	Households	No	Energy saving	No	No	No	Yes	Real-life monitoring

[a] Available effortlessly for anyone to play in April–May 2022
[b] Real-life rewards for participation or playing well (in addition to energy savings resulting from a possible behavioral change)
[c] Aspects directly concerning demand response or demand management
[d] Aspects directly concerning energy communities or shared energy resources
[e] A direct link to real-life events (e.g. rewards or real-life energy consumption reflected in-game)
[1] Participants received a $10 gift card and entered a raffle for more valuable gift cards
[2] Unofficial download links exist, but no Google Play page
[3] Board game listed but out of stock
[4] Available, but requires Adobe Flash player, which is no longer supported in many web browsers
[5] Gift cards were awarded for the best performer and randomly to participants in the field study of the game

be more universal instead of focusing on specific residences, if the energy consumption of a certain location is a key gameplay factor.

A noteworthy finding of this study is that the vast majority of games presented in the records are not available for anyone to effortlessly download and play during the time of writing this paper (April–May 2022). Only four out of the 31 mentioned and assessed games could be downloaded, which implies that the games are/were available only for a closed audience. In majority of cases, the authors were not able to find the official web pages or download links (in e.g. Google Play) for the games. If a web page associated with a game was available, the game itself was not accessible. An unofficial download link was identified for *Reduce Your Juice*, and *Eco Ego* was still online, but required Adobe Flash player that is no longer supported in many web browsers during the writing of this paper. One of the four downloadable games, *Changing the Game – Neighbourhood*, features a physical game board, which was, at the moment of writing this paper, out of stock with no statement of whether restock was to be expected available or not.

B. DEMAND RESPONSE & ENERGY COMMUNITY ASPECTS

Demand response means shifting the consumer's energy consumption to times when electricity is most available or is at its cheapest. Only four games featured aspects concerning demand response: *Social Mpower, Sharebuddy, DLT Energy game*, and *Changing the Game – Neighbourhood.* The number of demand-response-related games can be considered quite low. Possible reasons for this can be that the energy pricing models in many countries do not follow the dynamic energy spot pricing. The fixed cost of electric energy does not provide any incentives for the regular consumer to engage in demand response, and thus, serious games featuring it are not as popular as games based on more universal themes such as energy conservation.

Five games had aspects regarding energy communities or shared energy resources: *Social Mpower, Social Power Game, Changing the Game – Neighbourhood, Electric City*, and *DLT Energy Game*. Two out of the five games, *Social Mpower* and *DLT Energy Game*, were specially designed for energy community members. The rest are more focused on general shared energy resources instead of energy communities or similarly functioning entities. Energy communities as a concept are even more novel than demand response, which explains the lack of games designed to teach people on them. A problem with serious games for energy communities is also that the case for which the game is designed can be very specific, and therefore, the audience will be very small.

Below, the games with demand response and/or energy community or shared energy resources are described in more detail. The presence of identified key features (demand response, shared energy resources) is also listed with each game.

1) SOCIAL MPOWER

In *Social Mpower* [21], [22], [23], [24], [25], multiple players share a common energy pool, from where only a limited amount of power can be drawn in any moment. The players must coordinate with the in-game chat interface when each player can draw power from the common energy pool, ensuring that every household gets what it needs but does not overload the supply. The game is based on a 3D world where the players live in virtual houses and move their avatars around and perform daily activities. **Identified features:** demand response, shared energy resources.

2) SHAREBUDDY

Sharebuddy [55] is a casual mobile game that features tracking of the electricity and water consumption of the player's real-life apartment. The game presents a timeline displaying the most suitable time to use electricity, and if the player succeeds in demand response, the player will be rewarded with points that can be used to unlock different arcade-style minigames for the player's enjoyment. **Identified feature:** demand response.

3) DLT ENERGY GAME

DLT Energy Game [53] is a game focused on peer-to-peer energy trading or shared energy resources. The game aims to raise the trust and understanding of distributed ledger technologies (DLT) when they are deployed into use in distributed energy production systems. A distributed ledger, such as a blockchain, is proposed. Peer-to-peer trading of energy using cryptocurrency is discussed in the record, and a serious game is proposed to help people better understand how the system works. The game has an emphasis on displaying energy transactions instead of inner workings of the blockchain. **Identified features:** demand response, shared energy resources.

4) CHANGING THE GAME – NEIGHBOURHOOD

Changing the Game – Neigbourhood [48] is a serious board game where the players cooperate in their imaginary neighborhood to arrange their energy supply while trying to minimize their CO_2 emissions. The players set their consumption and emissions target and value their options as the game is played with cards that provide energy saving techniques. **Identified features:** demand response, shared energy resources.

5) SOCIAL POWER GAME

Social Power Game [16] is a mobile serious game that places the players in an energy saving contest. The players are split into teams of their own neighborhoods, each with an own shared energy resource. The players complete tasks on efficient use of the team's energy resources, and the energy consumption history and task completions are displayed to illustrate how everyone and their team is doing. The players are awarded with virtual badges if they manage to do well. **Identified feature:** shared energy resources.

6) ELECTRIC CITY

Electric City [50] is a resource management game designed for Android tablet computers. In the game, each player is placed in a neighborhood on an island, where their goal is to ensure the survival of their house by obtaining and managing resources, one of them being electricity. The players can either build their own production or negotiate deals between other players to get access to their electricity resources. The game allows direct peer-to-peer trading of electricity; however, it does not award or penalize for doing or not doing it. **Identified feature:** shared energy resources.

IV. CONCLUSION

Serious games are widely studied in the literature, and the energy and electricity sector is one of the fields where various serious games are implemented. While engineers may find aspects of the power distribution system self-explanatory, the plain concept of energy can be complicated for laypeople to grasp. Therefore, many serious games focus on universal and simple concepts such as energy conservation and optimal use of electricity in people's homes. These kinds of games include very basic quiz and puzzle games where the player is, e.g., set to pick whether they should use LED or incandescent lighting in their home or whether they should operate their washing machine full or half-full. On the contrary, some of the games go much further than that and focus on, e.g., working together to share a common energy resource pool so that everyone's virtual avatar can live their life without compromising on the quality of life and the sufficiency of the limited common power resource.

As mentioned above, the vast majority of the identified games are no longer available for play. This is most likely because the project in which the game was released has come to an end. Many games were designed to be played for a fixed period of time and/or by a closed audience, and the effect of playing the game was assessed with pregame and postgame surveys or with an analysis of the players' energy consumption habits before, during, and after the game period. These kinds of studies on serious games seem common, but games made for anyone to play regardless of whether the game development project is over or not are not commonplace. Studies conclude that serious games are a viable tool for raising awareness of energy consumption habits, but the viability of the tool is reduced if the game is available for a select group of participants for a limited period of time.

Based on the findings of this review, there are research gaps related to serious games with an emphasis on energy communities with shared energy resources where demand response is taken into effect. Three games, *Social Mpower, Changing the Game – Neighbourhood*, and *DLT Energy Game*, featured both demand response and energy community aspects, but they did not feature a link to real-life events. A serious game where energy community members could practice optimizing their energy usage and engage in demand response where the events of their actual home are reflected in the game has not, to the authors' knowledge, been implemented yet. This kind of a game would suit as a tool to see how different co-owned energy resources could be shared in the best and fairest manner. However, this raises an issue with the availability of the game, as it is difficult to make the game available for anyone to play if the game is focused on real-life homes and what happens in them. Therefore, a middle-ground solution where the game could be played based on a real place of residence or a simulated one could be the most optimal solution. The simulation could be based on e.g. an offline energy consumption database of real residences or on a energy consumption model made using the characteristics of an average apartment or house, depending on the preferred scenario. Based on all this, a novel serious game with the following features could be implemented:

- The game is based on an energy community with shared PV resources.
- The game rewards the player for good demand response actions.
- There is an option between real-life source of data and a simulation.

Meeting these criteria would introduce a novel serious game to the field. The target audience of such a game would focus on the owners of an apartment in a multifamily residential building participating in an energy community, or a detached house with a local energy community. Besides experimenting on possible energy distribution and sharing schemes, this kind of a serious game has the potential to raise awareness of energy communities and promote the spread of PV systems and distributed production of electricity, which is proven to be crucial in the rollout of renewable energy and fighting against climate change.

REFERENCES

[1] Z. Yuan, P. C. Wu, and Y.-C. Chen, "Optical resonator enhanced photovoltaics and photocatalysis: Fundamental and recent progress," *Laser Photon. Rev.*, vol. 16, no. 2, 2022, Art. no. 2100202.

[2] A. Simola, A. Kosonen, T. Ahonen, J. Ahola, M. Korhonen, and T. Hannula, "Optimal dimensioning of a solar PV plant with measured electrical load curves in Finland," *Sol. Energy*, vol. 170, pp. 113–123, Jun. 2018.

[3] *Directive (EU) 2018/2001 of the European Parliament and of the Council of 11 December 2018 on the Promotion of the Use of Energy From Renewable Sources*, Eur. Parliament Council, 2018.

[4] *Directive (EU) 2019/944 of the European Parliament and of the Council of 5 June 2019 on Common Rules for the Internal Market for Electricity and Amending Directive 2012/27/EU*, Eur. Parliament Council, 2019.

[5] J. Mao, M. Jafari, and A. Botterud, "Planning low-carbon distributed power systems: Evaluating the role of energy storage," *Energy*, vol. 238, Jan. 2022, Art. no. 121668.

[6] P. Puranen, A. Kosonen, and J. Ahola, "Techno-economic viability of energy storage concepts combined with a residential solar photovoltaic system: A case study from Finland," *Appl. Energy*, vol. 298, Sep. 2021, Art. no. 117199.

[7] M. R. Herrmann, D. P. Brumby, and T. Oreszczyn, "Watts your usage? A field study of householders' literacy for residential electricity data," *Energy Efficiency*, vol. 11, pp. 1703–1719, Oct. 2018.

[8] K. L. van den Broek, "Household energy literacy: A critical review and a conceptual typology," *Energy Res. Social Sci.*, vol. 57, Nov. 2019, Art. no. 101256.

[9] European Commission, Directorate-General for Energy. (2019). *Clean Energy for All Europeans*. Publications Office. [Online]. Available: https://data.europa.eu/doi/10.2833/9937

[10] R. Dörner, S. Göbel, W. Effelsberg, and J. Wiemeyer, *Serious Games: Foundations, Concepts and Practice*. Cham, Switzerland: Springer, 2018.

[11] D. Huynh, L. Zuo, and H. Iida, "Analyzing gamification of 'Duolingo' with focus on its course structure," in *Proc. Int. Conf. Games Learn. Alliance*, Dec. 2016, pp. 268–277.

[12] X. Wu, S. Liu, and A. Shukla, "Serious games as an engaging medium on building energy consumption: A review of trends, categories and approaches," *Sustainability*, vol. 12, no. 20, pp. 1–16, 2020.

[13] M. Casals, M. Gangolells, M. Macarulla, N. Forcada, A. Fuertes, and R. V. Jones, "Assessing the effectiveness of gamification in reducing domestic energy consumption: Lessons learned from the EnerGAware project," *Energy Buildings*, vol. 210, Mar. 2020, Art. no. 109753.

[14] R. F. Mulcahy, R. McAndrew, R. Russell-Bennett, and D. Iacobucci, "'Game on!' Pushing consumer buttons to change sustainable behavior: A gamification field study," *Eur. J. Marketing*, vol. 55, no. 10, pp. 2593–2619, 2021.

[15] G. Schweiger, L. V. Eckerstorfer, I. Hafner, A. Fleischhacker, J. Radl, B. Glock, M. Wastian, M. Rößler, G. Lettner, N. Popper, and K. Corcoran, "Active consumer participation in smart energy systems," *Energy Buildings*, vol. 227, Nov. 2020, Art. no. 110359.

[16] B. Behi, A. Arefi, P. Jennings, A. Pivrikas, A. Gorjy, and J. P. S. Catalao, "Consumer engagement in virtual power plants through gamification," in *Proc. 5th Int. Conf. Power Renew. Energy*, 2020, pp. 131–137.

[17] P. Makris, N. Efthymiopoulos, D. J. Vergados, E. Varvarigos, V. Nikolopoulos, J. Papagiannis, A. Pomazanskyi, B. Irmscher, K. Stefanov, K. Pancheva, and A. Georgiev, "SOCIALENERGY: A gaming and social network platform for evolving energy markets' operation and educating virtual energy communities," in *Proc. IEEE Int. Energy Conf. (ENERGYCON)*, Jun. 2018, pp. 1–6.

[18] P. Davison, S. Blake, A. Spencer, E. Burton, and S. Lee-Favier, "Activating residential demand side response to relieve network congestion," in *Proc. CIRED Workshop*, 2016, pp. 1–4.

[19] M. A. Zehir, K. B. Ortac, H. Gul, A. Batman, Z. Aydin, J. C. Portela, F. J. Soares, M. Bagriyanik, U. Kucuk, and A. Ozdemir, "Development and field demonstration of a gamified residential demand management platform compatible with smart meters and building automation systems," *Energies*, vol. 12, no. 5, p. 913, 2019.

[20] M. J. Page, J. E. McKenzie, P. M. Bossuyt, I. Boutron, T. C. Hoffmann, C. D. Mulrow, L. Shamseer, J. M. Tetzlaff, E. A. Akl, S. E. Brennan, and R. Chou, "The PRISMA 2020 statement: An updated guideline for reporting systematic reviews," *Systematic reviews*, vol. 10, no. 1, p. 11, 2021.

[21] A. Bourazeri and J. Pitt, "Social Mpower: A serious game for self-organisation in socio-technical systems," in *Proc. Int. Conf. Self-Adapt. Self-Organizing Syst.*, Dec. 2014, pp. 199–200.

[22] A. Bourazeri and J. Pitt, "A game-based approach for collective action in self-organising socio-technical systems," in *Proc. Int. Conf. Self-Adaptive Self-Organizing Syst.*, Dec. 2014, pp. 175–176.

[23] A. Bourazeri and J. Pitt, "Collective awareness for collective action in socio-technical systems," in *Proc. IEEE 8th Int. Conf. Self-Adapt. Self-Organizing Syst. Workshops*, Sep. 2014, pp. 90–95.

[24] A. Bourazeri and J. Pitt, "Collective attention and active consumer participation in community energy systems," *Int. J. Hum. Comput. Stud.*, vol. 119, pp. 1–11, Nov. 2018.

[25] A. Bourazeri and J. Pitt, *An Agent-Based Serious Game for Decentralised Community Energy Systems* (Lecture Notes in Computer Science: Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics), vol. 8861. Cham, Switzerland: Springer, 2014.

[26] M. Casals, M. Gangolells, M. Macarulla, A. Fuertes, V. Vimont, and L. M. Pinho, "A serious game enhancing social tenants' behavioral change towards energy efficiency," in *Proc. Global Internet Things Summit (GIoTS)*, 2017, pp. 1–6.

[27] M. Gangolells, M. Casals, M. Macarulla, and N. Forcada, "Exploring the potential of a gamified approach to reduce energy use and carbon emissions in the household sector," *Sustainability*, vol. 13, no. 6, p. 3380, 2021.

[28] M. Gangolells, M. Casals, N. Forcada, and M. Macarulla, "Life cycle analysis of a game-based solution for domestic energy saving," *Sustainability*, vol. 12, no. 17, p. 6699, 2020.

[29] P. Ponce, A. Meier, J. I. Méndez, T. Peffer, A. Molina, and O. Mata, "Tailored gamification and serious game framework based on fuzzy logic for saving energy in connected thermostats," *J. Cleaner Prod.*, vol. 262, Jun. 2020, Art. no. 121167.

[30] R. J. Hafner, S. Pahl, R. V. Jones, and A. Fuertes, "Energy use in social housing residents in the uk and recommendations for developing energy behaviour change interventions," *J. Cleaner Prod.*, vol. 251, pp. 1–12, Sep. 2020.

[31] R. J. Hafner, A. Fuertes, S. Pahl, C. Boomsma, R. V. Jones, M. Casals, and M. Gangolells, "Results and insight gained from applying the EnergyCat energy-saving serious game in UK social housing," *Int. J. Serious Games*, vol. 7, no. 2, pp. 27–48, 2020.

[32] B. Hedin, A. Lundstrom, M. Westlund, and E. Markstrom, "The energy piggy bank—A serious game for energy conservation," in *Proc. 5th IFIP Conf. Sustain. Internet ICT Sustainability*, 2018, pp. 1–6.

[33] J. D. Fijnheer and H. van Oostendorp, *Steps to Design a Household Energy Game* (Lecture Notes in Computer Science: Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics), vol. 9599. Cham, Switzerland: Springer, 2016.

[34] A. Gustafsson and M. Bång, "Evaluation of a pervasive game for domestic energy engagement among teenagers," in *Proc. Int. Conf. Adv. Comput. Entertainment Technol.*, New York, NY, USA, 2008, pp. 232–239.

[35] L. Gamberini, N. Corradi, L. Zamboni, M. Perotti, C. Cadenazzi, S. Mandressi, G. Jacucci, G. Tusa, A. Spagnolli, C. Björkskog, M. Salo, and P. Aman, "Saving is fun: Designing a persuasive game for power conservation," in *Proc. 8th Int. Conf. Adv. Comput. Entertainment Technol.*, New York, NY, USA, 2011, pp. 1–7.

[36] A. Gustafsson, M. Bång, and M. Svahn, "Power explorer: A casual game style for encouraging long term behavior change among teenagers," in *Proc. Int. Conf. Adv. Comput. Enterntainment Technol.*, New York, NY, USA, 2009, pp. 182–189.

[37] H. Kimura and T. Nakajima, "Ecoisland: A persuasive application to motivate sustainable behavior in collectivist cultures," in *Proc. 6th Nordic Conf. Hum.-Comput. Interact., Extending Boundaries*, New York, NY, USA, 2010, pp. 703–706.

[38] V. Rai and A. L. Beck, "Play and learn: Serious games in breaking informational barriers in residential solar energy adoption in the United States," *Energy Res. Social Sci.*, vol. 27, pp. 70–77, Apr. 2017.

[39] Y. rock Zou, N. Mustafa, N. A. Memon, and M. Eid, "ECO ECO: Changing climate related behaviors for cellphone-based videogames," in *Proc. IEEE Int. Symp. Haptic, Audio Vis. Environ. Games (HAVE)*, Oct. 2015, pp. 1–5.

[40] M. M. Nadzir and B. Pillay, "A mobile game approach for energy conservation awareness," in *Proc. 16th Int. Conf. Ubiquitous Inf. Manage. Commun. (IMCOM)*, 2022, pp. 1–4.

[41] S. Seebauer, M. Berger, K. Kettl, and M. Moser, "Green gang vs. captain carbon. integration of automated data collection and ecological footprint feedback in a smartphone-based social game for carbon saving," in *Proc. 5th Int. Conf. Games Virtual Worlds Serious Appl.*, 2013, pp. 1–2.

[42] L. Whittaker, R. Russell-Bennett, and R. Mulcahy, "Reward-based or meaningful gaming? A field study on game mechanics and serious games for sustainability," *Psychol. Marketing*, vol. 38, no. 6, pp. 981–1000, 2021.

[43] R. Mulcahy, R. Russell-Bennett, and D. Iacobucci, "Designing gamified apps for sustainable consumption: A field study," *J. Bus. Res.*, vol. 106, pp. 377–387, May 2020.

[44] A. Yam, R. Russell-Bennett, M. Foth, and R. Mulcahy, "How does serious m-game technology encourage low-income households to perform socially responsible behaviors?" *Psychol. Marketing*, vol. 34, no. 4, pp. 394–409, 2017.

[45] T. Swinton, J. Little, R. Russell-Bennett, R. Mulcahy, R. McAndrew, and C. Passion, "Reduce your juice digital social marketing program (LIEEP): Final report," CitySmart, Brisbane, QLD, Australia, 2016.

[46] G. Mylonas, J. Hofstaetter, A. Friedl, and M. Giannakos, "Designing effective playful experiences for sustainability awareness in schools and makerspaces," in *Proc. ACM Int. Conf.*, 2021, pp. 1–9.

[47] M. Bayley, S. Snow, J. Weigel, and N. Horrocks, "Serious game design to promote energy literacy among younger children," in *Proc. ACM Int. Conf.*, 2020, pp. 531–537.

[48] M. Lanezki, C. Siemer, and S. Wehkamp, "'Changing the game-neighbourhood': An energy transition board game, developed in a co-design process: A case study," *Sustainability*, vol. 12, no. 24, pp. 1–18, 2020.

[49] A. Wagner and D. Galuszka, "Let's play the future: Sociotechnical imaginaries, and energy transitions in serious digital games," *Energy Res. Social Sci.*, vol. 70, Dec. 2020, Art. no. 101674.

[50] A. Singh, H. W. Van Dijk, B. O. Wartena, N. R. Herrera, and D. Keyson, "'Electric city': Uncovering social dimensions and values of sharing renewable energy through gaming," in *Proc. Conf. Hum. Factors Comput. Syst.*, vol. 18, 2015, pp. 1519–1524.

[51] T. Csoknyai, J. Legardeur, A. A. Akle, and M. Horváth, "Analysis of energy consumption profiles in residential buildings and impact assessment of a serious game on occupants' behavior," *Energy Buildings*, vol. 196, pp. 1–20, May 2019.

[52] P. Fraternali and S. L. H. Gonzalez, *An Augmented Reality Game for Energy Awareness* (Lecture Notes in Computer Science: Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics), vol. 11754. Cham, Switzerland: Springer, 2019.

[53] J. W. Veeningen and N. B. Szirbik, "Using serious gaming to discover and understand distributed ledger technology in distributed energy systems," in *Proc. IFIP Int. Conf. Adv. Prod. Manage. Syst.*, vol. 535, 2018, pp. 549–556.

[54] O. Garay Garcia, C. E. van Daalen, E. Chappin, B. van Nuland, I. Mohammed, and B. Enserink, *Assessing the Residential Energy Rebound Effect by Means of a Serious Game* (Lecture Notes in Computer Science: Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics), vol. 10825. Cham, Switzerland: Springer, 2018.

[55] R. S. Brewer, N. Verdezoto, T. Holst, and M. K. Rasmussen, "Tough shift: Exploring the complexities of shifting residential electricity use through a casual mobile game," in *Proc. Annu. Symp. Comput.-Hum. Interact. Play*, 2015, pp. 307–318.

[56] B. Cowley, "The QUARTIC process model for developing serious games: 'Green my place' case study," in *Digital Da Vinci: Computers in the Arts and Sciences*. New York, NY, USA: Springer, 2014, pp. 143–172.

[57] R. N. Madeira, A. Silva, C. Santos, B. Teixeira, T. Romão, E. Dias, and N. Correia, "Ley! Persuasive pervasive gaming on domestic energy consumption-awareness," in *Proc. ACM Int. Conf.*, 2011, pp. 1–2.

[58] P. Fraternali, S. Herrera, J. Novak, M. Melenhorst, D. Tzovaras, S. Krinidis, A. E. Rizzoli, C. Rottondi, and F. Cellina, "Encompass—An integrative approach to behavioural change for energy saving," in *Proc. Global Internet Things Summit (GIoTS)*, 2017, pp. 1–6.

[59] A. Nilsson, M. Wester, D. Lazarevic, and N. Brandt, "Smart homes, home energy management systems and real-time feedback: Lessons for influencing household energy consumption from a Swedish field study," *Energy Buildings*, vol. 179, pp. 15–25, Jun. 2018.

MIKKO NYKYRI (Member, IEEE) was born in Finland in 1993. He received the B.Sc. and M.Sc. degrees from the Lappeenranta University of Technology (LUT), in 2017 and 2018, respectively. He is currently pursuing the D.Sc. (Tech.) degree with the Laboratory of Applied Electronics, LUT School of Energy Systems. His main research interests include utilization of distributed ledger technologies and serious games on solar energy optimization in domestic environments. He has also worked in data analytics, machine learning, and the IoT in industrial predictive maintenance.

TOMMI J. KÄRKKÄINEN (Member, IEEE) was born in Finland in 1987. He received the B.Sc., M.Sc., and D.Sc. (Tech.) degrees from the Lappeenranta University of Technology (LUT), Lappeenranta, Finland, in 2010, 2011, and 2015, respectively.

He is currently a Postdoctoral Researcher with the LUT School of Energy Systems. His main research topic is the reliability of power electronic devices and systems, and the utilization of machine learning algorithms to improve the reliability and productivity of various systems.

SALLA ANNALA received the D.Sc. (Tech.) degree from the School of Energy Systems, Lappeenranta University of Technology (LUT), in 2015. She works as a Postdoctoral Researcher with the School of Energy Systems, LUT. Her research interests include end-users' role in the energy transition, energy communities, and market and regulatory arrangements supporting utilization of demand response and other distributed energy and flexibility resources.

PERTTI SILVENTOINEN (Member, IEEE) was born in Simpele, Finland, in 1965. He received the M.Sc. degree in electrical engineering, the Licentiate of Technology degree in applied electronics and control systems, and the D.Sc. (Tech.) degree with the focus on EMC in electronics from the Lappeenranta University of Technology (LUT), Finland, in 1993, 1997, and 2001, respectively. Since 2008, he has been a Full Professor in applied electronics at LUT. His research interests include analog signal processing and measurement systems, power line communication applications, EMC measurement technology, and power electronic systems in various forms.

• • •

Publication III

Nykyri, M., Kärkkäinen, T.J., Levikari, S., Honkapuro, S., Annala, S., and
Silventoinen, P.

The impact of intracommunal network service pricing on the economic feasibility of an energy community

Reprinted with permission from
2023 19th International Conference on the European Energy Market (EEM)

The Impact of Intracommunal Network Service Pricing on the Economic Feasibility of an Energy Community

Mikko Nykyri, Tommi J. Kärkkäinen, Saku Levikari, Salla Annala, Samuli Honkapuro, and Pertti Silventoinen
LUT University
Lappeenranta, Finland
Email: mikko.nykyri@lut.fi

***Abstract*—As people aspire to reduce energy expenditures, local photovoltaic installations that are co-owned by multiple single-family homes are gaining interest. Energy communities are formed, where the members together agree on the methods of energy allocation. As the households are likely to rely on using the local distribution system operator grid, a network service charge is imposed on the intracommunal energy transmission from the solar installation to the houses, affecting its economic viability. This paper presents how energy balance settlement can be carried out using a blockchain-based ledger that would allow differentiation of intracommunal and extracommunal network services in the form of possible pricing reduction for the intracommunal network service. Even a 50% reduction, on average, increases the savings for the six-household community under study by approx. 16.42%. However, even without any pricing reductions, shared photovoltaic installations can be viable and the energy allocation can be carried out without major investments in infrastructure.**

***Index Terms*—Solar energy, Energy community, Smart grids**

I. INTRODUCTION

Local small-scale energy production with photovoltaic (PV) installations is gaining popularity worldwide. The cost of initial investment is decreasing, making the decision to become a "prosumer", i.e., a producer–consumer, of electrical energy more appealing. In addition to individual single-family homes investing in PV installations, co-owned PV systems are gaining interest [1], [2]. These systems can range from rooftop PV systems in multifamily residential buildings to shared PV installations in suburban or rural areas.

Shared PV resources either have to have their own distribution grid or rely on an existing distribution system operator (DSO) grid to transfer the produced energy to the households. Building a separate distribution grid only for sharing the locally produced energy is not efficient since the households, even if a PV installation is present, require a grid connection because the energy consumption of the buildings can exceed the PV system capacity. Therefore, it is reasonable to use the existing DSO grid for energy transmission between the prosumers and the PV installation. The downside of the use of the DSO grid is that a network service charge is imposed even when transmitting energy from the co-owned PV installation to the installation owners' residences. From the DSO's side, this transmission is usually considered equal to the transmission of electricity from the energy supplier (e.g., a large power plant) to the users. If the network service charge is applied to local-scale transmission from the PV installation to the users, its pricing may end up reducing the benefits of local PV installations if the cost of energy that could just be bought from the energy supplier through the DSO grid is low enough.

Methods to make the use of the existing grid more affordable are studied widely. Arrangements called *energy communities* are often proposed as a viable solution for the utilization of the existing network infrastructure and as a platform for setting rules for co-owned energy production sharing. Energy communities are legal entities defined in the European Union (EU) legislation [3], and they are designed for enabling the rollout of local energy production and energy sharing. However, despite being prospective, energy communities are not without problems. Questions are often raised, e.g., on cost allocation [4], and designing a tariff mechanism is problematic when also considering consumer acceptance, universal benefit, and efficiency [5]. There are numerous methods to carry out the energy sharing within an energy community. Possible methods include energy aggregators and distributed ledger technologies. For instance, the energy balance settlement and PV energy sharing within an energy community can be implemented with a blockchain-based ledger with smart contracts [6]. This allows the participating residences to retain their status as individual households in the open retail electricity market while being entitled to low-cost local PV energy.

This paper studies how the co-owned PV energy sharing differs when comparing an energy community where the participating residences are apartments in a multifamily residential building with one where the participating residences are single-family homes. The effect of intracommunal network service pricing on the economic viability of a shared PV installation in an energy community consisting of single-family homes is also studied. In the context of this paper, the intracommunal network service means the transfer of energy between the PV installation and the consumption sites.

The problems are approached with a presentation of a use case scenario of how the blockchain-based energy balance settlement ledger and the energy allocation principles

---

The authors gratefully acknowledge The Center for Economic Development, Transport and the Environment Häme for funding the FarmEnergy Rural Energy Community project.

979-8-3503-1258-4/23/$31.00 ©2023 IEEE

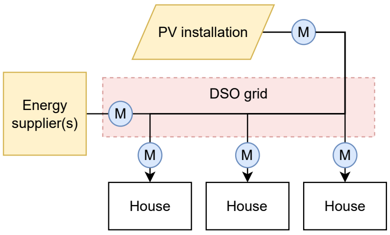


Fig. 1. Energy sharing architecture in an energy community formed of single-family homes. The wiring between the houses and the PV installation is part of the DSO network.

described in [6] can be employed in a single-family home energy community located in a suburban or rural environment with a shared PV installation separate from the buildings. The economical benefits of such a system are studied with a simulation using real data on energy consumption, PV installation production, and energy cost.

II. TECHNICAL FRAMEWORK

Energy communities have been studied as a method of sharing locally produced energy. Earlier pilots and research projects have typically focused on areas that are outside the EU and without an open retail electricity market, e.g., the Brooklyn Microgrid [7] and the peer-to-peer trading/microgrid projects in western Australia [8] and Switzerland [9]. However, the EU legislation requires that the members of an energy community do not lose their rights as household customers, and one such right is the freedom to choose their energy supplier. Therefore, energy communities without the ability to participate in the open market may be unfeasible or at least unappealing. In a case where an energy community does not allow participation in an open retail electricity market, the energy community can feature an energy aggregator, which is responsible for the allocation, distribution, and purchasing of energy in an energy community [10]. This aggregator acts as the intermediate between the energy community and the open retail electricity market [11], and the members of the energy community are in a customer relationship with the aggregator and not with the energy suppliers themselves.

When the members of an energy community remain as participants in the open retail electricity market, it means that any deficit energy they need is purchased by the members themselves with their own contracts between them and the energy supplier instead of a centralized aggregator [6]. This allows the members to select the source of their energy needs that are not fulfilled by the local PV installation, and also keeps the energy community in line with the Finnish and EU legislation on electricity markets [12]. In this case, the energy aggregator can be redundant, and it can be replaced with, e.g., a blockchain-based energy balance settlement ledger, which allows secure energy consumption data storage, data processing, and energy allocation by using automatic smart contracts [6]. Sometimes, the need for an aggregator is justified because of the need for a central entity that all the members can trust. A blockchain allows distributed data storage that is tamper-proof [13], and therefore, it can be considered an effective way to replace the aggregator.

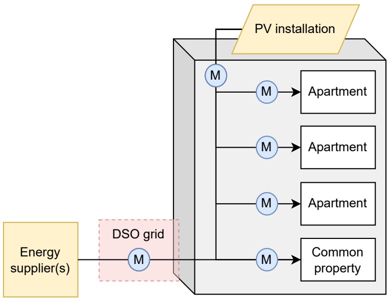


Fig. 2. Energy sharing architecture in an energy community formed of apartments in a multifamily residential building. The wiring inside the building is not part of the DSO network.

The EU mandates its Member States to implement the roll-out of smart meters in Directive 2019/944 [3], which is a way to both enable dynamic energy pricing and promote solutions like formation of energy communities. On the other hand, the EU legislation stating that energy community members must not lose their rights as household customers can be seen as a factor discouraging the formation of an energy community when comparing with a location where there is no open retail electricity market. In these areas, the arrangements can be more straightforward, but, on the other hand, they lack the consumer-side flexibility to choose their supplier of electrical energy.

A. *Single-Family Home Energy Community*

The electrical energy distribution architecture in a single-family home energy community (Fig. 1) differs from an energy community within a single multifamily residential building (Fig. 2). These two have some similarities: all of the consumption locations are connected to a low-voltage distribution grid, and they can be considered to have a single entry point, which may or may not be (virtually) metered. However, there are differences in the ownership of the transmission infrastructure. In a single-family home energy community, the power lines connecting the buildings together are owned by the DSO and located on different properties. In a multifamily residential building, the transmission lines inside the building are not necessarily owned by the DSO, but any transmitted energy is considered to use the DSO grid, because the meters are, at least in a Finnish setting, owned by the DSO. In addition, possible electric vehicle charging is carried out behind household-specific metering instead of communal metering in a multifamily residential building.

Regardless of who owns the distribution architecture within the energy community, a set of rules between the community members and the infrastructure owner (i.e., the DSO) has to be established. In addition to an agreement made with the infrastructure owner, an agreement between the participants of the community is necessary to ensure fair sharing of the energy. Fairness as a concept is difficult to determine, but with a prior contract, all participants will have agreed on the sharing terms and rules, which reduces confusion about the sharing practices. If a participant or participants are unsatisfied, they have the opportunity to opt out from the energy community altogether. The voluntary participation in energy communities is also stated in the EU legislation, meaning that people cannot be forced to participate in an energy community.

B. Sharing of PV Energy

Sharing of the co-owned energy can be carried out in various ways. Obviously, the sharing logic should be based on agreed-upon rules, but whether the rules are fair or not can be a difficult question to answer. The energy allocation can be performed, e.g., by the energy aggregator [11] or automatically like in [6], where the rules are by design easy to understand to promote simplicity of the sharing logic, as many people may find concepts related to electricity and energy difficult to comprehend [14], [15]. Dynamic energy tariffs can also be perceived as complex [16]. Local renewable energy sharing is often proposed to be implemented with active prosumer participation methods like energy auctioning [17]–[20]. Whether the sharing arrangement in [6] where each residence is granted an equal ratio of its energy consumption as affordable PV energy is fair or not is a difficult question to answer, but favoring easy-to-understand systems compared with more complex setups, despite them showing a promise to be effective, can be argued to be beneficial to promote the rollout of renewable energy systems.

In a multifamily residential building (Fig. 2), the energy consumption consists of the consumption of the apartments and the common property. In a single-family home energy community (Fig. 1), the electric power consumption of the community consists only of the energy consumption of the individual households. In multifamily residential buildings there are also some common facilities that need energy to maintain conditions suitable for housing. These common facilities include, e.g., ventilation and hallway lighting. If common facilities exist, it is justified to supply power to them first, because being common means that the energy cost of these facilities ends up being covered by the residents who use them. However, because in a energy community consisting of individual single-family homes there are no common facilities to be powered, the produced PV energy can be directly supplied to the participating households.

In this study, the energy allocation is based on the logic that every household is allocated an equal ratio of its energy consumption as local PV energy. The allocation can be calculated by Eqs. (1) and (2) afterward from history data, or in near real time after each balancing period in the electricity market has passed. The balancing period in this study is one hour. The ratio of the PV energy to the total energy needs R_{PV_i} is

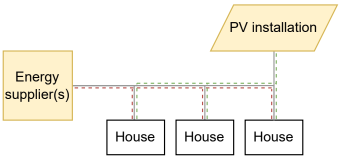


Fig. 3. Intracommunal (green) and extracommunal (red) network services can be considered different: the intracommunal transmission occurs between the houses and the PV installation and the extracommunal between the energy supplier(s) and the houses.

$$R_{\mathrm{PV}_i} = \frac{E_{\mathrm{PV}}}{\sum E_{\mathrm{H}_i}} \tag{1}$$

where E_{PV} is the amount of PV energy produced in the co-owned PV installation, and $\sum E_{\mathrm{H}_i}$ is the combined energy consumption of all the participating households of the energy community. The values used in Eq. (1) are values over a fixed balancing period in the electricity market.

The amount of PV energy allocated to each household $E_{\mathrm{PV,H}_i}$ can then be calculated by

$$E_{\mathrm{PV,H}_i} = E_{\mathrm{H}_i} R_{\mathrm{PV}_i} \tag{2}$$

where E_{H_i} is the total energy consumption of the household. Thus, each household will need to purchase $E_{\mathrm{PV,H}_i}$ less power from the grid, which promotes economic benefit and enhances the energy self-sufficiency of the household. In situations where the PV production exceeds the combined energy consumption of the energy community ($R_{\mathrm{PV}_i} > 1$), the remaining energy is sold back to the grid.

The study in [6] was based on the premise that the intracommunal network service could be waived altogether with a deal made between the energy community and the DSO, because all the intracommunal energy transmission takes place within a single building and does not enter the DSO network, even if the meters inside the building were owned by the DSO. In a suburban and especially in a rural setting, this kind of a deal may not be viable because of the distance between the consumption sites, and therefore, the local DSO will likely place a network service charge for the intracommunal energy transmission because the transmitted energy is likely to use the DSO network. Longer distances mean that the distribution grid is more expensive to keep in shape, as the wiring within a multifamily residential building is relatively low-maintenance and affordable when compared with, e.g., underground cabling or overhead power lines. The DSO pricing of the network services should reflect the real costs that the transmission imposes on the network. In a multifamily residential building, the cost is minimal, if existing at all, since the intracommunal wiring, i.e., the electrical wiring inside the building, is often not owned by the DSO. In a suburban or rural environment, the network is owned by the DSO, but the transmission

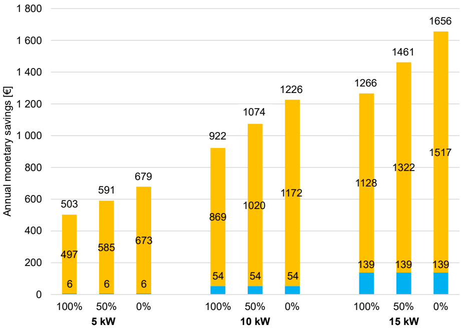


Fig. 4. Annual monetary savings in € for the whole community with PV installation capacities of 5, 10, and 15 kW when the intracommunal network service pricing is 0%, 50%, and 100% of the standard DSO network service pricing. The savings consist of the monetary benefit from the discounted service charges (yellow) and the benefit from sold energy (blue). The monetary benefits from sold energy are minor. For easier examination and comparison of the values, the values have been rounded up or down to the nearest whole euro.

distances and costs may not necessarily be comparable with the transmission from the energy supplier to the community. The energy-supplying energy company can be located much farther away. Still, it can be argued that the intracommunal and extracommunal network services should be differentiated (Fig. 3).

III. SIMULATION

The energy sharing method was tested with a simulated energy community consisting of six single-family homes. The simulation was performed using real-world energy consumption data from households located in Lappeenranta, Finland along with PV installation production data from the rooftop PV installation at the authors' university. The university PV production was scaled down to match installation capacities of 5, 10, and 15 kW. The appropriate electric energy costs were fetched from the NordPool spot price database from the days of the data. However, because the energy consumption and cost data were from 2014, which during the writing of this paper was nine years ago, the energy cost does not reflect the situation in 2023. Therefore, the hourly spot prices were scaled up with a factor of 4.28 to make the *average energy cost* (0.036 €/kWh) of the data set match the average energy cost of the year 2022 (0.154 €/kWh). The cost of electricity transfer was 0.0465 €/kWh as per the pricing of the local distribution system operator in the Lappeenranta region. The households' energy consumption varied between 12 099.7 kWh/a and 20 148.59 kWh/a, the average and median consumptions being 14 316.75 kWh/a and 13 499.41 kWh/a, respectively. The households selected for the study are regular homes that do not have a district heating connection, thus better representing a suburban or a rural setting than a home where the main form of heating is district heating. Based on the energy consumption figures, the households can be assumed to be heated primarily with electric heating. However, to the authors' knowledge, the selected homes were not participating in an energy community and did not have any local PV production. Thus, the data set represents average single-family homes with no special incentives to change their energy consumption habits.

TABLE I
COMBINED TOTAL ANNUAL ENERGY COSTS WITH DIFFERENT INTRACOMMUNAL NETWORK SERVICE PRICINGS AND PV CAPACITIES (ROUNDED TO THE NEAREST WHOLE EURO)

PV capacity	Intracommunal network service pricing		
	0%	50%	100%
No PV	€17 518 (All scenarios)		
5 kW	€16 839	€16 927	€17 014
10 kW	€16 292	€16 444	€16 596
15 kW	€15 862	€16 057	€16 251

The simulation was based on one full year of the aforementioned data. In order to find out how the intracommunal network service charges affect the economic viability of the PV installation, the system performance was tested with three different scenarios of intracommunal energy transfer cost contracts between the energy community and the DSO: 100% full price, 50% price, and free transmission. The sum of total energy expenses of all households was collected in each scenario. The simulation was performed three times with different shared PV installation capacities of 5, 10, and 15 kW. During times when the PV installation production exceeds the energy consumption of the energy community, all the households are powered without cost. The remaining energy is sold to the grid.

IV. RESULTS & DISCUSSION

In the simulation, the total annual expenditure on energy for the six single-family homes in the baseline scenario without any PV implementation is €17 517.69 (Table I). This sum contains also the DSO network service charges for the energy transmission between the energy supplier and the houses. When a PV installation is added, the annual costs are reduced. The annual reduction in cost for the whole community is between €503.22 and €1655.71, depending on the PV installation capacity and the intracommununal network service pricing (Fig. 4). The savings are calculated by subtracting the annual cost of energy in each scenario from the annual energy cost when there is no PV installation present (the baseline scenario). The revenue gained for the energy community by selling the excess energy to the grid in situations when the PV production exceeds the total energy consumption of the community is added to each of the calculated figures. The annual revenue from selling energy to the grid depends only on the installed PV capacity, and the network service pricing for this to-grid transmission is approximated by making a reduction to the revenue by making it yield one-third of the current energy retail price. For 5, 10, and 15 kW installations, the annual revenues are €5.73, €53.55, and €138.66, respectively. When there is no PV installed, there is no intracommunal network service and all the energy transmission is considered extra-communal (energy transmission from the energy supplier to the homes).

The results show that the community can receive monetary benefit even with a relatively small 5 kW PV installation. Increasing the installation capacity and decreasing the intracommununal network service pricing both increase the monetary savings. The effects are seen when the different installation capacities (5, 10, and 15 kW) are assessed individually as intracommunal network pricing reductions are introduced, and the monetary savings are compared with a situation where the full DSO pricing is charged for intracommunal network services. With a 5 kW installation, halving the intracommunal network service pricing from 100% to 50% will increase the monetary savings by 17.45%. With 10 kW and 15 kW installations, the values are 16.45% and 15.37%, respectively. When examining the increase in savings when the network service charges are removed altogether, the saving rates are 34.91%, 36.16%, and 30.74% when compared with full price. The saving percentage is thus not significantly dependent on the installation capacity, but rather on the network service pricing. This is because a PV installation will generate economic benefit even if the full DSO pricing is used for intracommunal network services.

To achieve the full economic benefits described in this paper, the DSO would have to waive the intracommunal network service charges altogether when transmitting energy from the PV installation to the households. The residents would only pay for the energy transmission from the energy supplier to the apartments when there is a deficit in PV production. This can be considered an unlikely situation, because the DSO will not likely offer its services for free. However, if a contract between the energy community and the DSO could be made, it would allow more affordable pricing for short-distance transfer between the PV installation and the residences. For instance, with a contract allowing a 50% reduction in intracommunal network service pricing, a shared 10 kW PV installation would yield annual savings of roughly €1074 for the community. Still, even without any reductions in pricing, a similarly sized system allows annual savings of over nine hundred euros and shows that PV systems can be viable. That being said, the intracommunal network service pricing could be a point to consider when dimensioning shared PV installations. The assessment of the effect of the initial investment and maintenance costs of a PV installation was left outside the scope of this paper.

Although the simulation scenario presented in this paper focuses on the energy infrastructure in Finland, similar kinds of cost structures are applied also in other parts of the world. Dynamic pricing of electrical energy is becoming more common, and the conditions present in the simulation are also present at least in the Nordic countries or Northern Europe.

V. CONCLUSION

Investing in a shared PV installation can reduce the financial burden of the initial investment when multiple families take part in financing the initial cost. There are numerous methods for sharing the profits (the produced PV energy), e.g., formation of an energy community, where instead of an energy aggregator, the energy balance settlement is handled with a blockchain-based ledger and smart contracts. The energy can be automatically shared between the shareholders of the PV installation based on rules that are agreed upon together by the energy community. This kind of an arrangement mitigates the need for active participation like bidding and auctioning of the produced PV energy, and allows effortless access to local energy while the households maintain their customer relationship to energy suppliers in the open retail electricity market.

Sharing a PV installation between single-family homes in a suburban or rural environment requires the use of the DSO network for intracommunal energy transmission from the PV installation to the houses where the energy is consumed. If the DSO imposes full network service charges on this, which it is entitled to, the economic benefits from the system can be almost approx. 35% lower than in a situation where the intracommunal network service charges are waived. Still, even with full network service pricing, the simulations show that implementing a shared PV system can bring reductions in the electric bill of each house. This is promising when considering the potentially rising energy costs and reducing PV installation costs. DSO tariffs have to be nondiscriminatory for both the members and nonmembers of the energy community. Hence, further research is required to determine the cost-reflective pricing of intracommunal energy transfers within a rural energy community.

ACKNOWLEDGMENT

We thank Lappeenrannan Energia Oy for providing the energy consumption data for this research.

REFERENCES

[1] P. Augustine and E. McGavisk, “The next big thing in renewable energy: Shared solar,” *The Electricity Journal*, vol. 29, no. 4, pp. 36–42, 2016.

[2] G. Michaud, “Perspectives on community solar policy adoption across the united states,” *Renewable Energy Focus*, vol. 33, pp. 1–15, 2020.

[3] *DIRECTIVE (EU) 2019/944 OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 5 June 2019 on common rules for the internal market for electricity and amending Directive 2012/27/EU*. 2019.

[4] N. Li, R. A. Hakvoort, and Z. Lukszo, “Cost allocation in integrated community energy systems - a review,” *Renewable and Sustainable Energy Reviews*, vol. 144, p. 111001, 2021.

[5] M. B. Roberts, A. Sharma, and I. MacGill, “Efficient, effective and fair allocation of costs and benefits in residential energy communities deploying shared photovoltaics,” *Applied Energy*, vol. 305, p. 117935, 2022.

[6] M. Nykyri, T. J. Kärkkäinen, S. Levikari, S. Honkapuro, S. Annala, and P. Silventoinen, “Blockchain-based balance settlement ledger for energy communities in open electricity markets,” *Energy*, vol. 253, p. 124180, 2022.

[7] E. Mengelkamp, J. Gärttner, K. Rock, S. Kessler, L. Orsini, and C. Weinhardt, “Designing microgrid energy markets: A case study: The brooklyn microgrid,” *Applied Energy*, vol. 210, pp. 870–880, 2018.

[8] S. Wilkinson, K. Hojckova, C. Eon, G. Morrison, and B. Sandén, “Is peer-to-peer electricity trading empowering users? evidence on motivations and roles in a prosumer business model trial in australia,” *Energy Research and Social Science*, vol. 66, 2020.

[9] A. Wörner, L. Ableitner, A. Meeuw, F. Wortmann, and V. Tiefenbeck, “Peer-to-peer energy trading in the real world: Market design and evaluation of the user value proposition,” *4th International Conference on Information Systems. (ICIS 2019)*, 2019.

[10] D. Fioriti, A. Frangioni, and D. Poli, “Optimal sizing of energy communities with fair revenue sharing and exit clauses: Value, role and business model of aggregators and users,” *Applied Energy*, vol. 299, p. 117328, 2021.

[11] S. Abapour, B. Mohammadi-Ivatloo, and M. Tarafdar Hagh, “A bayesian game theoretic based bidding strategy for demand response aggregators in electricity markets,” *Sustainable Cities and Society*, vol. 54, p. 101787, 2020.

[12] *9.8.2013/588 Sähkömarkkinalaki §72 [Finnish Electricity Market Act]*. 2013.

[13] C. Patsonakis, S. Terzi, I. Moschos, D. Ioannidis, K. Votis, and D. Tzovaras, “Permissioned blockchains and virtual nodes for reinforcing trust between aggregators and prosumers in energy demand response scenarios,” in *2019 IEEE International Conference on Environment and Electrical Engineering and 2019 IEEE Industrial and Commercial Power Systems Europe (EEEIC / I&CPS Europe)*, pp. 1–6, 2019.

[14] M. R. Herrmann, D. P. Brumby, and T. Oreszczyn, “Watts your usage? a field study of householders’ literacy for residential electricity data,” *Energy Efficiency*, vol. 11, pp. 1703–1719, 2018.

[15] K. L. van den Broek, “Household energy literacy: A critical review and a conceptual typology,” *Energy Research & Social Science*, vol. 57, p. 101256, 2019.

[16] P. Layer, S. Feurer, and P. Jochem, “Perceived price complexity of dynamic energy tariffs: An investigation of antecedents and consequences,” *Energy Policy*, vol. 106, pp. 244–254, 2017.

[17] L. He and J. Zhang, “A community sharing market with pv and energy storage: An adaptive bidding-based double-side auction mechanism,” *IEEE Transactions on Smart Grid*, vol. 12, no. 3, pp. 2450–2461, 2021.

[18] T. D. Hutty, A. Pena-Bello, S. Dong, D. Parra, R. Rothman, and S. Brown, “Peer-to-peer electricity trading as an enabler of increased pv and ev ownership,” *Energy Conversion and Management*, vol. 245, p. 114634, 2021.

[19] J. Lin, M. Pipattanasomporn, and S. Rahman, “Comparative analysis of auction mechanisms and bidding strategies for p2p solar transactive energy markets,” *Applied Energy*, vol. 255, p. 113687, 2019.

[20] Z. Li and T. Ma, “Peer-to-peer electricity trading in grid-connected residential communities with household distributed photovoltaic,” *Applied Energy*, vol. 278, p. 115670, 2020.

Publication IV

Nykyri, M., Kärkkäinen, T.J., Annala, S., Naukkarinen, J., and Silventoinen, P.
Tutorial Serious Game for Demonstrating Demand Response in an Energy Community

Reprinted with permission from
2023 IEEE PES Innovative Smart Grid Technologies Conference Europe (ISGT-Europe)
(In press)

ACTA UNIVERSITATIS LAPPEENRANTAENSIS

1087. MALACINA, IRYNA. Zooming in and out: The strategic management of innovation across multiple levels of complex supply networks. 2023. Diss.

1088. SORE, SARISEELIA. Impact of information system capabilities on business value creation: Aspects of IT-producing and IT-consuming companies. 2023. Diss.

1089. IMMONEN, EERO. Advances in optimal design of shapes and processes by computational fluid dynamics. 2023. Diss.

1090. LAVOYE, VIRGINIE. Augmented reality in consumer retail: a presence theory approach. 2023. Diss.

1091. HÄRKÖNEN, KALEVI. Smart buildings in the green energy transition. 2023. Diss.

1092. TSYTSYNA, EVGENIYA. Motives, uncertainties, and imbalances in the evolution of a sustainable business ecosystem. 2023. Diss.

1093. JÄÄSKELÄINEN, ATTE. Business model innovation opportunities when news has become a public good. 2023. Diss.

1094. ADEDIPE, TAIWO. Atmospheric boundary-layer characteristics and their significance in wind energy and urban air quality assessment. 2023. Diss.

1095. SOSUNOVA, INNA. Model and guidelines for designing Internet-of-Things-enabled smart waste management system in smart cities. 2023. Diss.

1096. VUORELA, JYRI. Operative business development through system model and changing business structures. 2023. Diss.

1097. TRIAPITCIN, ILIA. Knowledge injection method for real-time decision support. 2023. Diss.

1098. RÄISÄNEN, OTTO. Open data in distribution network asset management. 2023. Diss.

1099. MATELA, MIKA. Procurement improvement in the public agency. 2023. Diss.

1100. SHAH, DIPAL. Quantification of synchronization. 2023. Diss.

1101. GHAFOURI, MEHRAN. Thermomechanical finite element simulation of welding, and elevated-temperature mechanical behaviour of high and ultra-high strength steels. 2023. Diss.

1102. NEUVONEN, RIKU. Numerical ductile fracture assessment of weldments in direct-quenched, ultra-high-strength steel. 2023. Diss.

1103. HUPPONEN, MARI. Long-term evolution of greenhouse gas emissions from municipal solid waste management. 2023. Diss.

1104. WANG, QI. Dynamic analysis and parameter identification for robotic manipulators. 2023. Diss.

1105. KIMPIMÄKI, JAAN-PAULI. From observation to insight: Computational abduction and its applications in sustainable strategy research. 2023. Diss.

1106. YIN, RUOCHEN. Research on key technologies for lightweight maintenance operations of the remote handling system for a fusion reactor. 2023. Diss.

1107. MUNIR, QAISAR. Designing printing parameters for geopolymer concrete prepared from construction and demolition waste and industrial side streams. 2023. Diss.

1108. ROHANI RAFTAR, HAMIDREZA. Assessment of weld root fatigue strength of load-carrying fillet welded joints using notch stress approaches and finite element analysis. 2023. Diss.

1109. SADIQA, AYESHA. Sustainable energy transition for Pakistan: Assessing the role of energy, water supply, social and gender equity dimensions. 2023. Diss.

1110. GHOREISHI, MALAHAT. The role of artificial intelligence in circular value creation: A conceptual framework and evidence from case studies. 2023. Diss.

1111. SUURONEN, JARKKO. On numerical implementation of α-stable priors in Bayesian inversion. 2023. Diss.

1112. PIILI, HEIDI. A conceptual, holistic framework to overcome limitations and constraints of design in laser based powder bed fusion of metals: Case novel separation and purification units. 2023. Diss.

1113. LOPATINA, ANASTASIIA. From alternative sources of cellulose to ultrafiltration membranes. 2023. Diss.

1114. MARTTINEN, KATI. Toward more sustainable supply management: Practices, determinants, and enablers for ensuring sustainability across multiple supply chain tiers. 2023. Diss.

1115. HU, HAO. Development of hybrid microdevices composed of Ni-Mn-Ga and silicon layers: fabrication and metrology. 2023. Diss.

1116. MARAIA, RAMONA. Bayesian likelihood for intractable data. 2023. Diss.

1117. ULLAH, MEHAR. Framework for digitalizing different industrial sectors via the internet of things. 2023. Diss.

1118. SIHVONEN, TUOMAS. Adaptive binning and spatial profile partial least squares methods in scanning electron microscopy energy-dispersive X-ray spectroscopy and satellite hyperspectral pansharpening. 2023. Diss.

1119. VOIPIO, VILLE. The role of radio-frequency identification in the sustainable digital transformation of the supply chain. 2023. Diss.

1120. WICKER, REBECCA. Bioprospecting for Nordic photosynthetic consortia for wastewater treatment, carbon capture, and value creation. 2023. Diss.

1121. SAUD, ALI. Sustainable recovery of nitrogen from sewage sludge. 2023. Diss.

1122. SHABBOUEI HAGH, YASHAR. Sigma-point Kalman filtering in physics-based digital twin applications: Synchronization between simulation and real world. 2023. Diss.

1123. KALITEEVSKII, VASILII. Artificial Inventiveness: Towards AI supported model-driven systematic conceptual design. 2023. Diss.

1124. TIKKA, VILLE. On load modeling of electric vehicles : energy system viewpoints. 2024. Diss.

LUT
University

ISBN 978-952-412-051-7
ISBN 978-952-412-052-4 (PDF)
ISSN 1456-4491 (Print)
ISSN 2814-5518 (Online)
Lappeenranta 2024