RIGA TECHNICAL UNIVERSITY

Roberts Lazdiņš

DEVELOPMENT OF PROSUMER-CONSUMER ENERGY COMMUNITY PLANNING TOOL AND METHODOLOGY

Summary of the Doctoral Thesis

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RIGA TECHNICAL UNIVERSITY
Faculty of Computer Science, Information Technology and Energy
Institute of Power Engineering

Roberts Lazdiņš
Doctoral Student of the Study Programme “Smart Power Systems”

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Scientific supervisor
Professor Dr. sc. ing.
ANNA MUTULE

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DOCTORAL THESIS PROPOSED TO RIGA TECHNICAL UNIVERSITY FOR THE PROMOTION TO THE SCIENTIFIC DEGREE OF DOCTOR OF SCIENCE

To be granted the scientific degree of Doctor of Science (Ph. D.), the present Doctoral Thesis has been submitted for the defence at the open meeting of RTU Promotion Council on 20 June 2024 at 10.00 at the Faculty of Computer Science, Information Technology and Energy of Riga Technical University, 12/1 Āzenes Street, Room 306.

OFFICIAL REVIEWERS

Associate Professor Dr. sc. ing. Romāns Petričenko
Riga Technical University

Professor Dr. sc. ing. Irina Oļeiņikova
Norwegian University of Science and Technology, Norway

Professor Dr. sc. ing. Saulius Gudžius
Kaunas University of Technology, Lithuania

DECLARATION OF ACADEMIC INTEGRITY

I hereby declare that the Doctoral Thesis submitted for review to Riga Technical University for promotion to the scientific degree of Doctor of Science (Ph. D.) is my own. I confirm that this Doctoral Thesis has not been submitted to any other university for promotion to a scientific degree.

Roberts Lazdiņš ……………………………. (signature)
Date: ………………………

The Doctoral Thesis has been written in English. It consists of an Introduction, three chapters, conclusions, 49 figures, 15 tables, and three appendices; the total number of pages is 102, including appendices. The Bibliography contains 95 titles.

CONTENTS

INTRODUCTION

Background and relevance of the study

The European Union (EU) has taken a significant leap towards attaining climate neutrality through the implementation of a set of legislation acts: Clean Energy for All Europeans package [1] and Fit for 55 [2]. Their common goal is to set the balance between making decisions at the EU and national levels to promote energy efficiency and renewable energy (RE).

By approving the Clean Energy for All Europeans packages' revised Renewable Energy Directive (2018/2001/EU) [3] in 2018 and the Electricity Directive (2019/944) [4] in 2019, the EU has paved the way for expanded integration of renewable energy sources (RES) at local and household level. Furthermore, directives mentioned above have officially recognised and defined a new energy sharing concept known as energy communities (EnCs).

To determine different guidelines, operational tasks, expected goals, objectives and their adoption flexibility in EU Member States national legislation, Directive 2018/2001/EU and Directive 2019/944 have defined two types of EnCs: **renewable energy communities** and **citizen energy communities**.

Furthermore, the aforementioned directives [3], [4] have determined additional emphasis for the effective and economically justified implementation of EnCs in the EU Member States:

- Member States shall provide an enabling **framework** to promote and facilitate the development of EnCs.
- **Distribution system operator must cooperate** with EnCs to facilitate energy transfers.
- Member States must develop **tools and mechanisms** to facilitate access to finance, technical and other community-related information.

Latvia, as an EU Member State, has identified the EnC concept and its implementation plan as **one of the priorities** in the transformation of the energy system. Specifically, this is stated in Latvia's National Energy Climate Plan (NECP) for 2021–2030 [5] and in legislation amendments.

In order to successfully integrate EnCs into the existing electricity supply system, NECP has proposed the following action plan points:

- Renewable energy self-production, self-consumption, and EnCs must be able to operate in an **economically justified environment without technical, financial or legislation barriers**.
- Development of EnC mutual electricity trading mechanism using a **peer-to-peer** business model.
- Creating **legislation and an environment** that supports and encourages the establishment of EnCs.

In order to take the first steps towards achieving NECP's determined and EnC-related goals, Latvia's legislation has adopted legislative changes in **Energy Law** [6] and **Electricity Market Law** [7], thus starting to resolve legislative barriers. Energy Law defines EnC as "a legal entity that deals with energy – mainly from renewables electricity and other types of renewable energy obtained from energy resources – production, selling, sharing, consumption and storage of electricity, provision of demand response service, electric provision of vehicle charging service, energy efficiency service or other energy services". Moreover, the Electricity Market Law has defined the following operational guidelines of EnCs (specifically, electricity EnCs):

- Members or shareholders are **electricity consumers and prosumers** which are connected by a single system operator system.
- Electricity must be shared within one trading interval. Electricity not consumed **immediately** is not accumulated for sharing in another trading interval but **must be sold to the electricity trader at the agreed price**.
- System objects that participate in electricity sharing activities **cannot participate in the net metering system, net settlement system, or system of certificates of origin of electricity**.

In spite of the legislative support for establishing EnCs at both the EU and national levels, the broad and successful development and implementation of EnCs in Latvia encounters certain technical and information access challenges. Due to historically implemented support measures for RE microgeneration – the net metering system [7] and state aid for the purchase of photovoltaic panels and wind generators [8] – in 2022, in Latvia, there were more than **12 000 prosumers** [9] (and 904 717 household electricity users connected to the electricity distribution grids [10]), for which the maximum installed power of electricity generation source was below **11.1 kW** [9]. In addition, the assessment study has determined that only 14 % of total electricity consumers (including prosumers) in Latvia would be willing to participate in EnCs [11]. This suggests that there is a low willingness to participate in EnCs. Moreover, prosumers are **geographically scattered** and **comparatively few** when compared to the overall number of electricity consumers.

Furthermore, amendments to the Electricity Market Law have determined that prosumers' self-consumption of generated electricity must be at least 80 % of the annual amount produced from RES [12]. Consequently, this reflects the relatively **limited amount of electricity** they could share within an EnC.

Bearing in mind all the abovementioned, the limited number of prosumers and low amount of shareable electricity is insufficient for forming a large-scale, multi-prosumer and multi-consumer EnCs based on existing conditions. Thereby, there is **considerable** and **high potential** for forming a prosumer and a conventional electricity consumer EnCs, thus fostering a **stronger sense of community** and **promoting RE accessibility** for those who cannot install their own RES.

It is important to highlight that the implementation of EU directives into national legislation and the existing variations in legislation among the EU Member States contribute to differences in EnC regulations and legal frameworks across countries. Thereby, the legal **framework for EnCs is not standardised and unified among the EU Member States** [13]–[15]. As a result, tools that have been developed for the planning and modelling of EnCs in specific countries

are difficult to apply or are not even compatible to evaluate the efficiency and economic feasibility of EnCs in other countries [15], including Latvia.

Considering the aforementioned, Latvia's electricity consumers lack a framework to discern the potential advantages of electricity-sharing activities and prerequisites for the creation and participation in prosumer-consumer EnCs. Moreover, the lack of a tailored **EnC planning tool** suitable for Latvia's specific conditions complicates the assessment of potential benefits. Both EU directives [3], [4] and Latvia's NECP [5] have indicated the importance and necessity of the aforementioned tool that could be a basis and an indicator for the determination of EnCs economic viability and justification. This proactive approach would be beneficial not only from the electricity consumer and prosumer point of view but also for **policymakers**, thereby assessing the effectiveness of state aid and the effect of existing legislation on the economic indicators of EnCs.

Hypothesis, objective and tasks of the Thesis

Hypothesis

A comprehensive framework centred on the electricity users and outlining the economic benefits of energy sharing can facilitate EnC implementation in Latvia.

Objective and tasks

The objective of the Doctoral Thesis is to develop a prosumer-consumer EnC planning tool tailored to Latvia's legislation and energy transition goals to demonstrably bridge knowledge gaps, clarify the economic viability and benefits of electricity-sharing for potential members of EnC, policymakers and other stakeholders.

To achieve the stated objective, the following tasks are determined:

1. Review legislation acts, scientific publications and media sources to determine EnC implementation requirements, guidelines, possible challenges and setbacks.
2. Develop a methodology and modelling tool for planning prosumer-consumer EnC initiatives under Latvia's legislation and energy transition goals.
3. Study the variable factor effect on the economic feasibility and sustainability of prosumer-consumer EnCs through case study and scenario modelling.

Research methods and tools

To enhance the research transparency, studies presented in the Doctoral Thesis were performed using widely available and user-friendly tools. Additionally, the author of the Thesis developed algorithms used in research studies at the Riga Technical University Institute of Power Engineering.

Chapter 1 involved empirical review and **PESTLE analysis** of diverse information sources: scientific publications (using **Scopus, Web of Science, IEEE Xplore and Science Direct databases**) and media sources to gather a **broad spectrum** of energy experts' and public viewpoints on EnC implementation progress, setbacks and challenges. Additionally, Microsoft Excel was used to collect and summarise key information from the publications and other information sources.

In **Chapter 2**, a prosumer-consumer **EnC planning tool** was developed based on a proposed peer-to-peer approach using accumulated funds and the acquisition of external funding. To promote its accessibility for potential EnC members, researchers, policymakers, and other stakeholders, the EnC planning tool is freely available on the **GitHub platform**. Furthermore, the Microsoft Excel environment was used to develop analysis graphs, figures, and illustrations.

In **Chapter 3**, the variable factor effect on economic feasibility and sustainability of prosumer-consumer EnCs are determined using **modelled case studies and scenarios**. Freely available Ninja_europe_pv_v1.1 and "Sadales Tīkls" **data repositories** were utilised for gathering input information on PV system electricity generation and household electricity consumption profiles. Furthermore, Microsoft Excel is used to collect input data, acquiring output data and detailed results of the study and developing analysis graphs, figures, and illustrations.

Scientific novelty

To facilitate and motivate the establishment of EnCs under Latvia's existing EnC and prosumer-related legislation and energy transition goals, a planning tool for prosumer-consumer EnCs was developed, thus **promoting open-access** electricity sharing and EnC modelling activities in Latvia. The tool incorporates a sophisticated and comprehensive algorithm that **determines power and cash flows** within the EnC and between the EnC and electricity trader using the electricity distribution grid. Additionally, the tool enables the calculation of prosumers' and consumers' **economic benefits** from participation in the EnC, along with an analysis of net present value related to the purchase of RES-based generation source. Thus, this developed **planning tool serves as an effective means** for demonstrating the economic viability of prosumer-consumer EnCs in Latvia. It also acts as a **catalyst** and provides rationale and openness for the proposed EnC to be implemented in other countries (if necessary, adapting and modifying it to the respective legislative guidelines).

Considering the operational approach of the tool, it **comprehensively models** prosumers' and consumers' **electricity tariff** plans (whether fixed or dynamic), **hourly electricity generation and consumption**, the amount of **external funding** received for the purchase and installation of electricity generation source and **financial indicators**, such as capital and operational expenditures, as well as determining how these expenditures can be repaid (whether from **initial investments** or through a **bank loan**). This flexibility allows the planning tool to simulate a **diverse range** of prosumer and consumer EnCs. Such adaptability enables the tool to **develop a broad spectrum of case studies and scenarios** involving EnC members' electricity consumption and electricity generation, as well as financial obligations among EnC members, the distribution grid operator, and the electricity trader.

Practical significance of the research

The work carried out during the development of this Thesis has contributed to the following research projects:

- "*Management and Operation of an Intelligent Power System (I-POWER)*", funded by the Latvian Council of Science (2018–2021).
- "*Supporting Energy Communities – Operational Research and Energy Analytics (SECOREA)*", funded by the ERA-NET Cofund grant under the CHIST-ERA IV Joint Call on Novel Computational Approaches for Environmental Sustainability (2019 – 2024).

Furthermore, research activities within the Thesis were carried out with financial support from the European Social Fund within Project No. 8.2.2.0/20/I/008, "Strengthening of PhD students and academic personnel of Riga Technical University and BA School of Business and Finance in the strategic fields of specialization" of the Specific Objective 8.2.2, "To Strengthen Academic Staff of Higher Education Institutions in Strategic Specialization Areas" of the Operational Programme "Growth and Employment", as well as from Riga Technical University's Doctoral Grant programme.

The developed planning tool and methodology can serve not only as a determinant of the efficiency of potential prosumer-consumer EnCs and information dissemination means to inform the public about EnCs, but also as an **auxiliary tool for policymakers** to model the effectiveness of the amount and type of state aid, as well as the effect of existing legislation and potential legislation amendments on the viability and sustainability of the prosumer and consumer EnCs under the proposed business model. By being freely available on GitHub, the **planning tool can empower students, researchers, and energy enthusiasts** with valuable insights into the operation and development of EnCs, thus increasing their **knowledge and interest in RE and energy-sharing**-related activities.

Author's contribution

The literature review regarding EnC implementation guidelines, experiences, challenges and setbacks was carried out by the author of the Thesis in close collaboration with the Associate Professor D. Žalostība under the supervision of Professor A. Mutule. The author contributed to all stages of this work, particularly in the investigation, publication collection, review, analysis, publication writing, as well as the creation of visualisation materials.

The review of existing business models, development of the proposed EnC business model, prosumer-consumer EnC planning tool and modelling of case studies and scenarios was carried out by the author of the Thesis under the supervision of Professor A. Mutule. The author of the Thesis carried out publication collection, business model review and analysis, development of planning tool and its guidelines, collection of input data, case studies and scenario modelling, publication writing, as well as the creation of visualisation materials.

Approbation of the results

The research results included and related to this Thesis have been presented by the author at the following scientific conferences.

1. 2020 IEEE 61st International Scientific Conference on Power and Electrical Engineering of Riga Technical University (RTUCON), 5–7 November, 2020, Riga, Latvia.
2. 2021 IEEE 62nd International Scientific Conference on Power and Electrical Engineering of Riga Technical University (RTUCON), 15–17 November 2021, Riga, Latvia.
3. 2022 IEEE 63rd International Scientific Conference on Power and Electrical Engineering of Riga Technical University (RTUCON), 10–12 October 2022, Riga, Latvia.
4. 2023 IEEE 64th International Scientific Conference on Power and Electrical Engineering of Riga Technical University (RTUCON), 9–11 October 2023, Riga, Latvia.

The results related to the Thesis have been presented by the author at the following international scientific workshops and events.

5. 1st follow-up meeting and workshop of the Latvia Country Desk, COME RES project, 6 October, 2022, Riga, Latvia.
6. World Congress of Latvian Scientists (Science Slam Competition), 27–29 June 2023, Riga, Latvia.
7. Workshop No. 4: Digital power system protection and control, Nordic–Baltic Co-Simulation Platform Towards Increasing the Stability of AC/DC Transmission Grids (COSPACT), 23–24 November, 2023, Trondheim, Norway.

The results included in the Thesis have been published in the following peer-reviewed scientific publications (indexed in Scopus/Web of Science).

1. **R. Lazdins** and A. Mutule, "Operational Algorithm for Natural Gas Boiler and Heat Pump System Optimization with PV Panel" in *2020 IEEE 61th International Scientific Conference on Power and Electrical Engineering of Riga Technical University (RTUCON)*, Riga, Latvia, 2020, pp. 1–4, doi: 10.1109/RTUCON51174.2020.9316571.
2. **R. Lazdins**, A. Mutule, and E. Kairisa, "Feasibilty Study in Energy Community Business Model Development for Latvia", in *2021 IEEE 62nd International Scientific Conference on Power and Electrical Engineering of Riga Technical University (RTUCON)*, Riga, Latvia, 2021, pp. 1–5, doi: 10.1109/RTUCON53541.2021.9711730.
3. **R. Lazdins**, A. Mutule and D. Zalostiba, "PV Energy Communities—Challenges and Barriers from a Consumer Perspective: A Literature Review", *Energies*, vol. 14, art. no. 4873, 2021, doi: 10.3390/en14164873.
4. **R. Lazdins** and A. Mutule, "Scenario simulation of a small-scale energy community management", in *2022 IEEE 63th International Scientific Conference on Power and Electrical Engineering of Riga Technical University (RTUCON)*, 2022, pp. 1–5, doi: 10.1109/RTUCON56726.2022.9978828.
5. T. Korõtko, F. Plaum, T. Häring, A. Mutule, **R. Lazdins**, O. Borščevskis, A. Rosin, and P. Carroll, "Assessment of Power System Asset Dispatch under Different Local Energy

Community Business Models", *Energies*, vol. 16, art. no. 3476, 2023, doi: 10.3390/en16083476.

6. **R. Lazdins** and A. Mutule, "Impact of Variable Factors on the Viability and Efficiency of Energy Communities: A Scenario Simulation Study in Latvia", in *2023 IEEE 64th International Scientific Conference on Power and Electrical Engineering of Riga Technical University (RTUCON)*, 2023, pp. 1–5, doi: 10.1109/RTUCON60080.2023.10413190.

The results included in the Thesis have been accepted for publication in the following peer-reviewed publications (indexed in Scopus/Web of Science).

7. **R. Lazdins** and A. Mutule, "Assessment of Various Factors Affecting Economic Indicators in Prosumer and Consumer Energy Communities: A Case Study in Latvia", *Latvian Journal of Physics and Technical Sciences*, 2024.

Other results obtained during the development of the Thesis have been published in peer-reviewed scientific publication (indexed in Scopus/Web of Science).

8. J. Stakens, A. Mutule, and **R. Lazdins**, "Agriculture Electrification, Emerging Technologies, Trends and Barriers: A Comprehensive Literature Review", *Latvian Journal of Physics and Technical Sciences*, vol. 60, pp. 18–32, 2023, doi: 10.2478/lpts-2023-0015

Structure of the Thesis

The Thesis is written in English. It comprises introduction, three main chapters, conclusions, bibliography with 95 references and three annexes. It contains 49 figures and 15 tables. The volume of the Thesis is 102 pages.

Chapter 1 is dedicated to identifying EnC implementation challenges in Latvia and in other countries that could emerge in Latvia after the post-establishment of EnCs. Within the framework of the chapter, recommendations are provided to help overcome challenges and setbacks by developing the prosumer-consumer EnC planning tool.

Within the framework of **Chapter 2**, a review of existing EnC business models is carried out. Within the framework of the chapter, the existing legislation related to Latvia's EnCs is also considered. As a result of the review of business models and related legislation, a peer-to-peer approach-based business model with accumulated funds and external funding modification is proposed. In addition, the chapter presents the prosumer-consumer EnC planning tool, which is based on the proposed business model.

Chapter 3 presents models of three baseline EnCs, incorporating several case studies and scenarios to assess the effect of various factors on the economic feasibility and viability of the prosumer-consumer EnC under the proposed business model. Modelling results lead to recommendations for potential EnCs' members, legislators, policymakers and other stakeholders. These recommendations focus on prerequisites that can enhance the economic viability and operational efficiency of the EnCs under the proposed business model.

1. IMPLEMENTATION OF ENERGY COMMUNITIES

1.1. The background to the implementation of energy communities

Tackling the challenges of global warming and the security of energy supply requires substantial changes in energy systems. As of 2021, the energy supply sector was the leading emitter of carbon dioxide, contributing approximately 25 % of total emissions [16]; thus, discussions about the direction of energy transformation and the structure of a decarbonised energy system have arisen.

While large energy systems could converse towards RE, thus requiring a large amount of financial resources, non-governmental organisations and scholars have proposed a shift towards household-scale and more decentralised systems [17].

The first stage of the decentralisation of the electricity system was the transition of electricity users (consumers) to active users (also known as “prosumers”) by installing RE-based electricity generation sources, thereby promoting environmental neutrality, increasing households’ autonomy, security of electricity supply and reducing the overall cost of electricity. [18, 19]

To accelerate the transition towards clean energy through local community engagement around renewable energy projects [20] and increase electricity consumers’ participation in RE consumption and electricity efficiency measures [21], the EU has defined two energy-sharing concepts: “renewable energy communities” (RECs) [3] and “citizen energy communities” (CECs) [4].

Although EnCs are widely adopted across the EU [22], [23], their acceptance rate is inconsistent throughout the Member States. As indicated in [24]–[26], Latvia has not established fully operational EnCs. Considering the widespread adoption of EnCs and the benefits associated with their establishment, their absence is linked to existing challenges and setbacks for their formation and integration into the electricity supply system. Identifying and overcoming these challenges is essential for promoting the sharing of electricity and fostering the establishment of EnCs, as emphasised in the Latvia’s NECP [5].

To identify them in Latvia and by looking at experiences of EnCs implementation in other countries, the upcoming sections will focus on pinpointing and reviewing the challenges and setbacks using the PESTLE analysis approach [27], thus dividing findings into four areas of interest: policy, economic, technical, and social.

1.2. Identified energy community implementation challenges in Latvia

Pinpointing identified challenges in scientific literature, project deliverables, and reports for Latvia is one of the key factors in assessing the national-level EnC implementation actions and progress in overcoming them from different perspectives. Moreover, by additionally collecting the opinions of the public and experts, we could develop a more comprehensive understanding of the challenges and opportunities associated with EnC development from the electricity users' and non-governmental institutions’ point of view.

Despite of the amendments and legislative changes of Energy Law and Electricity Market Law, the establishment of EnCs in Latvia remains challenging due to the lack of regulations from the Cabinet of Ministers outlining procedures for electricity sharing, responsibilities, oversight and EnC operating distance [7], [28]. This indicates an underdeveloped framework for EnCs, and, as mentioned in [29], existing policies do not explicitly support community energy projects and initiatives. It has drawn criticism from the public and energy experts and frustration over the apparent delay in developing related regulations. This, in turn, creates an impression of legislators being hesitant to introduce EnCs in Latvia [30].

Regarding economic EnC implementation challenges, [29] indicates that existing support instruments for RE are not sufficient to effectively facilitate the development of EnCs in Latvia, thereby suggesting diversification of support schemes to financially support not only the creation of EnC but also the developing economic incentives for planning and operational activities. Experts and the public sector highlight a deficiency in information and tools for assessing the viability and payback period of potential EnCs. Without a clear economic benefit forecast, the adoption of EnCs among electricity consumers might be limited and even non-motivating [30], [31].

Electricity Market Law has defined that members of EnC must be under the same electricity trader before the start of operations, as EnC must conclude an electricity-sharing agreement with that electricity trader [7]. This reluctance could result in the loss of existing electricity trader offers and discounts, creating the potential for increased electricity tariffs and overall costs for certain members of the EnC. By combining this challenge with the low number of prosumers and their geographical distribution [9], [10], as well as the low amount of electricity available for sharing after their self-consumption [8], [12], the establishment of a large-scale EnC in Latvia may be considered insufficient.

The stakeholder survey conducted by [28] has clearly indicated that due to the absence of regulations and solutions to the aforementioned challenges, awareness of the EnC concept in the public and policy attention toward EnCs and their potential benefits is notably low, thus indicating a lack of willingness to participate in energy sharing and cooperation activities [29].

Nevertheless, Latvia's experience with EnC implementation is too low for the number of publications and their descriptive analysis of challenges to comprehensively identify setbacks that may arise after the widespread development of EnCs. Thereby, the review of the experiences and identified challenges in other countries would broaden the horizons in the direction of other difficulties, which, for the time being, are yet not possible to identify in Latvia.

1.3. Identified energy community implementation challenges in other countries

To gain insights into potential challenges that might appear after the establishment of EnCs, this section explores implementation and acceptance challenges beyond the borders of Latvia by reviewing a thematic set of scientific literature from policy, economic, technical, and social perspectives [32].

Authors of [33] point out that government policies and support schemes in the Baltic States are key factors for the actions to increase the attractiveness and installed capacity of RES, thus motivating the creation of EnCs. Findings from the United States indicate that the electric utility companies' lobbying efforts can impede the progression of legislation acts [34]. The lack of EnC-related legislation can be attributed not only to the lack of support from utilities but also to insufficient involvement from other stakeholders [35]. Overall, this indicates the weak dialogue between stakeholders, as well as the availability of information towards RES and electricity-sharing options. In addition, the lack of policy and acceptance challenges can be caused by a non-existence of specific and different target group communication and information dissemination plans [36], [37]. Moreover, the publication regarding Spain [38] indicates that the EnC policy related to electricity-sharing has had a greater economic effect than the policy concerning electricity pricing for the sale of excess energy outside the borders of EnC. The aforementioned study has determined the necessity for a structured approach and how these policies and their interactions can increase EnCs' overall efficiency.

Type of remuneration and state aid [36], as well as an increased level of self-consumption and determined electricity sharing and selling tariff and pricing system [39], are key factors that affect the payback period of EnCs. To determine the efficiency and viability of the EnC, modelling tools under various business models have been developed in numerous software [40]–[43]. While these software applications and modelling techniques enhance the design and planning, their use requires purchasing licenses and high programming skills, and they may pose user-friendliness and other challenges for electricity users. The proposed and developed modelling tool blanks and scenarios are not universally applicable due to variations in EnC-related legislations, business models and operational restrictions across different countries. Furthermore, [44] highlights that current business models are relatively complex and difficult to follow, thus creating a demand for greatly simplified business, financial payment and mutual settlement models.

The Swiss experience indicates that younger individuals with higher incomes and less conservative attitude are more willing to participate in EnCs [45]. Similarly, a study conducted in Pakistan [46] identifies overall electricity costs, income levels, education and information accessibility about the advantages of EnCs as key factors affecting social acceptance and adoption rates. Another survey [47] concludes that the technological forms and equipment used in EnCs are not decisive factors for willingness to participate.

It can be concluded that EnC implementation challenges outside Latvia are linked to the lack of related legislation, communication, information and proposal exchange between the parties involved, thus leading to conflicts of interest and non-support stance. Additionally, literature sources indicate the absence of easily understandable business models and the limited availability of user-friendly EnC modelling and planning tools. To offer strategies for overcoming the identified challenges in Latvia and other countries, the following section presents recommendations and suggestions to help overcome these challenges.

1.4. Discussions and conclusions for overcoming the identified challenges

To expedite the implementation of EnCs in Latvia, it is crucial to formulate a strategy for overcoming the identified challenges and setbacks and offer corresponding recommendations. This section consolidates the findings from reviewed literature sources regarding Latvia and other countries and presents suggestions on how these challenges can be surmounted.

The regulation of the Cabinet of Ministers can be considered as the key factor that hinders the creation of EnCs in Latvia from a legislative point of view. To expedite this process and align it with the needs of all stakeholders, the responsible Ministries should conduct consultation activities. These consultations should extend beyond industry representatives. Regarding the account for shared electricity, it could be recommended to assign this responsibility to both the electricity trader and the system operator's existing data processing activities, thus bypassing the need to establish dedicated platforms for tracking the quantity of shared electricity between the members of EnC and the electricity trader.

Despite the ongoing networking and information dissemination efforts related to EnCs, it is recommended to persist in information dissemination initiatives. Enhanced information accessibility would not only foster awareness and education among electricity users but also encourage cross-sectoral development and discussions concerning EnCs.

To justify the creation of multi-prosumer EnCs, it is necessary to increase the total number of prosumers in Latvia. This can be achieved by executing the aforementioned initiatives aimed at disseminating information, highlighting not only the implementation advantages of EnCs but also emphasising the benefits of becoming a prosumer.

To validate the economic justification and efficiency of establishing EnCs, it is crucial to concentrate on the planning and justification of their activities. The development of an EnC planning tool specifically designed for use in Latvia would address almost all aforementioned EnC implementation challenges. It would effectively showcase the economic advantages of EnCs, motivate interest in EnCs among the public and substantiate the effectiveness of external funding and its effect on the EnC, thereby making it applicable and useful not only to electricity consumers and prosumers but also to legislators and policymakers. Different tools are already used for EnC modelling and planning activities but their utility is constrained in terms of application, legislations of individual countries, and used business models [48]. This limitation renders them to be less or even not usable under Latvia's legal and RES environment. Hence, with the motivation to address identified challenges and bearing in mind the limited number of prosumers and their relatively low amount of shareable electricity, a substantial and well-founded demand exists for a planning model centered around prosumer and conventional consumer EnCs.

To encourage the establishment of EnCs in Latvia and assess the potential advantages to potential participants, the following chapter delves into the formulation of a planning tool specifically designed for prosumer and consumer EnCs, as well as a detailed description of the associated modelling activities.

2. DEVELOPMENT OF PROSUMER AND CONSUMER ENERGY COMMUNITY PLANNING TOOL

2.1. Determination of mutual interconnection between prosumer and consumer

To increase electricity users' engagement in EnCs, it is crucial to offer them an easy-to-understand and most appropriate mutual interconnection strategy (as a business model) regarding cost allocations and electricity-sharing activities, thus providing transparency regarding EnC operations.

Latvia's NECP identifies the development of a new market model based on a P2P approach as a key foundation for EnC implementation [5]. Despite its potential use, other business model aspects could enhance the efficiency of this model.

Grant-based business model [45], [49] has indicated the necessity for electricity-sharing actions between EnC members using determined tariffs to make EnCs economically sustainable. Moreover, external funding could significantly improve the payback period. Multi-agent business model [49]–[51] has proven that electricity-sharing and payment activities must be managed by one independent actor. Despite the widespread adoption of energy cooperative business models [49], [52], Latvia's Electricity Market Law has determined that only electricity prosumers and consumers can participate in EnCs, thus not allowing independent electricity producers to participate in electricity sharing. The aforementioned business model modification has shown that the EnC income can be directed into accumulated funds and be used for energy efficiency, repayment of electricity source, and other related expenses without gaining a direct profit to a specific member of the EnC. The use of a virtual power plant business model [49], [53] in Latvia can be challenging due to the lack of aggregators [54], as well as aggregation regulations on EnCs. Although the use of a P2P business model [22], [49], [53] is determined to be suitable under Latvia's existing legislation and EnC development and implementation plans, the P2P electricity trading platform can be replaced by assigning its tasks and duties to the electricity trader and the system operator's existing data processing and management systems.

By integrating elements from each examined business model and enhancing them with the P2P approach, a business model for the EnC planning tool is proposed (Fig. 2.1).

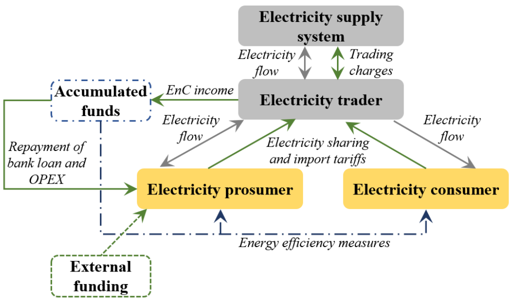

Fig. 2.1 Proposed EnC business model [55]

However, it is important to align it with the additional constraints and operational guidelines using a comprehensive examination of the legislative framework. The limitations included in the business model and the operating principle of the model itself are discussed in the next section.

2.2. Restrictions and guidelines

The primary objective of this section is to arrange the previously suggested business model with Latvia's existing legislation, thus incorporating specific operational guidelines and technological solutions for efficient electricity sharing within the EnC.

Electricity Market Law has defined that members of EnC must be connected to one system operator, and electricity sharing must be done independently through it. Furthermore, EnCs are not entitled to autonomously managing (owning, renting, buying, etc.) the electricity grid. Electricity sharing must be done with the help of system operator infrastructure managed by electricity trader. EnC members must sign an electricity- sharing contract, as well as a contract with an electricity trader. Despite the study that determined that a net metering system could be efficiently used for sharing activities within the EnC [56], the Electricity Market Law specifies that the amount of generated electricity not immediately consumed by the members of EnC is not accumulated for sharing in another trading interval but must be sold to the electricity trader at the agreed price. Furthermore, system objects (consumers and prosumers) participating in electricity-sharing activities cannot participate in the net metering system, net settlement system, and the system of certificates of origin of electricity. Finally, members of EnC simultaneously cannot participate in other EnCs [7].

Energy Law has defined that the primary purpose of the EnC is not to make a financial profit but to provide economic, social and environmental quality improvements to the members or shareholders of EnC. The profit obtained by the EnC is not distributed or paid out as dividends but is invested to achieve the goals set by the EnC's determined statutes. In addition, the Ministry of Economics must develop support programs for EnCs that use only renewable energy resources, including support for commercial activities. [6]

The historic adoption of the net metering system, allowing prosumers to virtually store excess electricity in the distribution grid after self-consumption, has resulted in a lack of installed electricity storage (battery) systems among these prosumers. Furthermore, a well-cited study [57] highlights that battery inclusion is economically justified only when a prosumer's self-consumption is lower than 75 % of the electricity generated. Therefore, the inclusion of a battery system is not economically viable when prosumers' or EnCs' self-consumption level is over 80 %.

Taking into account existing legislation regarding prosumer and EnC operational restrictions and the aforementioned study regarding batteries, a visual representation of the proposed one prosumer and one consumer EnC is provided in Fig. 2.2.

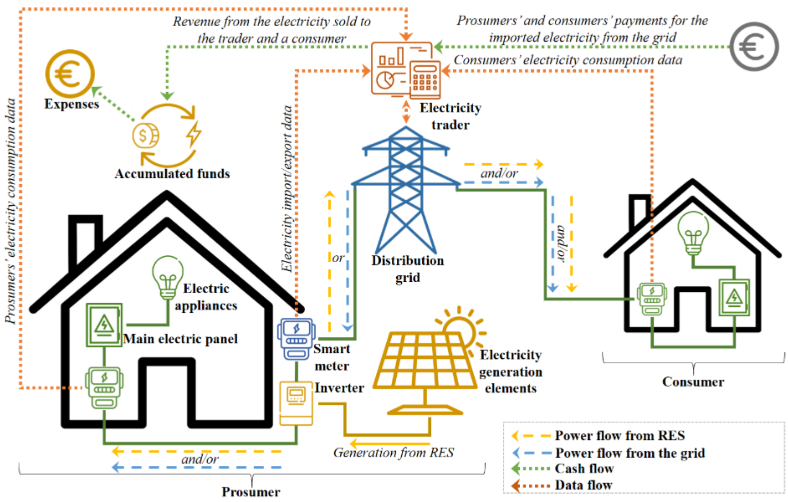

Fig. 2.2 Visualisation of proposed prosumer and consumer EnC [58].

To ascertain the economic feasibility of EnCs under the proposed business model, it is necessary to develop a tool to plan electricity-sharing and selling activities according to each EnCs objectives and goals. Subsequently, the following section provides a comprehensive description of the proposed EnCs planning tool.

2.3. Prosumer and consumer energy community planning tool

The primary objective of the proposed EnC planning tool is to effectively model the power flows between the members of EnC and electricity trader using the electricity distribution grid and to calculate payments for received or exported amount of electricity. To describe the activities included in the proposed planning tool, the section presents the calculations included in this tool.

To determine the EnC electricity production base, the amount of electricity hourly generated from RES, P_{RES}^{t} , can be expressed as

$$P_{RES}^{t} = P_{RES\ cap.} \cdot \delta_{RES}^{t} \cdot \Delta_{\%}^{y}, \tag{2.1}$$

where $P_{RES\ cap.}$ – the total capacity of the installed electricity source (kW);

δ_{RES}^{t} – hourly coefficient which determines the amount of electricity hourly generated from 1 kW of installed capacity (kWh/kW);

$\Delta_{\%}^{y}$ – annual coefficient (%) of element degradation of installed RES.

Prosumers' hourly consumed amount of electricity from its own electricity generation source, $P_{RES\rightarrow Pros.}^{t}$, can be determined as

$$P_{RES\rightarrow Pros.}^{t} = \begin{cases} P_{RES}^{t}, if\ P_{RES}^{t} < W_{Pros.}^{t} \\ W_{Pros.}^{t}, if\ P_{RES}^{t} \geq W_{Pros.}^{t} \end{cases}, \tag{2.2}$$

where $W_{Pros.}^{t}$ is prosumers' hourly electricity consumption (kWh).

When an electricity generation source cannot cover prosumers' electricity consumption, it can be covered by electricity import from the grid. To determine the amount of electricity imported ($P^t_{grid \to Pros.}$) the following formula is used:

$$P^t_{grid \to Pros.} = \begin{cases} W^t_{Pros.} - P^t_{RES \to Pros.}, if\ P^t_{RES} < W^t_{Pros.} \\ 0, if\ P^t_{RES} \geq W^t_{Pros.} \end{cases}. \tag{2.3}$$

If the produced amount of electricity is higher than the prosumers' consumption, the excess is shared with the consumer using the grid. Hourly amount of excess electricity available for sharing with the consumer $P^t_{RES,excess}$ can be determined as

$$P^t_{RES,excess} = \begin{cases} 0, if\ P^t_{RES} < W^t_{Pros.} \\ P^t_{RES} - P^t_{RES \to Pros.}, if\ P^t_{RES} \geq W^t_{Pros.} \end{cases}. \tag{2.4}$$

When the prosumer decides to pay for the electricity generated by its own electricity source, the prosumer's hourly electricity tariff for the amount of electricity received from the generation source with value-added tax (VAT) $c^t_{Pros.\ EnC+VAT}$ can be determined as follows:

$$c^t_{Pros.\ EnC+VAT} = c^t_{Pros.\ EnC} \cdot (1 + VAT), \tag{2.5}$$

where $c^t_{Pros.\ EnC}$ is prosumers' determined electricity tariff for the received electricity from its own generation source without VAT (EUR/kWh).

In this case, prosumers' hourly payments for the amount of electricity received by its own generation source $C^t_{EnC \to Pros.}$ can be determined as

$$C^t_{EnC \to Pros.} = P^t_{RES \to Pros.} \cdot c^t_{Pros.\ EnC+VAT}. \tag{2.6}$$

When the prosumer receives electricity from the grid, the tariff regarding only the electricity cost component provided by the electricity trader must include VAT. Accordingly, the prosumers' hourly electricity tariff for the amount of electricity received from the grid with VAT $c^t_{Pros.\ grid+VAT}$ can be determined as

$$c^t_{Pros.\ grid+VAT} = c^t_{Pros.\ grid} \cdot (1 + VAT), \tag{2.7}$$

where $c^t_{Pros.\ grid}$ is prosumers' electricity component tariff for the received electricity from the grid without VAT (EUR/kWh).

Prosumers' hourly payments for the received amount of electricity from the grid $C^t_{grid \to Pros.}$ (without other grid tariff components) can be determined as

$$C^t_{grid \to Pros.} = P^t_{grid \to Pros.} \cdot c^t_{Pros.\ grid+VAT}. \tag{2.8}$$

To determine prosumers' annual payment for the electricity received from the grid, it must also include other cost components: the charge for the supply of electricity and the charge for the connection maintenance [59]. Annual overall electricity costs (including other grid cost components) for the prosumer when participating in the EnC, $C^y_{Pros.with\ EnC+VAT}$ can be defined as

$$C^{y}_{Pros.with\ EnC+VAT} = \Sigma C^{t}_{EnC\rightarrow Pros.} + \Sigma C^{t}_{grid\rightarrow Pros.} + (\Sigma P^{t}_{grid\rightarrow Pros.} \cdot c_{supply\ (grid).Pros.} + I_{conn.Pros.} \cdot c_{maintenance\ (grid).Pros.} \cdot 12) \cdot (1 + VAT), \tag{2.9}$$

where $c_{supply\ (grid).Pros.}$ – prosumers' tariff for the supply of electricity from the distribution grid without VAT (EUR/kWh);

$I_{conn.Pros.}$ – maximum rated current of prosumers' connection (A);

$c_{maintenance\ (grid).Pros.}$– prosumers' costs for connection maintenance without VAT (EUR/A/month).

Annual overall electricity costs for the prosumer when it does not participate in the EnC, $C^{y}_{Pros.without\ EnC+VAT}$ can be expressed as

$$C^{y}_{Pros.without\ EnC+VAT} = \Sigma C^{t}_{grid\rightarrow Pros.} + (\Sigma P^{t}_{grid\rightarrow Pros.} \cdot c_{supply\ (grid).Pros.} + I_{conn.Pros.} \cdot c_{maintenance\ (grid).Pros.} \cdot 12) \cdot (1 + VAT). \tag{2.10}$$

Consumers' hourly consumed amount of electricity from the prosumer $P^{t}_{RES,excess\rightarrow Cons.}$ can be calculated as follows:

$$P^{t}_{RES,excess\rightarrow Cons.} = \begin{cases} P^{t}_{RES,excess}, if\ P^{t}_{RES,excess} < W^{t}_{Cons.} \\ W^{t}_{Cons.}, if\ P^{t}_{RES,excess} \geq W^{t}_{Cons.} \end{cases}, \tag{2.11}$$

where $W^{t}_{Cons.}$ is consumers' hourly electricity consumption (kWh).

When the prosumer cannot fully cover the consumers' electricity consumption, consumers' hourly amount of electricity imported from the grid ($P^{t}_{grid\rightarrow Cons.}$) can be calculated as follows:

$$P^{t}_{grid\rightarrow Cons.} = \begin{cases} W^{t}_{Cons.} - P^{t}_{RES,excess\rightarrow Cons.}, if\ P^{t}_{RES,excess} < W^{t}_{Cons.} \\ 0, if\ P^{t}_{RES,excess} \geq W^{t}_{Cons.} \end{cases}. \tag{2.12}$$

If there is an excess amount of electricity after covering EnC members' consumption, it must be sold to the electricity trader. To determine its hourly amount ($P^{t}_{excess\rightarrow trader}$), the following calculation is used:

$$P^{t}_{excess\rightarrow trader} = \begin{cases} 0, if\ P^{t}_{RES,excess} < W^{t}_{Cons.} \\ P^{t}_{RES,excess} - P^{t}_{RES,excess\rightarrow Cons.}, if\ P^{t}_{RES,excess} \geq W^{t}_{Cons.} \end{cases}. \tag{2.13}$$

To bring income to the EnC from the amount of electricity shared with the consumer, a sharing tariff without VAT $c^{t}_{Cons.\ EnC}$ is introduced. It can be determined using the following formula:

$$c^{t}_{Cons.\ EnC+VAT} = c^{t}_{Cons.\ EnC} \cdot (1 + VAT), \tag{2.14}$$

where $c^{t}_{Cons.\ EnC+VAT}$ is electricity-sharing tariff within EnC, including VAT (EUR/kWh).

With the help of Formulas (2.11) and (2.14), it is possible to determine consumers' hourly expenses regarding the consumption of prosumers' shared electricity (including VAT) $C^{t}_{EnC\rightarrow Cons.\ (with\ VAT)}$ by using the following calculation:

$$C^t_{EnC\rightarrow Cons.\ (with\,VAT)} = P^t_{RES\rightarrow Cons.} \cdot c^t_{Cons.\ EnC+VAT}. \tag{2.15}$$

Consumers' annual cost of the amount of electricity received from the prosumer (including VAT) can be determined as

$$C^y_{EnC\rightarrow Cons.\ (with\,VAT)} = \Sigma C^t_{EnC\rightarrow Cons.\ (with\,VAT)}. \tag{2.16}$$

Consumers' hourly expenses regarding the consumption of prosumers' shared electricity (excluding VAT) $C^t_{EnC\rightarrow Cons.\ (without\,VAT)}$ can be calculated as

$$C^t_{EnC\rightarrow Cons.\ (without\,VAT)} = P^t_{RES\rightarrow Cons.} \cdot c^t_{Cons.\ EnC}. \tag{2.17}$$

The annual cost of the consumer for the amount of electricity received from the prosumer (excluding VAT) $C^y_{EnC\rightarrow Cons.\ (without\,VAT)}$ can be determined as

$$C^y_{EnC\rightarrow Cons.\ (without\,VAT)} = \Sigma C^t_{EnC\rightarrow Cons.\ (without\,VAT)}. \tag{2.18}$$

To calculate the consumers' electricity tariff for imported electricity from the grid (with VAT and without other grid cost components) $c^t_{Cons.\ grid+VAT}$, the following formula is used:

$$c^t_{Cons.\ grid+VAT} = c^t_{Cons.\ grid} \cdot (1 + VAT), \tag{2.19}$$

where $c^t_{Cons.\ grid}$ is consumers' electricity component tariff for imported electricity from the grid, excluding VAT (EUR/kWh).

Consumers' hourly payments for the amount of imported electricity from the grid (including VAT and without distribution grid tariff components) $C^t_{grid\rightarrow Cons.}$ can be calculated with the following formula:

$$C^t_{grid\rightarrow Cons.} = P^t_{grid\rightarrow Cons.} \cdot c^t_{Cons.\ grid+VAT}. \tag{2.20}$$

Consumers' annual costs for the amount of received electricity by participating in the EnC (including VAT and other grid cost components) $C^y_{Cons.with\ EnC+VAT}$ can be calculated as follows:

$$\begin{gathered} C^y_{Cons.with\ EnC+VAT} = C^y_{EnC\rightarrow Cons.\ (with\,VAT)} + \Sigma C^t_{grid\rightarrow Cons.} + \\ (W^t_{Cons.} \cdot c_{supply\ (grid).Cons.} + \\ I_{conn.Cons.} \cdot c_{maintenance\ (grid).Cons.} \cdot 12) \cdot (1 + VAT), \end{gathered} \tag{2.21}$$

where $c_{supply\ (grid).Cons.}$ – consumers' tariff for the supply of electricity from the grid without VAT (EUR/kWh);

$I_{conn.Cons.}$ – maximum rated current of consumers' connection (A);

$c_{maintenance\ (grid).Cons.}$– consumers' costs for connection maintenance without VAT (EUR/A/month).

Consumers' annual costs for the amount of received electricity by not participating in the EnC (including VAT and other grid cost components) $C^y_{Cons.without\ EnC+VAT}$ can be calculated:

$$C^{y}_{Cons.without\ EnC+VAT} = \Sigma W^{t}_{Cons.} \cdot c^{t}_{Cons.\ grid+VAT} + \\ (\Sigma W^{t}_{Cons.} \cdot c_{supply\ (grid).Cons.} + \\ I_{conn.Cons.} \cdot c_{maintenance\ (grid).Cons.} \cdot 12) \cdot (1 + VAT). \tag{2.22}$$

Three distinct funding sources can be utilised in the proposed planning tool to secure the initial investments for the acquisition of RES-based electricity generation source in the EnC: external funding (state aid, donations or grants from third persons and organisations), voluntary investment contributions by the members of EnC and bank loan. It is noteworthy that, given the responsibility of the prosumer for ensuring electricity sharing with the help of the installed generation source, the planning model assumes that the prosumer is accountable for attracting these financial funds and repaying the essential bank loan.

Combined one-time investment contributions by the members of EnC I_0 can be defined as

$$I_0 = I_{0,Pros.} + I_{0,Cons.}, \tag{2.23}$$

where $I_{0,Pros.}$ – prosumers' initial investment payment (EUR);
$I_{0,Cons.}$ – consumers' initial investment payment (EUR).

Calculation of the total CAPEX, including VAT-related expenses, can be expressed as

$$CAPEX = (C_{CAPEX\ per\ kW} \cdot P_{PV\ cap.}) \cdot (1 + VAT) - C_{grants}, \tag{2.24}$$

where $C_{CAPEX\ per\ kW}$ – the value of CAPEX related to an installed generation source capacity of 1 kW without VAT (EUR).
C_{grants} – the amount of received external funding (EUR).

To assess the necessity for a bank loan to cover CAPEX and determine the required amount of the loan, the following formula is used:

$$C_{bank \to EnC} = \begin{cases} 0, if\ I_0 \geq CAPEX \\ CAPEX - I_0, if\ I_0 < CAPEX, \end{cases} \tag{2.25}$$

where $C_{bank \to EnC}$ is the amount of bank loan to fully cover the remaining part of CAPEX (EUR).

Annual bank loan payment amount $C^{y}_{EnC \to bank}$ can be calculated as follows:

$$C^{y}_{EnC \to bank} = \begin{cases} C_{bank \to EnC} \cdot (1 + i_{\%,bank}) \cdot \\ \dfrac{i_{\%,bank} \cdot (1 + i_{\%,bank})^{y_{loan}}}{((1 + i_{\%,bank})^{y_{loan}}) - 1}, when\ y \leq\ y_{loan} \\ 0, when\ y >\ y_{loan}, \end{cases} \tag{2.26}$$

where y_{loan} is loan duration (years) and $i_{\%,bank}$ is the loan interest rate (%).

Calculation of the annual operational costs $OPEX^{y}$ (including VAT) can be expressed as

$$OPEX^{y} = (C^{y}_{OPEX\ per\ kW} \cdot P_{RES\ cap.}) \cdot (1 + VAT), \tag{2.27}$$

where $C^{y}_{OPEX\ per\ kW}$ is annual operational costs related to an installed generation source capacity of 1 kW without VAT (EUR).

To calculate EnCs' received hourly income from the amount of electricity sold to the electricity trader $C^t_{excess \rightarrow trader}$, the planning tool applies the following formula:

$$C^t_{excess \rightarrow trader} = P^t_{excess \rightarrow trader} \cdot c^t_{excess \rightarrow trader}, \tag{2.28}$$

where $c^t_{excess \rightarrow trader}$ is electricity traders' electricity purchase price without taxes (EUR).

To include the incoming cash flow from prosumer cost savings due to the self-consumption in net present value (NPV) calculations, the annual payment that the prosumer would pay for the amount of electricity received from the grid if the generation source were not installed, is calculated as follows:

$$\begin{gathered} C^y_{el.Pros. \rightarrow trader.without\ RES} = \Sigma(W^t_{Pros.} \cdot c^t_{Pros.\ grid+VAT}) + \\ (\Sigma W^t_{Pros.} \cdot c_{supply\ (grid).Pros.} \\ + I_{conn.Pros.} \cdot c_{maintenance\ (grid).Pros.} \cdot 12) \cdot (1 + VAT). \end{gathered} \tag{2.29}$$

By calculating (2.29), it is possible to determine prosumers' annual cost savings $\Delta C^y_{pros \rightarrow grid\ (with.without\ RES)}$ regarding the reduction of the amount of imported electricity due to the self-consumption of electricity:

$$\begin{gathered} \Delta C^y_{pros \rightarrow grid\ (with.without\ RES)} = \Sigma C^t_{grid \rightarrow Pros.} + (\Sigma P^t_{grid \rightarrow Pros.} \cdot c_{supply\ (grid).Pros.} \\ + I_{conn.Pros.} \cdot c_{maintenance\ (grid).Pros.} \cdot 12) \\ \cdot (1 + VAT) - C^y_{el.Pros. \rightarrow trader.without\ RES}. \end{gathered} \tag{2.30}$$

The annual overall incoming cash flow of the EnC ($Income^y_{EnC,RES}$), which will also be used to determine NPV, is calculated as follows:

$$\begin{gathered} Income^y_{EnC,RES} = C^y_{EnC \rightarrow Cons.\ (without\ VAT)} + \Sigma(P^t_{RES \rightarrow Pros.} \cdot c^t_{Pros.\ EnC}) + \\ \Delta C^y_{pros \rightarrow grid\ (with.without\ RES)} + \Sigma C^t_{excess \rightarrow trader}. \end{gathered} \tag{2.31}$$

The annual outcoming cash flow $Expenses^y_{EnC,RES}$ consists of two components: the OPEX charges of the installed generation source and annual repayment of the bank loan:

$$Expenses^y_{EnC,RES} = OPEX^y + C^y_{EnC \rightarrow bank}. \tag{2.32}$$

To ascertain whether the installed electricity source generates higher income than expenses, it is essential to calculate the annual net cash flow $R^y_{EnC,RES}$:

$$R^y_{EnC,RES} = Income^y_{EnC,RES} - Expenses^y_{EnC,RES}. \tag{2.33}$$

The planning tool uses NPV as a main economic indicator for the evaluation of installed electricity source present value of an investment, evaluating the value of installed electricity generation sources over their 20-year lifespan after applying a discount rate and investment contributions by the prosumer. To calculate annual NPV (NPV^y), the following formula is used:

$$NPV^y = -I_{0,Pros.} + \sum\nolimits_{i=1}^{y} \frac{R^y_{EnC,RES}}{\left(1 + i_{\%,d}\right)^y}, \tag{2.34}$$

where $i_{\%,d}$ is discount rate (%).

Prosumers' annual income from the electricity sold (or transferred under net settlement system) to the electricity trader without participating in the EnC $C^{y}_{Pros\rightarrow trader,without\ EnC}$ (excluding taxes) can be calculated as follows:

$$C^{y}_{Pros\rightarrow trader,without\ EnC} = \Sigma(P^{t}_{RES,excess} \cdot c^{t}_{excess\rightarrow trader}). \tag{2.35}$$

Prosumers' overall economic benefits from participating in the EnC, $EB^{y}_{Pros.}$,can be expressed as

$$EB^{y}_{Pros.} = I_{0,Cons.} + \sum_{i=1}^{y}(-\Sigma C^{t}_{EnC\rightarrow Pros.} + C^{y}_{EnC\rightarrow Cons.\ (without\ VAT)} + \Sigma \mathrm{C}^{\mathrm{t}}_{\mathrm{excess\rightarrow trader}} - C^{y}_{Pros\rightarrow trader,without\ EnC}). \tag{2.36}$$

Consumers' overall economic benefits from participating in the EnC, $EB^{y}_{Cons.}$, can be calculated as follows:

$$EB^{y}_{Cons.} = -I_{0,Cons.} + \sum_{i=1}^{y}(\ C^{y}_{Cons.without\ EnC+VAT} - C^{y}_{Cons.with\ EnC+VAT}). \tag{2.37}$$

It can be mentioned that direct income from the EnC operation must be spent to increase overall energy efficiency to its members or other measures to improve their welfare (without making a direct profit), thus diverting the direct income into the accumulated fund (AF). for the planning tool to determine the amount of cash in this fund in each year, AF^{y}_{EnC}, the following calculations can be used. The annual amount of cash located in EnC's AF after coverage of annual bank loan payment and OPEX will be zero if

$$(C^{y}_{EnC\rightarrow bank} + OPEX^{y}) \geq (C^{y}_{EnC\rightarrow Cons.\ (without\ VAT)} + \Sigma(P^{t}_{RES\rightarrow Pros.} \cdot c^{t}_{Pros.\ EnC}) + \Sigma C^{t}_{excess\rightarrow trader}). \tag{2.38}$$

Otherwise

$$AF^{y}_{EnC} = C^{y}_{EnC\rightarrow Cons.\ (without\ VAT)} + \Sigma(P^{t}_{RES\rightarrow Pros.} \cdot c^{t}_{Pros.\ EnC}) + \Sigma C^{t}_{excess\rightarrow trader} - \left(C^{y}_{EnC\rightarrow bank} + OPEX^{y}\right). \tag{2.39}$$

The total amount of cash in EnCs accumulated funds in a specific year can be calculated as follows:

$$\Sigma AF^{y}_{EnC} = \textstyle\sum_{i=1}^{y} AF^{y}_{EnC}. \tag{2.40}$$

The following calculation is used to determine the prosumer annual self-consumption level:

$$SC^{y}_{Pros.,\%} = \frac{\Sigma P^{t}_{RES\rightarrow Pros.}}{\Sigma P^{t}_{RES}} \cdot 100\%. \tag{2.41}$$

Prosumer self-consumption level is affected not only by the electricity consumption and generation amounts but also by interconnecting and adjusting these values to each other. Thus the overlap of consumption and generation schedule plays an important role in achieving the required self-consumption level.

To prioritise study transparency and seek open validation and user empowerment, the developed prosumer-consumer EnC planning tool is freely available and open-source on the GitHub platform [60].

2.4. Discussion and conclusions

To provide Latvia's electricity users with a tool which would be used to determine prosumer and consumer EnC's economic viability, the chapter reviewed existing business models, thereby analysing the potential of their implementation in Latvia. Considering that Latvia's NECP has defined the use of the P2P approach to ensure the operation of EnCs, it was concluded that this approach can serve as a basis for the EnC planning tool.

After reviewing the operation of grant-based, multi-agent, energy cooperatives and virtual power plant business models, the P2P model was supplemented with the possibility to receive external funding for the purchase of electricity generation source, as well as to use AF to cover the payment of the bank loan and operational expenditures, and to implement energy efficiency measures for the members of the EnC in the future. The proposed business model is adapted to the current restrictions of Latvia's legislation and other related guidelines.

The EnC planning tool was developed based on the proposed business model. It serves the dual purpose of assessing the feasibility and economic justification for establishing potential prosumer and consumer EnCs and being used by legislators and policymakers to evaluate the advantages and disadvantages of implementing such a business model. Moreover, the planning tool can serve as a basis to assess the effect of future legislation changes not only in the context of Latvia but also in other countries (if necessary, adapting and modifying it to the respective legislative guidelines).

The proposed tool can be used to analyse the impact of various factors (such as generation, consumption, tariff structures, and investment sources) on the viability of EnCs under the proposed business model. This, in turn, allows to develop recommendations and prerequisites for potential stakeholders on factors and circumstances that would affect the effectiveness of the proposed EnCs.

Bearing in mind the aforementioned, the next chapter examines various factors that affect the economic viability and justification of the proposed EnC through modelling case studies and scenarios.

3. RECOMMENDATIONS TO IMPROVE ECONOMIC FEASIBILITY AND SUSTAINABILITY OF PROSUMER AND CONSUMER ENERGY COMMUNITY

Energy Law has determined that the Ministry of Economics (in cooperation with the Ministry of Environmental Protection and Regional Development) must develop and publish guidelines for forming EnCs, including recommendations regarding support of EnCs and participation in them [6]. To contribute to the development of the aforementioned recommendations, the planning tool is used to offer insights into how the values of various factors and their associated metrics may affect the overall viability of determined EnC cases.

3.1. Assumptions

The main assumptions were introduced in baseline EnC modelling.

- Electricity consumption profiles for the members of EnC are determined using [61], [62]. Prosumer and consumer use differentiated pricing tariffs of "Sadales tīkls" for electricity distribution system services under the "Basic-1" tariff plan and connection parameters of 3 phases and 20 A [63].
- Photovoltaics (PV) system is used as the electricity generation source. Electricity generation profiles are based on [64], [65]. Moreover, the value of CAPEX related to an installed generation source capacity of 1 kW without VAT is determined from [66].
- EnC is formed using a newly purchased PV system. The prosumer is assumed to be the owner of the electricity generation source thereby it is not assigned a tariff for the amount of electricity received from the PV panels.
- External funding for the purchase of PV system in baseline EnCs is determined using the amount of state aid mentioned in [8].
- Tariffs and prices related to electricity sharing, sales, and imports from the grid are fixed and have constant values.

The following sections will delve into the introduction of the baseline EnC cases along with the variables used in the case studies and scenarios.

3.2. Baseline energy communities used in case study and scenario modelling

Baseline EnCs are considered prosumer and consumer EnCs, which differ from each other in terms of electricity consumption and electricity generation, thus forming a wider set of results of the developed case studies and scenarios (see Table 3.1).

Table 3.1

Data of Baseline EnCs

Data	Values		
	EnC No.1	EnC No.2	EnC No.3
Installed capacity of PV system (kW)	3	3	4
Prosumers' average monthly electricity consumption (kWh)	780	780	1050
Consumers' average monthly electricity consumption (kWh)	175	300	175
Amount of external funding (EUR)	1800	1800	2200

Each baseline EnC includes the following unified data (without taxes):

- PV degradation coefficient: 0.5 %/year [58].
- Consumers' tariff for the received electricity from the prosumer: 0.16 EUR/kWh.
- Electricity traders' price for the purchase of excess electricity from the EnC: 0.14 EUR/kWh.
- Electricity cost tariff component for the purchase of electricity from the grid: 0.18 EUR/kWh.
- Prosumers' and consumers' connection to the grid: 3 phases, 20 A [63].
- Costs related to the supply of electricity from the grid: 0.03985 EUR/kWh [63].
- Costs related to connection maintenance: 0.92 EUR/A/month [63].
- PV system CAPEX of the capacity of 1 kW: 958 EUR/kW [66].
- Annual OPEX: 1.2 % of the cost of PV system [59].
- Loan duration: 5 years.
- Bank loan interest rate: 5.9 % [67].
- Discount rate: 9.96 % [68].
- Prosumers' initial investments: 50 % of total CAPEX.
- Consumers' initial investments: 0 % of total CAPEX.
- VAT: 21 % [69].

The next section determines the effect of generation, consumption and external funding level on baseline EnCs defined indicators: NPV, AF, and prosumers' and consumers' economic benefits from the participation in the EnC (PEB and CEB, respectively).

3.3. Determination of NPV, AF, PEB, and CEB values in baseline energy communities

By utilising the planning tool under the proposed business model and information from the baseline EnCs, NPV, AF, PEB, and CEB values are calculated.

When looking at a side-by-side comparison between baseline cases, it can be concluded that the indicator values and payback period used are highly affected by electricity consumption level and installed PV panel capacity. Considering that baseline cases included electricity sharing tariff, which is higher than electricity traders' determined price for the purchase of an excess amount of electricity from the EnC, NPV and AF increases and the payback period shortens when consumers' electricity consumption is high, thus generating higher EnC income. This, in turn, can help to cover EnC expenses related to bank loan repayment and annual OPEX. Moreover, with increased consumers' electricity consumption and the ratio between the aforementioned tariff and price, CEB and PEB values increase. Despite the increased installed PV system capacity in EnC No3, total CAPEX also increases, which can lead to higher EnC expenses. Consequently, it lowers NPV and extends the payback period, as the determined sharing tariff and electricity traders' purchase price may compensate for related expenses at a lower rate.

In order to determine how these indicator values of the used baseline EnCs are affected by the various factors and their respective values, case studies and their related results are discussed in the next section.

3.4. Case study and scenario modelling

Case studies (CS) and respective scenarios (SC) are modelled with the help of the developed EnC planning tool (see Table 3.2).

Table 3.2

Case Study Scenarios

CS	Description	Base value	Values in each SC				
			SC1	SC2	SC3	SC4	SC5
I	Consumers' tariff for the received electricity from the prosumer (EUR/kWh)	0.16	0.16	0.16	0.16	0.18	0.20
	Electricity traders' price for the purchase of excess electricity from the EnC (EUR/kWh)	0.14	0.09	0.16	0.18	0.14	0.14
II	Electricity cost tariff component for the purchase of electricity from the grid (EUR/kWh)	0.18	0.16	0.20			
III	CAPEX related to installed generation source capacity of 1 kW (EUR/kW)	958	641	1427			
IV	Loan duration (years)	5	3	7			
V	Amount of external funding (EUR)	No.1, No.2: 1800	1500	2100	0		
		No.3: 2200	1900	2500			
VI	Prosumers' initial investments (% of total CAPEX)	50	100	0	50	50	
	Consumers' initial investments (% of total CAPEX)	0	0	0	5	50	

Case Study I showed that NPV and AF increase when consumers' tariff for the received electricity from the prosumer and electricity traders' price for the purchase of excess electricity from the EnC is relatively high. However, the value of PEB reduces when the electricity sharing tariff is lower than the electricity traders' determined price for the purchase of excess amount of electricity from the EnC. Moreover, if the electricity sharing tariff is lower than the electricity cost tariff component for the purchase of electricity from the grid, CEB increases due to the cost savings related to shared electricity consumption.

Case Study II determined that the lower electricity cost tariff component reduces the benefits of installing the PV system, thus extending the payback period and reducing the NPV value.

The results of Case Study III indicated that the cost of the PV system is one of the most important factors that can affect the EnC's economic viability and sustainability. Under the lowest CAPEX related to a PV system capacity of 1 kW, EnC's payback period was reduced to under 3 years (a shorter period than the duration of the bank loan); however, under the highest CAPEX related to a PV system capacity of 1 kW, the value of NPV reduced significantly and the payback period in this scenario was longer than the lifetime of the PV system.

Results of Case Study IV indicated that a longer duration of the bank loan can slightly increase the NPV and reduce the payback period. Nevertheless, at the selected CAPEX related to the PV system capacity of 1 kW in baseline EnCs cases, none of the baseline cases reached a positive NPV value during the loan duration. When the total CAPEX is high, the bank may hesitate to approve a loan if the payback period for the PV system exceeds the duration of the bank loan. When looking at the AF values at different loan durations, the AF increases when the duration is the shortest; however, a shorter bank loan duration can lead to greater financial burden on the prosumer, as the loan must be repaid in a shorter term.

By examining the results of Case Study V, it can be concluded that external funding can considerably reduce the total CAPEX, the amount of bank loan, and the payback period. If external funding is not acquired, the NPV value significantly decreases, and the payback period for baseline EnCs in this scenario is longer than the lifetime of the PV system.

The results of Case Study VI indicated that if prosumer fully covers total CAPEX with initial investments, the payback period is not significantly affected compared to baseline cases. Moreover, by fully covering the initial costs of the PV system, the AF increases. If total CAPEX is fully covered by the bank loan and without any initial investments by the members of EnC, the NPV in the bank loan period experiences a rapid decline; however, after the bank loan duration, it increases and the PV systems' payback period shortens compared to baseline cases. If the consumer makes one-time payment for the coverage of initial investments, it can increase NPV and PEB, but reduce CEB. If the consumer makes initial investment payments, the sharing tariff should be low enough (or even non-existent) and the consumer's electricity consumption and the received amount of electricity from the prosumer should be high enough to make CEB a positive value.

3.5. Discussion and conclusions

In order to contribute to the development of recommendations for the establishment of EnCs mentioned in the Energy Law, case study and scenario modelling were conducted with the help of the developed planning tool. The goal was to analyse how different factors and their potential values can affect the economic viability and efficiency of prosumer and consumer EnCs under the proposed business model using four specifically defined indicators: NPV, AF, PEB, and CEB.

The following recommendations can be put forward to increase economic justification, feasibility, and sustainability of prosumer and consumer EnCs:

- For the purchase and installation of a PV system, EnC members must select the dealer with the most competitive offer (the lowest CAPEX related to a PV system capacity of 1 kW), thus reducing the payback period, increasing NPV, and reducing the amount of necessary initial investments and bank loan (if applicable).
- EnC members should assess the market electricity price forecast to ascertain, if the savings generated through self-consumption and reduction of imported electricity from the grid are sufficient to offset the overall expenses associated with purchasing and maintaining a PV

system. Cost savings related to self-consumption increase when the electricity cost tariff component for the purchase of electricity from the grid is relatively high.

- Legislators and policymakers must acknowledge that providing state aid for the purchase of electricity generation sources can notably enhance the economic sustainability of EnCs. Consequently, it is advisable to introduce state aid for EnCs to partially cover the initial costs at the same or higher level than what is set for individual prosumers. Moreover, potential EnC members should acquire additional external funding to lower the payback period of an installed PV system.
- If a bank loan is used to partially or fully cover the total CAPEX, the prosumer must assess whether the ratio between the discount rate and the bank interest rate, as well as the EnC income and the prosumer's private financial funds, are sufficient to make the loan payment at the respective loan duration, as well as to assess the effect of the bank loan to AF value over the determined period. Moreover, to receive a bank loan, the prosumer must be sure that the payback period of the installed PV system is shorter than or equal to the duration of the loan repayment. The results of the modelled scenarios showed that the payback period can be significantly reduced by installing a PV system with the lowest CAPEX related to a PV system capacity of 1 kW.
- If the consumer makes one-time initial investments for the purchase and installation of a PV system, EnC participants must assess whether the amount of electricity to be shared and the consumers' electricity consumption are high enough to generate positive economic benefits for both the prosumer and the consumer. In addition, consumers' partial coverage of the PV systems' initial costs opens the possibility of reducing or excluding the sharing tariff for the amount of electricity received from the prosumer, which, in turn, can reduce the necessary amount of the bank loan or even allow to cover the total CAPEX only with initial investments.
- If a sharing tariff is introduced to increase the EnC income and the cash flow in AF, then the PEB will increase if the sharing tariff is higher than the electricity traders' price for the purchase of excess electricity. However, CEB can be increased when the sharing tariff is lower than the electricity cost tariff component for the purchase of electricity from the grid. It can be mentioned that PEB and CEB are also affected by the amount of consumers' one-time initial investments.

Among the above-mentioned recommendations, there is a mutual connection and the dependence of the respective values on each other. The effect of each included factor also depends on the individual level and profile of electricity consumption of each EnC member, the capacity of the installed electricity generation sources, the amount of electricity produced, and the priorities of the EnC itself. These priorities could be related not only to the payback of the installed generation source but also to determining the economic benefits of each participant and their objective to save or not to save funds for future energy efficiency measures.

CONCLUSIONS

- The development of a planning tool for prosumer-consumer EnCs, based on Latvia's legal framework and local RES availability, confirms the hypothesis of the Doctoral Thesis. This tool promotes the involvement of prosumers and consumers in EnCs, fostering electricity-sharing collaboration and advancing Latvia's energy transition goals. Through modelled case studies, scenarios, and analysis, the Thesis demonstrates recommendations to enhance the viability, justification, and feasibility of prosumer-consumer EnCs in Latvia, paving the way for more sustainable and engaged electricity-sharing actions.
- The tasks of the Thesis have been successfully carried out:
  - A review of legislation acts, scientific publications, and media sources was conducted to determine EnC implementation requirements, guidelines, and possible challenges and setbacks.
  - A methodology and a modelling tool were developed for planning prosumer-consumer EnC initiatives under Latvia's legislation and energy transition goals.
  - The variable factor effect on the economic feasibility and sustainability of prosumer-consumer EnCs was studied through case study and scenario modelling.
- The introduction of EnCs in Latvia faces challenges and setbacks related to a lack of regulations, information dissemination activities, support measures, planning tools, complex business models, low number of prosumers, a small amount of electricity available for sharing, low acceptance and willingness-to-participate rate.
- The developed EnC planning tool and methodology address almost all the aforementioned challenges: showcase the economic advantages of EnCs, motivate interest in EnCs among the public and substantiate the effectiveness of external funding, thereby making it applicable and useful not only to electricity users, but also to legislators and policymakers. A business model is proposed based on the P2P approach (as mentioned in Latvia's NECP) with AF, and external funding acquisition modification. The planning tool determines the consumption of produced electricity, evaluates mutual electricity sharing activities, determines cost allocation and proposes specifically defined EnC viability and feasibility characterising indicators: NPV, AF, PEB, and CEB. The planning tool can serve as a basis to assess the economic viability of EnC not only in the context of Latvia, but also in other countries (if necessary, adapting and modifying it to the respective legislative guidelines).
- To prioritise study transparency and user empowerment, the developed prosumer-consumer EnC planning tool is freely downloadable and open-source on GitHub platform.
- To contribute to the development of guidelines for the formation of EnCs (as mentioned in Energy Law), the modelled case studies and scenarios indicate that EnC viability can be increased by selecting a dealer with the lowest electricity generation system costs, acquiring external funding and when electricity cost tariff component for the purchase of electricity from the grid is relatively high. Moreover, the feasibility of the proposed EnC is affected by the amount of bank loan and its duration, the ratio between interest and discount rates, the sharing tariff and purchase price for the excess amount of electricity, and the used initial investment allocation mechanism.

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Roberts Lazdiņš was born in 1996 in Gulbene. He received a Bachelor's Degree of Engineering Science in Electrical Engineering in 2018 and a Master's Degree in Power and Electrical Engineering in 2020 from Riga Technical University. He has worked at the Institute of Power Engineering of RTU since 2020. Currently, he is a researcher at this institute. His scientific interests are related to renewable energy resources, energy communities, and local energy systems.