

Faculdade de Engenharia da Universidade do Porto



Managing Value Transactions in Energy Communities

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Resumo

Este trabalho apresenta os Créditos de Energia (CE), unidades digitais equivalentes a 1 kWh, como mecanismo de transação de valor P2P adaptado a Comunidades de Energia Renovável (CER). Propõe-se um sistema que regista a geração, o consumo e as trocas de CE entre membros, suportando desde trocas diretas entre pares até à mediação pela Entidade Gestora do Autoconsumo Coletivo (EGAC), permitindo um controlo contabilístico fiável das transações e a adaptação a uma ampla variedade de modelos de negócio, mercados locais e tarifários sociais.

A carência de um meio eficiente para contabilizar e remunerar trocas internas em CER motiva a criação de CE, que permitem alocar custos e benefícios de forma equitativa, incentivar a flexibilidade de consumo e integrar serviços comunitários. Os objetivos chave incluem definir o conceito de CE, especificar o fluxo de emissão e troca, modelar mercados internos e avaliar o impacto social e económico desta abordagem.

Para desenvolver o conceito de Créditos de Energia (CE), procedeu-se a uma revisão bibliográfica e normativa sobre Comunidades de Energia Renovável, seguida da especificação teórica dos CE e da implementação de um protótipo de *Energy Credit Management System* (ECMS). Validou-se o modelo através de simulações num caso de estudo real com quatro edifícios, usando dados de geração e consumo em intervalos de 15 minutos.

Através de uma simulação horária ao longo de um ano, aplicada a uma comunidade de energia realista, testaram-se diversas configurações e modelos de transação, demonstrando a viabilidade e a robustez do sistema proposto. Os resultados obtidos evidenciam que é possível implementar um novo conceito de transitividade energética, capaz de assegurar justiça, rastreabilidade contabilística e adaptabilidade regulatória, constituindo um contributo relevante para a evolução dos modelos de partilha de energia em contexto comunitário.

Os Créditos de Energia revelam-se um mecanismo flexível e transparente para transações em CER, promovendo igualdade de distribuição de benefícios e incentivando comportamentos sustentáveis. A abordagem mostrou-se tecnicamente viável e economicamente promissora, com ganhos para produtores, consumidores e gestor comunitário.

Abstract

This dissertation introduces Energy Credits (ECs), digital tokens each representing 1 kWh, as a peer-to-peer value-exchange mechanism designed for Renewable Energy Communities (RECs). The proposed framework records EC generation, consumption and transfers among members, ranging from direct P2P swaps to mediation by the Collective Self-Consumption Managing Entity (EGAC), thus supporting a variety of business models, local markets and social tariff schemes.

The absence of an efficient method to account for and remunerate internal REC exchanges motivated the development of ECs, which enable equitable cost-benefit allocation, incentivise demand-side flexibility and integrate community services. Core aims included formalising the EC concept, specifying issuance and transfer workflows, modelling internal market structures and evaluating associated economic impacts.

A comprehensive literature and regulatory review informed the theoretical specification of ECs, followed by the implementation of a prototype Energy Credit Management System (ECMS). Model validation was conducted via simulations on a four-building case study, utilising 15-minute interval generation and consumption data.

Hourly simulations over a full year, applied to a realistic community scenario, demonstrated the feasibility and robustness of the ECMS across diverse transaction configurations. Results confirm that ECs establish a novel energy-transitivity paradigm, delivering transparent accounting, regulatory compliance and fair distribution of benefits, advancing the state of the art in community energy sharing.

By decoupling energy generation from immediate consumption, ECs offer a flexible, transparent mechanism that fosters equitable stakeholder engagement and sustainable practices. The approach has been shown to be technically viable and economically advantageous, yielding tangible benefits for producers, consumers and community managers alike.

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Nomenclature

ADENE	The Agency for Energy (<i>Agência para a Energia</i>)
CIEG	Costs of General Economic Interest (<i>Custos de Interesse Económico Geral</i>)
CPE	Delivery Point Code (<i>Código de Ponto de Entrega</i>)
CPEc	Consumption Delivery Point Code (<i>Código de Ponto de Entrega de Produção</i>)
CPEp	Production Delivery Point Code (<i>Código de Ponto de Entrega de Consumo</i>)
DAG	Directed Acyclic Graphs
DEEC	<i>Departamento de Engenharia Electrotécnica e de Computadores</i>
DGEG	Directorate General for Energy and Geology (<i>Direção Geral de Energia e Geologia</i>)
DLT	Distributed Ledger Technology
DSO	Distribution System Operator
EC	Energy Credits
ECMS	Energy Credit Management System
EGAC	Collective Self-consumption Managing Entity (<i>Entidade Gestora do Autoconsumo Coletivo</i>)
EHV	Extra-High Voltage
ERSE	Energy Services Regulatory Authority (<i>Entidade Reguladora dos Serviços Energéticos</i>)
GDPR	General Data Protection Regulation
HV	High Voltage
IA	Storage Installation (<i>Instalação de Armazenamento</i>)
IC	Consumption Installation (<i>Instalação de Consumo</i>)
IU	Utilization Installation (<i>Instalação de Utilização</i>)
FEUP	<i>Faculdade de Engenharia da Universidade do Porto</i>
MV	Medium Voltage
PPA	Power Purchase Agreements
PNEC 2030	The National Energy and Climate Plan 2030 (<i>Plano Nacional de Energia e Clima 2030</i>)
REC	Renewable Energy Community
RESP	Public Service Electricity Grid (<i>Rede Elétrica de Serviço Público</i>)
RND	Medium Voltage Distribution Network (<i>Rede Nacional de Distribuição</i>)
RNT	High Voltage Transmission Network (<i>Rede Nacional de Transmissão</i>)

<i>TAR</i>	Network Access Tariffs (<i>Tarifa de Acesso à Rede</i>)
TIN	Tax Identification Number
TSO	Transmission System Operator
<i>UA</i>	Storage Unit (<i>Unidade de Armazenamento</i>)
<i>UPAC</i>	Production Unit for Self-Consumption (<i>Unidade de produção para Autoconsumo</i>)
VAT	Value-added Tax

Chapter 1

Introduction

1.1 - Contextualization

The traditional centralized energy system is shifting towards more decentralized and collaborative models, driven by the increasing integration of renewable energy sources, digitalization, and regulatory changes. This transformation has led to the emergence of Renewable Energy Communities (RECs), where prosumers and local stakeholders collectively manage energy generation, consumption, and sharing to optimize self-sufficiency and sustainability.

The concept of RECs was formally introduced in the EU Directive 2018/2001, which mandates that Member States ensure that household consumers can participate in energy communities, granting them the right to produce, consume, store, and share renewable energy within their community. By promoting a localized and participatory approach to energy management, RECs have the potential to democratize the energy transition, empowering consumers to contribute actively to decarbonization efforts [1].

Portugal has embraced this model by implementing a legal framework facilitating REC adoption. The National Energy and Climate Plan (PNEC 2030), approved by the Council of Ministers, sets ambitious targets, aiming for 47% to 51% of final energy consumption to come from renewable sources by 2030 [2]. Additionally, regulatory measures have been introduced to simplify licensing procedures and expand the geographical limits for REC participants, particularly in low-density areas [3].

Despite their advantages, the operationalization of RECs still faces significant challenges, particularly concerning managing value transactions among community members. Traditional electricity markets are designed for centralized supply chains, making it difficult to account for energy exchanges in a distributed setting efficiently. Current administrative

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processes for energy sharing within RECs rely on rigid frameworks and intermediaries, limiting their flexibility and economic efficiency.

A key challenge is the lack of an efficient and transparent mechanism for value transactions within RECs. The ability to fairly allocate costs and benefits among members, track energy contributions, and facilitate direct energy exchanges is critical for ensuring these communities' financial sustainability and scalability. Without a robust transaction system, the economic viability of RECs remains uncertain, and incentives for participation may be weakened.

One promising approach to address this issue is the implementation of Energy Credits (ECs) as a digital transaction mechanism. ECs function as non-monetary energy accounting units, enabling the transparent and flexible energy exchange among REC members. Unlike direct kWh compensation, ECs introduce greater adaptability, allowing energy transactions to be decoupled from real-time constraints and enabling additional functionalities such as peer-to-peer (P2P) trading, flexibility rewards, and incentive schemes for community services.

This dissertation aims to design and specify a peer-to-peer (P2P) value transaction mechanism tailored for RECs, leveraging the potential of Energy Credits to streamline operations and enhance economic sustainability. By addressing the technical and regulatory challenges associated with decentralized energy exchanges, this work seeks to contribute to Renewable Energy Communities' scalability and long-term viability, aligning with the broader energy transition and decarbonization goals.

1.2 - Motivation

The transition towards a decentralized and collaborative energy system, driven by Renewable Energy Communities (RECs) growth, requires new mechanisms to manage energy transactions efficiently and fairly. In the traditional model, electricity is generated by large producers, distributed by network operators, and consumed by end-users with little or no control over their energy sources. However, RECs introduce a more dynamic relationship between production and consumption, enabling members to share energy surpluses and optimize the use of renewable sources. Despite this potential, the lack of efficient transaction mechanisms makes the current model bureaucratic, inflexible, and reliant on intermediaries, hindering its large-scale adoption [4].

Currently, energy transactions within RECs rely on fixed or dynamic allocation coefficients, which are administratively determined and applied at regular intervals. This limits consumers' ability to adjust their energy exchanges autonomously and prevents the implementation of more flexible economic models, such as local energy markets, demand response incentive schemes, or energy solidarity mechanisms [5].

In this context, this dissertation proposes developing a novel value transaction concept for RECs: Energy Credits (ECs). While existing approaches include compensation schemes in

local energy markets and blockchain-based energy-sharing models, none introduce a fully decentralized, scalable, and non-monetary mechanism that optimizes the exchange of electricity and community services within RECs. Thus, ECs represent an innovative solution, developed specifically for this research, addressing gaps in the current state of the art.

Unlike direct kWh-based metering, ECs function as digital transaction units, offering greater flexibility and traceability of energy exchanges within the community. This approach provides multiple advantages, allowing renewable energy to be managed more efficiently, without the temporal and operational constraints of conventional models.

One of the main benefits of ECs is the decoupling of energy generation from its immediate transaction, enabling REC members to accumulate, store, or exchange credits based on their needs. This allows for the creation of incentive mechanisms, where consumers who provide demand-side flexibility can be rewarded with additional credits, encouraging behaviours that benefit both the community and grid stability. Moreover, ECs enable the integration of non-energy contributions, allowing members to be compensated for maintenance, management, or technical support services within the community.

Another fundamental aspect is the potential of ECs to reduce energy poverty, creating a fairer and more inclusive model. While conventional energy markets operate with fixed prices set by external entities, RECs can establish internal redistribution mechanisms, allowing surplus energy to be donated or exchanged at reduced costs to support vulnerable consumers. This reinforces the role of RECs not only as an energy model but also as a social and community-based model, promoting the democratization of renewable electricity access [6].

To structure the adoption of ECs within RECs, a robust management system is required to ensure transaction traceability and security. The approach proposed in this dissertation is based on implementing a peer-to-peer (P2P) value transaction mechanism, in which ECs are issued, exchanged, and consumed digitally, allowing for a transparent, auditable, and scalable model. By operating as an additional digital layer within the existing energy infrastructure, ECs simplify energy sharing, allowing its distribution, storage, and commercialization to be managed more efficiently and autonomously by community members [7].

In conclusion, through its implementation, RECs are expected to evolve towards a more sustainable and economically viable model, encouraging greater consumer and producer participation, increasing grid resilience, and fostering a fair and participatory energy transition. Also, it is expected to provide direct benefits to people, such as lowering electricity bills, helping to provide flexibility to the electricity system through demand-response and storage, and contributing to reducing energy consumption [57, 58].

1.3 - Research Questions

Introducing the Energy Credits (ECs) concept as a value transaction mechanism within Renewable Energy Communities (RECs) raises several fundamental questions this dissertation seeks to explore. While RECs represent a promising model for democratizing renewable energy access, their efficient implementation still faces operational, economic, and regulatory challenges. ECs emerge as an innovative solution to facilitate energy exchanges within the community, but their feasibility, impact, and user acceptance require in-depth analysis.

One of the first aspects to address concerns the functional and operational feasibility of ECs within RECs. Currently, energy-sharing mechanisms rely on direct kWh measurements, regulated by external entities that determine allocation coefficients and associated tariffs. ECs propose a decentralized and flexible model, allowing community members to exchange energy and services directly without the immediate need for monetary conversions. However, how can this new value transaction model be technically viable and compatible with existing infrastructures? Will the development of new digital platforms and control mechanisms be necessary to integrate ECs without compromising grid stability and transaction security?

Beyond technical feasibility, it is crucial to understand how ECs can impact the internal economy of RECs and their financial sustainability. Introducing a new value mechanism may influence how members participate in the community and how energy benefits are distributed. Therefore, it is essential to answer the question: How does adopting ECs alter value flows within the community? Can this model increase the profitability of decentralized energy production, reduce operational costs, and encourage greater participation from consumers and small producers? To address these questions, different implementation scenarios must be evaluated, analyzing the effects of ECs on energy redistribution, cost reduction, and incentives for active community engagement.

Another fundamental aspect concerns community members' acceptance of ECs. While ECs introduce new possibilities for optimizing energy consumption and sharing, their adoption will depend on user perceptions regarding transparency, ease of use, and direct benefits. Therefore, this dissertation explores the barriers and key factors influencing the adoption of ECs. Do consumers easily understand how energy credits work? What types of governance models and transaction rules can enhance trust among members and ensure community-wide acceptance? These questions are critical in designing an EC system that is intuitive, fair, and accessible to all participants.

Additionally, it is vital to examine the regulatory implications of implementing ECs. Currently, consumer energy exchanges are subject to strict regulations, including taxation and specific tariff structures. Creating a parallel transaction system within RECs could pose challenges regarding legal compliance. Thus, a central question will be: to what extent can ECs be implemented without conflicting with existing regulations? Will developing new legal frameworks and policy support be necessary to enable widespread adoption of this concept?

Objectives

Finally, this dissertation explores how ECs can contribute to integrating complementary services within RECs, such as flexibility management and social support mechanisms. The current energy-sharing model does not allow members to be rewarded for adjusting their consumption based on renewable generation or for contributing to community services. ECs could introduce new incentives for grid balancing and energy poverty mitigation within RECs. Therefore, it is crucial to answer the question: how can ECs create new incentives for active energy management and support vulnerable consumers within the community?

By addressing these research questions, this dissertation will validate the technical feasibility of ECs and assess their economic, social, and regulatory impact, providing an innovative model for managing value transactions in energy communities.

1.4 - Objectives

This dissertation aims to develop the Energy Credits (ECs) concept specifications and define the market models for value transactions based on ECs within Renewable Energy Communities (RECs). This work aims to create an innovative model that allows REC members to conduct energy transactions flexibly, transparently, and efficiently, overcoming the limitations of traditional systems based solely on kWh measurements. To achieve this global objective, the following specific objectives have been defined:

- Define the concept of Energy Credits (ECs) and establish their theoretical and operational foundation, distinguishing them from existing compensation systems in local energy markets and identifying their advantages and challenges.
- Specify the mechanism for issuing, transacting, and consuming ECs, ensuring that it functions within the REC infrastructure and is compatible with current energy metering and monitoring technologies.
- Develop a market model for EC transactions among community members, including rules for credit valuation, incentives for participation, and community governance mechanisms.
- Explore the regulatory implications of using ECs, identifying potential legal challenges and proposing strategies for their integration in compliance with existing legislation.
- Examine the potential of ECs to foster additional services within RECs, such as flexibility mechanisms, energy efficiency incentives, and support for vulnerable consumers.
- Validate the EC model through simulations or case studies, demonstrating its practical applicability and benefits compared to conventional energy transaction models.

Achieving these objectives will provide a robust framework for implementing ECs, demonstrating their technical, economic, and social feasibility, and contributing to developing new approaches to value management within Energy Communities.

Chapter 2

Energy Communities and Value Transactions

This chapter is structured to provide a comprehensive foundation for the dissertation, beginning with the characterization of Renewable Energy Communities (RECs).

2.1 - Framework for Energy Communities

To fully understand RECs, it is essential to break down the concept into its various components and perspectives. This section provides a structured framework that examines RECs from multiple angles, facilitating a clearer understanding of their organizational aspects, operational models, business structures, and value transaction mechanisms. By analysing these dimensions separately, the following sections will offer a more comprehensive view of how RECs function and interact within the broader energy ecosystem.

2.1.1 - Definition and Objective of Renewable Energy Communities

Firstly, the definition of Renewable Energy Communities is addressed in Directive (EU) 2018/2001 of the European Parliament and the Council, dated December 11, 2018. Due to the growing need for independence from fossil fuels, the cited directive sets objectives for promoting the use of energy from renewable sources within Member States. Measures such as providing information, technical and financial support, simplifying bureaucratic processes, adapting tenders to the needs of communities, and enabling direct compensation should be implemented if they meet the applicable requirements for small installations [1].

In this context, a REC is an organizational model that enables the production, sharing, and consumption of renewable energy among its members. RECs primarily aim to provide environmental, economic, or social community benefits for their shareholders or members

located near renewable energy projects or the local areas where they operate, rather than financial profits [1].

This directive establishes a solid framework for the increasing integration of renewable energy across European territory. It has been reviewed and amended by Directive (EU) 2023/2413 of the European Parliament and the Council, dated October 18, 2023 (RED III Directive). This strengthens the overall target for Member States to expand renewable energy consumption from 32% to 42.5% by 2030, accelerating the current pace of renewable energy deployment and accelerating the European Union's reduction of its dependency on Russian fossil fuels [8].

Under Portuguese legislation, geographical proximity between the members of a REC and the renewable energy production facilities is a crucial criterion for its definition. The regulations establish specific distance limits to determine whether a community qualifies as a REC, setting the conditions for connecting production units to consumption points within the electrical grid. Specifically, in Decree-Law No. 99/2024, of December 3, this criterion is detailed in Article 83. According to this, the connection between Self-Consumption Production Units (*UPACs*) and Utilization Installations (*IU*) can occur through a direct line or an internal network, or via the Public Service Electricity Network (*RESP*), respecting specific distance limits. The distance between the *IU* and the *UPAC* must not exceed 2 km for installations connected to the low-voltage network unless both are connected to the same transformer station. In the case of connections to the Medium Voltage Distribution Network (*RND*) or the High Voltage Transmission Network (*RNT*), proximity is defined by the connection to the same substation. If this connection does not exist, maximum distance limits are set at 4 km for Medium Voltage, 10 km for High Voltage, and 20 km for Extra-High Voltage. In low-density areas, these values may be doubled [3].

Although the legislation governing Renewable Energy Communities establishes maximum distance requirements between entities, such limitations are unnecessary and do not align with the principles of energy optimization. The fundamental goal of a REC is to balance local energy production and consumption, reducing the reliance on external energy flows. This can be achieved without requiring physical proximity between members, as energy distribution and accounting can be managed virtually.

RECs can adopt different social and economic organizational structures depending on their specific needs and local context. These communities may be structured as cooperatives, associations, condominiums, industrial complexes, cultural or professional communities, and family units. This diversity in organizational models allows RECs to adapt to different economic and social settings, promoting greater participation and engagement from local stakeholders.

2.1.2 - Stakeholders Associated with RECs

In a Renewable Energy Community context, various agents play essential roles in operation and management. These members, represented by their **Tax Identification Number (TIN)**, include the REC and its members and external entities supporting its operation, regulation, and technical assistance.

Regardless of the business or management model adopted, it is crucial to understand these agents' functions and interactions to ensure the REC's success.

Therefore, this subsection provides a detailed description of the key agents involved:

- **Consumers:** any entity that uses electricity or other forms of energy to meet its needs without the intent to resell it. This includes households, businesses, and institutions, which balance supply and demand within the power system.
- **Consumer-producers (*prosumers*):** can use the energy they generate for their needs and inject surplus energy into the grid or share it within an energy community.
- **Associative entities:** such as cooperatives, associations, condominiums, and industrial parks, are organizations formed under a shared TIN to pursue a common purpose, often related to economic, social, or environmental benefits.
- **Energy producers:** entities dedicated solely to generating electricity, typically from renewable sources such as photovoltaic systems, batteries, or hybrid systems. Unlike consumer-producers, they do not consume the energy they generate for their needs but instead supply it to the grid or energy communities.
- **Investors:** entities that finance energy infrastructure, providing the necessary capital for developing renewable energy projects, grid expansion, and storage solutions. They are not consumers themselves.
- **Grid Operators (DSO):** responsible for the distribution activity, including the construction, operation, and maintenance of the distribution grid and, where applicable, its interconnections, as well as ensuring the long-term grid capacity guarantee [7].
- **Energy supplier:** an entity whose primary activity involves the wholesale and retail buying and selling of electricity, acting on its behalf or representing third parties. It may also perform functions of aggregating electricity consumption and/or production.
- **Metering managers:** are responsible for monitoring energy consumption and production, ensuring accurate measurement and data collection for billing, grid management, and energy balancing. In the Portuguese framework, this role is carried out by the Distribution System Operator (DSO).

- **Software providers:** for community management and optimization, develop digital solutions that enable the efficient operation of RECs.
- **Installation and maintenance service providers:** to ensure the proper operation and longevity of energy infrastructure within RECs. These entities are responsible for deploying renewable energy systems, such as solar panels, batteries, and inverters, and maintaining and troubleshooting equipment to optimize performance and reliability.

The operation of a REC relies on the interaction of various stakeholders, from consumers and *prosumers* to investors, grid operators, and service providers. Each entity is crucial in energy management, regulatory compliance, and infrastructure optimization. Their collaboration ensures efficient value transactions, enabling the sustainability and success of the REC.

2.1.3 - Assets and Installations Related to a REC

Each installation within a REC is associated with a metering unit, identified by a Delivery Point Code (*CPE*), which is unique and consists of 20 digits. This unit may be bidirectional, meaning it can recognize the flow of energy in both directions, thus requiring both a Production Delivery Point Code (*CPEp*) and a Consumption Delivery Point Code (*CPEc*). Only one of the aforementioned *CPE* codes will be present if the unit is unidirectional. [6]

Next, various elements potentially related to a REC are presented, along with the type of *CPE* associated with each:

- **Consumption Installation (IC):** Identified by a *CPEc* and a *CPEp* when integrated with *UPACs* or *UAs*.
- **Centralized production installation:** A REC structure consisting of one (or more) large-scale *UPACs* dedicated exclusively to renewable energy production and shared within the community.
- **Self-consumption installation:** Small individual generators used by consumer-producers, defined by both a *CPEp* and a *CPEc*.
- **Centralized storage installation:** Typically defined by a *CPEp* and a *CPEc*, it allows bidirectional energy flow to balance energy supply.
- **Self-consumption with storage installation:** Hybrid systems combine local production and storage, meaning they have both *CPEp* and *CPEc*.

The assets and installations within a REC define the structural and operational framework that enables energy production, consumption, and storage. The assignment of Delivery Point Codes (*CPEs*) ensures precise identification and traceability of energy flows, distinguishing between consumption, production, and storage systems. The classification of installations, ranging from centralized production and storage units to self-consumption systems, directly influences how energy is managed and exchanged within the community. This

infrastructure plays a fundamental role in shaping the mechanisms of energy allocation and value transactions, ensuring efficient integration of renewable resources while complying with regulatory requirements.

2.1.4 - Asset Sizing and Number of Members

The size and composition of a Renewable Energy Community can vary depending on its structure, energy needs, and the number of participants. As shown in Figure 2.1, different models exist to accommodate various scales and consumption patterns:

- **Distributed models:** Typically consist of small-scale domestic self-consumption systems, where multiple consumers, such as households, share locally produced renewable energy.
- **Industrial models:** Designed for large-scale self-consumption, these RECs involve a limited number of industrial or commercial consumers with high energy demands.
- **Condominium systems:** These models aggregate multiple energy consumers within a building or a group of buildings, enabling collective self-consumption and efficient energy distribution.
- **Centralized production and storage systems:** Feature large-scale renewable energy production units, supplying energy to multiple consumers within a defined proximity.
- **Hybrid models:** Combine different configurations, integrating distributed generation, centralized storage, and various consumer types to optimize energy use and flexibility. They can be tailored to meet specific community needs and regulatory frameworks.

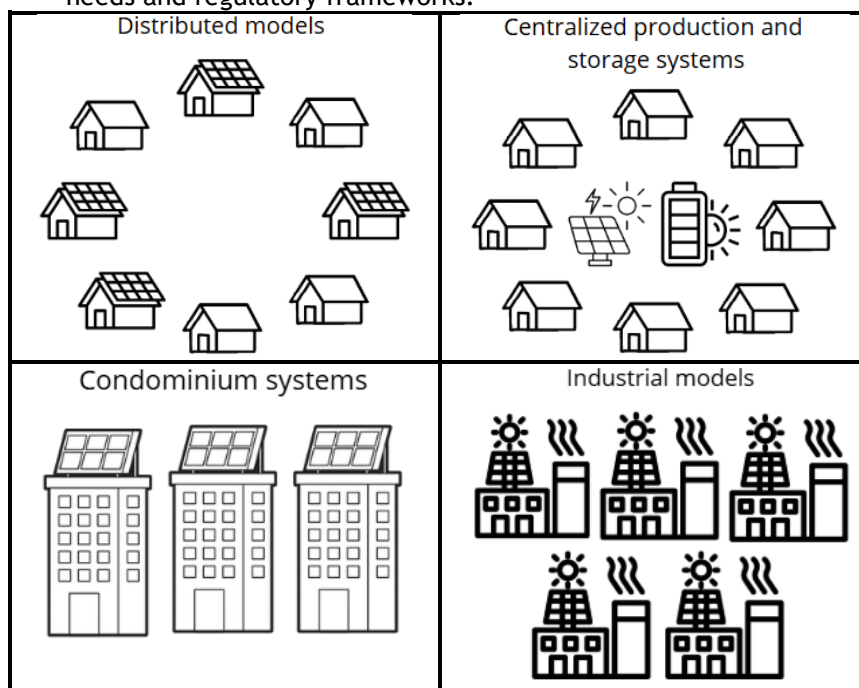


Figure 2.1 - Asset Sizing Models in Renewable Energy Communities.

The asset sizing and composition of a REC directly influence its operational efficiency and scalability, and the dynamics of value transactions within the community. The various models presented enable flexibility in adapting to different consumer profiles and energy demands, ensuring optimized self-consumption, distribution, and energy exchange.

By selecting the appropriate structure, whether distributed, industrial, condominium-based, centralized, or hybrid, RECs define how energy ownership and trading mechanisms operate, shaping the financial flows between participants. This directly impacts the economic sustainability of the REC, the incentives for participation, and its alignment with regulatory frameworks.

2.1.5 - Ownership of Equipment and Energy

The ownership of infrastructure and the energy generated in a REC can vary depending on the involved entities:

- **Consumers:** Individual ownership of small-scale self-consumption installations (e.g., residential solar panels) or large industrial installations for private use.
- **Community:** Collective ownership through cooperatives, associations, or condominium-based models, where the energy produced is shared among members.
- **Independent producers:** Entities that own production assets and sell energy directly to consumers or the REC, acting as third-party suppliers.
- **Investors (suppliers or service companies):** Various financing models exist, allowing investors to profit from the energy infrastructure while enabling communities to access renewable energy:
 - I. **Lease model:** Consumers or the community pay rent for the use of the equipment, while the investor retains ownership.
 - II. **Community leasing:** The REC leases the infrastructure, distributing costs among its members.
 - III. **Partial ownership model:** The investor owns a portion or all of the generated energy, while the consumer or community may retain ownership of the equipment.

The infrastructure and energy ownership structure within a REC plays a crucial role in defining value transactions and economic flows. Whether energy is owned individually, collectively, or by independent producers and investors, these models determine how energy is allocated, traded, and monetized within the community.

The involvement of external investors through leasing or partial ownership further influences the financial sustainability of the REC. Clearly defining ownership is essential for establishing transaction mechanisms, ensuring fair energy distribution, and aligning with regulatory and market frameworks.

2.1.6 - Consumption Management in Communities

Effective consumption management in Renewable Energy Communities extends beyond energy production coordination, requiring flexible and strategic load control to maximize efficiency and self-sufficiency within the REC.

Various strategies can be applied to balance energy demand with local generation:

- **Direct control:** the community or the grid operator actively manages loads and battery storage systems to optimize self-consumption and grid interaction. This approach includes real-time monitoring and automation.
- **Indirect control:** price signals and dynamic tariffs encourage behavioural changes instead of directly adjusting loads. Consumers are incentivized to shift consumption to periods of high renewable generation, reducing peak demand and improving cost-effectiveness.
- **Centralized storage management:** community storage solutions, where a shared battery system, often housed in a dedicated facility within the community, stores excess renewable energy. This allows for optimized redistribution, reducing energy waste and enhancing grid stability.
- **Community load control:** Certain communitarian loads, such as refrigeration, water pumping, desalination, and electric vehicle (EV) charging, can be centrally managed to align with renewable energy availability.

The consumption strategies listed above are depicted in Figure 2.2.

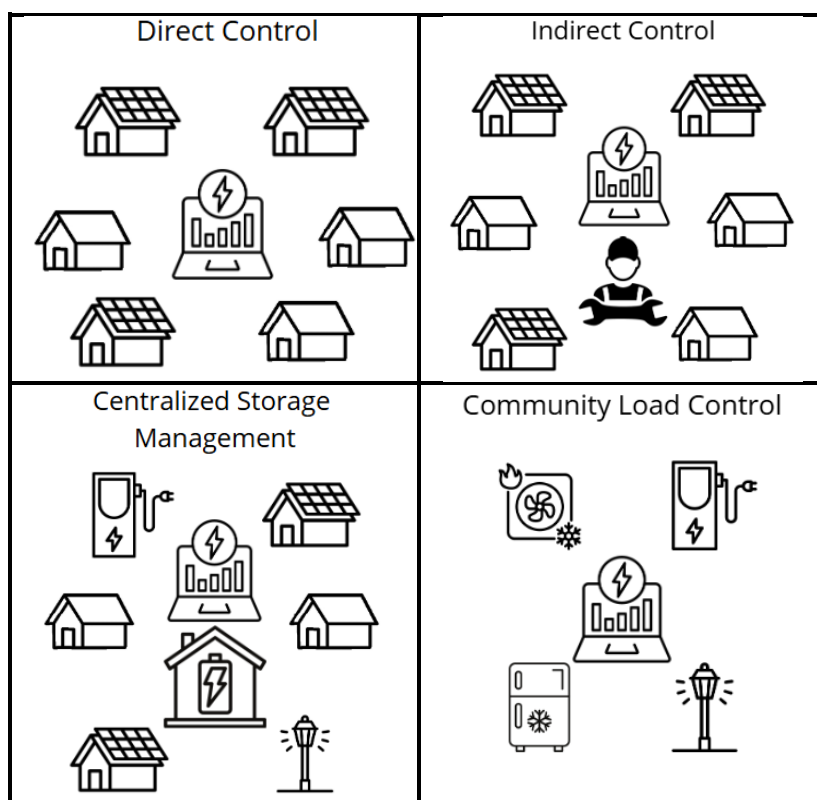


Figure 2.2 - Consumption management strategies.

RECs can better align consumption with renewable generation by implementing direct and indirect control mechanisms, centralized storage, and community load management.

2.1.7 - Organizational and Information Flow in RECs

This subchapter bridges the virtual allocation methods (Section 2.1.7.1) and the EGAC's operational duties (Section 2.1.7.2) by outlining how 15-minute smart-meter data from the DSO is processed, allocated via coefficients, and turned into both physical energy flows and financial settlements.

2.1.7.1 - Virtual allocation method

The fundamental objective of a REC is to share energy among its members, ensuring that locally generated renewable electricity benefits the community before being exported to the grid. However, this energy sharing cannot be achieved physically, as electricity flows according to the laws of electromagnetism and not by direct allocation from one consumer to another.

A virtual allocation method is required to overcome this limitation, allowing the fair distribution of the generated energy among participants based on predefined rules. This virtual allocation ensures that each member receives an appropriate share of the community's production, aligning with economic, regulatory, and technical constraints while maximizing self-consumption within the REC.

Thus, this aspect is paramount in this context, as the energy allocation method directly impacts the economic feasibility of REC projects.

The sharing models are divided by different types of coefficients, namely [7]:

- **Fixed coefficients:** Calculated every 15 minutes and established to account for factors such as differentiating weekdays from holidays or weekends and seasonal variations managed by the EGAC.
- **Variable coefficients:** Determined based on specific criteria, such as prioritization or actual consumption recorded during each period, according to the time intervals defined by ERSE regulations.
- **Combination of both methods:** Applied following ERSE regulations.

For a better understanding of the two types of existing coefficients, we refer to equations 1 and 2, which correspond to the fixed and variable coefficients, respectively. It is evident from equation 1 that the total energy produced by the Renewable Energy Community (CER), E_p , is distributed among its constituent consumers according to their respective fixed coefficients.

$$E_i = \frac{c_i}{\sum_i c_i} \sum_i E_p \quad (1)$$

Regarding equation 2, it can be observed that the total energy produced by the Renewable Energy Community is allocated by the Distribution System Operator (DSO) based on the energy shortfall to be supplied during each quarter-hour period, indexed to the consumption of each participant, thereby calculating each respective variable coefficient, $E_{c,i}$.

$$E_i = \frac{E_{c,i}}{\sum_i E_{c,i}} \sum_i E_p \quad (2)$$

Critically, we can observe that the main advantage of fixed coefficient allocation lies in its operational simplicity. However, it has the disadvantage of resulting in energy surpluses that are inevitably injected into the grid. On the other hand, using variable coefficients allows the DSO to manage energy more efficiently, as it considers the net consumption of each meter, promoting a more accurate allocation of the generated energy.

2.1.7.2 - Energy measures management

In Portugal, the Collective Self-consumption Managing Entity (EGAC) is responsible for managing the energy sharing and the physical and financial administration of the community. Its functions include:

- I. **Information management:** ensuring access to and control over consumption and production data associated with the community's Delivery Point Codes (CPEs).
- II. **Energy distribution management:** communication of energy sharing coefficients and management of the community's production and storage units.
- III. **Commercial relationships:** entering contracts with the energy supplier for the purchase of electricity for the community's internal consumption, contracts with the Distribution System Operator (DSO) for network access tariffs (TAR), and contracts with the aggregator or energy supplier for the sale of energy surpluses.

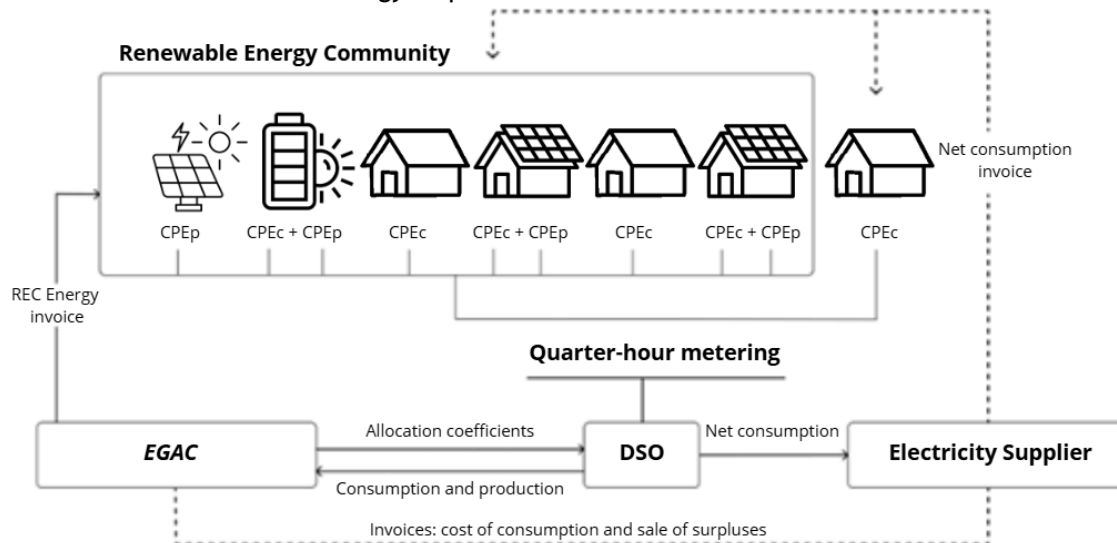


Figure 2.3 - Role of EGAC and Interaction with Stakeholders in a REC, adapted from [5].

Referring to Figure 2.3, the *EGAC* plays a central role in managing Renewable Energy Communities. It is responsible for managing the internal grid, interacting with the DSOs, energy suppliers, and other involved agents, and overseeing the energy production sharing among community participants. The *EGAC* also holds contracts related to energy surpluses and may establish agreements with the DSO to pay network access tariffs, should energy be shared through the *RESP*.

The DSO is responsible for collecting consumption and production data from the installations on a 15-minute basis and transmitting this information to relevant entities such as the *EGAC* and retailers. For REC participants, the DSO processes the allocation coefficients provided by the *EGAC*, separating portions of renewable energy and grid energy. This results in two independent invoices: one issued by the retailer and another by the *EGAC*. For non-REC participants, the DSO transmits consumption data directly to the retailer, generating a traditional invoice based on net consumption.

2.2 - Value Transaction

Value transactions within a Renewable Energy Community encompass various mechanisms for energy exchange, depending on the entities involved and the direction of energy flow. These transactions ensure efficient energy distribution, financial sustainability, and the integration of renewable resources within the community, which are:

Business-to-Consumer (B2C) and Grid-to-Consumer (G2C) Transactions: In Business-to-Consumer (B2C) transactions, an energy supplier, either a utility company or a renewable energy community, provides electricity to end consumers. This is the traditional energy supply model, where consumers pay for the energy they consume based on a predefined tariff. When applied within a REC, this model allows locally generated renewable energy to be distributed among members, often at lower rates than conventional utility prices. Similarly, in Grid-to-Consumer (G2C) transactions, the electrical grid acts as a supplier, delivering energy to consumers when local generation is insufficient.

Community-to-Consumer (M2C) Transactions: represent one of the most common energy exchange models in RECs, where an energy community or cooperative distributes locally generated power among its members. This model facilitates collective self-consumption, ensuring that energy produced within the community is fairly allocated based on demand and availability. A typical example is a rural energy community generating wind power and distributing it among participating households and businesses. Additionally, M2C fosters community engagement, as members actively participate in energy distribution and storage management decision-making processes.

Peer-to-peer (P2P) Transactions: enable *prosumers* to exchange energy directly without requiring mediation from a central utility or grid operator [60, 61]. These transactions

rely on digital platforms incorporating blockchain, smart contracts, and the Internet of Things (IoT) to enhance automation, security, and efficiency [62]. Blockchain ensures transparency and immutability, while smart contracts enable automated agreements between buyers and sellers. IoT devices such as smart meters also monitor real-time energy production and consumption, optimizing supply and demand matching. As reviewed in section 2.2.2.2, blockchain-based platforms play a critical role in securing transaction records and fostering trust within the community.

The decentralization, transparency, and autonomy provided by P2P transactions promote energy self-sufficiency, reduce dependency on external suppliers, and facilitate the development of localized energy markets. A survey conducted in Poland [59] with 753 prosumers found that more than half are willing to participate in P2P trading, motivated by the potential to reduce energy losses and overall costs. Moreover, the flexibility of this trading model allows for real-time price negotiation, maximizing economic returns for producers and consumers. [26]

Business-to-business (B2B) Transactions involve energy exchanges between companies operating in the energy market, such as agreements between large-scale producers, industrial consumers, retailers, and distributors. In a REC context, this model applies when local businesses within the community establish energy supply contracts with each other or with an aggregated energy producer from the REC. An example is a long-term power purchase agreement between a renewable energy cooperative and a large industrial consumer within the community.

Consumer-to-grid (C2G) Transactions: occur when an individual prosumer injects surplus energy into the grid, typically receiving financial compensation through feed-in tariffs or net metering schemes. A typical example is a household with rooftop solar panels exporting excess electricity to the national grid when local consumption is low. While this model ensures that renewable energy is utilized efficiently, it is less common in RECs, as communities prioritize internal energy distribution before exporting to the grid. However, C2G remains relevant when the community produces more energy than it can store or consume locally.

Consumer-to-Community (C2M) Transactions: occur when individual prosumers inject surplus energy into the community grid rather than exporting it to the external network. In this model, a household or business with excess solar generation can feed energy into a shared storage system or microgrid, making it available to other members before any external sale occurs. This model is widely used in RECs, as it prioritizes internal energy circulation, enhances self-consumption rates, and reduces transmission losses.

Community-to-Grid (M2G) and Community-to-Business (M2B) Transactions involve energy communities selling surplus electricity to the national grid or external companies. This model is particularly relevant when a REC consistently generates more energy than its members require, allowing the excess to be monetized. For instance, a community microgrid with an

aggregated group of solar PV installations might sell surplus energy to grid operators or industrial consumers outside the REC. These transactions can serve as a revenue stream for the community but must be carefully managed to balance economic benefits with self-sufficiency goals. Some RECs adopt dynamic pricing contracts to optimize profits while ensuring energy remains affordable for internal use.

Business-to-Grid (B2G) Transactions: involve commercial energy producers or retailers selling power to grid operators (DSO/TSO). Within a REC, this model applies when the community acts as an aggregator, managing multiple energy producers and negotiating external sales. A practical example is a solar farm owned by the REC selling electricity to the grid during peak demand periods. This model ensures that excess community-generated energy is efficiently utilized while providing financial returns to community members.

Table 2.1 presents a summary of all the previously discussed models.

Table 2.1 - Energy transaction types.

Transaction Type	Entities	Description	Example
Business-to-Consumer (B2C) and Grid-to-Consumer (G2C)	From: Energy supplier (utility or REC) To: Consumer	Traditional energy supply model where consumers pay for energy from a supplier or the grid. In RECs, locally generated energy is distributed among members, while the grid serves as a backup.	A household in a REC receives energy from the community, but draws from the grid at night.
Community-to-Consumer (M2C)	From: REC or cooperative To: Community member	Locally generated energy is fairly distributed among REC members, supporting collective self-consumption.	A rural energy community shares wind-generated power among houses.
Peer-to-Peer (P2P)	From: <i>Prosumer</i> To: <i>Prosumer</i>	Direct energy exchange between consumers/producers, facilitated by digital platforms, often using blockchain for secure transactions.	A homeowner with excess solar power sells it directly to a neighbour within the REC.
Business-to-Business (B2B)	From: Energy companies To: Energy companies	Energy supply agreements between businesses, including large producers, retailers, and distributors, within or outside an REC.	A renewable energy cooperative signs a long-term contract with an industrial consumer in the community.
Consumer-to-Grid (C2G)	From: <i>Prosumer</i> To: Grid operator (DSO/TSO)	Prosumer injects surplus energy into the grid, receiving compensation through tariffs or net metering. Less common in RECs, as local consumption is prioritized.	A household with rooftop solar sells excess electricity to the national grid.
Consumer-to-Community (C2M)	From: <i>Prosumer</i> To: Community grid	Excess energy is fed into the community's shared storage or microgrid before external sale, enhancing self-consumption and reducing losses.	A business with surplus solar generation contributes to the REC's battery system.
Community-to-Grid (M2G) and Community-to-Business (M2B)	From: REC To: Grid operator or external company	RECs sell surplus electricity to the grid or external businesses, creating a revenue stream while balancing internal needs.	A solar-powered REC sells excess energy to an industrial consumer outside the community.
Business-to-Grid (B2G)	From: Energy producer or retailer To: Grid operator (DSO/TSO)	Commercial energy producers sell electricity to the grid. In RECs, this applies when the community acts as an aggregator for multiple producers.	A solar farm owned by an REC sells energy to the grid during peak demand.

2.2.1 - Legal and Financial Representation of Value

Representing energy transactions within a Renewable Energy Community involves legal and financial considerations that influence how value is exchanged, recorded, and regulated. Establishing a clear framework for these transactions is essential to ensure transparency, compliance with existing legislation, and the financial sustainability of RECs. The legal and economic representation of value in a REC can be established through digital certificates or digital currency transactions, each serving a distinct function in energy-related exchanges. While both are digital mechanisms for attributing value, they differ fundamentally in their nature, purpose, and role in energy transactions.

Digital certificates, such as Guarantees of Origin (GOs), prove that a certain amount of electricity was generated from renewable sources. They do not directly facilitate energy trading but serve as verification tools that enhance traceability and accountability in renewable energy markets. In contrast, digital currency transactions involve the direct exchange of monetary value and can enable P2P energy trading. However, their implementation within RECs raises challenges related to financial regulation, volatility, and compliance with banking laws.

A more flexible alternative is utility tokens, which function as internal value units within an REC, allowing energy credits to be transacted without direct monetary exchange. Utility tokens, such as Energy Credits (ECs), provide a mechanism for exchanging energy and related services without being classified as financial assets. This distinction simplifies regulatory compliance while enabling efficient and decentralized value transactions.

This section analyses digital certificates, digital currencies, and utility tokens to compare these approaches, highlighting their advantages, regulatory implications, and suitability for RECs. A structured comparison will illustrate how each mechanism impacts transaction security, transparency, scalability, and regulatory compliance.

Implementing energy credits also requires considering regulatory frameworks, which define the legal conditions under which these transactions can occur. While some countries allow for more flexible REC transaction mechanisms, others impose stricter financial regulations, particularly when credits are convertible into fiat currency. Understanding these legal constraints is crucial for designing energy credit systems that comply with existing policies while fostering innovation in decentralized energy trading.

Another critical aspect is monetization and taxation, which directly affect the financial feasibility of energy credit systems. The classification of ECs, whether as a form of barter, an energy commodity, or a taxable asset, determines their legal treatment and the tax obligations associated with their exchange. Additionally, compliance with data protection regulations such as the General Data Protection Regulation (GDPR) is essential to safeguard transaction data and protect REC members' privacy.

This section explores these topics in-depth, offering a structured approach to understanding the legal and financial considerations associated with Energy Credits in RECs. By examining the different mechanisms for representing value, their regulatory challenges, and economic implications, this analysis will contribute to defining a robust and compliant framework for value transactions in energy communities.

2.2.1.1 - Digital certificates

A digital certificate symbolizes a specific product or service, as proof of origin, ownership, or entitlement. In the context of Renewable Energy Communities (RECs) and value transaction management, digital certificates are essential for ensuring traceability, transparency, and verifiability of energy attributes, providing an immutable record of transactions. This mechanism is particularly relevant in the renewable energy sector, where ensuring accountability and reliability in electricity sourcing is critical [17, 46].

One of the most well-known applications of digital certificates in the energy sector is using Guarantees of Origin (GOs), which certify that a given amount of electricity was generated from renewable sources [17, 42-44]. These certificates do not represent physical energy but rather an attribute of that energy. For example, when a consumer purchases electricity from the grid, there is no physical distinction between electrons derived from fossil fuels and renewable sources. However, through GOs, consumers can acquire certificates that guarantee that an equivalent amount of renewable electricity has been generated and injected into the grid, thus promoting a market model based on traceability and sustainability. [17]

Beyond GOs, green certificates have gained significant importance as instruments that enhance transparency in electricity markets and facilitate the purchase of green electricity products [46]. These certificates function as tradable assets, allowing organizations and individuals to demonstrate their commitment to sustainability while enabling renewable energy producers to sell their guarantees on voluntary markets [47, 48]. This dual function ensures that buyers can use them as evidence of the renewable nature of their consumed electricity, reinforcing the credibility and trustworthiness of renewable energy claims [45]. [17]

The role of green certificates has evolved over time, serving two primary purposes. Initially, they were regulatory support instruments designed to incentivize the adoption of renewable energy technologies, particularly in the electricity sector [49, 50]. More recently, they have been widely used for disclosure purposes, allowing renewable energy producers to provide verifiable proof of the origin of their electricity, thus increasing transparency within the energy market [51, 52]. This enables consumers and organizations to make informed energy choices that align with sustainability goals, further reinforcing the role of digital certificates as key enablers of green energy markets [46]. [17]

2.2.1.2 - Digital Currency

With the digitalization of energy markets and the adoption of technologies such as blockchain, digital certificates have evolved to enhance the security and efficiency of energy transactions. Blockchain provides immutability, traceability, and decentralization benefits, enabling the development of secure platforms for issuing, transferring, and verifying energy certificates. This reduces fraud risks and simplifies auditing processes [20].

Moreover, recent studies have highlighted that blockchain-based digital certificates improve trust and security in certification systems and provide organizational and strategic benefits, including cost reduction, enhanced decision-making, and increased transparency in renewable energy certification [21].

Digital currency transactions refer to the exchange of value through digital assets that are not necessarily tied to a specific product but serve as an autonomous medium of exchange. In the context of RECs, digital currency transactions can facilitate peer-to-peer (P2P) energy trading, allowing participants to buy, sell, or store energy credits in a decentralized manner. Unlike digital certificates, which represent the characteristics of a product (such as Guarantees of Origin for renewable electricity), digital currencies operate independently as a unit of account, store of value, or means of payment.

According to Falaiye et al. [18], digital currencies present challenges in standardization and financial reporting due to their volatility and lack of universal regulatory frameworks. This issue is particularly relevant for RECs that aim to introduce tokenized energy credits as a tradeable asset within their local economies. Central bank digital currencies (CBDCs) are also emerging as a potential solution for integrating digital payments into mainstream financial systems while ensuring regulatory oversight [19]. This aspect is critical for RECs, as the adoption of energy tokens must align with national monetary policies to avoid classification as unregulated financial instruments.

Thus, digital currency transactions in RECs must balance the flexibility of decentralized trading with compliance to existing financial regulations, ensuring that energy exchange remains transparent, secure, and legally recognized.

2.2.1.3 - Utility tokens

Utility tokens represent value within specific ecosystems, such as Renewable Energy Communities (RECs). Unlike digital currencies like Bitcoin, which function as global mediums of exchange, utility tokens are designed for internal transactions, ensuring that value circulates within the community without direct exchange for fiat currency. They are not a technology but a conceptual framework that enables the transaction of goods and services while avoiding classification as financial instruments. Their localized nature promotes economic resilience, fostering self-sufficiency and enhancing community engagement in energy exchanges.

Energy Credits (ECs) can be framed as utility tokens since they symbolize energy value within RECs. Their use is limited to internal exchanges, such as trading energy or compensating for goods and services, without external monetary conversion. This intrinsic localization reinforces their role as a flexible and efficient transactional unit, ensuring that energy value remains within the community, reducing dependency on external financial systems, and simplifying compliance with regulatory frameworks. Furthermore, by eliminating the need for direct monetary transactions, ECs minimize exposure to market volatility and facilitate peer-to-peer (P2P) trading, empowering consumers and prosumers to participate actively in decentralized energy management.

In countries with flexible regulations, like Portugal, utility tokens offer a robust model that avoids the need for financial or banking licenses, saving much time [27, 34-39]. This streamlined approach accelerates the implementation of community-based energy transactions, promoting local energy autonomy. Even in stricter jurisdictions such as France or Germany, this approach remains viable when the non-financial nature of these tokens is established, ensuring compliance while enabling efficient and localized energy exchanges. Given their ability to enhance liquidity, encourage sustainable investment, and promote self-sufficiency within RECs, utility tokens, exemplified by Energy Credits, present the most effective model for managing energy transactions in renewable communities.

2.2.1.4 - Comparison of Digital Certificates, Digital Currencies, and Utility Tokens

According to the information presented in the preceding two subchapters, Table 2.2 provides a summary.

Table 2.2 - Comparison of Digital Certificates, Digital Currencies, and Utility Tokens in RECs.

Feature	Digital Certificates (e.g., Guarantees of Origin)	Digital Currency	Utility Tokens (e.g., Energy Credits)
Role	Certifies that electricity consumed originates from renewable sources.	Enables monetary transactions for energy trading, including P2P, C2M, and M2C exchanges.	Facilitates energy value transactions within the community without requiring external financial systems.
Energy Transaction Model	Does not enable direct energy trading; only certifies renewable generation.	Enables direct energy trading with market-driven prices.	Enables internal energy exchanges through a closed-area credit system.
Regulatory Requirements in RECs	Well-defined regulatory frameworks exist in most jurisdictions.	Requires compliance with financial laws, potentially needing a banking license.	Requires careful classification to avoid financial regulation, but is generally easier to implement.

Impact on Local Energy Autonomy	Limited - relies on national or supranational certification entities.	High - enables independent trading but can be influenced by financial institutions and market volatility.	High - promotes self-sufficiency and keeps value circulating within the REC.
Economic Stability for RECs	Stable - not subject to financial market fluctuations.	Volatile - value of digital currencies can fluctuate significantly.	Stable - value remains fixed within the community, independent of external markets.
Implementation Complexity in RECs	Moderate - requires centralized certification processes and audits.	High - requires compliance with financial regulations and secure exchange platforms.	Low - can be implemented with local governance, avoiding financial regulation hurdles.
Transaction Costs for REC Members	Low - primarily administrative costs for certification.	High - may involve transaction fees, exchange rate fluctuations, and regulatory costs.	Low - internal transactions eliminate the need for financial intermediaries.
Scalability for Energy Trading	Limited - not designed for direct trading, only for energy origin certification.	High - can support global energy markets but with significant regulatory barriers.	High - scales well within communities while preserving local economic value.

The comparative analysis in Table 2.2 demonstrates that Utility Tokens are the most efficient solution for managing energy value transactions within RECs. While Digital Certificates ensure traceability and regulatory compliance, their role is limited to certification without enabling direct energy exchanges. Digital Currencies, on the other hand, offer flexibility and liquidity but face significant regulatory challenges and market volatility. Utility Tokens, such as Energy Credits, balance stability, local autonomy, and ease of implementation, enabling efficient internal transactions without reliance on external financial systems. This makes them ideal for fostering a sustainable and decentralized energy market.

2.2.1.5 - Regulation: Legal Requirements for the Implementation of Energy Credit Transactions

The regulation of energy credit transactions depends on how these credits are classified within each country's legal framework. One of the main challenges faced is the licensing requirement for conducting financial transactions, especially when these involve the conversion of credits into fiat currency. Any entity engaging in digital financial transactions within the European Union may require authorization from a financial regulatory authority, such as the Central Bank or other supervisory bodies overseeing the financial sector.

In some countries, such as Portugal and Greece, there is greater flexibility for systems based on energy credits, if they are used exclusively within the community and are not directly convertible into fiat currency. However, countries like Belgium, France, and the United Kingdom enforce stricter regulations, requiring specific licensing even for systems operating within closed networks.

Additionally, regulatory frameworks establish fiscal and accounting obligations for transactions, particularly when they involve the exchange of Energy Credits (ECs) for euros. The Energy Credit Management System (ECMS) ensures all transactions are recorded and audited, maintaining compliance with the applicable legal framework.

2.2.1.6 - Monetization and Taxation

The legal framework for Energy Credit (EC) transactions in Renewable Energy Communities (RECs) is inherently complex, influenced by the nature of ECs as symbolic units tied to energy value. Their classification, whether as financial instruments, securities, or symbolic value records, determines the regulatory obligations for entities managing these transactions, such as the Collective Self-consumption Managing Entity (*EGAC*). This classification impacts licensing requirements and dictates the extent of their use within or outside the REC.

Taxation is a critical aspect of the financial framework. Transactions involving ECs, whether exchanging them for euros, goods, or services, can be subject to tax obligations, including value-added tax (VAT) or income tax. For example, the exchange of ECs for euros to settle energy consumption costs or to attract investment for renewable energy projects constitutes a taxable event. Consequently, REC operators must establish robust systems to ensure compliance with local tax laws, including accurate accounting, reporting, and tax collection procedures.

Data protection is another cornerstone of the regulatory framework. Since EC transactions involve sensitive personal and transactional data, compliance with regulations such as the General Data Protection Regulation (GDPR) is mandatory. Operators must implement measures to safeguard participants' privacy, ensuring that data is securely stored and processed. This includes encrypting transaction records, enforcing access controls, and adhering to transparency requirements to foster trust within the community.

Consumer protection laws also play a pivotal role, particularly given the involvement of non-professional participants in RECs. Regulatory measures aim to ensure fair practices, prevent misleading information, and protect users from potential abuses. For instance, community members must be informed transparently about how ECs are managed, traded, and valued, particularly when monetary exchanges are involved.

The legal and financial framework surrounding EC transactions is designed to balance innovation in energy credit management with robust regulatory oversight.

2.2.2 - Supporting Technologies for Value Transactions

To enable efficient and secure value transactions within Renewable Energy Communities, various digital technologies have been developed to facilitate traceability, automation, and decentralization. While blockchain has emerged as a leading solution for

ensuring trustless, transparent, and tamper-proof transactions, it is not the only approach. Other technological infrastructures, such as centralized digital registries, Directed Acyclic Graphs (DAGs), and agent-centric models like Holochain, offer alternative methods with distinct advantages and limitations. The selection of an appropriate transaction framework must consider security, scalability, compliance, and operational efficiency, ensuring seamless integration with existing energy systems and regulatory frameworks. The following sections explore the fundamental blockchain architecture, compare alternative distributed ledger technologies (DLTs), and evaluate their suitability for managing value transactions within RECs.

2.2.2.1 - Centralized digital registries

Centralized digital registries are systems where a single authority manages and stores data, commonly used in government and institutional settings. While structured and controlled, they present vulnerabilities such as single points of failure, data security risks, and limited transparency, making them susceptible to cyberattacks, manipulation, and corruption [22].

From a regulatory perspective, centralized registries must comply with the General Data Protection Regulation (GDPR), which enforces strict data privacy, consent management, and the right to be forgotten. However, these registries often struggle with compliance due to insufficient transparency and access control mechanisms [22].

Additionally, the centralized nature of these systems increases the risk of data monopolization, where restricted access prevents independent verification of information, potentially undermining public trust. Whether caused by human factors or technical failures, errors in data entry or processing can lead to inaccurate records, delays in updates, and even data loss due to system malfunctions. Furthermore, the high vulnerability of centralized registries to cyberattacks makes them attractive targets for hackers, threatening data integrity and security. Given these challenges, modernizing state registries through more secure and transparent technologies like blockchain is increasingly considered a potential solution.

2.2.2.2 - Blockchain

Blockchain is a decentralized ledger technology that ensures digital transaction security, transparency, and efficiency. In the energy sector, it helps integrate RE, efficient energy trading, grid management, and much more [27-33]. By integrating smart contracts, which are automated executable programs stored on-chain, blockchain automates processes such as surplus energy trading, reducing operational costs and enhancing the reliability of energy transactions, as seen in Figure 2.4. Instead of relying on centralized entities, blockchain allows for direct, trustless exchanges between community members, promoting energy autonomy within RECs [15].

As illustrated in Figure 2.4, blockchain technology provides a comprehensive set of services that are particularly valuable for the energy sector and especially relevant within

RECs. One of the core functionalities is identity authentication, which ensures that only authorized users can access and participate in energy transactions. This is achieved through cryptographic protocols that verify the identity of each participant, thereby preventing fraud and unauthorized access. Traceability is another fundamental service, enabling full tracking of each unit of energy from its generation to its final consumption. This capability ensures transparency and validates the renewable origin of electricity in REC environments.

Contract management is facilitated using smart contracts, which automatically execute predefined agreements between community members. These programmable contracts eliminate the need for intermediaries, reduce administrative overhead, and ensure that transaction conditions are met reliably and consistently. In addition, deal-making is streamlined by blockchain platforms, allowing peer-to-peer negotiation of prices, volumes, and delivery conditions. This encourages the emergence of dynamic local energy markets and fosters more autonomous and decentralized energy trading models.

Trusted access ensures that only verified and authorized entities can interact with the system, providing integrity and auditability of all transactions and records. This is particularly relevant when dealing with sensitive data such as energy consumption, credit allocation, or community incentives. Finally, data sharing enables all authorized stakeholders, including grid operators, REC managers, and regulatory authorities, to access relevant information transparently and securely. Real-time access to data such as transaction volumes, energy balances, or anomaly alerts enhances operational efficiency and decision-making. Together, these services enable the effective sharing of information in the energy market, laying the foundation for secure, transparent, and decentralized value management within Renewable Energy Communities.

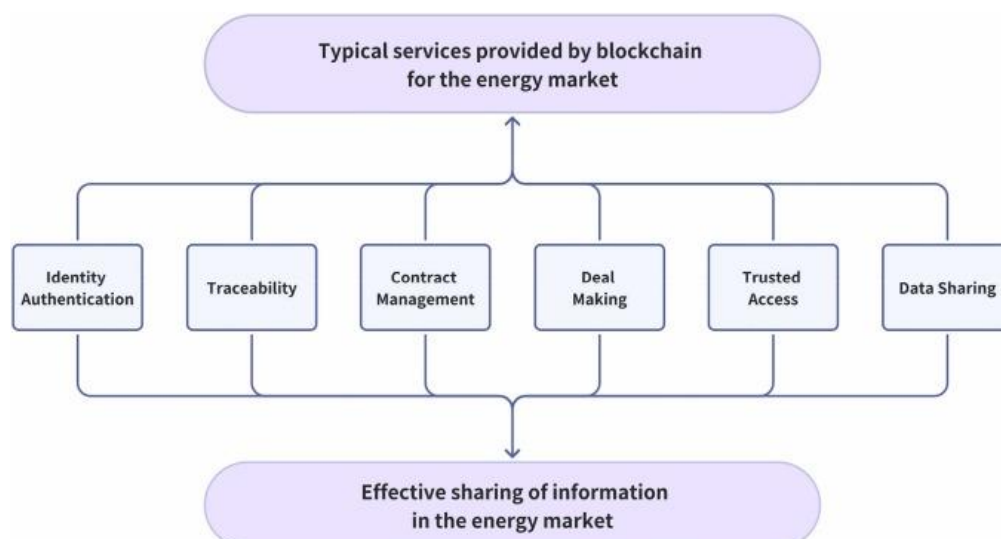


Figure 2.4 - Typical services provided by blockchain [16].

An increasing number of organizations, including government agencies, are leveraging blockchain technology for digital certificates [21, 53-56].

Therefore, blockchain should not be viewed as an isolated solution but as a complementary infrastructure to existing energy market mechanisms. Its full potential is realized when integrated with regulatory frameworks and energy management systems, ensuring compliance while maximizing efficiency in value transactions within RECs [15].

Blockchain addresses these issues by decentralizing data storage, ensuring immutability, auditability, and cryptographic security. Unlike centralized systems, blockchain maintains a distributed ledger, reducing the risk of data tampering while enabling automated access control through smart contracts. Nevertheless, challenges such as scalability limitations and high implementation costs must be considered. A hybrid model integrating blockchain with centralized registries could provide an optimal balance between security, transparency, and regulatory compliance. [22]

2.2.3 - Blockchain Models: UTXO vs. Account-Based Approaches

Additionally, blockchain platforms can differ in structure and process transactions, impacting their suitability for energy credit management within RECs. Two primary models exist: Unspent Transaction Output (UTXO)-based blockchains (e.g., Bitcoin, Litecoin) and account-based blockchains (e.g., Ethereum) [63].

In an **account-based blockchain**, as shown in Figure 2.5, transactions function similarly to bank accounts, where each account maintains a balance updated with each transaction [65]. This model is particularly effective for integrating smart contracts, as seen in Ethereum, where contracts autonomously manage asset balances and execute predefined rules for energy trading [66]. Account-based models enable more complex interactions, such as decentralized peer-to-peer (P2P) energy transactions and automated billing mechanisms [67], making them well-suited for REC applications that require high transaction flexibility. [64]

Furthermore, this model is inherently more adaptable to smart contract applications, making it the preferred choice for decentralized applications (DApps) and the core of Web 3.0 development [69].

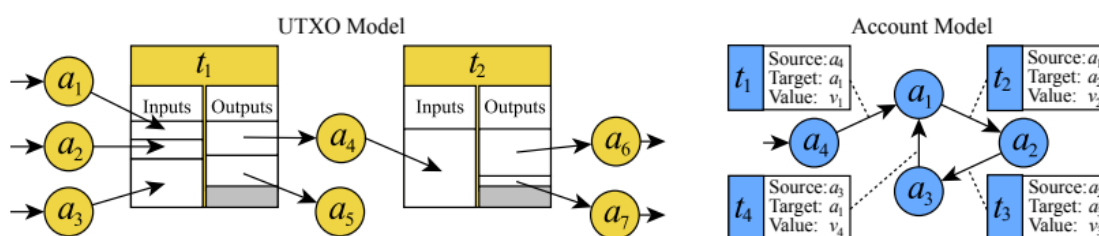


Figure 2.5 - In the UTXO model, transactions (i.e., t_1 , t_2) between addresses (a_i) can consist of multiple inputs and outputs. In the account model, every transaction has only one source and target address. [64]

On the other hand, **UTXO-based blockchains** operate differently by tracking unspent transaction outputs, requiring that each output is fully consumed in a subsequent transaction

[68]. This structure enhances transaction privacy by obscuring direct links between inputs and outputs, making it more difficult to trace individual energy transactions. However, the complexity of processing UTXO-based transactions may pose challenges for seamless integration with smart contract functionalities [64, 63]. Many existing privacy-preserving techniques are explicitly designed for UTXO-based blockchains, emphasizing their distinct security advantages [69].

Choosing between these two models is crucial for blockchain applications in energy credit management. While UTXO-based blockchains provide enhanced security and privacy, account-based models offer better adaptability for smart contract automation and real-time energy trading. The selection should align with the REC's objectives, balancing transparency, automation, and regulatory compliance to optimize the efficiency of energy credit transactions.

2.2.3.1 - Comparison between Centralized digital registries and Blockchain

Adapted from [1], Table 2.3 compares the advantages and disadvantages of blockchain technologies with traditional centralized systems for public registries.

In summary, for RECs, blockchain technologies provide greater transparency, security, and user control, ensuring trust in energy transactions and data integrity. However, the choice between UTXO-based and account-based blockchains significantly impacts their applicability.

UTXO-based blockchains enhance privacy and security through transaction chaining but introduce complexity in tracking and integrating smart contracts. In contrast, account-based blockchains simplify transaction management and enable seamless smart contract automation, making them more suitable for dynamic energy trading environments. Nevertheless, scalability and regulatory challenges remain barriers to widespread adoption.

On the other hand, centralized systems offer more straightforward implementation and faster transactions but pose risks of corruption, cyberattacks, and limited transparency, which can undermine trust among community members. Choosing the right approach is crucial to balancing security, efficiency, and regulatory compliance in RECs.

Table 2.3 - Comparison between centralized digital registries and blockchain.

Criterion	UTXO-based blockchains	Account-based blockchains	Centralized systems
Transparency of processes	High transparency due to transaction chaining; complex tracing due to multiple input/output transactions.	High transparency with a clear account balance model and easier transaction tracking.	Limited transparency: access to data is usually controlled by a central authority.
Corruption risks	Lower risk due to transaction immutability, but privacy-preserving techniques can obscure traceability.	Lower risk with full transaction visibility and identifiable account balances.	High risk of corruption due to centralized control and the possibility of hidden changes.
Data security	High security through cryptographic transaction validation; enhanced privacy but difficult reversibility.	High security with cryptographic protection and smart contract control, but account-based tracking may increase exposure.	Less reliable protection, there is a single point of failure. Vulnerability to cyberattacks.
User control	Users control transaction outputs but require multiple addresses to maintain privacy.	Users control account balances directly with straightforward management and smart contract integration.	Limited control: users cannot independently manage access to their data.
GDPR Compliance	More complex to adapt to GDPR due to transaction immutability and address reuse.	Easier GDPR compliance with account-based access control and permissioned smart contracts.	It is easier to implement GDPR compliance, including the right to be forgotten, but data control may be limited.
Speed of transactions	Slower due to handling multiple transaction outputs and higher computational requirements.	Faster as transactions update account balances directly without needing multiple outputs.	Faster transaction processing due to centralized control.
Scalability	Scalability issues due to the need to track every transaction output separately.	More scalable, as only account balances need updating, reducing blockchain bloat.	Easier to scale with a centralized architecture.
Cost of implementation	High due to more complex data structures and privacy-enhancing techniques.	Moderate due to smart contract development but lower computational costs per transaction.	Lower implementation costs, but support costs can be high during failures or attacks.
Legal and regulatory challenges	More difficult compliance due to privacy-enhancing features and transaction immutability.	Easier regulatory compliance due to clear tracking of account balances and identities.	Easier to comply with legal regulations, including GDPR, but transparency and access issues are possible.
Ensuring data integrity	High integrity, but privacy mechanisms can complicate audits.	High integrity with transparent account balances, simplifying regulatory oversight.	Integrity issues may occur due to human error, technical failures, or lack of transparency of changes.

2.3 - Pioneering Projects

The transition to decentralized and community-based energy systems has led to numerous pioneering projects exploring new energy exchange mechanisms, particularly in P2P contexts. These initiatives aim to enable more democratic, efficient, and localized energy trading, often leveraging digital platforms and distributed ledger technologies (DLTs) to facilitate secure and transparent transactions. The selected projects in this section reflect the diversity of technological and organizational approaches tested across different regions, focusing on tokenization, smart contracts, and blockchain-based platforms to manage renewable energy flows and economic value within communities. Reviewing these cases makes it possible to identify best practices, recurring challenges, and the technological maturity of current solutions for managing value transactions in RECs.

In recent years, several pilot projects have been commercially implemented worldwide. According to [27, 26, 41], here is a list of the main ones:

WePower is an energy trading company that pioneered the tokenization of energy data using blockchain technology. In a pilot project in Estonia, the company converted 24 TWh of real-world energy data into 39 billion Smart Energy Tokens, each representing one kWh of electricity. This initiative demonstrated the feasibility of secure, transparent, and decentralized energy trading at scale. [27, 40]

The project, developed in collaboration with Elering, Estonia's Transmission System Operator (TSO), leveraged the country's 100% smart meter coverage and Estfeed data-sharing platform to ensure secure and GDPR-compliant access to aggregated energy data. The platform lets consumers purchase green energy directly from producers, reducing reliance on intermediaries. [40]

In 2018, WePower raised \$40 million in the largest-ever energy sector ICO, funding further development of its blockchain-based platform. The project validated the use of Ethereum smart contracts for energy transactions and highlighted scalability challenges, leading to the adoption of hybrid solutions. [40]

By digitizing energy assets, WePower has set a precedent for blockchain-driven energy markets, enhancing grid efficiency, market transparency, and the integration of decentralized renewable energy sources.

SunContract, launched in Slovenia in 2018, is a blockchain-based P2P platform enabling the buying and selling of electricity. It promotes energy autonomy by allowing consumers and producers to set prices and trade directly through an energy pool. Transactions are facilitated using SunContract tokens, and smart contracts ensure transparency. [11]

Power Ledger, founded in 2016 in Australia, is a P2P energy trading platform using blockchain to enable residential and commercial units to share excess energy. It supports

battery sale, storage, and microgrids, like SkyHomes, which uses solar PV for renewable energy. The platform uses a dual token model for transparent and fair energy exchanges within communities. [13]

The Brooklyn Microgrid, launched in April 2017 in Brooklyn, New York, is a blockchain-based platform enabling solar panel residents to sell excess energy. Energy transactions are secured with smart meters and blockchain, allowing automatic trades via smart contracts. The platform connects to the commercial grid, using a double-auction system for energy allocation. [25]

The success of these platforms demonstrates the economic, environmental, and social benefits of decentralized energy markets, emphasizing the need for adaptable regulations, advanced technology, and active user involvement [26].

Although these pioneering projects offer valuable insights into the potential of decentralized energy systems and digital transaction mechanisms, none fully align with the model proposed in this dissertation. Most focus on direct monetary transactions or speculative tokenization models, often tied to external financial markets or cryptocurrencies. In contrast, the Energy Credit (EC) model presented here introduces a non-monetary, community-internal unit of account explicitly designed for Renewable Energy Communities. It emphasizes flexibility, inclusivity, and regulatory compatibility, enabling energy and service exchanges without the need for external intermediaries or financial licenses. By decoupling energy value from fiat currency and embedding social, technical, and governance mechanisms into the transaction system, the EC model advances a unique approach tailored to energy communities' practical and ethical needs.

Chapter 3

Design and Implementation of the Energy Credit Management System

This section defines the concept and purpose of Energy Credits (ECs) within Renewable Energy Communities. It explains how ECs function as a digital energy accounting unit, enabling flexible, transparent, and traceable transactions between community members. Additionally, it establishes the key stakeholders responsible for managing ECs, such as *prosumers*, consumers, the *EGAC*, and regulatory bodies, outlining their roles in governance, issuance, and compliance.

By structuring these elements, this section provides the fundamental principles necessary to understand ECs before addressing their practical applications, transaction mechanisms, and regulatory implications in the following sections.

3.1 - Conceptual Framework of Energy Credits in RECs

3.1.1 - Definition and Purpose of Energy Credits

Energy Credits are a decentralized energy accounting unit within Renewable Energy Communities, enabling flexible, transparent, and traceable energy transactions among participants. Unlike traditional kWh-based metering, ECs create an abstraction layer that separates the immediate physical flow of electricity from a symbolic, time-independent representation of its value. This allows *prosumers* to flexibly retain, trade, and allocate energy value within the community, decoupling energy transactions from real-time generation and consumption constraints and facilitating more efficient market interactions.

This mechanism aligns with the value transaction models introduced in section 2.2, where different energy trading structures, such as peer-to-peer (P2P), community-to-consumer (M2C), and consumer-to-community (C2M), require a well-defined accounting framework to ensure fair and efficient energy redistribution.

Each Energy Credit corresponds to 1 kWh, maintaining its energy value constant over time. However, its monetary value is dynamic, depending on market conditions and transaction timing. This value dynamics allows ECs to facilitate localized energy markets within RECs, enabling mechanisms such as P2P, M2C, and C2M trading, collective self-consumption balancing, and demand-side flexibility incentives, as previously discussed in Chapter 2. Additionally, ECs are defined as continuous and non-differentiable digital units, meaning that transactions can occur in fractional values, allowing for greater granularity in energy exchanges. This structure contrasts with the allocation methods currently used in RECs, which rely on predefined coefficients with a rigid quarter-hourly granularity, as mentioned in section 2.1.7.1.

The introduction of ECs offers an alternative model that transcends these limitations, enabling energy transactions that are neither strictly predefined nor entirely dependent on real-time grid conditions, as seen in Table 3.1. Instead, ECs allow community members to accumulate credits when surplus production occurs and redeem them when energy demand increases. They act as a flexible mechanism that integrates fixed and dynamic allocation benefits without their respective constraints.

Adopting Energy Credits in RECs addresses key challenges related to value transactions, grid balancing, and regulatory compliance. One of the main advantages of ECs is their ability to enhance flexibility in energy transactions by enabling decentralized and real-time energy trading between community members.

In summary, Energy Credits redefines value transactions in Renewable Energy Communities by introducing a digital energy accounting unit that enables greater transaction flexibility, scalability, and integration with emerging technologies. By addressing the inefficiencies of conventional allocation methods and enhancing market-driven energy redistribution, ECs support the long-term viability of RECs while aligning with the broader goals of the energy transition. The following sections will explore the specific mechanisms of EC issuance, transaction processes, and integration within the ECMS framework.

Table 3.1 - Energy Credits Influence.

Feature	Without Energy Credits	With Energy Credits
Energy Allocation	Energy is allocated strictly within predefined 15-minute intervals, based on physical measurements from electricity meters. Allocation is rigid and tied to real-time generation and consumption.	Energy can be allocated and transacted at different times from its physical measurement, allowing allocation to stakeholders who are not directly metered. The allocation does not require real-time generation, assuming that equivalent energy has been generated at some point.
Trading Mechanism	No direct trading; energy is assigned based on fixed or dynamic shares determined periodically.	Decentralized trading is enabled, allowing peer-to-peer (P2P), community-to-consumer (M2C), consumer-to-community (C2M) transactions, and REC-level energy markets.
Temporal Flexibility	Energy value cannot be stored beyond 15-minute intervals, leading to potential surpluses or shortages without compensation.	<i>Prosumers</i> can accumulate ECs when generating surplus energy and redeem them later, acting as a local value store for energy transactions.
Local Market	No local market interaction; energy allocation is purely administrative, based on metering.	Supports local markets, dynamic pricing, auctions, local spot prices, and bilateral P2P transactions.
Market Integration	Integration with external markets is limited to intermediary agents. Only Community-to-Business (C2B) or Community-to-Grid (C2G) models are allowed, where excess REC energy is sold.	EC pricing can be indexed to external electricity market prices, enabling a more diverse range of trading mechanisms. However, ECs cannot be transacted outside the REC.
Flexibility Mechanism	Flexibility markets operate through the EGAC, requiring conventional demand response mechanisms at the REC level.	Beyond traditional demand response, ECs enable flexibility incentives by allowing credits to be allocated as compensation for flexibility services within the REC.
Investment Incentive Mechanism	Investments in REC infrastructure require that equipment remains under investor ownership.	Investments can be converted into ECs, allowing investors to trade credits over the asset's lifetime, effectively transferring ownership to the REC.
Diversity of Traded Assets	Energy within the REC can only be bought or sold for monetary compensation via standard billing processes.	Energy in the form of ECs can be transacted for other energy-related services or exchanged for community-based contributions.
Social Benefits and Mechanisms	Transaction mechanisms for social benefits are limited to predefined rules set by the EGAC, with little flexibility for voluntary participation.	ECs allow donations or social transactions between REC members, offering freedom for members to set their own criteria for social energy distribution.
Adaptability to Internal REC Regulations	RECs define internal regulations with limited flexibility to manage value transactions beyond standard energy market rules.	While RECs have more flexibility in defining transaction rules, these must still comply with existing energy market regulations.
Transaction Transparency	Transactions are centrally managed by the EGAC or DSO, with limited participant visibility. The billing system is independent of energy management, making it difficult to audit externally.	Fully traceable via the ECMS, with each transaction recorded individually and accessible through digital ledgers. The accounting system is auditable by external entities.

Energy Credits introduce significant advantages in Renewable Energy Communities by enhancing flexibility, transparency, and efficiency in energy transactions. Unlike traditional allocation methods, ECs decouple energy generation from immediate consumption, allowing *prosumers* to store and trade energy value over time. This facilitates decentralized trading through peer-to-peer (P2P), community-to-consumer (M2C), consumer-to-community (C2M) and community-level markets, fostering greater participation and financial sustainability within RECs.

ECs also support market integration by enabling dynamic pricing and auction-based models while ensuring compatibility with existing regulations. Additionally, they promote investment by allowing asset ownership to be gradually transferred to the community and encourage social benefits through donation and redistribution mechanisms.

The enhanced transparency provided by the Energy Credit Management System (ECMS) ensures that all transactions are traceable and auditable, increasing trust and accountability within the community.

3.1.2 - Scope of Application in Renewable Energy Communities

Energy Credits (ECs) are designed to be a versatile and adaptable transaction mechanism applicable to all Renewable Energy Communities (RECs) types, regardless of their structure, size, or ownership model. The diversity of REC configurations, ranging from small residential cooperatives to large industrial and commercial communities, requires a flexible value transaction system that integrates different stakeholder roles, asset types, and business models. ECs provide this flexibility by enabling fair and efficient energy exchanges, promoting self-consumption optimization, and enhancing financial sustainability across various REC typologies.

RECs, including residential neighbourhoods, industrial parks, commercial zones, agricultural cooperatives, and mixed-use communities, can take different forms. In each of these cases, the management of energy transactions must accommodate a diverse set of participants, including individual consumers, *prosumers*, energy producers, investors, grid operators, and service providers. ECs facilitate seamless interactions between these stakeholders by providing a unified digital accounting unit that tracks energy contributions, consumption, and transactions within the community. This ensures equitable cost-sharing, incentivizes local energy generation, and fosters long-term member engagement.

From an infrastructure perspective, RECs can be based on various asset configurations, such as centralized production installations, distributed self-consumption systems, collective battery storage, and hybrid models. ECs offer a common transactional framework that allows energy produced in any of these configurations to be fairly allocated and traded among community members. This eliminates inefficiencies in surplus energy management, reducing

dependency on external suppliers while maximizing the financial returns of local renewable energy investments.

Ownership models within RECs can also vary significantly, ranging from individually owned assets to collectively managed energy infrastructure financed by investors or third-party entities. ECs provide a mechanism to facilitate gradual asset ownership transfer within a community, enabling investors to receive value through energy credits over time while ensuring the long-term sustainability of the REC. Additionally, ECs allow the monetization of non-energy services, such as maintenance, flexibility contributions, and community-driven initiatives, reinforcing their role as a comprehensive value management tool.

Regardless of the REC's scale, business model, or governance structure, ECs enhance operational efficiency by introducing a transparent and standardized transaction system. By allowing localized market interactions, supporting P2P energy trading, and integrating with demand-side flexibility mechanisms, ECs help RECs optimize energy flows and create resilient, self-sufficient energy ecosystems. Their integration within the ECMS further ensures regulatory compliance, transaction traceability, and adaptability to evolving market conditions.

In conclusion, ECs are not confined to a specific type of REC but instead serve as a universal transaction mechanism that aligns with the needs of different community models. Their ability to support decentralized energy exchanges, foster financial sustainability, and integrate various stakeholder interests makes them an ideal foundation for the future of energy communities, regardless of their structure, scale, or technological framework.

3.1.3 - Stakeholders and Governance Model

The successful implementation of an Energy Credit Management System (ECMS) within a Renewable Energy Community depends on a well-structured governance model and clearly defined roles for all stakeholders. The stakeholders involved in the ECMS mirror the broader organizational framework of RECs, ensuring that energy credit transactions align with the community's objectives, regulatory constraints, and technological capabilities.

The ECMS operates within the existing REC governance structure, meaning its stakeholders are the same actors responsible for decision-making, market interactions, and regulatory compliance within the community. The primary stakeholders include:

- **Prosumers and Consumers:** The core participants of the REC, where prosumers generate renewable energy and earn Energy Credits (ECs), while consumers rely on the ECMS to acquire credits for their electricity needs. Prosumers may decide whether to use their ECs for self-consumption, trade them within the REC, or store them for future use. Conversely, consumers acquire ECs through internal transactions, ensuring access to locally generated renewable energy.
- **Collective Self-consumption Managing Entity (EGAC):** This entity manages energy flows within the REC, ensures correct EC allocations, and enforces

regulatory compliance. The *EGAC* operates the *ECMS*, recording credit issuance, transfers, and redemptions based on real-time production and consumption data. It is key in preventing imbalances between EC transactions and actual energy availability.

- **REC Administrative Body:** The governing body defines the internal rules for EC transactions, including pricing models, trading conditions, expiration policies, and dispute resolution mechanisms. It ensures that EC trading remains aligned with the REC's energy-sharing goals, preventing speculative behaviours or market distortions.
- **Regulatory Authorities:** Since RECs operate under strict legal and policy frameworks, regulatory bodies oversee *ECMS* compliance with national and EU energy directives. They ensure that energy credits function as non-monetary value transactions within the REC and do not conflict with broader market regulations.
- **Software Providers:** Entities responsible for developing and maintaining the *ECMS* platform, integrating it with smart metering systems, digital wallets, and transaction registries. These providers ensure secure, automated, and transparent credit management, supporting blockchain-based verification or other digital ledger solutions where applicable.

The governance of the *ECMS* is embedded within the existing REC organizational structure, ensuring that all stakeholders operate under well-defined roles. *Prosumers* and consumers engage in energy credit transactions, while the *EGAC* oversees compliance, credit allocation, and market stability. The REC Administrative Body establishes rules for fair trading, while regulatory authorities ensure alignment with national and EU policies.

3.2 - Lifecycle and Functionalities of Energy Credits

3.2.1 - Issuance and Generation of Energy Credits

The issuance and generation of Energy Credits (ECs) within a Renewable Energy Community follow a structured process to ensure accurate accounting of energy transactions. ECs serve as a digital representation of energy value and enable the efficient management of energy flows among community members.

A fundamental principle of the EC system is the existence of a **zero-sum balance**. **For every positive credit issued to a contributing agent, an equivalent negative credit (debit) is recorded in the Community Wallet.** This ensures that the total volume of ECs in circulation always matches a corresponding deficit attributed to the REC. In this context, the issuance of credits occurs exclusively when the REC receives value from a community member without

providing any immediate monetary or energy compensation, except for the allocation of the ECs themselves.

Energy Credits can be generated through four distinct types of contributions by community agents:

1. **Renewable Electricity Injection:** This is the most common form of EC issuance. It occurs when a member injects surplus renewable energy into the REC's internal grid. This contribution may originate from an autonomous production unit (e.g., a shared PV plant) or the surplus production of a *prosumer*. The contributing member receives positive ECs in their personal wallet, while an equal number of negative ECs is registered in the Community Wallet.
2. **Asset Contribution:** ECs can also be issued when an agent contributes physical infrastructure to the REC. A typical case is when an investor installs a photovoltaic plant and transfers its ownership or operational benefit to the community. In return, the investor receives ECs in their wallet, reflecting the projected energy generation of the asset over a defined operational lifetime. This model supports asset-backed credit generation and long-term alignment between investment and community value.
3. **Financial Contributions:** An agent injects funds directly into the REC, purchasing ECs. The community receives the monetary contribution, and the agent's wallet is credited with a corresponding number of ECs. This approach enables capital inflow into the community while maintaining the zero-sum balance of the credit system.
4. **Service Provision:** Community members may also earn ECs by delivering non-energy services that support the functioning of the REC. These may include maintenance, operational support, data management, or facilities leasing. Upon validation by the REC's governance structure, such services are quantified and converted into an appropriate number of ECs credited to the contributor's wallet.

It is a core requirement of the EC system that the total volume of positive credits issued to contributing agents is always matched by an equivalent negative credit balance held by the REC. In operational terms, the Community Wallet will maintain a negative balance (aggregate ECs owed) while individual member wallets hold positive balances (credits owned). **The total debt of the community represents the circulating supply of Energy Credits**, which can later be used for internal energy transactions, service exchanges, or other community-defined purposes.

This balance principle can be formally expressed as:

$$\sum_{i=1}^n EC_i + EC_{REC} = 0 \quad (3)$$

Where:

- EC_i is the positive EC balance held by the i -th contributing member of the REC (with $i = 1, 2, \dots, N$),
- EC_{REC} is the EC balance recorded in the Community Wallet.

This equation ensures that the total amount of ECs issued to community members is always matched by a corresponding community-level liability, preserving a closed and auditable value system within the REC. Typically, the EC balance recorded in the Community Wallet, EC_{REC} , is negative, reflecting the total credits issued to members. However, in specific cases where the REC finances renewable energy systems or services on behalf of its members, the Community Wallet may temporarily hold a positive balance, representing a credit position resulting from these investments.

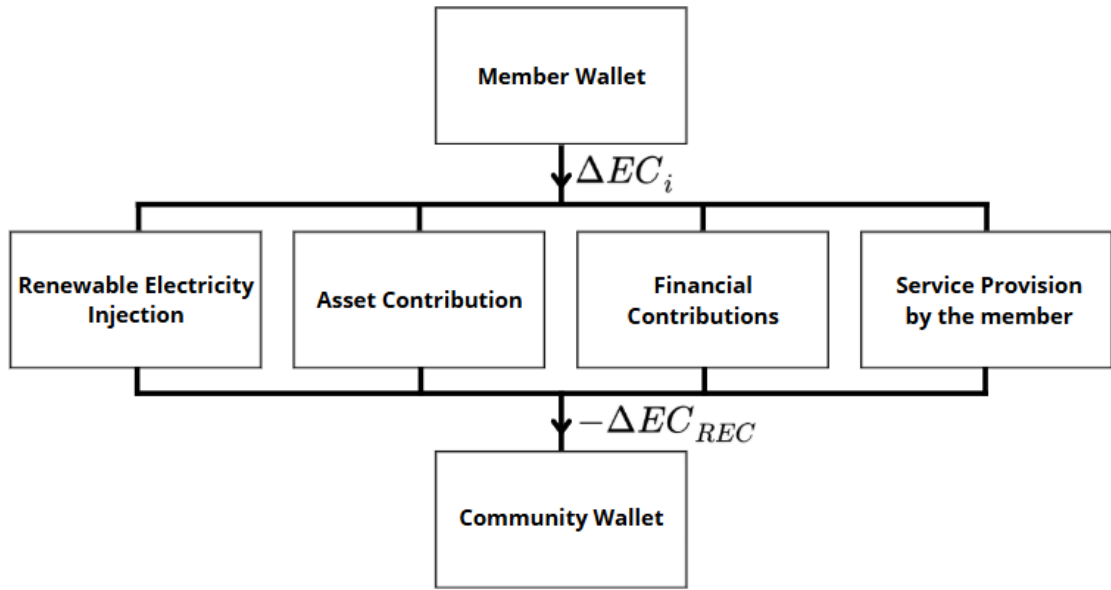


Figure 3.1 - Energy Credit issuance and allocation within a REC.

Thus, equation 4 depicts what happens in a single transaction between the consumer i and the REC:

$$-\Delta EC_{REC} + \Delta EC_i = 0 \quad (4)$$

Furthermore, we can also observe that the total debit equals the circulating supply of Energy Credits, as expressed in Equation 5.

$$EC_{CIR} = |EC_{REC}| = \left| \sum_{i=1}^n EC_i \right| \quad (5)$$

Regarding the generation of ECs, it follows strict principles to maintain transparency and avoid duplication of credit issuance:

- ECs have a constant energy unitary value of 1 kWh, ensuring that the recorded energy credit remains standardized across all transactions.

- The monetary value of an EC may fluctuate depending on the time of issuance and the prevailing market conditions at the time of settlement.
- ECs are continuous, meaning they can be transacted in fractional values (0.5 or 0.02 ECs, for instance), allowing precise accounting of energy transfers.
- ECs are non-differentiable, meaning they do not have a unique identifier for each unit, allowing for aggregation and summation into a single record.

Implementing a structured and regulated issuance process, the ECMS ensures that ECs accurately reflect energy production and financial contributions, promoting fair and transparent transactions within the Renewable Energy Community.

3.2.2 - Consumption of Energy Credits

The consumption of ECs refers to the process by which previously issued credits are eliminated from circulation through the receipt of value by a community member. In contrast to issuance, which occurs when a member gives value to the REC, consumption occurs when the REC provides value to one of its members without receiving any direct compensation, aside from subtracting credits from the member's wallet. As with issuance, this process adheres to the zero-sum balance principle, ensuring that an equivalent positive credit is recorded in the Community Wallet for every EC consumed (i.e., removed from a member's wallet).

Importantly, Energy Credits do not expire. Expiration would leave the underlying imbalance unresolved since it represents a quantified imbalance within the REC. ECs can, however, be cleared through settlement mechanisms, such as monetary compensation paid by the REC to the credit holder. This is not a separate process but rather one of the possible modalities through which ECs are consumed, and balance is restored.

As illustrated in Figure 3.2, ECs can be consumed through four primary mechanisms, each reflecting a form of value received by a community member:

1. **Electricity Consumption:** The most common mode of EC consumption occurs when a member uses electricity supplied by the REC. The electricity, a shared community asset, is "paid for" by subtracting ECs from the member's wallet. Simultaneously, an equivalent number of ECs is added to the Community Wallet, ensuring balance in the system.
2. **Equipment Use or Deployment:** In certain business models, the REC may install equipment (e.g., solar panels, batteries) for their private use on behalf of a member. This transfer of asset access is considered a form of value delivery by the community and results in a debit of ECs from the member's wallet and a credit to the Community Wallet. Over time, the member may generate new ECs from self-consumption, but the initial value received must be accounted for.
3. **Financial Settlement:** A member with a surplus of ECs may request to liquidate them through a financial settlement. In such cases, the REC pays a monetary value to the

member and, in return, cancels the corresponding ECs. This is treated as a consumption event from a credit accounting perspective: ECs are subtracted from the member's wallet and added to the Community Wallet.

4. **Service Provision by the REC:** The REC may offer its members technical support, maintenance, or operational management services. When a member benefits from such services, ECs are deducted from their wallet to compensate the community, and the equivalent is credited to the Community Wallet. This maintains an internal circulation of value without external transactions.

As a mirror to the issuance process, EC consumption reduces the negative balance of the Community Wallet, reflecting a reduction in the total circulating supply of Energy Credits. While rare, it is theoretically possible for the Community Wallet to reach a positive EC balance, indicating that the REC has received more value than it has provided. I.e., it holds unused "assets" in the form of pending obligations to its members.

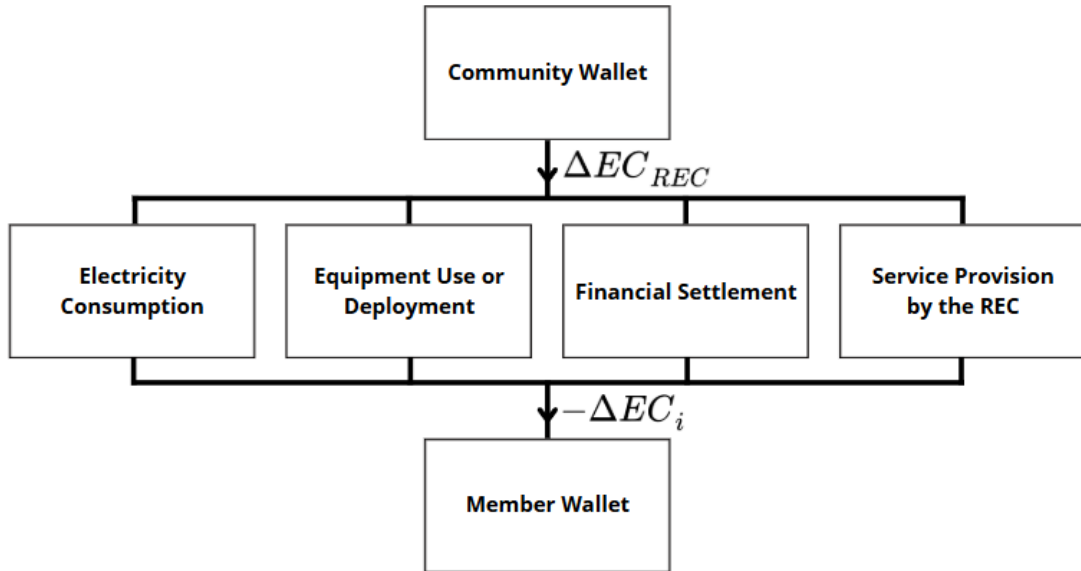


Figure 3.2 - Energy Credit consumption within a REC.

Thus, equation 5 depicts what happens in a single transaction between the consumer i and the REC:

$$-\Delta EC_i + \Delta EC_{REC} = 0 \quad (6)$$

Therefore, the Community Wallet's net EC balance is a key indicator of the REC's internal economic balance. Persistent deficits reflect outstanding obligations to contributors, while a surplus may indicate the underutilization of community resources. Monitoring this balance is essential for maintaining transparency and sustainability in the REC's energy accounting and can serve as a system's regulatory or operational health metric.

3.2.3 - Transaction of Energy Credits

The transaction and exchange of Energy Credits within a Renewable Energy Community enable flexible internal value transfers between members and between members and the community itself. These transactions are coordinated and recorded by the Energy Credit Management System (ECMS), which ensures consistency with the energy and governance structures of the REC.

Transactions are executed on a digital platform that transfers ECs between wallets. These can occur in several forms, as defined in Section 2.2:

1. **Peer-to-peer (P2P)**: between two individual members of the REC.
2. **Consumer-to-Community (C2M)**: from a member to the community.
3. **Community-to-Consumer (M2C)**: from the community to an individual member.

It is essential to clarify that an EC transaction is not the same as the issuance or consumption of credits, where ECs are created or eliminated as compensation for energy, financial investment, services, or equipment. Rather, an EC transaction transfers existing credits between two wallets. The total volume of ECs in circulation remains unchanged; only the ownership of those credits is updated.

Functionally, every EC transaction is a zero-balance transfer, as depicted in Figure 3.3:

1. A specified number of ECs is subtracted from the sender's wallet.
2. The exact number of ECs is added to the recipient's wallet.

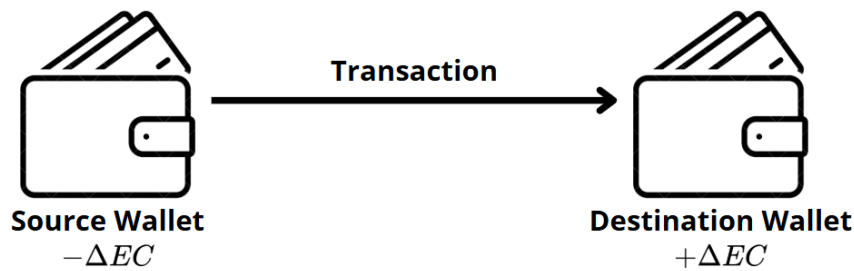


Figure 3.3 - EC transaction between two wallets.

While each transaction has a purpose, such as payment, exchange for goods or services, or a donation, that purpose is not encoded within the EC transaction itself. Instead, such context belongs to a higher-layer application, often called the Energy Credit Market Layer, where ECs are treated as tradable assets with an associated rationale for their exchange.

This separation of layers ensures the integrity of the ECMS as a neutral and ledger-based accounting tool while allowing flexibility for diverse economic, social, or operational interactions to emerge at the market level. The ECMS is, therefore, responsible for maintaining the technical and quantitative integrity of credit balances. In contrast, the interpretation and justification of those transactions occur externally in the ecosystem of applications and agreements built around the Energy Credit framework.

3.2.4 - Monetization: Conversion of ECs into Fiat Currency and External Value

The monetization of Energy Credits within a Renewable Energy Community enables members to convert their energy credit holdings into fiat currency or other external values. This process facilitates financial liquidity within the REC and incentivizes participation in renewable energy production.

The conversion of ECs into fiat currency can occur through different structured mechanisms, ensuring flexibility and adaptability to market conditions:

1. **Injection of Funds into the REC:** As defined in section 3.2.1 (Financial Contributions), members can inject funds directly into the REC in exchange for Energy Credits. This transaction is recorded within the ECMS as a credit issuance, where the agent's wallet is credited with a corresponding number of ECs, while the community receives the monetary contribution. This mechanism facilitates capital inflow into the REC while ensuring compliance with the system's zero-sum balance principle. The monetary value of the transaction is not stored directly in the ECMS transaction record. Still, it is instead specified in a digital contract, which also includes the corresponding EC transaction as proof of agreement.
2. **Sale of ECs to the EGAC:** As mentioned in section 3.2.2 (Financial Settlement), members can sell surplus ECs to the EGAC in exchange for a monetary amount. The transaction is recorded within the ECMS as a credit transfer between the member and the EGAC, with the financial settlement occurring through an external payment agreement. The monetary value of the transaction is not stored in the ECMS transaction record but is formalized in an invoice, which includes the corresponding EC transaction as a reference.
3. **Transfer of ECs Between Members (Peer-to-Peer Market Transactions):** Community members can engage in direct P2P transactions, transferring Energy Credits between their wallets within the ECMS. These transfers are recorded as simple credit movements without any implicit financial or contractual conditions. However, external to the ECMS, a parallel market mechanism or private agreement between the parties may define the monetary or service-based terms of the exchange, allowing members to negotiate value autonomously while maintaining the integrity of the EC system.
4. **Indirect Transactions via the REC (Community-Mediated Exchange):** This mechanism consists of two (previously mentioned) distinct but simultaneous processes: one agent acquires ECs from the REC by injecting funds (Financial Contributions). In contrast, another agent liquidates ECs by selling them to the REC in exchange for monetary compensation (Financial Settlement). By executing these two operations in parallel, the transaction effectively enables an indirect exchange of ECs between the agents, with the REC acting as an intermediary. Furthermore, it introduces a formal invoicing

process, as the REC mediates the transaction, allowing Agents A and B to avoid direct invoicing while ensuring regulatory compliance through two separate financial transactions with the community.

In summary, monetizing Energy Credits within a Renewable Energy Community provides multiple structured pathways for converting ECs into fiat currency or external value. These mechanisms, whether through direct financial contributions, settlements with the *EGAC*, P2P transactions, or community-mediated exchanges, ensure financial flexibility while maintaining the integrity of the EC system. By enabling both direct and indirect transactions, the REC fosters liquidity, facilitates regulatory compliance, and enhances participation in renewable energy initiatives, ultimately strengthening the sustainability and economic viability of the community.

3.2.5 - Operationalization of the ECMS

The operationalization of the Energy Credit Management System within a Renewable Energy Community ensures the accurate management of Energy Credits through structured processes that align with energy flows, financial transactions, equipment management, and service agreements. This section details the key operational mechanisms of the ECMS, covering energy injection and consumption, financial transactions, and using credits for equipment and services.

Firstly, the ECMS manages energy flows and updates members' credit balances based on renewable energy injection and consumption, as mentioned in section 3.2.1 (Renewable Electricity Injection) and 3.2.2 (Electricity Consumption). This process relies on data provided by the grid operator (E-Redes), ensuring accurate allocation and adjustment of EC balances:

1. **Energy Flow Measurement and Virtual Allocation:** The grid operator, E-Redes, measures and records renewable energy injections from members and community assets. These energy flows are then virtually allocated to the REC.
2. **Wallet Updates:** Based on the data received from E-Redes, the REC updates individual and community wallets within the ECMS, ensuring that each member's balance reflects their respective energy contributions and consumption.
3. **Periodic Credit Adjustments:** Whenever new data from E-Redes becomes available, the ECMS recalculates and adjusts EC balances accordingly, ensuring accuracy and transparency in the credit allocation process.

Regarding financial transactions within the ECMS, it follows structured mechanisms to facilitate the exchange of ECs for monetary value. These transactions require negotiation and agreement on pricing terms between the involved parties:

1. **Financial Settlement:** A member seeking to convert ECs into fiat currency must initiate a request. A negotiation phase follows, where the purchasing entity

and the seller agree on a price. Once an agreement is reached, the transaction is executed, and the ECs are deducted from the seller's wallet while a corresponding financial payment is made externally. To ensure legal and fiscal traceability, an invoice must be issued to certify the monetary exchange, serving as the formal document that validates the transaction.

2. **Financial Contributions:** Like financial settlements, financial contributions involve a member injecting funds into the REC in exchange for ECs. The transaction requires an agreement on the exchange rate, and upon confirmation, the member's wallet is credited with the corresponding ECs while the community receives the monetary contribution. Like the previous case, to ensure legal and fiscal traceability, an invoice must be issued to certify the monetary exchange, serving as the formal document that validates the transaction.
3. **Member-to-Member Financial Transactions:** It is also possible for one member to purchase ECs directly from another without EGAC intervention. In such cases, the ECMS records the credit transfer between wallets without registering monetary value. However, the transaction must be supported by a formal invoice between the members involved, as it involves a monetary exchange external to the ECMS.

The ECMS also facilitates the acquisition and deployment of equipment within the REC. Equipment-related transactions require contractual agreements and credit exchanges:

1. **Equipment Acquisition:** Members or the REC can exchange ECs for physical assets, such as renewable energy systems or storage units. The exchange value is determined through negotiation, and a formal contract defines the terms of the transaction, including the EC transfer process.
2. **Equipment Use or Deployment:** Instead of purchasing equipment outright, members can receive the installation of assets in exchange for ECs. A contractual agreement specifies the conditions under which the equipment is installed and when the corresponding EC transfer occurs. This mechanism allows members to access renewable energy infrastructure while compensating the REC through EC transactions.
3. **Member-to-Member Equipment Exchange:** A member may also provide equipment to another member in exchange for ECs. In these cases, the ECMS registers the credit transfer. Still, the transaction must be supported by a private contract outlining the equipment specifications, delivery terms, and credit value.

Services within the REC are managed through the ECMS and exchanged using Energy Credits (ECs), following structured agreements that ensure transparency, traceability, and fairness. These transactions are categorized as follows:

1. **Services Provided by Members to the REC:** Community members may offer services such as land leasing, equipment cleaning, or technical assistance to the REC. In return, they are compensated with ECs, credited to their individual wallets. These contributions are formalized through service contracts that specify the scope, value, and corresponding EC transfer rules, ensuring proper accounting and compliance.
2. **Services Provided by the REC to Members:** The REC may offer its members a range of services such as energy efficiency consultancy, maintenance of installed systems, or operational monitoring, like service bundles provided by commercial energy suppliers. ECs are deducted from the member's wallet according to predefined terms in exchange. These services are also governed by contractual agreements defining the service's nature, timing, and credit deduction schedule.
3. **Member-to-Member Service Provision:** One member can also provide a service directly to another (e.g., specialized maintenance or consultancy) in exchange for ECs. These EC transfers are registered in the ECMS, but the service itself must be formalized through a private contract, defining the nature of the service, execution terms, and compensation.

The operationalization of the ECMS ensures the seamless management of ECs across multiple transaction types, from energy allocation to financial settlements, equipment deployment, and service payments. By integrating structured processes, contractual agreements, and automated credit adjustments, the ECMS maintains transparency, accuracy, and efficiency within the REC. These mechanisms build upon the foundational principles discussed throughout Section 3.2, reinforcing a cohesive approach to credit and energy management. This structured approach facilitates the proper circulation of value, promotes fair exchanges, and enhances participation in renewable energy initiatives while maintaining the integrity of the EC system.

3.3 - Technical Implementation of ECMS

3.3.1 - Digital Infrastructure and Enabling Technologies

The digital infrastructure plays a fundamental role in ensuring the efficient, transparent, and secure management of Energy Credits (ECs). The Energy Credit Management System (ECMS), a tool embedded within the Collective Self-consumption Managing Entity (EGAC), is responsible for handling the generation, storage, and transfer of ECs. While the

community manages the ECMS, it is technically a cloud-based service where all essential data must be stored. To ensure full operational capability, the ECMS must provide functionalities for creating, consuming, and transferring ECs, along with advanced reporting and statistical tools that offer insights into the circulation of ECs within the system. Additionally, the platform should include supervision mechanisms, allowing external auditors or regulatory entities to access relevant data for system oversight, ensuring compliance, transparency, and accountability in managing energy credits.

The digital infrastructure supporting the ECMS consists of three main components:

1. **Energy Credit Management System (ECMS):** As the core of the infrastructure, the ECMS is responsible for processing all transactions, managing credit generation, and ensuring the system's integrity. Since it operates in the cloud, it centralizes and securely stores all measurement data from E-Redes, individual and community transactions, and wallet balances. Additionally, it serves as the verification mechanism for transactions, ensuring that EC transfers between wallets are correctly executed and recorded. Even during a temporary system failure, wallets retain transaction records, preserving the system's integrity.
2. **Member Wallet:** Each REC member has an individual digital wallet that acts as a secure repository for ECs. This wallet records and stores all transactions linked to the credits, allowing members to verify their balance and transaction history at any time. It also enables sending and receiving ECs, validating transactions, and securely storing transaction records, including public keys of both parties and private authentication codes.
3. **Community Wallet:** Managed by the EGAC, the community wallet functions similarly to member wallets but is controlled by designated community managers. This wallet is crucial in aggregating and redistributing ECs within the REC, ensuring that collective transactions, such as payments for shared infrastructure or services, are adequately managed. Like member wallets, it maintains a transaction history and provides real-time balance updates, ensuring transparency and accountability.

Combining these three components ensures a robust and decentralized digital infrastructure that facilitates secure and efficient EC transactions within the REC. The cloud-based ECMS provides centralized data management and verification, while member and community wallets guarantee transaction integrity even in cases of temporary system downtime. By integrating these elements, the digital infrastructure supports a transparent, traceable, and scalable Energy Credit System, reinforcing trust and efficiency within the energy community.

Chapter 4

Case Study

This chapter presents a detailed simulation of Energy Credit operations within a four-building Renewable Energy Community. Integrating real smart-meter data into the ECMS framework allows it to explore how credits are issued, shared, and settled among individual wallets (ED1-ED4), the *EGAC*, and an external investor.

Starting with a clear definition of roles and datasets in Section 4.1, step through production, consumption, surplus allocation, and credit monetization, illustrating how the ECMS underpins flexible, transparent energy-value exchanges.

4.1 - Case Study Characterization

This case study presents an internal energy credit system simulation within a Renewable Energy Community (REC) consisting of four residential buildings: ED1, ED2, ED3, and ED4. Therefore, it is a condominium system, according to Section 2.1.4.

Each building includes a consumer who participates in the community and holds an individual digital wallet managed through the Energy Credit Management System (ECMS), as shown in Figure 4.1.

In addition to the consumers, the system also includes the Collective Self-consumption Managing Entity (*EGAC*), which governs the REC and maintains its wallet, and an external investor, who owns production assets and participates in the energy credit economy. The data used in this case study is based on real energy measurements from an existing Renewable Energy Community, whose location must remain anonymous.

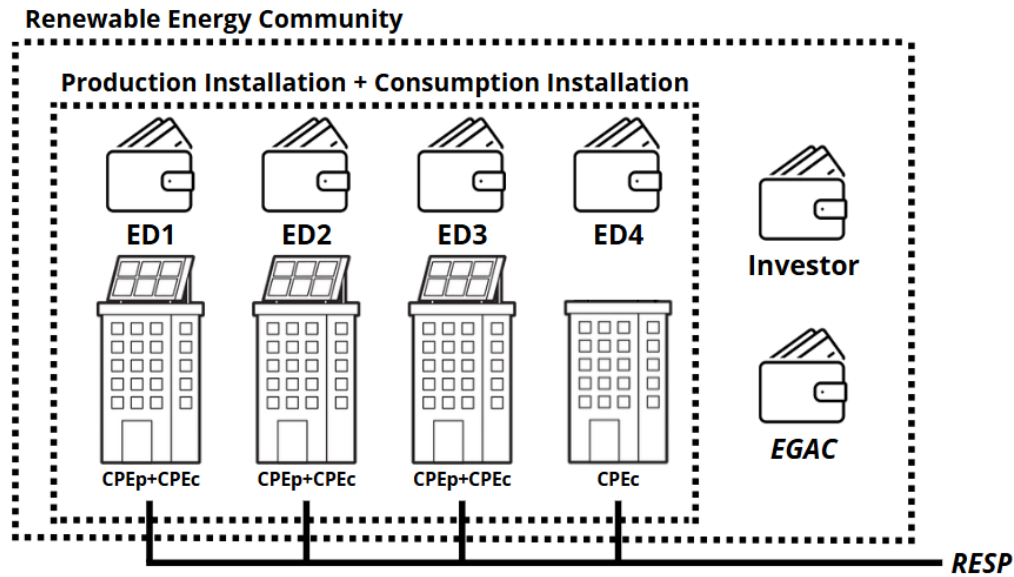


Figure 4.1 - Internal Architecture of the REC: Buildings, Wallets, and Entities.

This case study aims to analyse the flow of energy credits (ECs) and corresponding monetary settlements over a defined period, applying the rules and mechanisms described in Chapter 3. Each EC represents 1 kWh of renewable energy, and transactions are carried out according to generation, consumption, transfer events, financial contributions, and settlements.

Additionally, the system supports one-time and recurring transactions such as energy donations and service provision. Such interactions must be accurately reflected within the ECMS, impacting credit balances and corresponding financial records.

Credit pricing within the REC is fully dynamic and entirely negotiable between participants. ECs may be traded at any agreed value, including zero, so long as both buyer and seller consent.

The ECMS ensures that each transaction is registered in a traceable and auditable way. All credit transfers from generation, consumption, sale, donation, or service exchange are recorded between the relevant wallets. Importantly, although monetary values are settled externally, the system must keep track of all credit-related activity to ensure compliance with the zero-sum balance principle described in section 3.2.1.

This chapter will serve as the foundation for evaluating the monthly evolution of credit balances and monetary flows in the REC, enabling a comprehensive assessment of the ECMS functionality in a semi-realistic community scenario.

Table 4.1 - Case Study Overview: Roles, Assets, and Transactions

Component	Description
REC Members	Four residential buildings: ED1, ED2, ED3, ED4. Each has one consumer with a digital wallet.

Management Entity	EGAC: Governs the REC, operates through its wallet, and manages internal transactions.
External Investor	In scenarios 4 and 5 of chapter 5, owns the PV installations on ED1, ED2, and ED3. Holds a dedicated wallet.
ED1, ED2 and ED3	Prosumers: own and operate their own PV systems. They self-consume locally and inject any surplus into the REC.
ED4	Pure consumer with no PV. Purchases ECs from the EGAC or the investor; may also engage in P2P trades at negotiated prices.
Energy Credit (EC)	Each EC = 1 kWh. Used to account for generation, consumption, and transfers.
Credit Pricing	Fully dynamic and negotiable per transaction.
Financial Settlements and Contributions	Monetary flows are external to ECMS and settled via contracts or invoices.
ECMS Function	Records all EC operations to ensure traceability and compliance with the zero-sum principle.

This structural overview provides the foundational framework to understand the roles, ownerships, and interactions within the REC under study. By defining each agent's function, energy flows, and associated credit transactions, the case study is set for a detailed analysis of monthly credit movements and monetary settlements in the following sections.

4.2 - Case Study Data

The dataset used in this study spans a year, covering one entire year, with data recorded at 15-minute intervals. For each building $ED \in \{ED1, ED2, ED3, ED4\}$, the dataset includes two key parameters: the electric energy generated (kWh) by the on-site Production Unit for Self-Consumption (*UPAC*), and the electric energy consumed (kWh) within the building.

Three of the four buildings in the case study are equipped with a *UPAC* composed of monocrystalline photovoltaic modules, as detailed in Table 4.2.

Table 4.2 - Technical Overview of PV Installations in the REC

Building	Pmax STC (W)	Number of installed modules	Installed peak power (kWp)	Orientation
ED1	300	33	9.9	South
ED2	320	78	25.0	South
ED3	300	60	18.0	Southeast
ED4	-	-	-	-
TOTAL		171	52.9	

Finally, Table 4.3 provides an overview of the electricity tariff plans assigned to each building within the Renewable Energy Community. All buildings operate under a Tetra-Hourly tariff structure with a contracted power capacity of 41.41 kW, though their billing cycles differ between daily and weekly regimes.

The tariff plan applied to all buildings falls under the *BTE* category (*Baixa Tensão Especial*, or Special Low Voltage), which is typically designated for consumers with contracted power exceeding 41.4 kW.

This characterisation is essential for estimating the energy costs and evaluating the economic performance of the REC.

Table 4.3 - Tariff Plan Characterisation of Each Building.

Building	Cycle	Time Period	Plan	Contracted Power (kW)
Building 1	Daily	Four-Time Period	<i>BTE</i>	41.41
Building 2	Daily	Four-Time Period	<i>BTE</i>	41.41
Building 3	Weekly	Four-Time Period	<i>BTE</i>	41.41
Building 4	Weekly	Four-Time Period	<i>BTE</i>	41.41

This dataset provides a comprehensive foundation for analysing the internal energy flows and credit transactions within the REC, ensuring realistic conditions for testing the proposed value exchange model.

4.3 - Energy Surplus Virtual Allocation

The proportional distribution method based on consumption is adopted to allocate surplus energy within the REC, referring to the energy generated but not immediately consumed during each 15-minute interval. This mechanism, which follows equation 7, ensures that any excess production is fairly and efficiently shared among the community members according to their relative consumption levels during the same period, thereby maximising the utility of available renewable resources.

$$E_{repED.i} = \frac{CL_{ED.i}}{\sum_{i=1}^4 CL_{ED.i}} \times \sum_{i=1}^4 E_{excED.i} \quad (7)$$

Where:

- $E_{repED.i}$ - Energy allocated to building i .
- $CL_{ED.i}$ - Net consumption of building i .
- $E_{excED.i}$ - Surplus energy from building i .

A proportional allocation method based on net consumption was chosen for this case study due to its practical relevance and alignment with real-world implementations. This

approach is widely used and offers significant advantages in fairness and efficiency. By distributing surplus energy according to each member's consumption during the same 15-minute interval, the method ensures that the excess energy is directed to where it is needed most. Unlike fixed allocation coefficients, which may assign energy to buildings that are not consuming at a given moment, this dynamic method targets active demand, thereby maximising the value of renewable production and avoiding inefficient credit allocations. Consequently, it is considered the most appropriate and equitable strategy for internal surplus distribution within a REC.

4.4 - Characterisation of Energy Flows in the Renewable Energy Community

4.4.1 - Photovoltaic Energy Production

In this section, an analysis of the photovoltaic (PV) energy production from the *UPACs* included in the case study, specifically those installed in buildings ED1, ED2, and ED3, is carried out. This assessment provides a clearer picture of each building's contribution to the total renewable energy supply within the REC throughout the year, thus supporting further energy balance and redistribution analysis.

Table 4.4 shows the annual PV generation from each building. Building ED2 is the largest producer, with a yearly output of 39.568 MWh. In contrast, Building ED1 recorded the lowest production at 13.879 MWh. Building ED4 did not generate any energy during the analysed year due to the absence of a PV system. As a result, only three buildings contribute to the total community generation of 79.613 MWh.

Table 4.4 - Annual Energy PV Generation in each building

Building	Energy Produced by PV System (MWh)
ED1	13.879
ED2	39.568
ED3	26.166
ED4	0
Total	79.613

The monthly distribution of energy production from the *UPACs* installed in buildings ED1, ED2, and ED3, as shown in Figure 4.2, clearly reflects the seasonal variation in solar resource availability. During the summer months, particularly from May to August, these buildings show a noticeable increase in energy production. This is primarily due to higher average daily solar irradiance during this period, which results from longer daylight hours, a higher sun angle, and generally clearer skies. Conversely, in the winter, production significantly

decreases due to shorter days, a lower sun angle, more frequent cloud cover, and adverse weather conditions, which reduce the effective solar radiation reaching the photovoltaic panels.

This seasonal trend is typical of solar PV systems and highlights the strong dependence of production on climatic and astronomical factors. Once again, the chart reinforces the superior performance of the UPAC in ED2, which consistently shows the highest monthly values, likely due to a combination of greater installed capacity and better orientation.

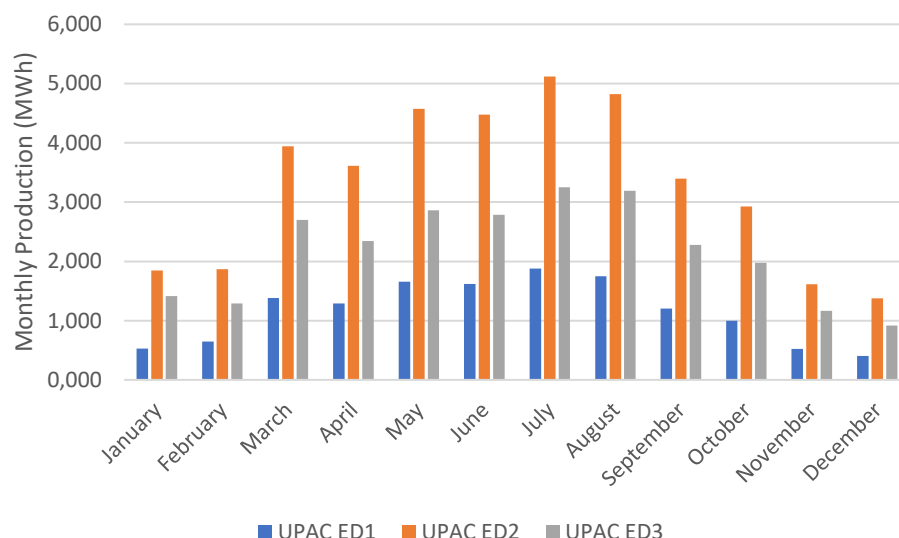


Figure 4.2 - Monthly distribution of PV energy production from the UPACs installed in each building.

The analysis of the hourly production profile of the *UPACs* across buildings ED1, ED2, and ED3 reveals a typical photovoltaic behaviour, with generation commencing at sunrise, gradually increasing to a peak around midday or early afternoon and then declining towards sunset.

According to Figure 4.3, the *UPACs* of buildings ED1 and ED2 peak in production at approximately 1:00 p.m., consistent with a south-facing orientation that optimises solar capture throughout the day. In contrast, the *UPAC* of ED3 reaches its peak around noon, likely due to an easterly orientation that enhances energy generation in the earlier hours but limits it during the afternoon.

Moreover, it is worth highlighting that the curve for ED2 displays the highest peak value and a broader base, suggesting superior performance sustained over a more extended portion of the day. This may be attributed to larger installed capacity and orientation, as shown in Table 4.2.

Case Study

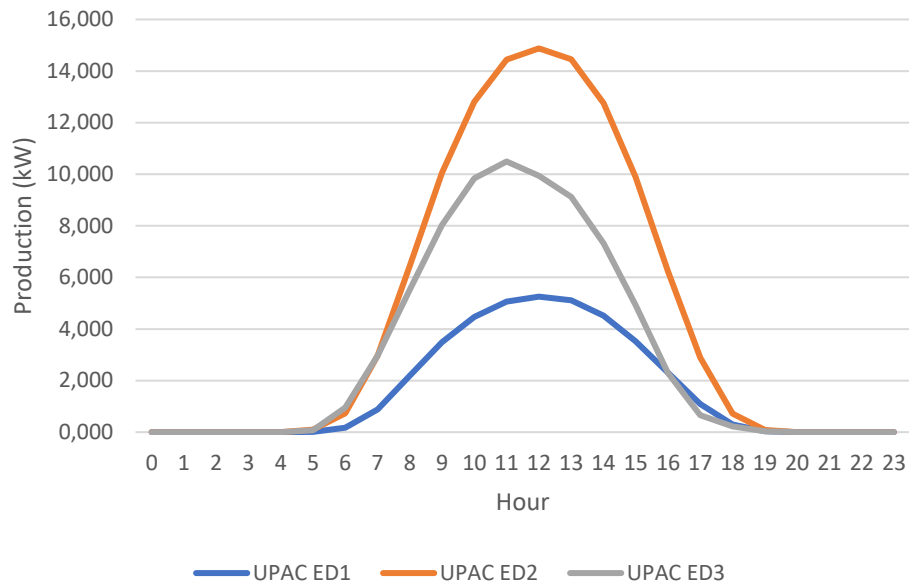


Figure 4.3 - Hourly production profile of the UPACs across the four buildings.

Posteriorly, the annual production of the *UPACs* was broken down by time-of-use daily periods: super off-peak, off-peak, mid-peak, and peak, as depicted in Tables 4.5 and 4.6, as it depends on whether it is summer or winter.

Table 4.5 - Summer daily time-of-use periods.

Period	Working days' Time Range	Saturday's Time Range	Sunday's Time Range
Super Off-Peak	02:15 - 06:00	02:15 - 06:00	02:15 - 06:00
Off-Peak	23:00 - 02:00, 06:15 - 08:00, 22:00 - 23:00	23:00 - 02:00, 06:15 - 08:00, 22:15 - 23:00	23:00 - 02:00, 06:15 - 08:00, 22:15 - 23:00
Mid-Peak	08:15 - 10:30, 13:15 - 19:30, 21:15 - 22:00	08:15 - 10:30, 13:15 - 19:30, 21:15 - 22:00	08:15 - 10:30, 13:15 - 19:30, 21:15 - 22:00
Peak	10:45 - 13:00, 19:45 - 21:00	10:45 - 13:00, 19:45 - 21:00	10:45 - 13:00, 19:45 - 21:00

Table 4.6 - Winter daily time-of-use periods.

Period	Working days' Time Range	Saturday's Time Range	Sunday's Time Range
Super Off-Peak	02:15 - 06:00	02:15 - 06:00	02:15 - 06:00
Off-Peak	00:00 - 2:00, 06:15 - 08:00, 22:15 - 00:00	00:00 - 2:00, 06:15 - 08:00, 22:15 - 00:00	00:00 - 2:00, 06:15 - 08:00, 22:15 - 00:00
Mid-Peak	08:15 - 9:00, 10:45 - 18:00, 20:45 - 22:00	08:15 - 9:00, 10:45 - 18:00, 20:45 - 22:00	08:15 - 9:00, 10:45 - 18:00, 20:45 - 22:00
Peak	9:15 - 10:30, 18:15 - 20:30	9:15 - 10:30, 18:15 - 20:30	9:15 - 10:30, 18:15 - 20:30

As shown in Figure 4.4, production during the super off-peak and off-peak periods is almost negligible across all buildings. This is expected since these periods occur primarily at night, with no solar irradiance. In contrast, most photovoltaic production is concentrated in the mid-peak and peak periods, from morning to early evening. Notably, the mid-peak period accounts for the highest share of annual generation, as it encompasses most of the sunlit hours, especially in the afternoon.

Building ED2 shows the highest production in mid-peak and peak periods, reinforcing its superior performance.

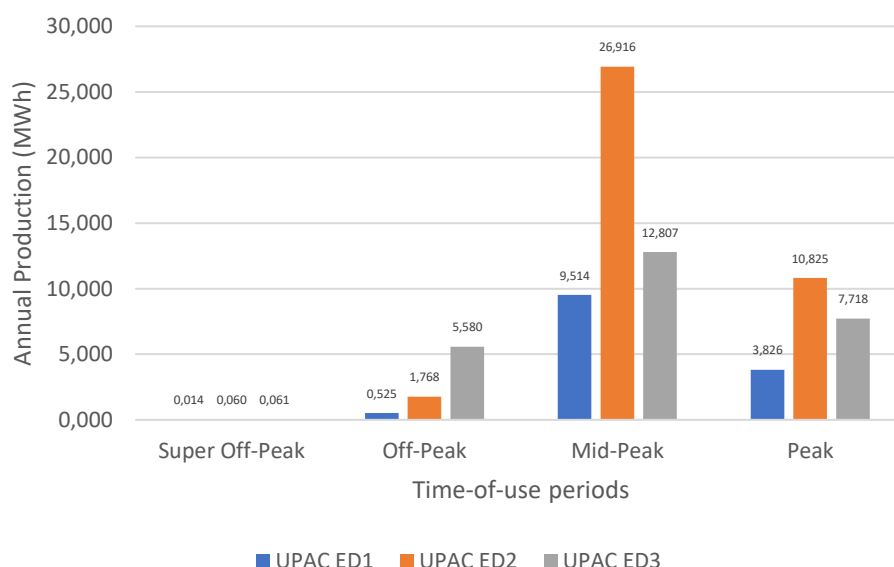


Figure 4.4 - Annual production of the UPACs by time-of-use periods.

To conclude this production characterisation, the analysis of the three active buildings' annual, monthly, and hourly photovoltaic (PV) production reveals significant trends for energy management within the REC. Production is significantly higher during summer due to increased solar irradiation, while winter yields are comparatively lower. Hourly profiles demonstrate that all production peaks occur during midday, with a slight shift between the UPACs, explained by the different orientations of the PV panels, especially the earlier peak in building ED3 due to an east-facing orientation.

Additionally, the breakdown by time-of-use periods shows that virtually all production occurs outside the super off-peak and night-time off-peak periods, highlighting the natural alignment of PV generation with daylight hours. Understanding this temporal distribution of production is crucial for aligning generation with consumption patterns and optimising the renewable energy community's self-consumption or energy sharing strategies.

4.4.2 - Energy Consumption

In this section, an analysis of the annual energy consumption in each building included in the case study is carried out. The objective is to understand the energy demand profile of

the REC, enabling a clearer perspective on the distribution of consumption across the different buildings, namely ED1 to ED4.

Table 4.5 summarizes the annual energy consumption in each building. As observed, Building ED1 shows the highest energy demand, reaching 75.747 MWh over the reference year. Conversely, Building ED2 recorded the lowest consumption, totalling 38.989 MWh.

The total energy consumption across all four buildings amounts to 232.129 MWh, constituting the total energy demand in this REC scenario.

Table 4.7 - Annual Energy PV Consumption in each building.

Building	Annual Energy Consumption (MWh)
ED1	75,747
ED2	38,989
ED3	57,993
ED4	59,401
Total	232,129

When comparing these values with the annual PV generation presented in Section 4.3.1, a noteworthy observation emerges: Building ED2 exhibits the highest generation (39.568 MWh) and the lowest consumption (38.989 MWh). This suggests that ED2 will likely maintain a net surplus over the year, reinforcing its potential role as a consistent energy provider within the community.

Further insights are revealed by examining the monthly distribution of consumption across the buildings, depicted in Figure 4.5. The figure shows that consumption tends to be higher during the winter months and lower during the summer months. This behaviour can be explained by the increased use of heating systems during colder periods, which significantly raises electricity demand, particularly in residential and service buildings like this REC.

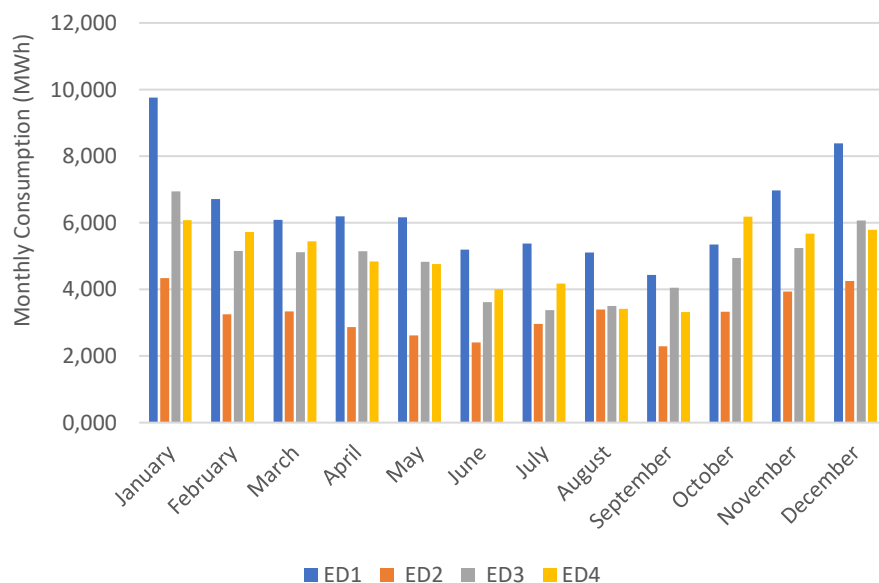


Figure 4.5 - Monthly distribution of energy consumption in each building.

The analysis of the hourly consumption profile, shown in Figure 4.6, indicates that energy demand is more concentrated between approximately 6:30 a.m. and 7:00 p.m. This pattern aligns with typical occupancy hours for residential buildings and service operations. Building ED1 consistently exhibits the highest consumption during these periods, reflecting its larger operational and energy needs than other buildings.

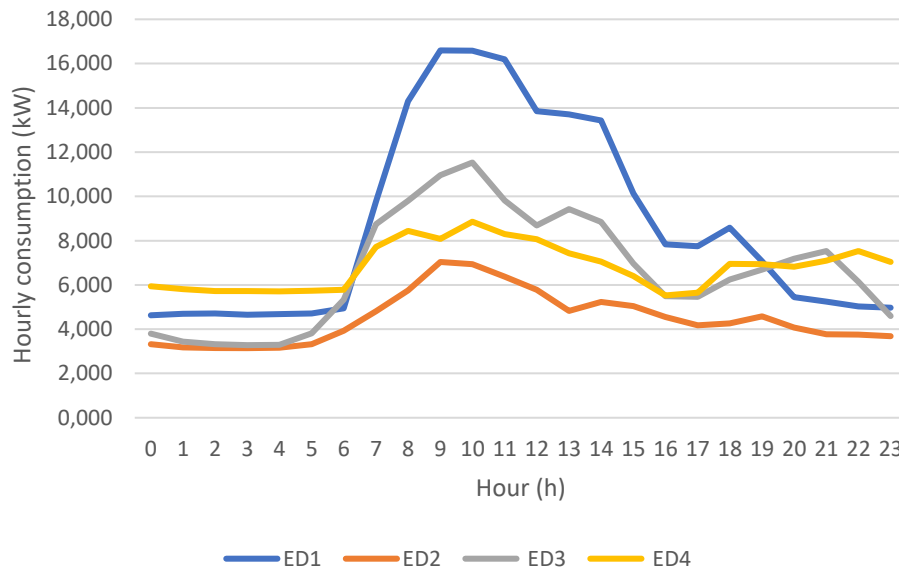


Figure 4.6 - Hourly consumption profile of the four buildings.

Additionally, the annual consumption by time-of-use periods, super off-peak, off-peak, mid-peak, and peak, is presented in Figure 4.7. It is observed that most of the energy consumption across all buildings occurs during the mid-peak period, which corresponds to daytime working hours. Again, ED1 stands out as the largest consumer across all time-of-use periods, reinforcing its dominant role in the energy dynamics of the REC.

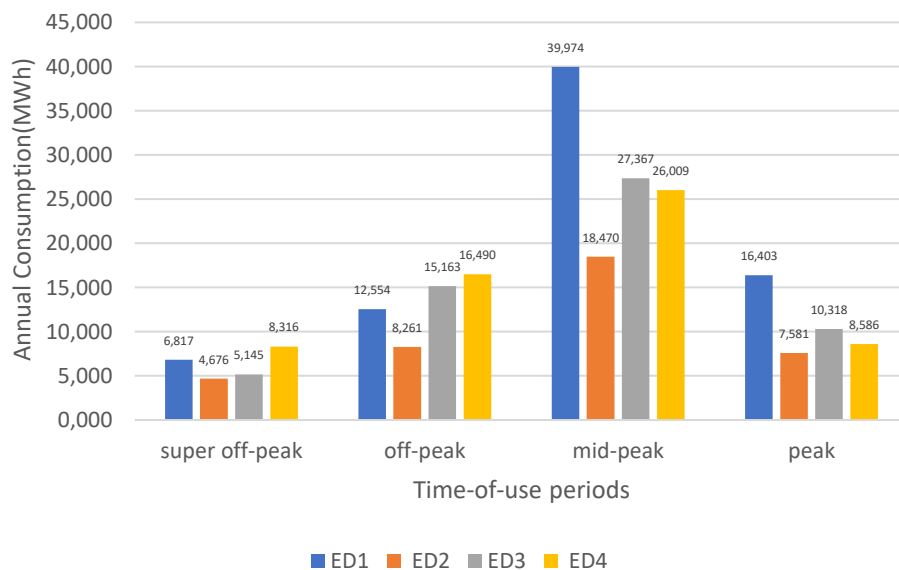


Figure 4.7 - Annual consumption of each building by time-of-use periods.

Understanding this temporal distribution of consumption is crucial for aligning it with the production profile and optimising self-consumption or energy-sharing strategies within the Renewable Energy Community.

4.4.3 - Analysis of Self-Consumption and Internal Grid Injection

Following the previous analyses focused on physical energy flows, this section examines two critical parameters: self-consumption and injected energy. Self-consumption refers to the share of energy produced by a building's UPAC consumed on-site during the same 15-minute interval. In contrast, injected energy refers to the surplus not immediately used by the producing building. It is thus fed into the internal REC grid, where it becomes available for potential redistribution to other community members. These indicators are fundamental for understanding the individual contribution of each producing building to the REC's energy balance.

Table 4.8 summarises the annual self-consumed and injected energy values for buildings ED1, ED2, and ED3.

Table 4.8 - Annual breakdown of self-consumed and injected energy for each building in the REC.

Energy (MWh)	ED1	ED2	ED3	ED4	Total
Self-consumption	13,580	16,528	18,263	-	48.371
Injected	0,298	23,04	7,903	-	31,242

The results show that Building ED3 achieved the highest level of self-consumption over the year (18.263 MWh), followed by ED2 (16.528 MWh) and ED1 (13.580 MWh). On the other hand, ED2 stands out for injecting a considerable amount of surplus energy into the internal REC grid (23.040 MWh), reinforcing its central role in supplying the community. ED1 injected the least amount (0.298 MWh), indicating that its production is almost entirely consumed locally.

The three producing buildings collectively self-consumed 48.371 MWh and injected 31,242 MWh into the REC grid. These values highlight the importance of redistribution mechanisms to optimise the usage of available renewable energy within the community.

Figure 4.8 illustrates the monthly distribution of injected energy per building. A clear seasonal trend can be observed, with injections peaking during the summer months (May to August), when solar irradiance is highest, and declining in winter due to reduced photovoltaic output. ED2 consistently dominates energy injection across all months, reinforcing its role as the most productive entity.

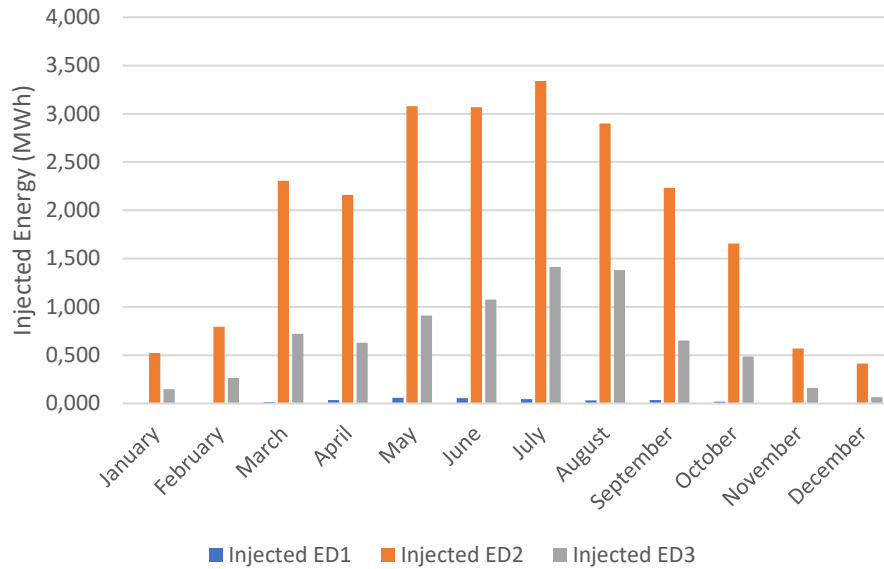


Figure 4.8 - Monthly distribution of energy injection in each building.

Figure 4.9 shows the average hourly injection profile throughout the day. The graph highlights that energy injection begins after sunrise, increases steeply, and peaks between 11:00 and 14:00, the highest solar intensity hours, before sunset. Once again, ED2 stands out with a significantly higher injection curve, especially during midday, compared to the other buildings.

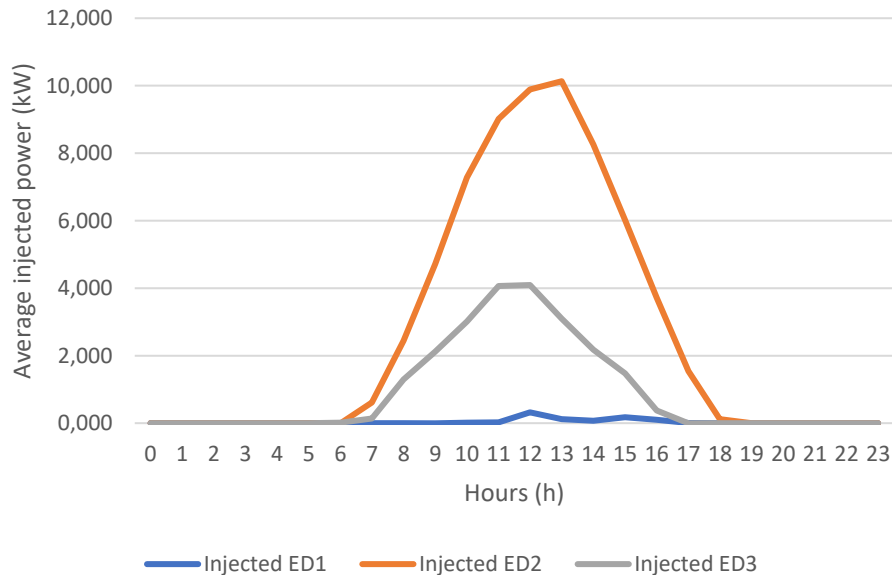


Figure 4.9 - Hourly injection profile of the four buildings.

Finally, Figure 4.10 categorises the annual energy injection according to time-of-use periods. Most injections occur during mid-peak hours, particularly for ED2, which accounts for 15.50 MWh during this interval. This pattern aligns with typical photovoltaic production curves and highlights the importance of synchronising energy consumption with periods of high solar generation to maximise self-consumption and minimise grid dependency.

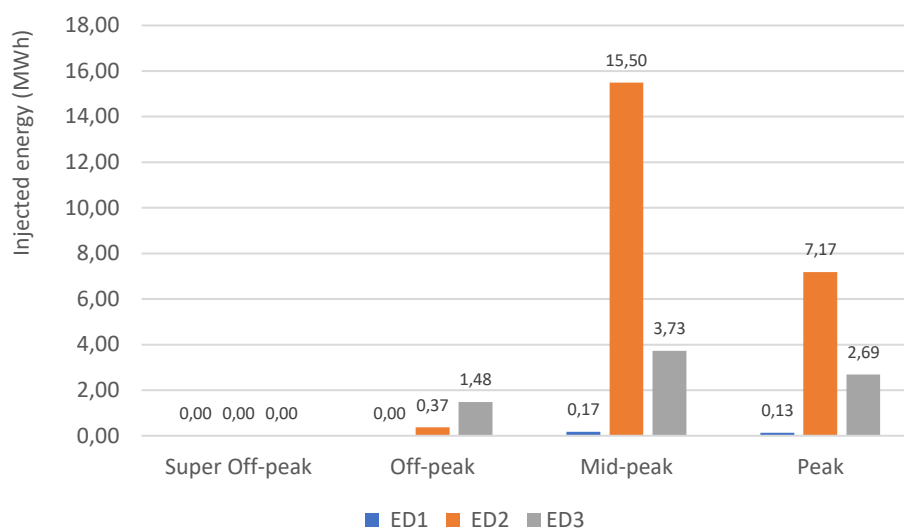


Figure 4.10 - Annual injection of each building by time-of-use periods.

Together, these observations provide a clear picture of how each building contributes to and interacts with the internal energy flow of the REC. Understanding these injection patterns is key to optimising redistribution, credit allocation, and long-term planning within the community.

4.4.4 - Allocation of Injected Energy within the REC

To further explore the physical layer of the Renewable Energy Community, this section focuses on the internal redistribution of surplus energy, that is, the portion of PV energy not self-consumed and injected into the internal REC grid for redistribution among members with net demand. Figure 4.11 illustrates the energy flow on 30 September 2020, between 09:00 and 09:15, providing a representative snapshot of how this redistribution process works in practice. During this interval, buildings ED1, ED2, and ED3 were generating electricity via their *UPACs*, while ED4, which does not have local generation capacity, relies entirely on imported or redistributed energy.

In this example, ED1 and ED3 fully self-consumed their production (1.25 kWh and 3 kWh, respectively), resulting in zero surplus. In contrast, ED2 produced 3.25 kWh and self-consumed 1.45 kWh, leaving a surplus of 1.8 kWh available for redistribution. ED4 had no production, a total consumption of 2.2 kWh, and therefore contributed no surplus to the internal REC network.

According to the proportional redistribution mechanism based on net consumption, ED2's surplus was shared among buildings with net demand: ED1 received 0.35 kWh, ED3 received 0.7 kWh, and ED4 received 0.75 kWh. The remaining unmet consumption in each of these buildings was sourced from the *RESP*, namely 0.65 kWh for ED1, 1.3 kWh for ED3, and 1.45 kWh for ED4. As the figure shows, this redistribution flow exemplifies the internal

cooperation dynamics within the REC and underlines the system's potential to reduce external grid dependency through local surplus sharing.

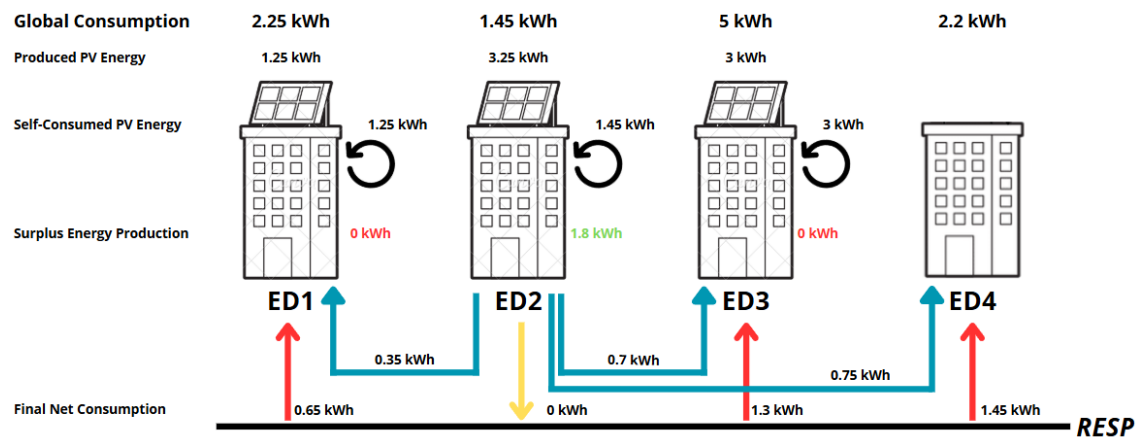


Figure 4.11 - Example of surplus energy redistribution within the REC on 30 September 2020, at 09:00.

The next step is to extend the redistribution process to the complete dataset for the entire year. Table 4.9 provides a comprehensive overview of the annual energy flows associated with each building in the REC. It includes key metrics such as global consumption, local production, self-consumed energy, energy injected into the REC, and energy imported from both the internal REC grid and the public grid (*RESP*). Notably, the total amount of “Energy Injected into the REC” matches the “Energy Received from the REC,” as these represent the surplus energy redistributed within the community. In contrast, the “Energy Injected into the *RESP*” reflects the share of surplus generation that remained unconsumed by any building during the respective 15-minute intervals, thus being exported to the public grid.

Table 4.9 - Annual Energy Flow Summary for Each Building in the REC.

Energy (MWh)	ED1	ED2	ED3	ED4	Total
Total Consumption	75.747	38.989	57.993	59.401	232.129
Produced Energy	13.879	39.568	26.166	-	79.613
Self-consumed Energy	13.580	16.528	18.263	-	48.371
Injected Energy	0.298	23.040	7.903	-	31.242
Energy Received from REC	9.657	0.007	1.271	9.508	20.442
Energy Injected into REC	0.081	15.508	4.853	-	20.442
Energy Injected into <i>RESP</i>	0.217	7.532	3.050	-	10.799
Consumption from the <i>RESP</i>	52.509	22.454	38.459	49.893	163.316

A particularly illustrative case is ED1, which benefited significantly from the internal redistribution mechanism despite its modest production capacity. With an initial injection of only 0.298 MWh, ED1 received 9.657 MWh from the REC, substantially reducing its dependence on the public grid. A similarly notable case is ED4, which has no local generation and relies entirely on external sources. Nevertheless, it received 9.508 MWh from the REC, showcasing

the system's ability to support buildings without generation through surplus energy shared by others. On the other hand, ED2, the leading energy producer, contributed the most to the REC, injecting 15.508 MWh, and still exported 7.532 MWh to the RESP, confirming its status as the primary energy supplier. These results underscore the importance of the redistribution mechanism in enhancing collective self-consumption and promoting energy equity across the community.

To complement these absolute values, Tables 4.10 and 4.11 provide relative metrics for a more intuitive comparison. Table 4.10 details the proportions of each building's consumption met through self-consumption, energy received from the REC, and energy imported from the *RESP*. Table 4.11, in turn, breaks down the use of produced energy, indicating how much was self-consumed, injected into the REC, or ultimately exported to the public grid.

Table 4.10 - Share of Energy Sources in Total Consumption.

	ED1	ED2	ED3	ED4	Total
Self-consumed Energy (% of consumption)	17.93%	42.39%	31.49%	0.00%	20.84%
Energy Received from REC (% of consumption)	12.75%	0.02%	2.19%	16.01%	8.81%
Energy Received from <i>RESP</i> (% of consumption)	69.32%	57.59%	66.32%	83.99%	70.36%

Table 4.11 - Allocation of Produced Energy.

	ED1	ED2	ED3	Total
Self-consumed Energy (% of production)	97.85%	41.77%	69.80%	60.76%
Injected Energy (% of production)	2.15%	58.23%	30.20%	39.24%
Injected into REC (% of production)	0.58%	39.19%	18.55%	25.68%
Injected into <i>RESP</i> (% of production)	1.57%	19.04%	11.66%	13.56%

The percentage indicators presented reinforce key insights regarding the energy dynamics within the REC. ED1, despite being the building with the lowest production capacity, exhibits a remarkably high self-consumption rate relative to its production (97.85%), indicating that almost all energy produced is utilised locally. However, due to its low generation and high consumption, it still depends significantly on external sources, with 69.32% of its annual demand met by the *RESP*. Conversely, ED2 stands out as the main generator, injecting 58.23% of its production, of which 39.19% was redistributed within the REC. This confirms its central role as a supplier of surplus energy. ED4, which lacks a *UPAC*, relies heavily on the public grid (83.99%), although it benefits from redistributed energy (16.01% of its consumption). Lastly, ED3 presents a balanced profile, with 69.80% of its production self-consumed and a meaningful contribution to the community through redistribution. These metrics collectively demonstrate the effectiveness of the redistribution mechanism in supporting buildings with limited or no generation capacity and enhancing energy autonomy across the REC.

To further explore the impact of redistribution at a finer temporal resolution, Figures 4.12 and 4.13 provide a comparative overview of the hourly profile of net electricity consumption imported from the *RESP* by each building within the REC, both before and after applying the surplus redistribution mechanism.

In Figure 4.12, before redistribution, Building ED1 exhibits the highest net consumption throughout the day, with a sharp peak occurring around 09:00, indicating a significant shortfall between its production and consumption. Conversely, ED2 maintains consistently lower levels of net consumption, reflecting its status as a building with substantial surplus generation capacity.

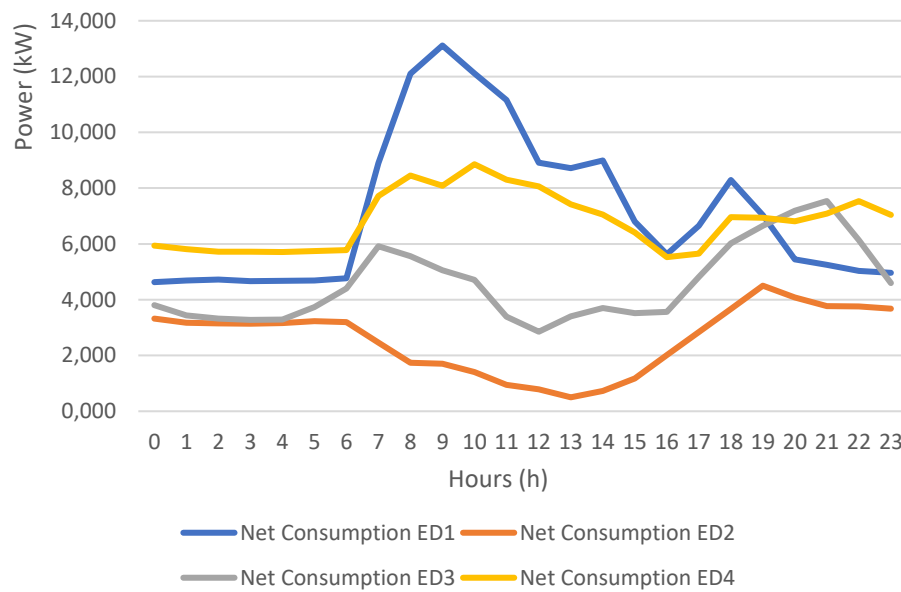


Figure 4.12 - Net consumption before allocation of surplus energy.

After implementing the redistribution mechanism (Figure 4.13), a marked reduction in net consumption is observed in Building ED1 during daylight hours, particularly between 09:00 and 14:00, which aligns with peak photovoltaic generation.

Before redistribution (Figure 4.12), ED1 reached a consumption peak of 13,113 kW around 09:00, whereas after redistribution, this value dropped to under 10,006 kW, evidencing a significant alleviation of the building's demand from the *RESP*. Additionally, Building ED4 shows a clear downward shift in its net consumption curve during the same period.

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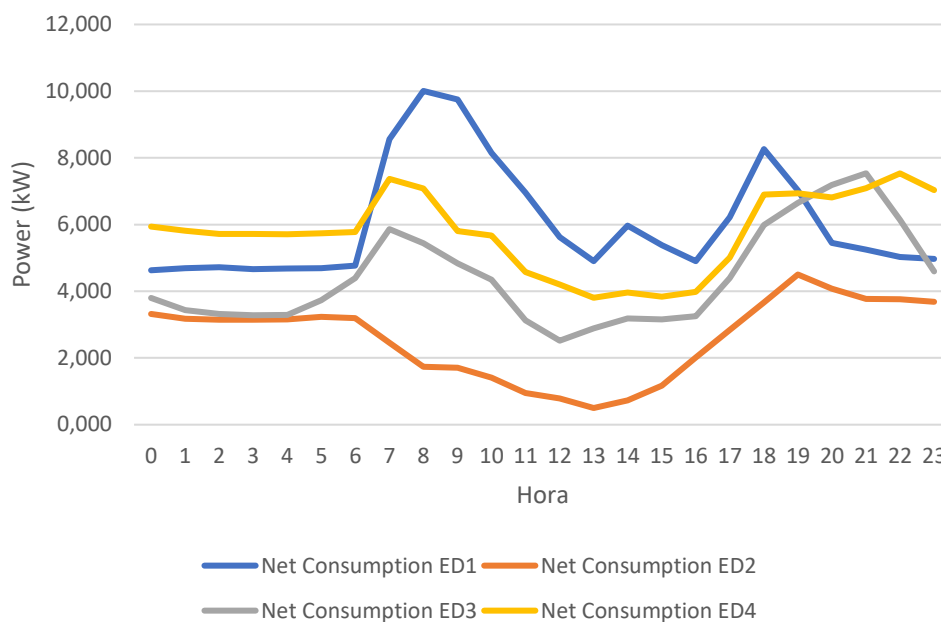


Figure 4.13 - Net consumption after allocation of surplus energy.

Overall, the comparison between Figures 4.12 and 4.13 demonstrates the effectiveness of the surplus redistribution mechanism in reducing the net energy imported from the public grid. Notably, the most significant improvements are observed in Buildings ED1 and ED4, where net consumption during solar production hours decreased substantially.

In Figure 4.14, before the redistribution of surplus energy, Building ED1 consistently exhibits the highest net consumption throughout most months, especially during winter, such as January and December, reflecting its limited generation relative to demand. Building ED4 also shows significantly high net consumption, particularly in colder months.

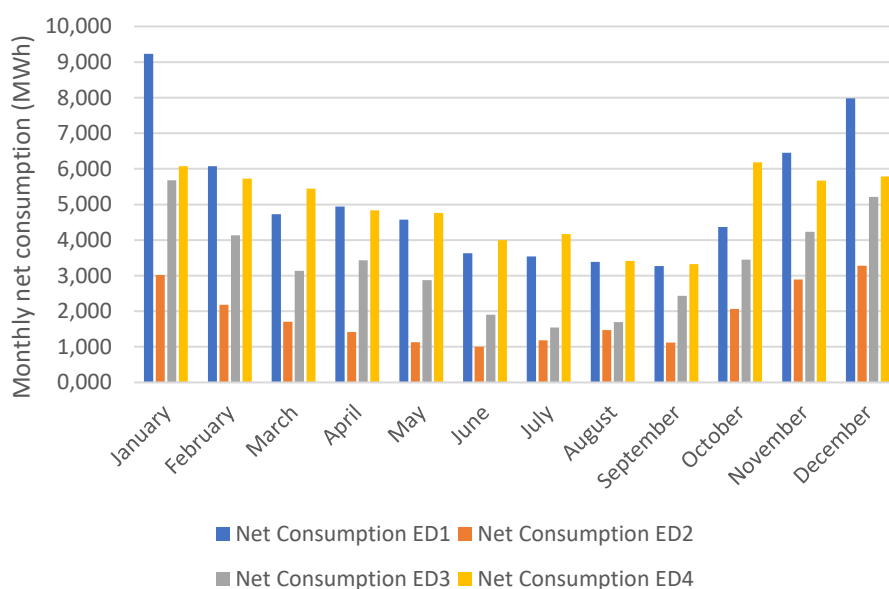


Figure 4.14 - Monthly net consumption before allocation of surplus energy.

The most significant reductions in net consumption are observed in ED1 and ED4, particularly during the summer period (June-September), when PV generation and surplus

availability across the REC are at their highest, enabling a more effective redistribution of excess energy from other buildings.

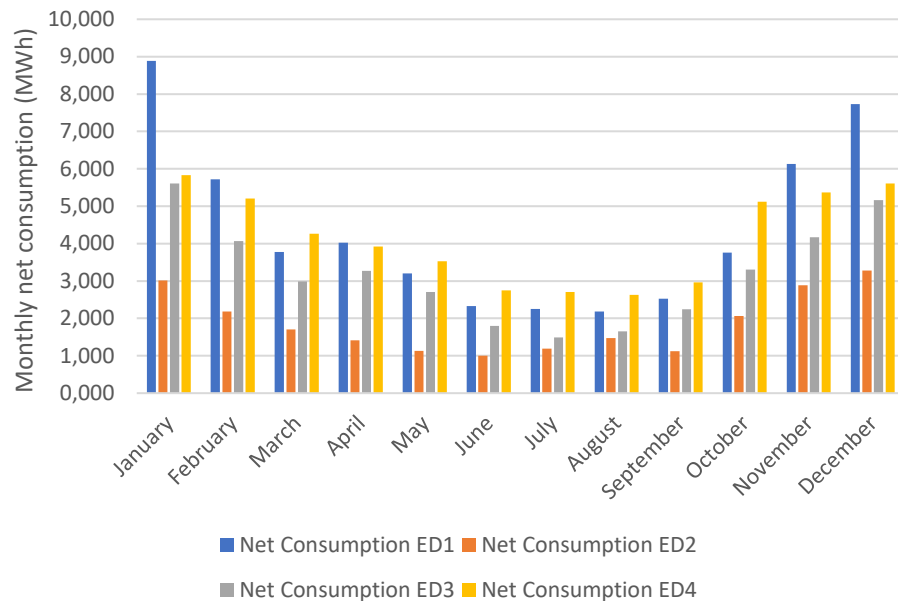


Figure 4.15 - Monthly net consumption after allocation of surplus energy.

The redistribution mechanism smooths inter-building disparities and brings monthly net consumption values closer.

Figures 4.16 and 4.17 illustrate the impact of surplus energy allocation on net consumption across time-of-use periods. Before redistribution (Figure 4.16), Building ED1 registered the highest net consumption during the mid-peak period, reaching 30.63 MWh, followed closely by ED4 with 26.01 MWh and ED3 with 18.29 MWh.

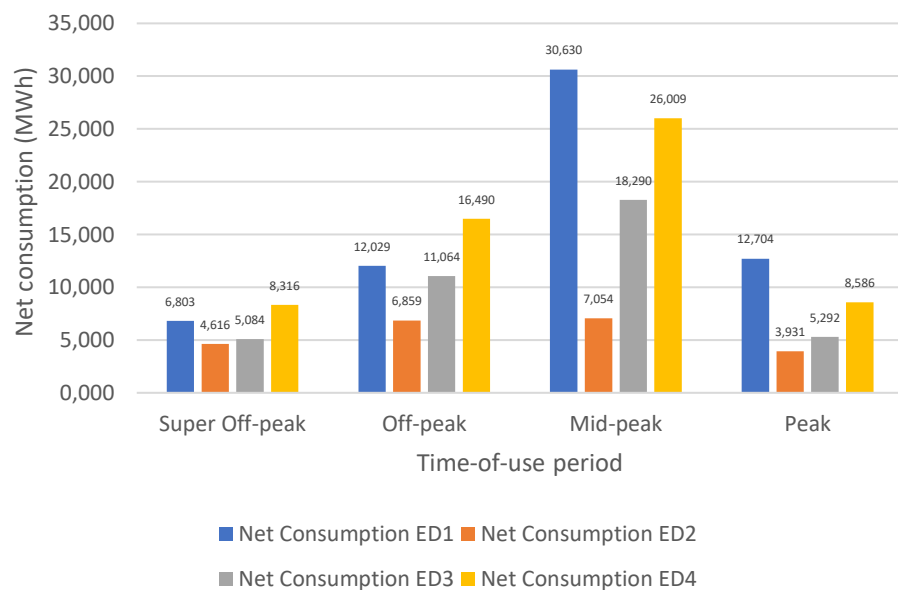


Figure 4.16 - Net consumption before allocation of surplus energy by time-of-use periods.

After redistribution (Figure 4.17), ED1's mid-peak net consumption decreased to 24.03 MWh, down from the initial 30.63 MWh, highlighting the effectiveness of surplus allocation in

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alleviating centralised demand during periods of high solar generation. ED4 also experienced a reduction, with its mid-peak consumption falling from 26.01 MWh to 21.14 MWh. In the peak period, ED1's net demand dropped from 12.70 MWh to 9.87 MWh, while ED4's decreased from 8.59 MWh to 6.05 MWh.

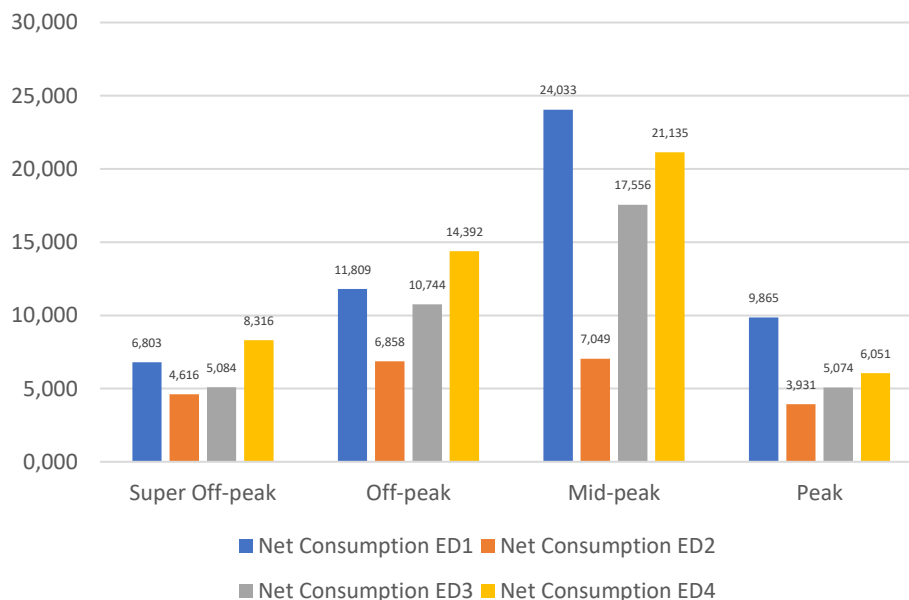


Figure 4.17 - Net consumption after allocation of surplus energy by time-of-use periods.

The differences in net consumption across time-of-use periods are more pronounced during mid-peak and peak periods because these intervals coincide with daylight hours when photovoltaic generation is highest; conversely, in super off-peak periods, during overnight, solar production is virtually non-existent, resulting in slight or no impact from surplus redistribution.

Finally, as seen in Table 4.9, Figure 4.18 provides a clear visual comparison of the hourly profile of energy injected into the *RESP* by each building before and after redistributing surplus energy. The dotted lines represent the original injected energy, the surplus that was not self-consumed, while the solid lines show the reduced injection after redistribution to other REC members.

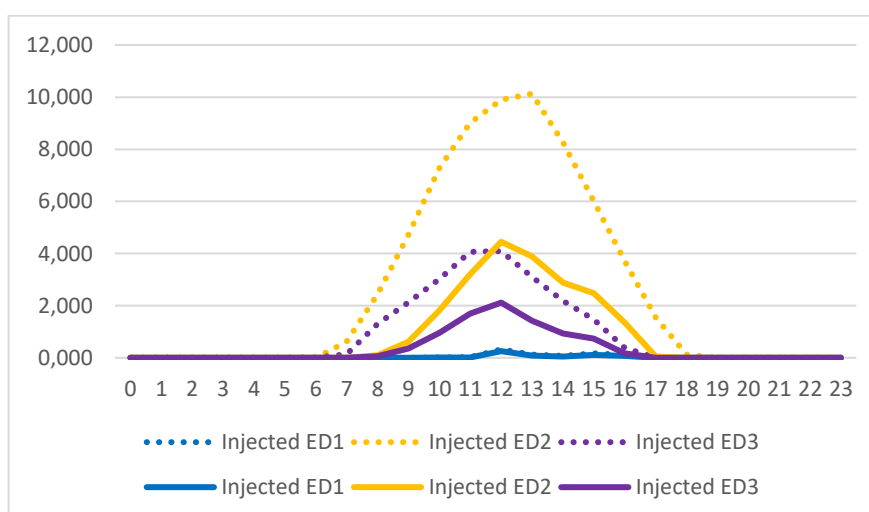


Figure 4.18 - Annual profile of injected energy into the *RESP* before and after surplus redistribution.

A substantial drop in injected energy is observable, especially for buildings ED2 and ED3. The shift from dotted to solid lines in Figure 4.18 highlights the effectiveness of the redistribution mechanism in significantly reducing the volume of surplus energy sent to the RESP. ED2 shows the most pronounced reduction, with its injection profile nearly halved during midday hours (showing a decrease of more than 5 kW), reaffirming its pivotal role as the primary source of redistributed surplus within the REC.

In conclusion, the analysis presented in this section demonstrates the tangible benefits of implementing a surplus energy redistribution mechanism within an REC. By reallocating unused PV energy based on proportional net consumption, the REC significantly reduced its dependency on the public grid, enhanced local energy self-sufficiency, and promoted a fairer distribution of available resources.

4.4.5 - Distribution of Surplus Energy Among Buildings

Following the implementation of the surplus redistribution mechanism, it becomes essential to analyse how energy flows were internally reallocated among the buildings in the REC. This section focuses on characterising the direction and magnitude of the energy transferred between each pair of buildings throughout the year.

Table 4.12 presents the annual redistribution matrix of surplus energy between buildings within the REC, specifying the quantities (in MWh) transferred from each origin building to each recipient.

Table 4.12 - Annual Energy Redistribution Matrix Between Buildings.

		Recipient (MWh)			
		ED1	ED2	ED3	ED4
Origin	UPAC ED1	-	0,000	0,007	0,074
	UPAC ED2	7,131	-	1,264	7,113
	UPAC ED3	2,526	0,007	-	2,321
	Total (MWh)	9,657	0,007	1,271	9,508

ED1 emerges as the primary recipient, having received 9.657 MWh over the year, followed closely by ED4 with 9.508 MWh, reflecting their roles as net consumers, with limited and no local production capacity, respectively. ED2 was the leading energy supplier, redistributing 7.131 MWh to ED1, 1.264 MWh to ED3, and 7.113 MWh to ED4. ED3 also contributed significantly, transferring 2.526 MWh to ED1 and 2.321 MWh to ED4. In contrast, ED2 received only 0.007 MWh throughout the year.

In summary, the redistribution matrix confirms the effectiveness of the surplus allocation mechanism in addressing consumption needs within the REC. Buildings with limited or no generation capacity, namely ED1 and ED4, benefited most from the internal energy flows, significantly reducing their reliance on the public grid.

Meanwhile, the consistent contribution of ED2 and, to a lesser extent, ED3, underscores the importance of surplus-generating members in maintaining the community's energy balance.

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This internal cooperation highlights the potential of energy sharing strategies to enhance equity and efficiency within decentralised energy systems.

Chapter 5

Implementation of the Energy Credits Management System

Following the virtual energy allocation process detailed in Chapter 4, which involved the proportional redistribution of surplus energy across community members in 15-minute intervals, this chapter introduces a new transactional layer: the Energy Credits (ECs) system. Built atop the energy flow data, this mechanism quantifies and monetizes energy exchanges between members of the Renewable Energy Community. Translating these energy interactions into digital credits ensures accurate, transparent, and equitable accounting of value transfers among stakeholders.

This layer facilitates periodic energy settlements and individual balance tracking. It enables various services such as peer-to-peer (P2P), member-to-community (M2C), and community-to-member (C2M) energy trading, investment remuneration, and service compensation.

The implementation of the Energy Credit Management System (ECMS) formalises the internal economy of the REC, providing the structural foundation for financial sustainability, long-term engagement, and regulatory traceability in decentralised energy communities.

5.1 - Integration of Energy Credit Transactions in Renewable Energy Communities

This subchapter presents a structured and progressive analysis of scenarios for implementing EC transactions within the REC. Building upon the previously established virtual energy allocation, the current approach introduces the Energy Credits Management System (ECMS) as a new transactional layer. Five distinct scenarios are explored, each introducing increasing levels of transactional complexity and stakeholder involvement.

The first scenario serves as a baseline, simulating the natural flow of ECs derived solely from virtual energy exchanges without direct credit transactions between members. Subsequent scenarios introduce additional dimensions, including P2P trading, centralised transactions mediated by the Collective Self-consumption Managing Entity (*EGAC*), and the integration of an investor entity that provides initial capital through credit ownership.

The final scenario combines all types of transactions, allowing maximum flexibility within the system. At the end of each scenario, a liquidation step is carried out to assess individual and collective financial outcomes.

This modular analysis enables a comprehensive evaluation of how different EC configurations affect internal energy value distribution, incentivisation mechanisms, and overall fairness in the REC.

5.1.1 - Scenario 1: Energy Credit Generation and Consumption Without Trading

In Scenario 1, credit balances are driven exclusively by the quarter-hourly energy flows recorded by E-Redes' smart meters and managed by the ECMS. Each 15-minute measurement of surplus injection into, or withdrawal from, the REC grid is translated one-for-one into energy credits, considering the fundamental equivalence of 1 EC equal to 1 kWh, as established in section 3.2.1. Whenever a building injects excess PV generation into the community, the ECMS automatically increments its wallet by the corresponding EC amount, G_d ; conversely, drawing energy from the community incurs an equivalent debit, C_d .

No P2P or *EGAC*-mediated transactions occur in this baseline case, meaning that all credit movements stem directly from the net flows between each building and the community grid. This setup ensures that our analysis reflects purely the local self-consumption optimisation and virtual energy allocation studied in Chapter 4.

The net change in each building's EC wallet for day d was obtained as:

$$\Delta W_d = G_d - C_d \quad (8)$$

By aggregating these daily balances over the year, the figures illustrate the cumulative generation (Figure 5.1), consumption (Figure 5.2), and resulting wallet trajectories (Figure 5.3) for each stakeholder.

In Figure 5.1, it is immediately apparent that ED2 dominates credit creation throughout the year, often generating over 100 EC in a single day, whereas ED1 and ED3 produce comparatively modest amounts, and ED4 remains flat at zero as it has no *UPAC*. Once again, this reflects ED2's large surplus photovoltaic output and ED1's and ED4's lack of generation capacity.

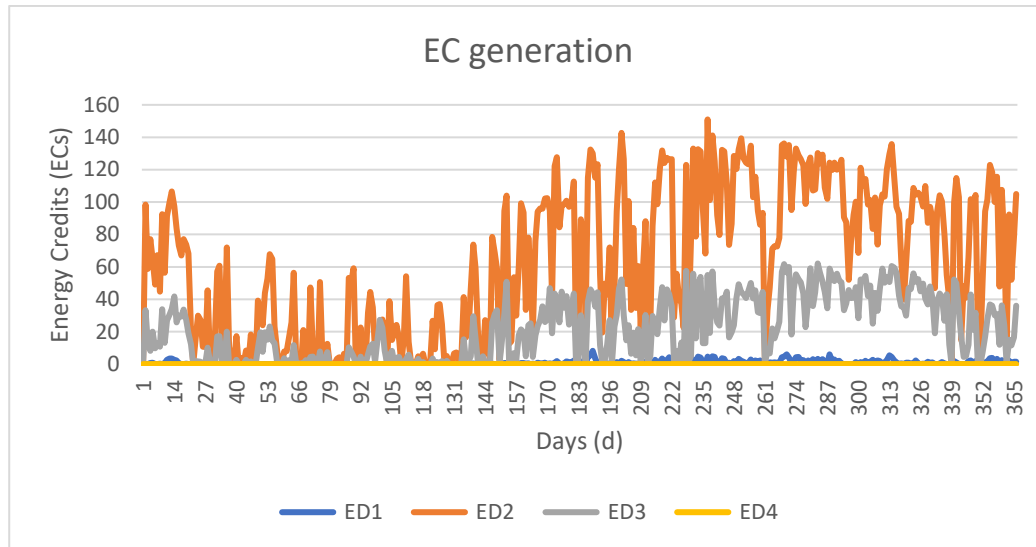


Figure 5.1 - Annual Energy credit generation in each building.

As shown in Figure 5.2, ED1 and ED4 show frequent high consumption peaks (up to 70 EC/day), indicating their reliance on credits to meet demand, while ED3's consumption remains minimal, and ED2 consumes almost none.

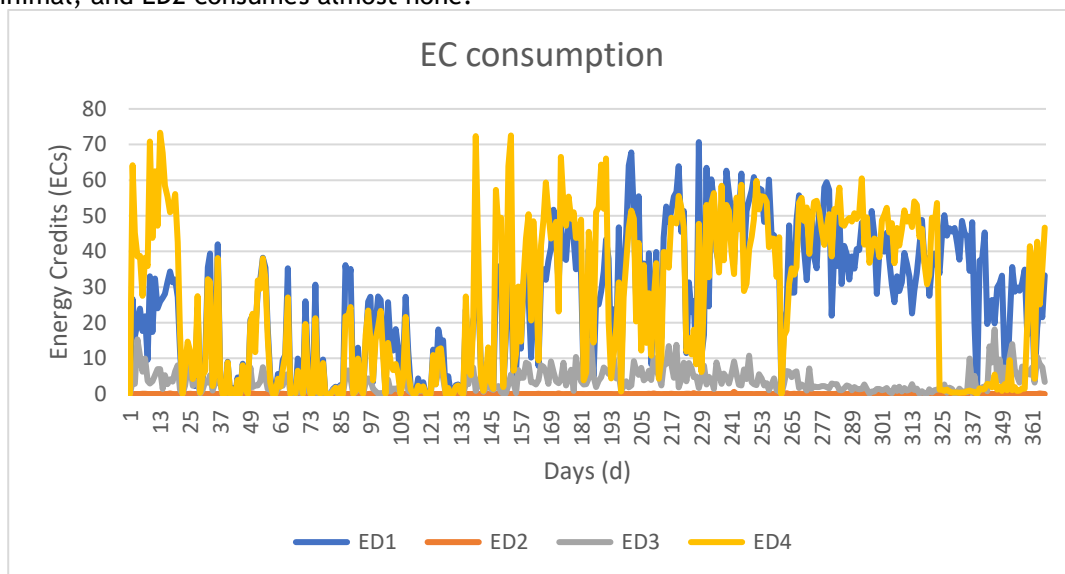


Figure 5.2 - Annual Energy credit consumption in each building.

Figure 5.3 illustrates how each stakeholder's EC wallet diverges over the year in Scenario 1 according to their net generation or consumption. ED2 steadily accrues credits thanks to its sizeable surplus injections, while ED3 builds a more modest balance. Conversely, ED1 and ED4 see their wallets drawn down into negative territory, reflecting their net reliance on community energy. The EGAC remains effectively neutral, and the fictitious wallet of the GRID mirrors the aggregate unconsumed surplus returned to the public network.

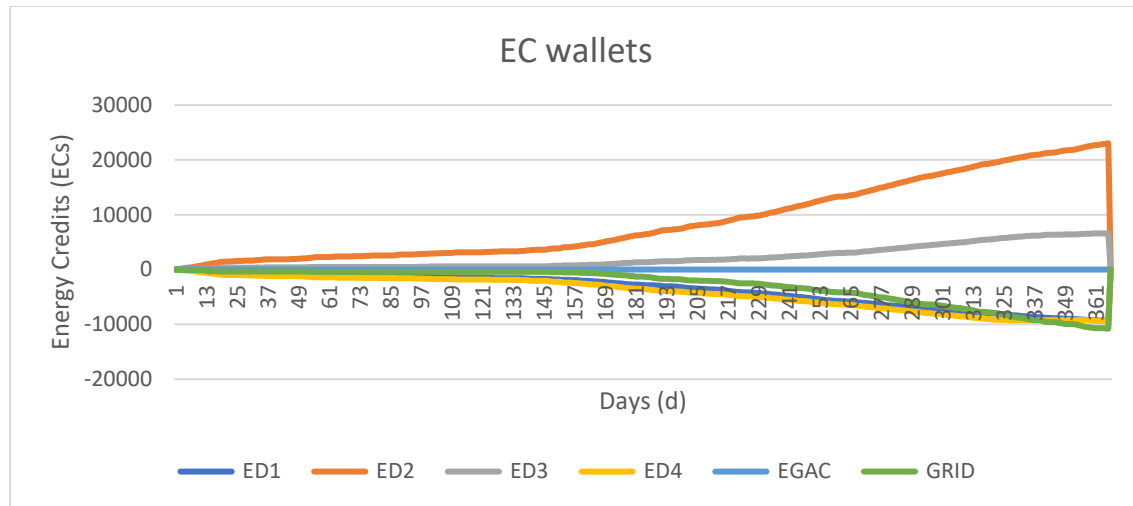


Figure 5.3 - Each stakeholder's Energy Credit wallet value throughout the year in scenario 1.

As summarised in Table 5.1, these end-of-year credit balances form the basis of the final settlement: ED2 and ED3 emerge as net providers (-23 033 EC and -6 632 EC respectively, indicating they are owed credit), whereas ED1, ED4, the *EGAC*, and the GRID settle as net consumers (9 358 EC, 9 508 EC, 0 EC, and -10 799 EC respectively, indicating they owe credit).

Negative values indicate credits handed in (and thus a cash payment received upon settlement), while positive values denote credits drawn down (and a corresponding payment made by the corresponding entity).

Table 5.1 - Scenario 1: Energy Credit Settlement Summary.

ED1	ED2	ED3	ED4	<i>EGAC</i>	GRID
9358	-23033	-6632	9508	0	10799

Scenario 1 highlights the inherent imbalance when buildings operate without direct EC trading. ED2's dominant credit generation contrasts sharply with the heavy consumption needs of ED1 and ED4, resulting in significant negative wallet trajectories for those buildings. These results underscore the limitations of a purely passive redistribution model and set the stage for subsequent scenarios, in which active trading and community-mediated transactions will be introduced to improve overall credit equity.

5.1.2 - Scenario 2: Direct Member-to-Member Credit Transfers

Scenario 2 introduces direct peer-to-peer (P2P) transactions among community members. In addition to the daily credit generation G_d and consumption C_d processes described previously, each building can now buy and sell ECs directly with one another at mutually agreed-upon rates. Importantly, trading pairs **may set any price they choose** or **elect to transact at zero cost** as a gift, reflecting the flexible nature of a truly decentralised market. These P2P exchanges are recorded in the ECMS as simple credit transfers. They allow members to optimise their balances by trading surplus for deficits without involving the *EGAC* or an investor.

As defined in Section 3.2.3, every P2P EC transaction is a zero-balance transfer, meaning the number of ECs debited from the sender's wallet is the same as the number credited to the recipient's wallet.

To account for the previous day's balance, the daily wallet update for the wallet i on day d can be written as:

$$W_{i,d} = W_{i,d-1} + G_{i,d} - C_{i,d} + T_{i,d} \quad (9)$$

Where:

$W_{i,d-1}$ is the balance of the wallet i at the end of day $d - 1$.

$G_{i,d}$ is its credit generation on day d .

$C_{i,d}$ is its credit consumption on day d .

$T_{i,d}$ is the net transaction for day d (positive if credits are received, negative if sent).

This recurrence relation ensures that each building's wallet properly accumulates production, deducts consumption, and reflects any direct trades with other members.

Therefore, Table 5.1 illustrates two peer-to-peer transactions in Scenario 2:

- **Transaction 1:** ED2 sends 1 000 EC to ED4 at €0.08/EC. As a result, ED2's wallet balance decreases by 1 000 EC (-1 000 kWh) and ED4's increases by 1 000 EC, while ED2 receives €80 and ED4 pays €80.
- **Transaction 2:** ED2 transfers 300 EC to ED1 at €0.10/EC. Consequently, ED2's balance falls by 300 EC, ED1's rises by 300 EC, and a payment of €30 flows from ED1 to ED2.

This example shows how the ECMS simultaneously updates wallet balances (in kWh) and records the associated monetary flows for each P2P trade.

Table 5.2 - Illustrative Peer-to-Peer EC Transactions in Scenario 2.

Wallet balance				Transaction (kWh)					Transaction (€)			
ED1	ED2	ED3	ED4	ED1	ED2	ED3	ED4	VALUE	ED1	ED2	ED3	ED4
-621	755	369	-134		-1000,0		1000,0	0,08	0	80	0	-80
-324	461	368	-136	300,0	-300,0			0,10	-30	30	0	0
-330	474	366	-142									

After the simulation of the transactions, Scenario 2's peer-to-peer trading structure (Figure 5.4) markedly reduces wallet imbalances compared to the baseline model in Figure 5.3. Under P2P exchanges, ED2's balance peaks at roughly 3 000 EC, far lower than the 24 000 EC observed when no trading occurred, while ED1 and ED4 maintain positions close to zero rather than plunging to -10 000 EC.

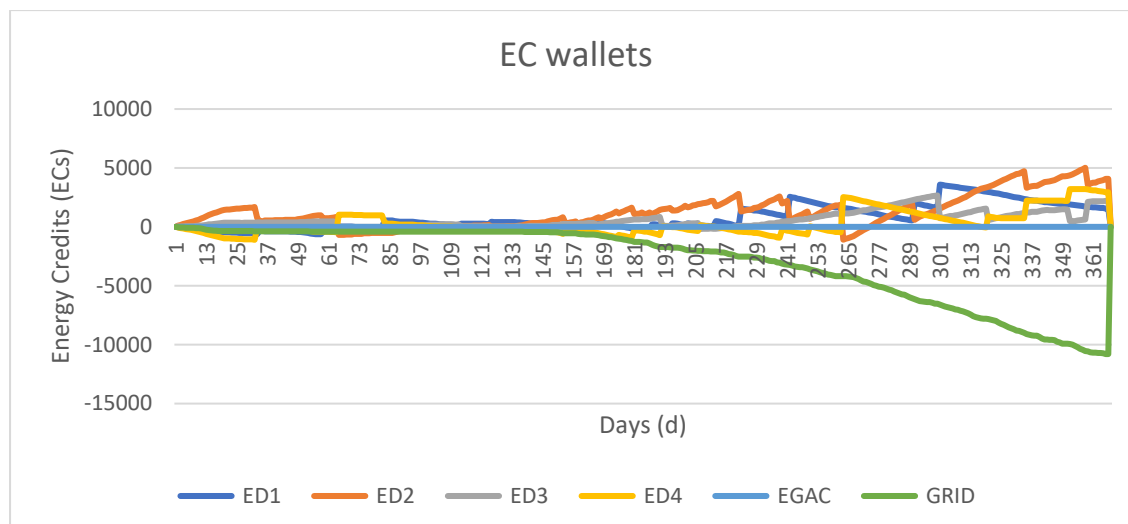


Figure 5.4 - Each stakeholder's Energy Credit wallet value throughout the year in scenario 2.

Table 5.2 reflects each building's net credit position at year-end.

Table 5.3 - Scenario 2: Energy Credit Settlement Summary.

ED1	ED2	ED3	ED4	EGAC	RESP
-1562	-4083	-2212	-2942	0	10799

These tighter, more moderate wallet trajectories highlight Scenario 2's effectiveness at distributing credits equitably among members, smoothing out extreme surpluses.

5.1.3 - Scenario 3: Centralised Trading via the EGAC

Building on the daily credit generation G_d and consumption C_d processes described previously, Scenario 3 replaces direct P2P exchanges with transactions routed exclusively through the Collective Self-consumption Managing Entity (EGAC). In this model, members purchase ECs from the EGAC or sell surplus credits back to it, rather than trading directly with one another, still respecting equation 9. These transactions are governed by the rules set out in Section 3.2.3, ensuring zero-balance transfers and regulatory compliance.

Figure 5.5 shows the EC wallet trajectories under EGAC-mediated transactions. ED2 steadily builds a surplus before tapering off, while ED1, ED3, and ED4 dip into negative balances as they draw on redistributed credits. The EGAC accumulates credits mid-year, then disburses them to deficit buildings, and the GRID ends at -10 799 EC, indicating final exports to the public grid.

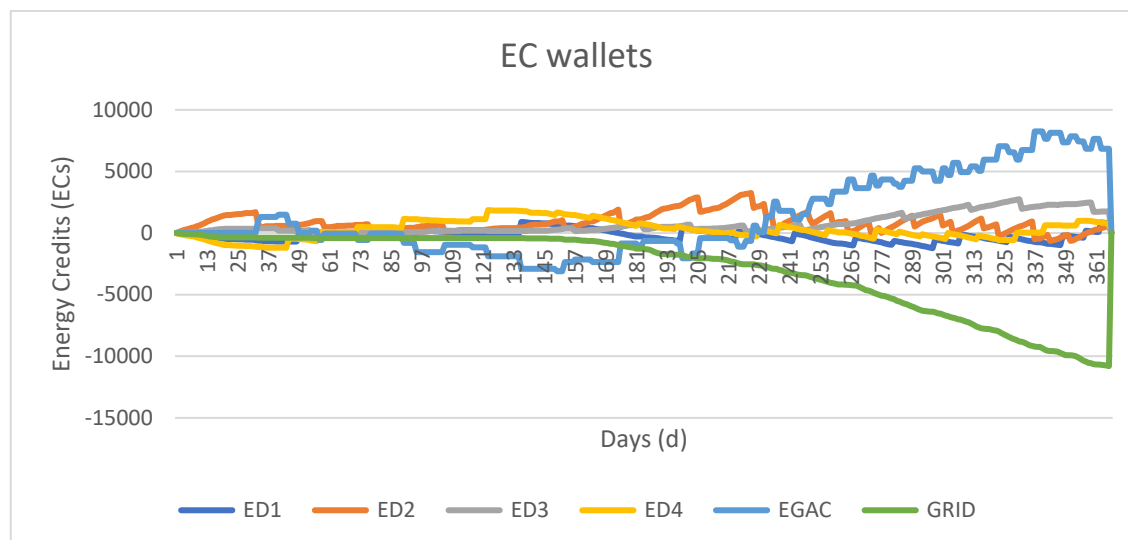


Figure 5.5 - Each stakeholder's Energy Credit wallet value throughout the year in scenario 3.

As shown in Figure 5.4, in the final settlement for Scenario 3, each stakeholder's EC balance was converted to a monetary settlement, resulting in the following net positions: ED1 paid out 792 EC, ED2 paid 633 EC, ED3 paid 1 782 EC, ED4 paid 742 EC, and the *EGAC* covered a net outlay of 6 850 EC. The *RESP* recorded a negative EC balance of 10 799 EC, reflecting its role as the ultimate recipient of surplus energy exported from the REC.

Table 5.4 - Scenario 3: Energy Credit Settlement Summary.

ED1	ED2	ED3	ED4	EGAC	RESP
-792	-633	-1782	-742	-6850	10799

As in all scenarios, these values sum to zero, confirming that all credits generated and redistributed within the community have been fully settled. The *RESP*'s negative balance represents the monetary reimbursement made by the community for the energy injected into the public grid during the year.

5.1.4 - Scenario 4: Hybrid P2P and Investor Transaction Model

In this scenario, each prosumer's wallet is initialised with a negative balance equivalent to the total credits their *UPAC* would generate over the year. This effectively represents an advance payment, a previewed case in Section 3.2.5, of rooftop panels to the investor. Building ED4, lacking local generation assets, naturally begins with a zero balance. No *EGAC*-mediated transactions occur; credit exchanges occur exclusively via direct peer-to-peer (P2P) trades and through the investor acting as both lessor and market counterparty.

It is also worth emphasising that the peer-to-peer exchanges simulated in Scenario 2 remain unchanged in this scenario, allowing for a direct comparison of the investor's impact on the system without altering the underlying trading dynamics.

Figure 5.6 depicts the annual evolution of each stakeholder's EC wallet under the hybrid P2P-investor model.

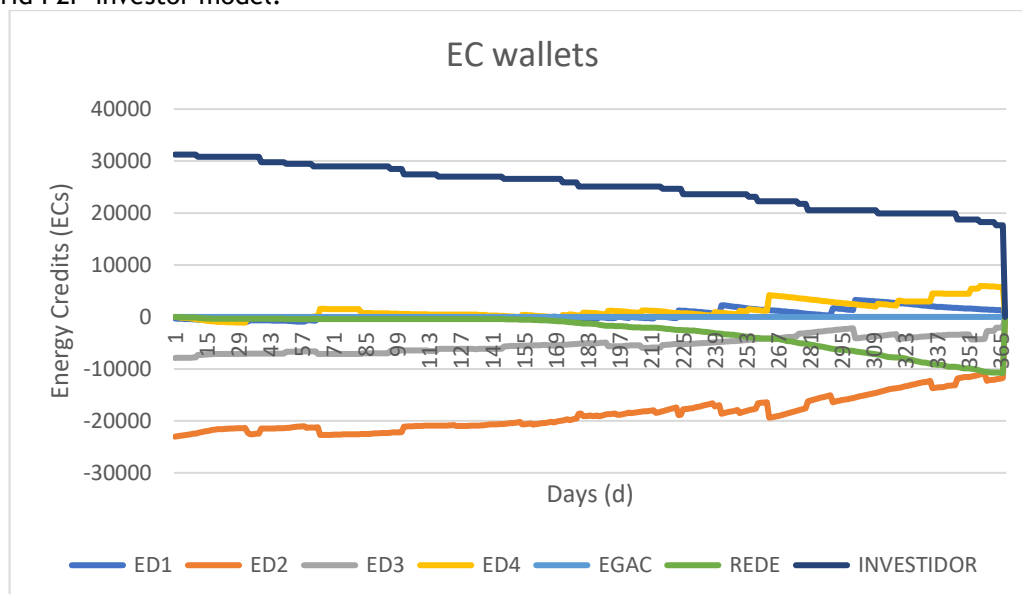


Figure 5.6 - Each stakeholder's Energy Credit wallet value throughout the year in scenario 4.

In the final settlement of Scenario 4, ED1 and ED4 each relinquish 1 263 EC and 5 692 EC, respectively, corresponding to monetary payments towards them, while ED2 and ED3 receive 11 757 EC and 2 041 EC in compensation. The *RESP* is credited with 10 799 EC for energy exports, and the investor refunds 17 642 EC to the community, with the *EGAC* remaining neutral.

Table 5.5 - Scenario 4: Energy Credit Settlement Summary.

ED1	ED2	ED3	ED4	EGAC	RESP	INVESTOR
-1263	11757	2041	-5692	0	10799	-17642

These net positions balance to zero, confirming that all credits have been fully reconciled. This outcome underscores the viability of the hybrid P2P-investor model, demonstrating its capacity to redistribute costs and revenues equitably among participants before complete settlement.

5.1.5 - Scenario 5: Full Market Model

In Scenario 5, all stakeholders, ED1 through ED4, the *EGAC*, and the investor, engage in energy credit exchanges, combining P2P trades, *EGAC*-mediated transactions, and investor lease operations. Daily wallet updates continue to follow the previously defined Equation 9. The P2P transaction and investor rules remain identical to those in Scenarios 2 and 4, while *EGAC* exchanges mirror the mechanisms introduced in Scenario 3.

For clarity, Figure 5.7 illustrates an example of some EC transactions in Scenario 5. It shows P2P exchanges, such as a service from ED4 to ED3 paid in ECs and a credit purchase by ED1 from ED2. The investor receives ECs in advance for equipment use agreements with ED1,

ED2, and ED3, as in Scenario 4. EC transactions also occur between the *EGAC* and the buildings, based on net production or consumption, and between the *EGAC* and the *RESP* to ensure a zero-sum energy balance. While not exhaustive, this figure exemplifies the diversity and simultaneity of possible value exchanges within the REC.

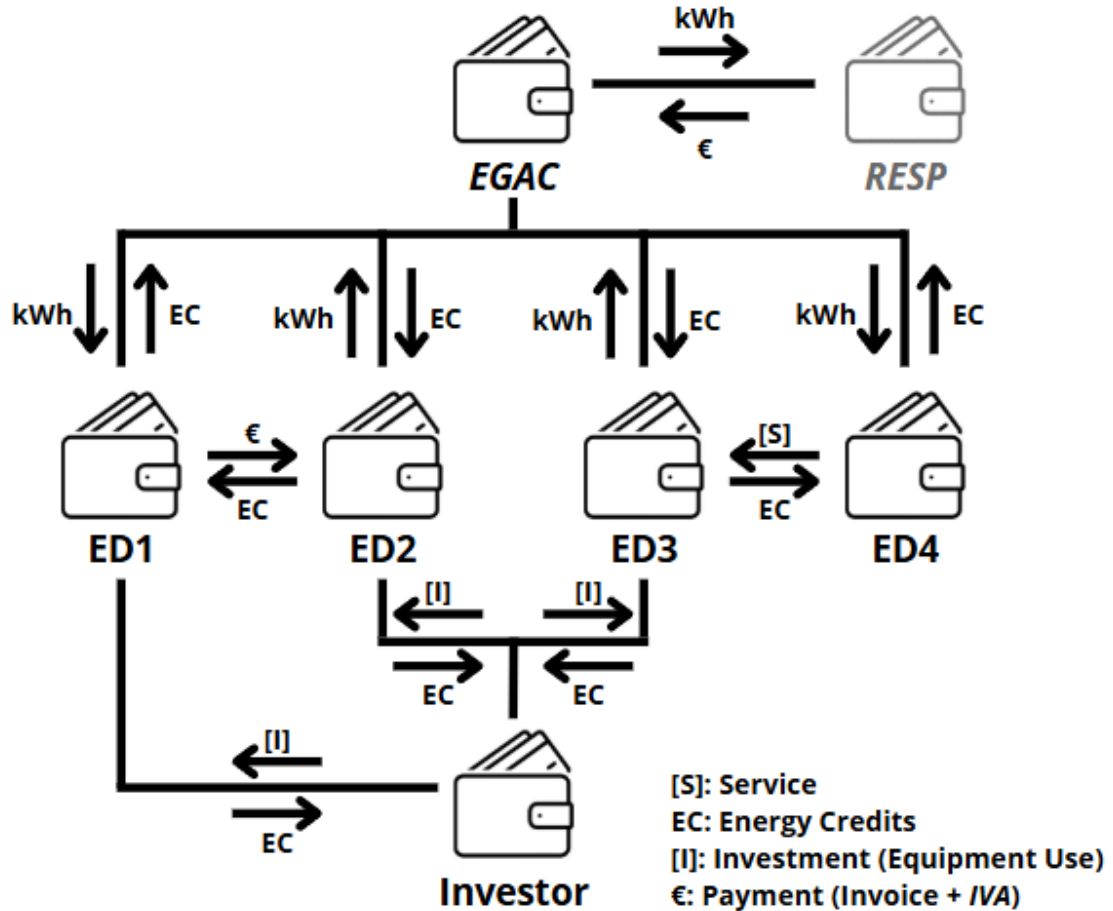


Figure 5.7 - Example of Energy Credit Flows in Scenario 5.

Figure 5.8 depicts the annual evolution of each stakeholder's EC wallet under the hybrid P2P-investor model.

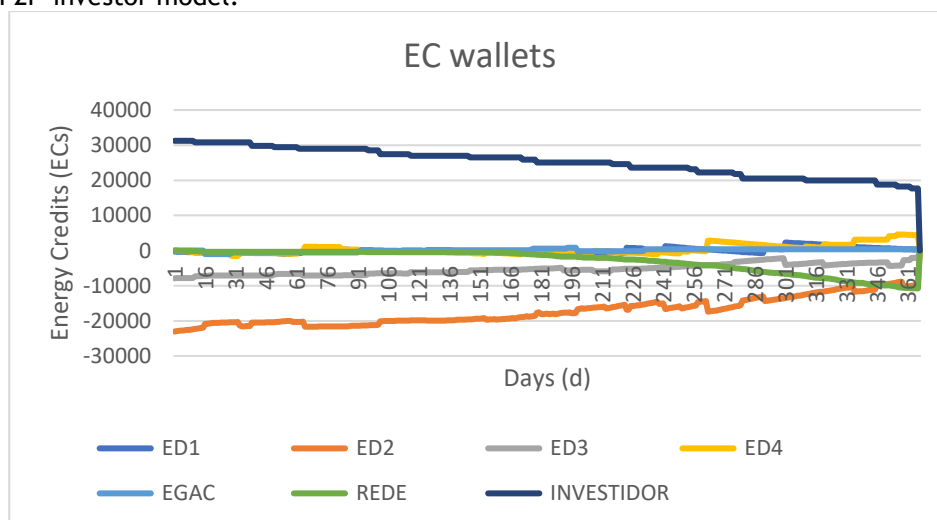


Figure 5.8 - Each stakeholder's Energy Credit wallet value throughout the year in scenario 5.

Table 5.6 shows the results of the final settlement of Scenario 5.

Table 5.6 - Scenario 5: Energy Credit Settlement Summary.

ED1	ED2	ED3	ED4	EGAC	RESP	INVESTOR
-263	9757	2041	-4342	-350	10799	-17642

The ECMS records show that ED1 and ED4 transferred 263 and 4 342 EC to the *EGAC* (receiving payment in return), while ED2 and ED3 received 9 757 and 2 041 EC from the *EGAC* (and made the corresponding payment). The *EGAC* settled at -350 EC, effectively balancing its intermediary role, and the *RESP* ended again with -10 799 EC, as expected. The investor's position closed at -17 642 EC, corresponding to the upfront lease receipts refunded at year's end. These figures sum to zero, confirming that all credit flows, across P2P, *EGAC*-mediated, and investor transactions, have been fully reconciled.

5.1.6 - Comparative Assessment and Takeaways

In conclusion, using Energy Credits endows the REC with an exceptionally flexible transactional layer that can accommodate virtually any market design or business model. Credits seamlessly adapt to trading arrangements via pre-contracted volumes, time-varying price signals, or advance payments.

They enable *prosumers* and consumers alike to negotiate bespoke deals, be they P2P swaps, *EGAC*-mediated exchanges, or investor leases, without requiring wholesale changes to the underlying metering or billing infrastructure. This versatility supports a rich diversity of operational scenarios. It lays the groundwork for future innovations, such as dynamic demand response programmes, community-wide auctions, or token-based reward schemes, all built upon the same transactional layer of the Energy Credits.

Chapter 6

Conclusion

This final chapter offers a comprehensive reflection on this dissertation's main findings and contributions, highlighting the technical and social relevance of the Energy Credits model within Renewable Energy Communities.

It revisits the research questions and objectives, assesses the extent to which they have been achieved, and discusses the broader implications of the proposed system. Additionally, it outlines potential future research directions, reinforcing the transformative potential of digital energy value transactions in decentralised community contexts.

6.1 - Final Considerations and Main Contributions

This dissertation introduced and implemented ECs as a novel digital transaction mechanism for RECs, where each EC represents 1 kWh of renewable generation. Against the backdrop of a decentralising energy sector, driven by increasing renewable integration, digitalisation, and new EU mandates such as Directive 2018/2001, RECs have emerged as participatory, local energy ecosystems that empower prosumers and stakeholders to produce, consume, and share clean electricity collectively.

The ECMS was developed to enable these communities to operate efficiently and transparently. This platform records all EC issuance, consumption, redistribution, and trading events in real time, ensuring a zero-sum energy balance and full auditability while complying with Portugal's PNEC 2030 targets for renewable uptake.

The conceptualisation and technical design of the ECMS were addressed in Chapter 3, where the lifecycle of ECs, covering issuance, consumption, P2P trading, and mediation by entities like the *EGAC* and investors, was defined. The chapter detailed the logical architecture, data structures, and transaction flows, establishing the foundation for its

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implementation in a real-world scenario. This theoretical framework enabled a shift from passive energy allocation methods to active, community-driven trading and redistribution mechanisms.

Chapter 4 presented a case study involving four buildings with different production and consumption profiles. Using 15-minute interval data, the chapter explored energy flows within the REC, applying traditional sharing models and testing a virtual redistribution of surplus energy. The analysis demonstrated increased self-consumption ratios and reduced injection into the public grid, laying the groundwork for introducing ECs. Furthermore, the internal energy dynamics characterization validated the technical assumptions necessary for the ECMS to operate effectively.

Finally, Chapter 5 explored five progressive implementation scenarios for the ECMS, ranging from fully centralised redistribution to fully decentralised trading, including the participation of an investor entity. These simulations illustrated how ECs can dynamically reconfigure value flows, offering new incentives and correcting imbalances within the community. The results confirmed the system's potential to enhance equity, provide transaction traceability, and promote economic efficiency across diverse stakeholder profiles. It was proven in Scenario 1 that ECs can serve as a reliable energy accounting system, recording all generation and consumption events with full traceability. Scenario 2 demonstrated the feasibility of direct peer-to-peer (P2P) transactions between members, confirming the flexibility and autonomy that ECs offer to individual prosumers. In Scenario 3, the ECMS enabled the EGAC to act as an effective intermediary, managing redistributions and ensuring fair value allocation across the community. Moreover, the system allows for energy transfers on a social basis without monetary exchange, facilitating donation or compensation mechanisms that can benefit vulnerable consumers.

The simulations further confirmed that ECs support a form of net metering, where excess generation can be virtually stored and later used to offset consumption. This ensures a dynamic balance between production and usage, promoting self-sufficiency within the REC. Additionally, the flexibility in credit valuation and transaction rules opens the possibility of supporting internal energy markets, where credits can be traded based on time-of-use, demand, or social priorities. The Energy Credits model introduces numerous advantages: decentralisation, flexibility, equity, support for non-monetary exchanges, and compatibility with technical infrastructures and regulatory frameworks.

6.2 - Research Questions: Discussion and Answers

The present subchapter aims to revisit and systematically address the following research questions outlined in Chapter 1, considering the results obtained throughout the dissertation:

- **How can this new value transaction model be technically viable and compatible with existing infrastructures? Will the development of new digital platforms and control mechanisms be necessary to integrate ECs without compromising grid stability and transaction security?**

The ECs model is technically viable because it acts as a digital layer over existing infrastructures, using data from smart meters without requiring changes to the physical grid. The ECMS, detailed in Chapter 3, enables the issuance, consumption, and trading of ECs based on 15-minute metering intervals, ensuring full traceability and compatibility with current systems (Sections 3.2 and 3.3).

As demonstrated in Scenario 1 of Chapter 5 (Section 5.1), the ECMS ensures a zero-sum balance and transparent energy accounting within the REC. While developing this digital platform is necessary, it does not interfere with physical energy flows, thus maintaining grid stability. Technologies like blockchain are discussed in Section 2.2.3.1, but are optional enhancements rather than core requirements. This confirms that ECs can be integrated securely and progressively with minimal disruption.

- **How does the adoption of ECs alter value flows within the community? Can this model increase the profitability of decentralized energy production, reduce operational costs, and encourage greater participation from consumers and small producers?**

The adoption of ECs does not change the physical amount of energy exported to the public grid, as observed, export values remained constant across all scenarios (Section 5.1). However, ECs significantly reconfigure the internal value flows within the REC. Instead of relying solely on static sharing coefficients, ECs introduce a dynamic mechanism for tracking, allocating, and exchanging energy value among members (Chapters 3.2 and 5.1).

Furthermore, the flexibility and autonomy introduced by ECs foster greater engagement from consumers and small producers, as members can interact with the system in new ways, accumulating, trading, or donating credits, beyond the constraints of conventional self-consumption models.

- **Do consumers easily understand how energy credits work? What types of governance models and transaction rules can enhance trust among members and ensure community-wide acceptance?**

The ECMS was designed to be transparent and user-friendly, helping consumers understand and trust the EC's system. As detailed in Section 3.3.1, each member has a digital wallet that stores their ECs, shows their balance and transaction history, and allows secure exchanges. This clarity supports user comprehension and confidence.

Trust is further reinforced through the community wallet, managed by the *EGAC*, and through supervision tools that enable audits and external oversight. The system supports P2P and *EGAC*-mediated transactions (Chapter 5), offering flexible governance options. These elements create a secure and accessible platform that encourages community-wide acceptance and participation.

- **To what extent can ECs be implemented without conflicting with existing regulations? Will developing new legal frameworks and policy support be necessary to enable widespread adoption of this concept?**

Implementing ECs is legally viable within RECs if they are used as non-convertible, internal utility tokens and not exchanged for fiat currency or traded on open markets. As discussed in Section 2.2.1 - Legal and Financial Representation of Value, ECs are best classified as utility tokens, simplifying compliance by avoiding their categorisation as financial instruments or securities.

This internal use within the REC allows ECs to operate without conflicting with current Portuguese regulations, particularly when managed by entities like the *EGAC*. However, Section 2.2.1.6 - Monetization and Taxation, highlights that if ECs are ever monetised, e.g., exchanged for fiat currency, they may become subject to taxation (VAT or income tax), and may trigger financial or licensing obligations. Furthermore, compliance with data protection (GDPR) and consumer protection laws is essential, especially when dealing with sensitive transaction data and non-professional users.

Therefore, while ECs can be implemented within a legally compliant REC framework, their widespread adoption, for example, inter-community exchanges, or integration into broader energy markets, would require new regulatory guidelines or policy adaptations. These should clarify the status of ECs, ensure consistent taxation practices, and support innovation while maintaining legal certainty and consumer protection.

- **How can ECs create new incentives for active energy management and support vulnerable consumers within the community?**

Energy Credits create new incentives for active energy management by introducing flexibility and diversity in value transactions within the REC. As shown in scenarios 2 to 5 (Section 5.1), members can engage in P2P exchanges, voluntary donations, or contractual agreements involving services and equipment, all managed through the ECMS.

Additionally, the programmable nature of ECs allows for tailored incentives, such as rewarding flexibility services or enabling compensation for community contributions beyond energy consumption.

At the social level, ECs support internal redistribution that benefits vulnerable consumers. The case study demonstrated that ECs can be shared or allocated without monetary exchange, enabling solidarity-based transactions within the REC.

Through structured agreements (for example, for equipment deployment, service provision, or donations), ECs can circulate to where they are most needed, promoting inclusion and energy equity. The operational capabilities of the ECMS, such as member-to-member service payments or community-to-member support (Section 3.2.5), make it possible to integrate complementary services like social support, technical assistance, or shared infrastructure use, reinforcing the role of ECs not only as a unit of energy value but as a tool for community empowerment and cohesion.

In summary, exploring the proposed Energy Credit model through the lens of the research questions confirms its technical feasibility, regulatory compatibility, and social and economic potential within Renewable Energy Communities.

6.3 - Compliance with Objectives

The present subchapter aims to assess whether the objectives outlined in Chapter 1 were effectively discussed throughout the development of this dissertation. Each objective is revisited considering the methodologies adopted, the systems designed, and the results obtained in the simulation case study.

- **Define the concept of Energy Credits (ECs) and establish their theoretical and operational foundation, distinguishing them from existing compensation systems in local energy markets and identifying their advantages and challenges.**

Energy Credits are introduced in Chapter 2 as symbolic digital units, each representing 1 kWh of renewable energy. Section 2.2.1 examines their legal and financial nature, contrasting ECs with instruments such as digital currencies and guarantees of origin, and discusses the monetisation and regulatory considerations in Section 2.2.1.6. Chapter 3, particularly Sections 3.2 and 3.2.5, then develops the operational framework for ECs within the Energy Credit Management System (ECMS), detailing issuance processes, wallet architecture, and transaction workflows.

The benefits of ECs, flexibility, transparency, decentralised governance, and support for social and market-based exchanges are illustrated throughout Chapter 5, highlighting potential regulatory and practical challenges.

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- **Specify the mechanism for issuing, transacting, and consuming ECs, ensuring that it functions within the REC infrastructure and is compatible with current energy metering and monitoring technologies.**

A comprehensive description of EC lifecycle processes is provided in Chapter 3. Section 3.2 details how 15-minute interval measurements supplied by E-REDES trigger EC issuance. Section 3.2.5 explains the virtual allocation of surplus energy, the automatic update of member wallet balances, and the handling of monetary settlements and non-monetary exchanges. Furthermore, Section 3.3.1 verifies that the cloud-based ECMS, including individual member wallets and the community wallet, integrates seamlessly with existing smart-metering infrastructure, maintaining transparent, secure EC management without altering physical energy flows.

- **Develop a market model for EC transactions among community members, including rules for credit valuation, incentives for participation, and community governance mechanisms.**

The designed and simulated market model based on ECs allows transactions among members of the REC using a digital unit of value (1 EC = 1 kWh), governed by configurable rules as described in Sections 3.2 and 5.1.

Credit valuation is addressed through bilateral agreements, and incentives are embedded in the system's ability to reward active participation and flexibility. For example, in Scenarios 2 to 5 (Chapter 5), members engage in voluntary donations, service exchanges, and multi-agent interactions, reflecting high participation potential. The EGAC handles governance through the community wallet, while trust and transparency are maintained via contract-based rules and digital auditability, as mentioned in Section 3.3.1.

- **Explore the regulatory implications of using ECs, identifying potential legal challenges and proposing strategies for their integration in compliance with existing legislation.**

Section 2.2.1 examines the legal and financial status of ECs as internal utility tokens, while Section 2.2.1.6 addresses monetization and taxation. This work identifies that Energy Credits (ECs), when used as internal utility tokens and not exchanged for fiat currency, can operate within the current Portuguese legal framework without being classified as financial instruments or securities. This classification simplifies compliance and avoids triggering licensing or banking obligations.

However, potential legal challenges are acknowledged, especially if ECs are monetised, for instance, exchanged for euros, which could lead to tax liabilities (VAT or income tax) and regulatory oversight. The thesis proposes that ECs remain confined

to internal REC use to ensure compliance and highlights the importance of adhering to data protection (GDPR) and consumer protection laws, given the involvement of non-professional users and sensitive transaction data. The work thus proposes a cautious but viable strategy for integration. It suggests that broader deployment would benefit from updated legal frameworks that clearly define the scope and boundaries of ECs in energy communities.

- **Examine the potential of ECs to foster additional services within RECs, such as flexibility mechanisms, energy efficiency incentives, and support for vulnerable consumers.**

Section 3.2.5 (Operationalization of the ECMS) shows that the ECMS supports various transactions beyond simple energy exchange. These include credit-based compensation for services, equipment deployment, and member-to-member exchanges, forming the basis for flexibility mechanisms and new services within the REC.

Scenarios 2 to 5 in Chapter 5 exemplify this potential, as members could donate credits, engage in voluntary exchanges, and reward services, all reflecting flexible and socially oriented applications. Moreover, the possibility of allocating ECs without monetary exchange enables targeted support to vulnerable members, reinforcing inclusion and equity.

- **Validate the EC model through simulations or case studies, demonstrating its practical applicability and benefits compared to conventional energy transaction models.**

The EC model simulation framework was developed in Chapter 4 and tested in Chapter 5 in a controlled environment representing a four-building REC, using 15-minute interval energy data and a structured transaction system managed by the Energy Credit Management System (ECMS).

As detailed in Section 5.1, five progressive scenarios were implemented, ranging from a baseline model without ECs to complex configurations involving P2P exchanges, investor participation, and multi-agent interactions. These simulations demonstrated the EC model's ability to reconfigure internal value flows, maintain a zero-sum balance, and accommodate various transaction types without affecting the physical energy exported to the grid. Compared to static self-consumption models, the EC approach proved more flexible, traceable, and inclusive, validating its technical and functional advantages over conventional systems.

6.4 - Future Work and Research Directions

This dissertation laid the groundwork for a new value transaction model within RECs, validated through a comprehensive simulation environment. However, to move from concept to real-world deployment, the next essential step involves developing a functional software application that supports the operational dynamics of the Energy Credit Management System (ECMS) described throughout this work.

This software would consist of two main components: a mobile application for community members and a centralised management platform for the *EGAC*, as referenced in Section 3.3.1. The mobile app, downloadable by each participant, would serve as a **personal wallet interface**, allowing users to view their EC balance, monitor transaction history, send and receive ECs, and interact with services or equipment provision agreements. Meanwhile, the centralised *EGAC* platform would enable **comprehensive system oversight**, including monitoring energy flows, redistributing credits, configuring community parameters, and potentially generating and assigning new wallets to members.

Future development should therefore focus on designing this digital infrastructure with a strong emphasis on usability, security, and compliance, ensuring that it mirrors the functionalities tested in the simulation and supports scalability and integration with real REC environments. This transition from theoretical validation to software implementation will be critical to fully unlocking the potential of energy credits in practice.

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Conclusion

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Appendix A

United Nations Sustainable Development Goals (SDGs)

This dissertation contributes to advancing several United Nations Sustainable Development Goals (SDGs), particularly those aligned with clean energy, sustainable communities, and climate action. The implementation of Energy Credits (ECs) as a decentralised, traceable, and inclusive value transaction model within Renewable Energy Communities (RECs) supports the following SDGs:

- **SDG 7 - Affordable and Clean Energy:**

The core objective of this work is to promote the local production, consumption, and sharing of renewable energy. By enabling transparent and equitable internal transactions through ECs, the model enhances access to affordable and clean energy at the community level.

- **SDG 11 - Sustainable Cities and Communities:**

The proposed EC system fosters energy resilience and autonomy within urban and rural communities. It empowers citizens and local stakeholders to manage collective energy and invest in shared infrastructure, contributing to more sustainable and participatory energy ecosystems.

- **SDG 12 - Responsible Consumption and Production:**

The ECMS supports more efficient energy use by aligning consumption patterns with local renewable generation. The model encourages behavioural shifts through

incentives and flexible credit flows that reduce dependency on centralised systems and promote conscious energy practices.

- **SDG 13 - Climate Action:**

By facilitating the integration and optimisation of renewable energy in local networks, ECs contribute to decarbonisation efforts and help reduce greenhouse gas emissions. The system also promotes energy equity, essential for transitioning to a low-carbon economy.

- **SDG 9 - Industry, Innovation and Infrastructure (indirectly):**

The development and potential future deployment of a digital platform based on ECs, including mobile apps and a centralised management interface, aligns with fostering innovation and building resilient, inclusive digital infrastructures within the energy sector.

Overall, this dissertation offers a concrete pathway for operationalising the principles of the SDGs through a technical solution that promotes energy sustainability, community empowerment, and digital innovation.