Digitalization of a Shared Hydrogen Storage System within an Energy Community using Smart Contracts

INTELLIGENT ELECTRICAL POWER GRIDS

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Abstract

As global efforts accelerate the transition towards renewable energy sources and decentralized energy systems, the challenge of managing surplus energy during off-peak hours becomes increasingly critical. Without effective and innovative storage solutions, excess capacity from renewable energy resources is being unexploited, reducing the efficiency and sustainability of these technologies. This thesis addresses this issue by proposing the integration of Shared Hydrogen Storage Systems (SHSS) within Energy Communities (ECs), providing a viable method for storing surplus energy as green hydrogen.

By converting and storing renewable energy into hydrogen, ECs can ensure a stable green energy supply, mitigating fluctuations and enhancing energy security. This research presents a modular energy-sharing architecture that integrates blockchain-based smart contracts, with algorithms for equitable distribution and trading of hydrogen capacity between community households. Simulations and case studies test the algorithms for hydrogen storage sizing and fair capacity allocation, while also exploring the potential of hydrogen-based heating systems.

The results showcase the critical role of hydrogen storage in increasing the efficiency of renewable energy systems, even during periods of low demand. Two models developed from the simulations demonstrate the practical dynamics of using hydrogen for long-term energy storage in urban environments. This work provides a framework for the practical implementation of shared hydrogen storage for electrification and heating, contributing to the transition towards decentralized, carbon-neutral urban energy infrastructures.

Abbreviations

Abbreviation	**Definition**
ACC	Adaptive Consumption Coefficient
AEL	Alkaline Electrolyzer
AFC	Alkaline Fuel Cell
BESS	Battery Energy Storage System
BRP	Balancing Responsible Party
CESI	Community Energy Share Index
DER	Distributed Energy Resources
EC	Energy Community
EMS	Energy Management System
EV	Electric Vehicle
EUV	Energy Uncertainty Variance
FCEV	Fuel Cell Electric Vehicle
HPI	Household Participation Index
LEM	Local Energy Market
LTS	Long-Term Storage
P2G2P	Power-to-Gas-to-Power
P2P	Peer-to-Peer
PEM	Proton Exchange Membrane
PEMFC	Proton Exchange Membrane Fuel Cell
RT	Real Time
SCI	Spatial Consumption Index
SHSS	Shared Hydrogen Storage System
SoC	State of Charge
SOEC	Solid Oxide Electrolyzer Cell
SOFC	Solid Oxide Fuel Cell
V2G	Vehicle-to-Grid
VPP	Virtual Power Plant

Contents

1 Introduction

The increasing share of **Distributed Energy Resources** (DERs) has brought about a significant shift in the energy system landscape, gradually shifting from traditional centralized models to more decentralized and community-driven configurations [1]. Within these decentralized energy structures, **Energy Communities** (ECs) appear crucial in steering the transition toward a cleaner and more sustainable future. These communities, typically defined as microgrids consisting of energy-interconnected households, energy storage technologies, and local DERs, predominantly rely on renewable energy sources instead of traditional fossil fuel-based power [2].

An innovative approach to managing surplus renewable energy involves its conversion into hydrogen for long-term energy storage. This thesis explores the integration of a **Shared Hydrogen Storage System** (SHSS) within ECs, focusing on developing an architectural framework that incorporates algorithms for equitable energy distribution and blockchain technology to manage energy interactions between community members. This design aims to enhance sustainability while focusing on increasing energy security and social welfare. By converting and storing surplus renewable energy to hydrogen, these communities can effectively mitigate the intermittency challenges associated with renewable energy sources, ensuring a continuous and reliable energy supply. Additionally, the integration of smart contracts within this framework facilitates a sophisticated configuration of **Local Energy Markets** (LEMs), improving communication, ensuring energy transparency, and enabling efficient energy transactions among community members without the need for third-party organizations.

Despite the growing interest in sustainable energy communities, there remains a significant gap in understanding and implementing shared utilities within these communities. Specifically, the potential of shared hydrogen storage in these settings is an under-explored area, with various sharing strategies and mechanisms only recently beginning to be discussed. Rather than aiming to fill these gaps, this research seeks to classify the existing knowledge and encapsulate it into a cohesive, modular architecture. This architecture is designed to seamlessly integrate into energy communities, enabling a more effective and practical adoption of shared hydrogen energy storage systems. By incorporating user preferences and trends, pioneering technologies, and utility-sharing strategies, this thesis aims to provide a comprehensive framework that can facilitate the implementation of hydrogen storage solutions within energy communities.

1.1 Research Gap

While significant progress has been made in developing sustainable housing and low-voltage energy grids, comprehensive strategies for shared utilities, particularly those involving hydrogen storage, remain largely under-explored. Hydrogen storage holds immense potential to enhance the reliability and efficiency of energy systems within ECs, however, it has not been thoroughly researched or practically implemented. The exploration of hydrogen storage in these settings is still in its early stages, with various sharing strategies and mechanisms only recently being discussed.

The gap in research, particularly towards creating an architectural framework for energy community households and sharing utilities, can be attributed to several key reasons:

- **Complex Stakeholder Behavior**: The varied and complicated behaviors of stakeholders within energy communities complicate the development of universal solutions. Each community contains individuals with distinct energy consumption patterns, preferences, and priorities, making it challenging to devise a one-size-fits-all architectural framework.
- **Diversity of Energy Communities**: Energy communities are diverse in composition, size, and energy needs. This kind of diversity necessitates tailored approaches to utility sharing, which are often lacking in current research due to the novelty and complexity of these communities.
- **Lack of Standardized Consumer Inputs**: The relatively recent conceptualization of energy communities and shared utilities entails a lack of standardized consumer feedback and energy data. This lack of input hinders the ability to design frameworks that effectively meet the varied needs of different communities.
- **Apprehension Towards Modern Technologies**: There is a prevailing fear of implementing modern technologies like hydrogen storage and advanced batteries in urban landscapes. Concerns about potential malfunctions, safety risks, perceived inadequate benefits, high maintenance costs, and apprehension toward operating cutting-edge systems contribute to this apprehension.
- **Economic Concerns**: The perceived high costs associated with the adoption of new technologies for energy storage and management deter many communities from exploring these options. Economic feasibility and cost-benefit analyses are often under-researched areas that need more attention.
- **Safety and Environmental Impact**: The potential safety hazards and environmental impacts of modern energy storage technologies are significant concerns. Fear of negative outcomes, whether real or perceived, inhibits the willingness of communities to adopt these innovations in their daily lives.

1.2 Research Objective

To overcome the aforementioned gaps in research, this thesis **aims to realize an architecture that supports the complex nature of ECs, safely introducing shared energy utilities and facilitating a blockchain-based environment for energy transactions.** The primary goal is to develop a modular architecture that applies to all ECs. The platform shall be easily managed by the EC administrator and shall be intuitive enough that all EC members can use it. The platform shall also have a straightforward interface to facilitate energy monitoring and energy trading among EC members.

Another key objective is to research and gather input from relevant stakeholders and residents of ECs to determine their energy requirements and preferences regarding shared utilities and hydrogen storage. This will help identify diverse energy consumption patterns and trends within the urban energy sector, as well as gauge the level of interaction desired from the proposed system. To collect these valuable data points, an **anonymous survey** will be conducted to acquire anonymous energy profiles from EC members and other relevant participants.

Additionally, together with the proposed architecture, it is crucial to investigate how much energy a long-term storage system should provide. To achieve this, several models will be developed to achieve optimal sizing of the shared hydrogen storage system alongside equitable capacity allocation among its stakeholders. The research will also explore the possibility of using hydrogen directly for heating. These models are crucial for calculating total EC energy requirements, required hydrogen capacity, and testing the possibility of simulating a blockchain-based LEM through **smart contracts**.

By realizing such a comprehensive and modular framework, ECs can achieve better integration of DERs, **Battery Energy Storage Systems** (BESS), and hydrogen followed by emerging shared utilities. This will allow optimized energy operation, system resilience, and energy transparency. To achieve this, the following thesis poses its foundations on the following research questions:

1. How can the optimal size for a shared hydrogen tank be determined?
2. Is it possible to facilitate H_2 heating within the energy community on an annual basis?
3. What mechanisms need to be designed to operate and integrate shared hydrogen storage within the community?
4. When is the introduction of shared hydrogen storage a sustainable long-term storage solution for the ECs of the future?

1.3 Previous Work

Research on integrating SHSS infrastructure within ECs has only recently been making notable progress [3]. Early studies demonstrated that shared storage enhances energy security, can reduce energy costs, and improves energy efficiency. However, specific investigations into hydrogen as a storage medium have highlighted the importance of efficiency and cost-effectiveness in hydrogen storage technologies [4]. These studies found that optimal community involvement in futures and spot markets is crucial for risk aversion and for increasing self-sufficiency levels of energy.

Implementing shared hydrogen storage requires robust governance frameworks and market mechanisms [5]. Innovations like blockchain technology and smart contracts have emerged as solutions to manage and automate energy trading within ECs, ensuring transparency, security, and efficiency. A functioning example that does not incorporate hydrogen is the Brooklyn Microgrid [6], [7].

Practical implementations in Germany's Sonnen Community [8] and the Brooklyn Microgrid in the USA highlight the potential of community-driven energy models. However, hydrogen storage in urban settings remains an under-explored field, and it is currently in the research phase. These examples demonstrate the successful deployment of shared storage systems and peer-to-peer trading platforms, underscoring the need for further research to introduce hydrogen infrastructure within urban ecosystems.

Future research directions focus on optimizing the size, capacity and efficiency of hydrogen storage systems, enhancing economic viability, and improving hydrogen production and utilization technologies. This thesis builds on these foundations by developing a comprehensive and modular framework to facilitate the practical implementation of hydrogen storage solutions and blockchain-based energy sharing, promoting sustainable and resilient energy communities.

1.4 Relevance of Research

The research addresses significant gaps in the current understanding and implementation of shared hydrogen storage systems within ECs. By integrating several subsystems, the study provides a comprehensive framework encompassing technological, economic, and social dimensions, offering a novel approach to storage capacity allocation and management.

The architecture will comprise models that combine the necessary subsystems for hydrogen production, storage, compression and allocation to ECs. Alongside algorithms for total energy demand calculation, the simulated EC households can facilitate hydrogen capacity transactions. The finalized architecture will facilitate realistic calculation of sustainable energy requirements for future ECs.

The findings can be valuable to policymakers developing guidelines for emerging ECs. The proposed governance frameworks and market mechanisms provide a foundation for regulatory structures supporting sustainable EC growth and community activism [9, 10]. Stakeholder engagement is a key element of this paper, while incorporating the perspectives of EC members ensures that the proposed solutions are realistic and can align with community needs. This participatory approach empowers stakeholders, promoting active involvement and ownership of the energy system, thereby enhancing social acceptability and the success of implemented solutions.

The integration of shared hydrogen storage systems can significantly improve the operation and efficiency of energy systems within ECs. Optimizing energy storage and distribution enhances overall energy infrastructure performance and contributes to a stable grid, even when high demands are evident. The use of smart contracts and blockchain technology for energy trading ensures transparency and security, leading to better resource management and improved energy allocation for community members [9, 10, 11].

1.5 Outline

The structure of this thesis is presented so that each aspect of the research is first explored and then used for the continuation of this thesis. The outline of the thesis is as follows:

1. **Introduction**
    - Provides an overview of the research context, research gap, research objectives and research questions, previous work, relevance of research, and outline.
2. **Literature Review and Emerging Research Frontiers**
    - Explores the dynamics of energy communities and the integration of shared hydrogen storage systems.
    - Reviews collaborative models for sustainable energy practices and for sharing utilities.
    - Examines the role of hydrogen storage in energy communities and the associated technical, economic, governance, and market strategies.
    - Investigates the use of hydrogen for heating in urban scenarios.
3. **Methodology**
    - Describes the research design, including the survey implementation and data analysis techniques.
    - Outlines the methodological approach to assessing the viability of hydrogen for urban heating.
    - Details the methods for optimal sizing calculation of shared hydrogen tanks, focusing on energy security and equipment longevity.
    - Introduces the PENELOPE architecture for the digitalization of shared utilities.
    - Introduces the `Complex Model` based on PENELOPE and the relevant algorithms.
4. **Applications**
    - Presents case studies illustrating the practical applications of the research findings.
    - Showcases the modular potential of the `Complex Model` through a series of scenarios.
    - Compares the results obtained from the `Benchmark Model` and the `Complex Model`.
    - Discusses the long-term sustainability and scalability of the proposed solutions.
5. **Conclusion**
    - Summarizes the key findings and implications
    - Discuss the central research question
    - Identify potential areas for future research.

2 Literature Review and Emerging Research Frontiers

The literature review chapter provides a comprehensive exploration of the dynamics of energy communities and the integration of shared hydrogen storage systems. It commences with **Section 2.1**, setting the stage with foundational concepts and characteristics of energy communities. **Section 2.2** examines collaborative models for sustainable energy practices, while **Section 2.3** delves into the role of hydrogen storage in energy communities. **Section 2.4** addresses economic, governance, and market strategies for shared hydrogen storage integration. Additionally, **Section 2.5** explores the use of hydrogen for heating in urban scenarios, and finally, the chapter concludes with **Section 2.6**, summarizing the essential findings and insights.

2.1 The Energy Community: Definition and Characteristics

The increasing share of **Distributed Energy Resources** (DERs) has brought about a notable shift in the local energy framework, moving away from a centralized top-down[1] towards a decentralized bottom-up[2] structure [1]. Within these decentralized energy systems, **Energy Communities** (ECs) emerge as pivotal players in steering the transition towards a cleaner and more sustainable future. These communities are typically microgrids encapsulating energy-interconnected households, storage technologies, and local DERs and predominantly rely on renewable energy sources instead of traditional fuel-based power systems generators [2].

Figure 1: Typical Layout of Interconnected housing with DERs and Storage [12]

The emergence of novel digital platforms for collaborative data exchange has significantly contributed to the proliferation and integration of ECs. These innovative socio-technical systems, which function as legal entities with diverse stakeholders, yield environmental, economic, and social benefits for a community [1], [13].

For this paper, the EC structure resembles that of a local neighborhood microgrid. All households feature **energy management systems** (EMSs) and are interconnected, allowing the users to monitor consumption in real-time and decide how energy is consumed. In addition, the EMS provides

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[1] Top-Down: The traditional structure in which directives flow hierarchically downwards.

[2] Bottom-up: Decisions originate from individual levels and move upwards. Community-driven initiatives are emphasized.

flexibility to the users by allowing their utilities to be shared within the community. The primary sources of carbon-neutral energy in this configuration typically are photovoltaics (PVs) and wind turbines, supplemented by a Battery Energy Storage System (BESS) to bolster grid resilience and manage surplus energy.

This research delves into the cutting-edge application of hydrogen as a shared **Long-Term Storage** (LTS) option, offering a sustainable means to supply the EC with carbon-free electricity year-round. To effectively integrate shared hydrogen storage within an EC, it is crucial to understand that beyond the physical installation and coordination needs, there is a need for user awareness about the technology. This understanding extends to how the technology fits into the stakeholders' daily lives, impacting their existing knowledge and routines. It's about bridging the gap between the technical aspects and practical, everyday applications and implications for the users. The ultimate goal is a "Business-as-Usual" approach, where the system operates with minimal user intervention, maximizing its benefits without adding to the users' responsibilities.

2.2 Collaborative Approaches in Energy: Sustainable Communities and Shared Utilities

Research highlighting noteworthy examples of urban energy collaboration is conducted to understand the importance of energy sharing within sustainable community living. By examining the following blueprints, insights into the origins and evolution of ECs are gained and their potential to advance sustainability and social cohesion in the future is explored. This analysis illuminates the pathways through which ECs contribute to a more sustainable and interconnected society.

2.2.1 Examples of Sustainable Energy Communities and Shared Utilities

The history of community-led energy initiatives dates back to the early 90s, when distributed energy resources were expensive to purchase and to be introduced to urban settings. The adoption of such technologies was influenced by factors such as government incentives, but also due to increased awareness of sustainability by the users.

Figure 2: Energy Community of Schönau, Germany [14]

Schönau Community (Germany) - Founded in 1991: The Schönau Power Supply (EWS Schönau) shown in Figure 2 is considered one of the earliest examples of a community-led energy initiative.

It started in 1991, when residents of Schönau were driven to action in the aftermath of the 1986 Chernobyl disaster, resulting in strong advocation for a regional transition to clean energy [15]. An action group was formed, which ultimately motivated and transformed the village's energy landscape to include DERs and inspired a national movement toward cleaner and more decentralized energy systems.

The example of EWS is noteworthy as it showcased how the users themselves helped the transition to renewable energy. The story serves as a testament to the power of **community activism** and shows that small communities are capable of taking control of their energy destiny, thus reducing reliance on traditional energy sources. Today, the EWS has over 185.000 supporters nationwide, while continuously financing new technologies in the sustainability domain and expanding its philanthropic outreach.

Sonnen Community (Germany) - Established in 2010: The Sonnen Energy Community in Germany, established in the 2010s, is another noteworthy EC example. The project had the vision to revolutionize the energy landscape in urban areas and to create decentralized and sustainable energy solutions. Sonnen quickly emerged as a pioneer in the energy sector by incorporating the concept of **Virtual Power Plants**[3](VPPs) with community-based battery storage. Until then, the idea of harnessing surplus energy in batteries and thus making it possible to be used later was not seen as a commercially successful possibility.

Figure 3: Sonnen Energy Community [8]

In the coming years, Sonnen became a global leader in commercial and residential battery solutions, offering several battery technologies ranging from indoor-rated, stackable battery systems to all-in-one outdoor solutions. Furthermore, Sonnen's VPP concept of "Sonnen Community" allows homeowners with Sonnen battery systems to share their surplus energy with each other. This **peer-to-peer** (P2P) energy-sharing model enhances energy independence and reduces reliance on traditional utility providers [16].

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[3] Virtual Power Plant: Cluster of small load and generation entities that are aggregated as a single market participant to provide systemic flexibility [1].

Brooklyn Microgrid (United States of America) - Established in 2016: The Brooklyn Microgrid, run by LO3 energy and supported by Siemens, is another EC example that brought something new to the realm of energy communities. Specifically, a focus on P2P energy trading has brought this decentralized energy system to be paired with **a blockchain-enabled transactive platform**, which facilitates secure and transparent energy transactions [6]. As a result, the EC members can buy and sell energy capacity through smart contracts in a local, decentralized energy market, making aggregated energy independence possible.

Figure 4: Rooftop Example inside the Brooklyn Microgrid [17]

The Green Village: The Green Village in the Netherlands is a pioneering living lab located at the Delft University of Technology campus. This energy community differs as it is designed as an innovative platform for sustainable development, focusing on the creation and testing of new technologies, energy systems, and approaches for a greener future. The village functions as a real-world testing ground where researchers, students, companies, and government entities collaborate to explore sustainable solutions in energy, water, mobility, and building materials. The goal lies in developing practical, scalable models that can be implemented in broader society to address environmental challenges [18].

Figure 5: Green Village in The Netherlands, Render by [19]

Among the technologies employed at the Green Village, there are also advanced energy systems that prioritize renewable sources, such as PVs and wind turbines, all integrated within an intelligent microgrid, which can optimize energy distribution and resource use [18]. The village also explores sustainable building techniques, using bio-based materials and innovative designs to reduce carbon footprints. Water management systems aimed at reducing consumption and recycling wastewater, along with green mobility solutions, are part of its comprehensive approach to sustainability. Finally, a gas network called the "Hydrogen Street" has already been laid out, allowing third parties to conduct practical research with hydrogen.

Table 1 outlines the attributes and technological implementations within the discussed ECs, highlighting their role in advancing sustainable urban development. These ECs are instrumental in not only validating technological innovations but also in delivering significant economic and social advantages. Moreover, their promotion of localized energy production and consumption promotes the development of an advanced decentralized and resilient energy grid.

Table 1: Technologies within Energy Communities

Technologies Implemented in EC	**EWS, GER**	**Sonnen, GER**	**Brooklyn Microgrid, USA**	**Green Village, NL**
Solar Power	X	X	X	X
Wind Power		X		X
Battery Energy Storage		X	X	
Hydrogen Energy Storage				
Virtual Power Plant Energy Trading		X	X	X
Energy Trading through Blockchain			X	

It is evident that an emergent frontier for ECs, yet to be actualized in practice and not in pilot sites, **is the integration of green hydrogen systems to harness energy from surplus DER electricity.** While the Green Village already incorporates hydrogen infrastructure and pipelines intended primarily for hydrogen-based heating solutions, **the ambition extends to adopting a P2P architecture similar to the Brooklyn Microgrid.** This approach aims to transform shared hydrogen storage capacities into a tradable commodity among participants of ECs, thereby enhancing the communal energy framework.

This ambition is crucial for the future of sustainable energy grids. Integrating hydrogen energy storage within ECs is essential for efficiently managing the excess energy supply from DERs. Instead of curtailing renewable energy production during periods of oversupply or switching off energy generation, the excess green energy can be converted into green hydrogen for later use [20]. This green hydrogen can be stored long-term and used for electricity generation, heating, or as a vehicle transportation fuel. This proposition, further improved by adopting a P2P energy trading mechanism, is the next logical step for correctly implementing hydrogen energy storage in emerging ECs, while also managing the inevitable oversupply of DERs during low demand periods [21], [22].

2.2.2 The Evolution of Energy Communities: Incorporating Shared Hydrogen Storage Systems

In this chapter, the evolution of ECs is assessed, focusing on emerging technologies relevant to the integration of hydrogen in urban settings and sustainable alternatives to already existing infrastructure. Furthermore, the option of hydrogen as a clean energy carrier and sustainable means of shared energy storage is explored.

Vehicle-to-Grid (V2G) Systems: These systems represent a transformative step in the evolution of urban transportation infrastructure, shifting the paradigm from internal combustion engines (ICEs) to more sustainable solutions that utilize battery energy, hydrogen, and electric motors. While electric vehicle (EV) technology is not new, its integration into urban infrastructure as a shared utility has gathered increasing attention.

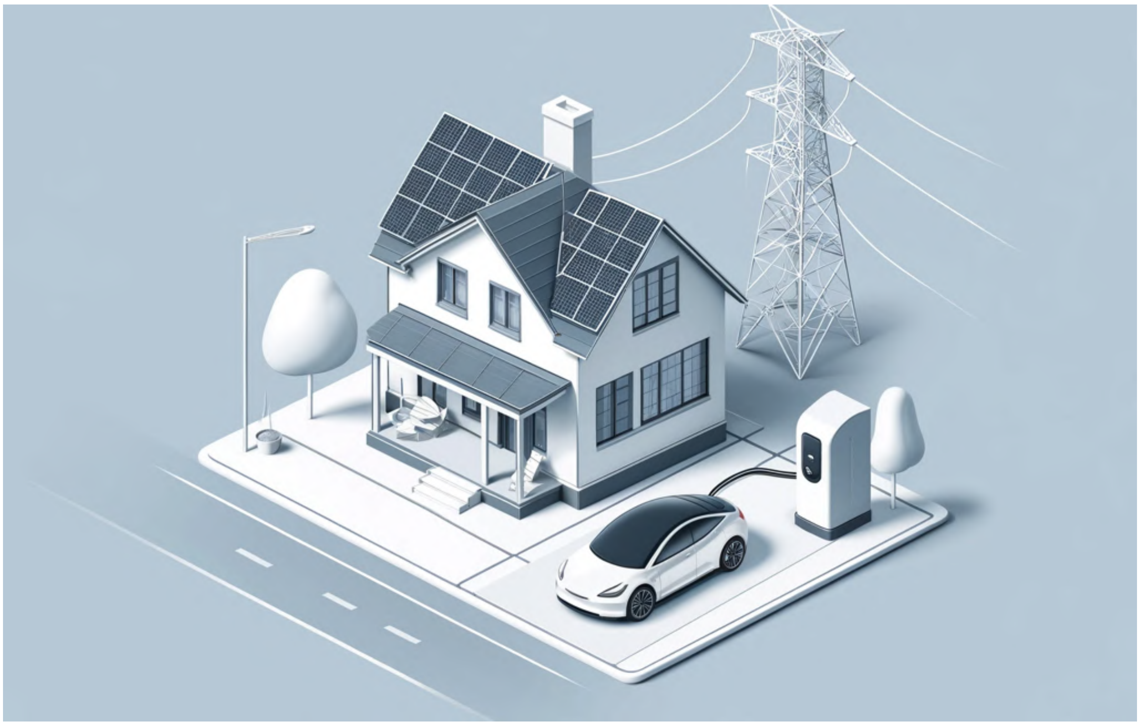

Figure 6: Vehicle-to-Grid Connected to H2 Infrastructure and Household (Render by Author)

Despite their environmental benefits to ICEs, EVs face criticism due to concerns related to battery production, electricity sourcing for charging, and disposal challenges [23]. In contrast, hydrogen fuel cell electric vehicles (FCEVs) present distinct environmental advantages. These include extended driving ranges, rapid refueling capabilities, and a comparatively smaller on-board battery. Additionally, due to the higher energy density of compressed hydrogen, FCVs offer enhanced scalability, making them particularly suited for larger vehicles. The research underscores that the adoption of FCVs in the transportation sector would significantly reduce greenhouse gas emissions in comparison to EVs and ICE cars [24]. Given their resemblance to current ICE trends, FCVs are likely to be incentivized and adopted more easily than EVs, thus facilitating their integration into emerging energy communities.

This integration promotes a more resilient and sustainable EC grid. Notably, ongoing research in the Green Village demonstrates the potential of FCEVs and V2G infrastructure to sustain residential areas autonomously and maintain energy neutrality [25]. This incorporation is a crucial step in facilitating the unification of vehicles into the energy grids of future ECs, underlining the role of FCEVs in advancing sustainable urban networks.

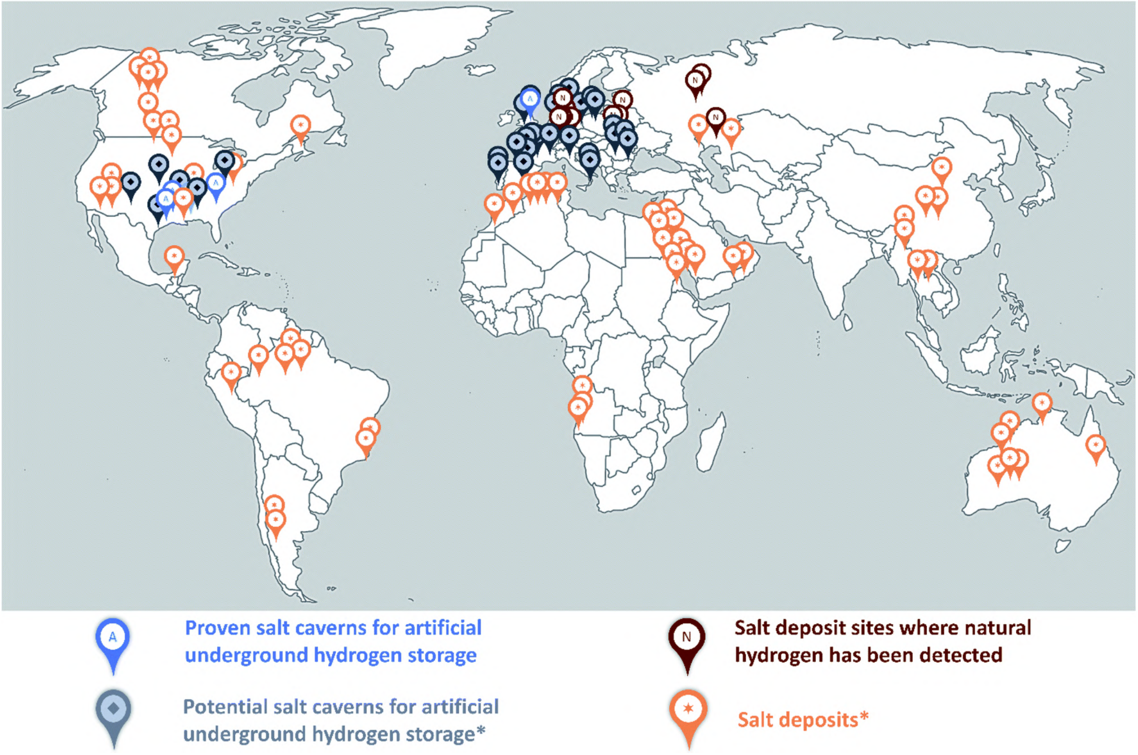

Figure 7: Locations of large underground hydrogen storage locations [26]

Advancements in Hydrogen Infrastructure: The assimilation of hydrogen storage in urban environments is gaining momentum due to the increasing focus on hydrogen infrastructure, particularly in the United States [27]. The country has witnessed significant advancements, with several locations already implementing underground hydrogen storage facilities [28], [26]. Additionally, the deployment of electrolyzers to utilize surplus electricity from DERs for hydrogen production is receiving attention like never before. California is leading in this area, targeting carbon neutrality by 2045 and actively pursuing the production of zero-emission hydrogen through **hydrogen hubs**. This approach is central to the state's strategy to decarbonize its electricity grid [29]. The state's initiatives, coupled with federal support and policies, reflect a growing emphasis on hydrogen as a key element in future energy strategies.

These initiatives indicate a strong potential for hydrogen to enhance EC resilience and sustainability. Furthermore, the introduction of even more examples of hydrogen energy systems will undeniably accelerate the facilitation of this technology into urban infrastructure. As the technology evolves and becomes more economically viable and accessible, it is beneficial to already prepare mechanisms and policies to ensure that **Shared Hydrogen Storage Systems** (SHSS) within ECs can be appropriately utilized.

2.3 Shared Hydrogen Storage as a Key Enabler for Sustainable ECs

Hydrogen storage stands at the forefront of innovation in sustainable ECs, offering a transformative solution to address the intermittent nature of **renewable energy sources** (RES) and optimize their integration into the energy landscape. As these communities increasingly rely on renewable resources, the need for effective energy storage systems becomes paramount to ensure a consistent and reliable energy supply. Hydrogen, as an energy carrier, holds immense promise in this regard. It not only provides a means to store surplus energy during periods of high generation but also allows for quick conversion back into electricity when demand peaks and more energy is needed. This **Power-to-Gas-to-Power** (P2G2P) approach not only extends the reach of renewable energy but also enables the creation of highly resilient and self-sufficient energy ecosystems.

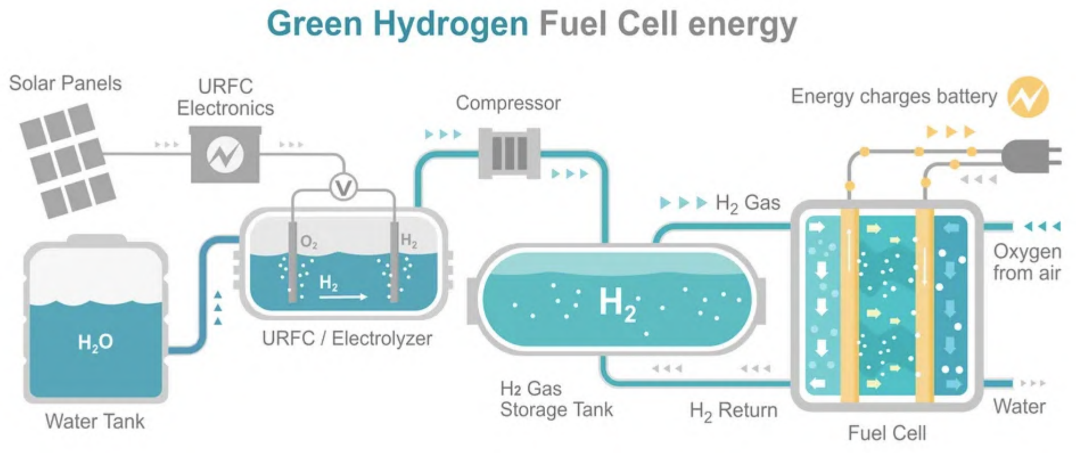

Figure 8: Green Hydrogen: Power-To-Gas-To-Power Conversion [30]

The successful deployment of hydrogen storage within energy communities requires a profound understanding of the technologies, materials, and infrastructure necessary to harness its full potential. This chapter delves into the subsystems realizing the P2G2P cycle, exploring various storage methods, subsystems, and their integration into the evolving landscape of energy communities. It examines the advantages, challenges, and real-world applications of hydrogen infrastructure, shedding light on its crucial role in driving the sustainable energy transition in urban environments.

2.3.1 The Power-to-Gas-to-Power Cycle: Overview and Subsystems

A P2G2P system is both an energy conversion process and a storage system. Surplus electricity from DERs is initially fed into an electrolyzer (power-to-gas). This hydrogen is then compressed and stored in typically large containers and can be converted back to electricity using a fuel cell system (gas to power). This process is not yet offered commercially as a complete system, as shown in Figure 8. This means that the recent and emerging implementations of P2G2P systems comprise different subsystems that are scaled for the specific application. For this paper, the discussed P2G2P system is scaled for several households featured within an energy community scenario.

2.3.2 Hydrogen Electrolyzers and Associated Investment Costs

Electrolyzers are crucial components in the transformation of surplus electricity into hydrogen. These devices operate on the principle of electrolysis, a process that splits water molecules into hydrogen and oxygen when an electric current is applied. When DERs are provided as the source of electricity, hydrogen gas is produced in a non-polluting manner [31], [32] and is referred to as green hydrogen.

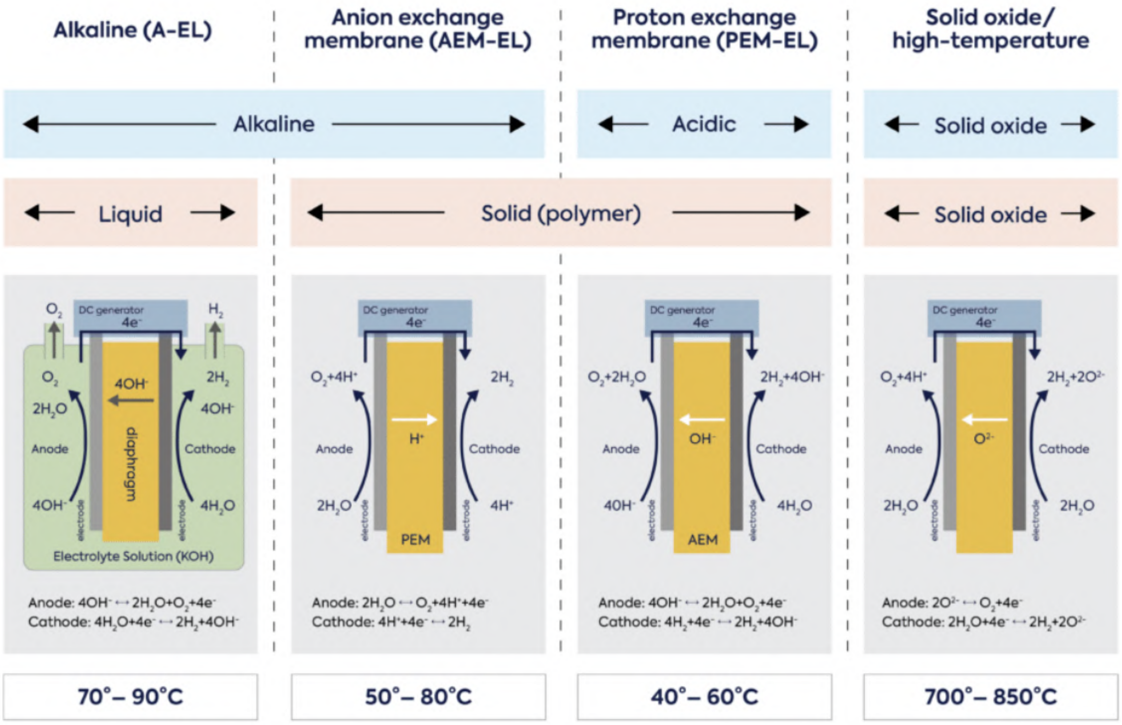

Figure 9: Characteristics of different electrolyzer technologies [33]

As shown in Figure 9, several types of electrolyzers are available, each with their unique attributes making them suitable for different use cases. **Alkaline electrolyzers** (AELs), made from inexpensive steel or nickel-alloy, are known for their long history of use and relatively low cost, making them suitable for large-scale applications. For electrolysis of electricity coming from DERs, **pressurized** alkaline electrolyzers offer suitable ramp-up and ramp-down times [34]. **Proton Exchange Membrane** (PEM) electrolyzers are highly efficient systems, provide fast response times, and are particularly well-suited for smaller-scale and mobile setups. Though recently commercialized, PEMs can only use distinct materials to withstand the corrosive acidic conditions of the process, thereby resulting in high capital costs for the system [35]. The applications of **Anion Exchange Membrane** (AEM) electrolyzers are currently investigated as a potentially competitive alternative to alkaline electrolysis, as they are made with affordable constructive materials and are expected to have similar performance to PEMs [34]. **Solid Oxide Electrolyzers** (SOECs), while less common, have shown potential for high-temperature operations and are being explored for specialized applications. This type of electrolyzer relies on abundant materials such as nickel, zirconia and steel. Currently in their pre-commercial state, its capital expenditures are higher than alkaline or PEM, but given that they are still in development, cost reductions are expected [36]. The relevant efficiencies of the mentioned technologies can be seen in Table 4 and Table 5.

When deciding on an implementation for an EC, one needs to consider the costs of both the **Electrolyzer Stack**[4] technology and the so-called **Balance of Plant**[5] (BoP). Table 2 considers both expenditures and presents the total investment cost including future projections for each respective technology. In addition, Table 3 based on [37] gives a detailed overview of the estimated costs. It is essential to highlight that increased deployment of the preceding technologies may result in a higher discrepancy in the projected numbers.

Table 2: Electrolyzer Investment Costs (US Dollars per Kilowatt)

Year of Research	Present	2030	2050	System Specifications	Source
Alkaline Electrolyzer					
2017	$700	$450	$450	5 MW	Fraunhofer, 2018 [38]
2019	$500 - $1400		$200 - $700	5 MW	IEA, 2019 [39]
2020	$500 - $1000			10 MW	IRENA, 2020 [40]
2022	$540 - $900			1 MW	OIES, 2022 [37]
2022	$600 - $1100			10 MW	Goldman Sachs, 2022 [41]
2022	$610	$344		30 MW	DOE, 2022 [27]
Proton Exchange Membrane Electrolyzer					
2017	$1460	$810	$510	5 MW	Fraunhofer, 2018
2019	$1100 - $1800	$650 - $1800	$200 - $900	1 MW	IEA, 2019
2020	$700 - $1400			5 MW	IRENA, 2020
2022	$667 - $1450			10 MW	OIES, 2022
2022	$800 - $1250			10 MW	Goldman Sachs, 2022
Solid Oxide Electrolyzer					
2017	$1410	$800	$500	<1 MW	Fraunhofer, 2018
2019	$2800 - $5600	$800 - $2800	$500 - $1000	<1 MW	IEA, 2019
2020	-		< $300	<1 MW	IRENA, 2020
2022	$2300 - $6667			<1 MW	OIES, 2022
2022	>$1850			<1 MW	Goldman Sachs, 2022
Anion Exchange Electrolyzer					
2020	$929 - $1279			1 MW	Ionomr, 2020 [42]
2022	>$931			<1 MW	OIES, 2022

Table 3: Electrolyzer Cost Overview according to OIES [37]

	Stack Price	Power Electronics	Gas conditioning	Balance of plant	Total Cost
Alkaline Electrolyzers	$270–450	$81–135	$81–135	$108–180	$540–900
PEM Electrolyzers	$400–870	$100–217.5	$67–145	$100–217.5	$667–1450
Solid Oxide Electrolyzers	$690–2000	$690–2000	$140–400	$780–2267	$2300–6667
AEM Electrolyzers	>$177	~$167.5	~$139.5	~$447	>$931

2.3.3 Electrolyzer Efficiency and Life Span

As the full load hours of an electrolyzer increase, the initial capital expenditure becomes less significant, with electricity costs emerging as the primary factor influencing the cost of renewable hydrogen production [33]. **Electrical efficiency**, defined as the ratio of electrical energy converted into the chemical energy of hydrogen, varies among different electrolyzer types, with solid oxide electrolyzer cells (SOEC) demonstrating the highest efficiency, as depicted in Table 4. Electrical efficiency is often expressed as the ratio of the Lower Heating Value (LHV)[6] or the Higher Heating Value (HHV)[7] of the produced hydrogen to the electrical energy consumed.

System efficiency, as shown in Table 5, encompasses not only the electrical efficiency of the electrolysis process but also incorporates additional energy losses and consumption associated with the entire system. This includes losses due to power conversion and auxiliary equipment such as air

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[4] Electrolyzer Stack: Multiple cells stacked, each containing an anode, cathode, and electrolyte, that are connected to increase efficiency and production capacity.

[5] Balance of Plant: All the supporting components and infrastructure necessary for the operation of the electrolyzer stack. This includes cooling, compression, purification, power electronics, and water treatment equipment.

[6] The LHV accounts for the heat released during combustion, excluding the heat of condensation of water vapor, assuming that the water remains in vapor form and the latent heat of vaporization is not recovered.

[7] The HHV represents the total amount of heat released when a fuel is completely burned, with the combustion products returned to their original pre-combustion temperature.

compressors, water purifiers, and heat exchangers, as well as the energy required to produce and deliver the input water. System efficiency thus provides a more comprehensive view of the overall energy efficiency of the hydrogen production setup.

Evaluating both electrical and system efficiencies is crucial when selecting an electrolyzer technology. Future projections must be considered, as advancements in technology and reductions in operational costs can significantly alter the comparative effectiveness of different systems. Anticipated improvements in efficiency and cost reductions can make one system more viable and cost-effective in the long term, influencing strategic decisions in hydrogen production infrastructure investments.

Table 4: Electrolyzer Electrical Efficiency

Present		Source
Alkaline Electrolyzer		
63% - 70%	LHV	IEA, 2019
50% - 68%	LHV	IRENA, 2020
68% - 77%	HHV	OIES, 2022
52% - 69%	LHV	Goldman Sachs, 2022
Proton Exchange Membrane Electrolyzer		
56% - 60%	LHV	IEA, 2019
50% - 68%	LHV	IRENA, 2020
70% - 80%	HHV	OIES, 2022
60% - 75%	LHV	Goldman Sachs, 2022
Solid Oxide Electrolyzer		
74% - 81%	LHV	IEA, 2019
75% - 85%	LHV	IRENA, 2020
80% - 90.8%	HHV	OIES, 2022
74% - 81%	LHV	Goldman Sachs, 2022
Anion Exchange Membrane Electrolyzer		
52% - 67%	LHV	IRENA, 2020
>74%	HHV	OIES, 2022
40% - 70%	LHV	Goldman Sachs, 2022

Table 5: Electrolyzer System Efficiency

Present	2050	Source
Alkaline Electrolyzer		
>60%	>75%	IRENA, 2020
58% - 65%	>75%	OIES, 2022
60% - 64%	75% - 80%	Goldman Sachs, 2022
60% - 65%		DOE, 2022
Proton Exchange Membrane Electrolyzer		
50 - 83%	>75%	IEA, 2019
50 - 83%	>80%	OIES, 2022
43 - 60%	80% - 85%	Goldman Sachs, 2022
Solid Oxide Electrolyzer		
>75%	>85%	IRENA, 2020
57% - 69%	85% - 95%	OIES, 2022
43% - 60%	85% - 95%	Goldman Sachs, 2022
Anion Exchange Membrane Electrolyzer		
45% - 55%	65% - 75%	IRENA, 2020
45% - 55%	65% - 75%	OIES, 2022

The choice of electrolyzer technology often depends on local electricity costs and availability. In areas with limited renewable electricity, more efficient but costly electrolyzers like SOEC are preferable, while in regions with abundant renewable energy, less expensive and efficient options like alkaline electrolyzers can be more suitable due to lower initial costs [33]. Admittedly, when considering ECs, selecting an electrolyzer is often contingent upon spatial limitations and the demographic density within the community. The expected life spans for each electrolyzer technology is another important aspect to consider and thus Table 6 summarizes the life span of the discussed technologies:

Table 6: Electrolyzer Life Span

Present	2050	Source
Alkaline Electrolyzer		
60.000 - 90.000	100.000 - 150.000	IEA, 2019
60.000 - 10.000	100.000	IRENA, 2020
60.000 - 100.000	-	OIES, 2022
60.000 - 90.000	-	Goldman Sachs, 2022
87.600	-	DOE, 2022
Proton Exchange Membrane Electrolyzer		
30.000 - 90.000	100.000 - 150.000	IEA, 2019
50.000 - 80.000	100.000 - 120.000	IRENA, 2020
50.000 - 90.000	-	OIES, 2022
30.000 - 80.000	-	Goldman Sachs, 2022
Solid Oxide Electrolyzer		
10.000 - 30.000	75.000 - 100.000	IEA, 2019
<20.000	100.000 - 120.000	IRENA, 2020
20.000 - 90.000	-	OIES, 2022
10.000 - 40.000	-	Goldman Sachs, 2022
Anion Exchange Membrane Electrolyzer		
>5.000	-	IRENA, 2020
30.000	100.000	OIES, 2022
5.000 - 9.000	-	Goldman Sachs, 2022

Given the varying efficiencies and operational characteristics of different electrolyzer technologies, PEM- and Solid Oxide Electrolyzers are particularly promising for energy communities. PEM electrolyzers are currently favored for their high efficiency of **60%** and rapid response times, making them suitable for integration with intermittent renewable energy sources. SOECs, with their superior efficiency and potential for high-temperature operations, offer significant long-term benefits despite higher initial costs. The choice between these technologies will depend on specific community needs, including the availability of renewable energy and budget considerations. However, both options represent advanced, future-proof solutions that align well with the goals of sustainability and resilience in ECs.

2.3.4 Hydrogen Storage Technologies

Hydrogen storage plays a vital role in the seamless integration of renewable energy sources into energy communities. As hydrogen is typically produced at low pressures from electrolyzers, it becomes imperative to increase its pressure for effective storage and transportation. A higher stored pressure of hydrogen allows for lower volumes to be achieved and allows for higher volumetric densities. This segment delves into various hydrogen storage technologies, highlighting the prominence of compressed hydrogen storage as the foremost option for energy communities.

Figure 10: Hydrogen Storage Infrastructure (Render By Author)

Compressed Hydrogen Storage: Among the physical hydrogen storage methods, gaseous hydrogen storage stands out as the most developed technology. Its ability to seamlessly integrate into existing energy infrastructures presents a significant advantage in implementing hydrogen storage in ECs. The technology is known for its quick discharge capabilities and flexible deployment opportunities [43]. Compressed hydrogen storage systems have been acclaimed for their safety [44], a feature that has been substantiated through their application in numerous fields, including fuel cell vehicles. Compressed hydrogen can be stored, similarly to natural gas, in large metallic vessels, however over the years, other types of vessels have been introduced, contributing towards safer and more efficient aspects of the technology.

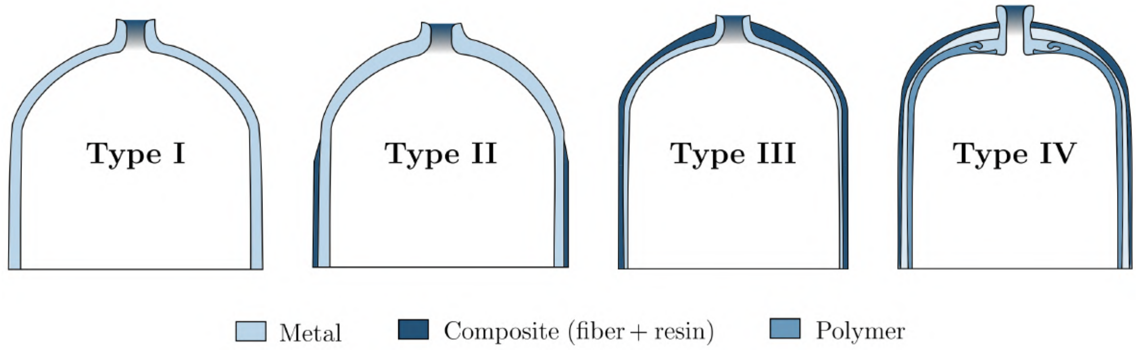

Figure 11: Hydrogen Storage Types [45]

The enhancements in compressed hydrogen storage vessels, as documented in [46] and [47], highlight the strides made towards improving the safety and storage capacity of these systems. The detailed examination of various compressed hydrogen vessel technologies in [47] provides a thorough analysis of the optimal storage methods tailored to specific applications. The summary of compressed hydrogen tank types alongside the recommended applications, as presented in Table 7, offers insight into the critical findings of this investigation. The total efficiency of compressed hydrogen storage, noted to be approximately **94%** [48], combined with its cost-effectiveness and scalability, positions it as an attractive solution for energy communities.

Table 7: Compressed Hydrogen Tank Types and Characteristics [47]

Tank Type	**Operating Pressure**	**Applications**
Type I (All-Metal)	Up to 200 bar (2,900 psi)	Industrial storage
Type II (Metal Liner)	Up to 350 bar (5,075 psi)	Transportation, Stationary storage
Type III (Non-Metallic Liner)	Up to 700 bar (10,153 psi)	Automotive industry
Type IV (All-Composite)	Up to 700 bar (10,153 psi) or higher	Fuel cell vehicles, High-performance applications

In the context of integrating renewable energy sources within ECs, the selection of an appropriate hydrogen storage technology is critical. Compressed hydrogen storage emerges not only as a mature and safe option but also as a method characterized by high efficiency and adaptability to a wide range of applications. The ongoing advancements in this field are geared towards enhancing the performance and reliability of storage vessels, further solidifying the position of compressed hydrogen storage as the preferable technology in the transition towards sustainable energy systems and utility sharing. Hydrogen compression technology is also advancing, introducing multi-stage compression systems to achieve quick and efficient hydrogen compression. [49] , [50]

Cryogenic Storage: While offering higher energy density, the process itself is energy-intensive, requiring about 30-40% [46] of the hydrogen's energy content for liquefaction at -253°C, which limits its immediate applicability for energy communities due to high costs and complex infrastructure requirements. Liquid hydrogen demands storage under very low temperatures, making it a less efficient and more complicated system than gaseous storage systems.

Solid-State Hydrogen Storage: Represents a promising technology with the potential for high storage densities and improved safety. Metal hydrides and chemical hydrogen storage systems are currently being explored for their potential in long-term storage applications with hydrogen. However, current challenges related to cost, kinetics of hydrogen absorption and desorption, and the weight of storage materials limit its widespread adoption in the short term.

Given the current technological landscape and considering the efficiencies and practicalities of these storage methods, **compressed hydrogen storage** stands out for usage in energy communities. Its relative simplicity, lower technological barriers, and compatibility with decentralized energy systems align well with the needs and capabilities of such communities. Furthermore, the introduction of compressed hydrogen storage represents a smoother transition towards utilizing hydrogen as it allows for the repurposing of existing gas pipelines. Reference [50] explains the necessary modifications that need to be made to use existing pipelines and comply with the necessary safety standards. Furthermore, in [51], a type IV tank is currently developed for commercial and industrial use, with a tank capacity of 56.8 kilograms in 700 bar pressure. This implementation can already be considered a safe and reliable option for introducing compressed hydrogen storage in ECs. The transmission of hydrogen within the P2G2P infrastructure is done with the help of multi-stage compressors[8]. For this paper, the energy consumption of the compression-decompression step is not considered. Finally, Table 8 summarizes the efficiencies found in [48], [50], [52], which will be used for the simulations of this paper.

Table 8: Hydrogen Storage and Compression Efficiency Table

Hydrogen Compression Efficiency	Hydrogen Storage Efficiency	Hydrogen Decompression Efficiency
94.5%	94%	98%

Further research and development into improving the efficiencies and reducing the costs of hydrogen storage technologies will be crucial in fully realizing the potential of hydrogen as a critical component of renewable energy systems in energy communities. This paper considers that the utilized hydrogen pipelines are transporting pure hydrogen within the EC and do not degrade over time. In the future, systems that combine hydrogen and natural gas in pipelines might be introduced. Finally, the option of storing hydrogen underground is another means to achieve lower temperatures and even greater system efficiencies.

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[8] Multi-Stage compressors allow for better temperature control upon compression and decompression. Controlled temperatures result in lower energy losses and overall less energy consumption for compression.

2.3.5 Fuel Cells: Hydrogen to Electricity Conversion

Once hydrogen is compressed and stored in large tanks, it can be efficiently employed within energy communities through fuel cell technology. Fuel cells are electrochemical devices that convert hydrogen and oxygen into electricity, heat, and water, offering a highly efficient and clean energy conversion process as illustrated in figure 12. Energy communities utilizing fuel cell technology benefit from its ability to efficiently convert stored hydrogen back into electricity, contributing to grid stability, reducing greenhouse gas emissions, and enabling distributed energy generation for local consumption.

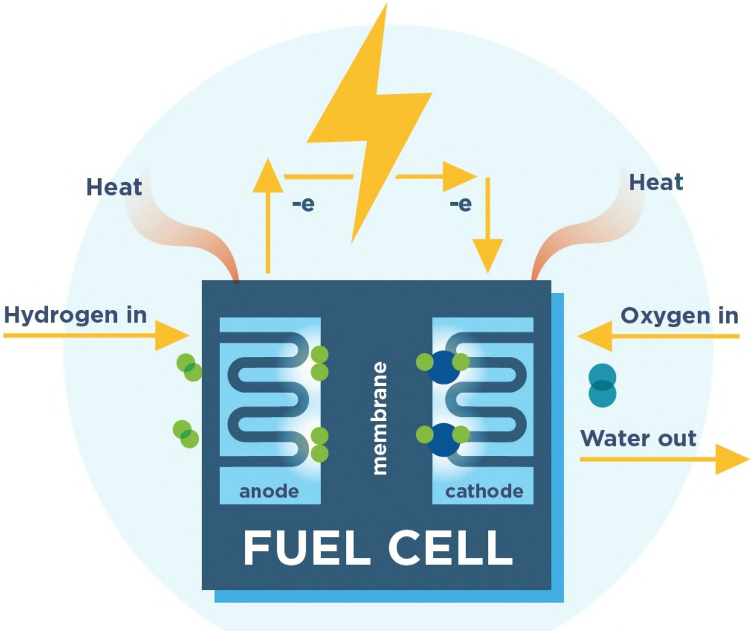

Figure 12: Fuel Cell Technology [53]

Different types of fuel cells, including **Proton Exchange Membrane Fuel Cells** (PEMFCs), **Solid Oxide Fuel Cells** (SOFCs), and **Alkaline Fuel Cells** (AFCs), can provide diverse options for energy communities. PEMFCs are known for their rapid start-up and responsiveness, making them suitable for applications requiring quick load-following capabilities [54]. SOFCs excel in high-temperature operations and can provide **Combined Heat and Power** (CHP) for heating and electricity generation. They too offer excellent ramp-up and ramp-down times and promise no performance degradation within their lifetime [55], also making them suitable for ECs. AFCs present simplicity and reliability, making them a viable option for energy community setups. The most important characteristics of fuel cells are summarized in tables 9 and 10 below:

Table 9: Comparison of Important FC Characteristics [56]

Fuel Cell Type	Operating Temperature	Typical Stack Size	Electrical Efficiency (LHV)
PEMFC	<120 °C	<1 kW - 100 kW	60%
SOFC	500 - 1000 °C	1 kW - 2 MW	60%
AFC	<100 °C	1 - 100 kW	60%

Table 10: Comparison of Costs and Applications of Different Fuel Cell Technologies [57]

Fuel Cell Type	Material Costs	Manufacturing Costs	Operational Costs	Primary Application
PEMFC	High	High	Low	Transportation, Portable Power
SOFC	Moderate	High	High	Stationary Power Generation
AFC	Low	Moderate	Low	Space, Limited Commercial Use

2.3.6 P2G2P Total System Ramping Times and Efficiency

In contemporary hydrogen production, PEM **electrolyzers** exhibit rapid operational adaptability, with **startup times ranging from seconds to a few minutes** and an ability to quickly adjust output levels. This ramping capability is particularly beneficial when coupled with fluctuating renewable energy sources, although their efficiency may decrease slightly at partial loads. Conversely, traditional **alkaline** electrolyzers have longer startup times, often **several minutes**, due to the need for precise control of electrolyte and temperature. Their response rate to changes in electricity supply is slower compared to PEM electrolyzers, making them less ideal for integration with variable renewable energy sources. However, they are valued for their durability and consistent performance in large-scale operations, particularly efficient at full capacity, making them suitable for steady, high-volume hydrogen production.

Fuel cells, on the other hand, generally have **longer startup times than electrolyzers**, **ranging from several minutes to about half an hour**. PEM fuel cells, known for quicker response times, can still take several minutes to adjust their power output in response to changing demands. This ramping rate is influenced by factors such as fuel cell type, stack size, and control system settings. Notably, the efficiency of fuel cells remains relatively stable across a wide range of operating conditions, although this can vary slightly with load fluctuation. The compression and decompression steps of a P2G2P cycle depend on the electrolyzer, fuel cell and storage tank technology used, thus it is difficult to also include it when calculating the ramping time of the complete system. However, it is safe to assume that decompression is highly efficient and can occur in parallel with the ramping of the fuel cell.

Figure 13: Open Render of a P2G2P Facility (Render By Author)

To conclude, when integrating a P2G2P system within an EC, it is prudent to allocate a **ramp-up duration of approximately thirty minutes** for the system to reach operational capacity. During this transient phase, the load demands of the energy community can be effectively managed by a BESS. **To ensure the longevity and durability of the system, it is recommended that the P2G2P system is activated no more than once daily for a predetermined period, referred to as the switching period, followed by a subsequent deactivation.** This operational strategy optimizes the P2G2P hydrogen system for equipment longevity, safety and energy security.

2.4 Mechanisms for Shared Hydrogen Storage Integration in ECs

This section delves into the components necessary for providing a structured framework that effectively allows the sharing of hydrogen energy between community households. To realize a framework for the effective sharing of hydrogen storage capacity within ECs, a review of standard practices in terms of governance, market-based instruments and asset pricing is done.

2.4.1 Economic Aspects of Shared Hydrogen Storage: Cost Allocation and Trading Dynamics

To facilitate the introduction of a shared good, in this case, hydrogen storage capacity among EC households, it is crucial to initially define a market mechanism. Through the application of an **automated** market mechanism, it is possible to share hydrogen in a similar way as with other shared utilities. This "business-as-usual" approach to hydrogen storage sharing will make it easier for an economy between households to be implemented, thereby quickly facilitating the integration of the proposed total system.

Smart Contracts and Blockchain Technology: The advent of blockchain technology and smart contracts has introduced a transformative approach to energy trading and cost allocation within distributed energy communities [58]. Blockchain, a decentralized ledger technology, provides an immutable and transparent record of transactions, fostering trust among participants. Smart contracts, digital contracts encoded on a blockchain, automatically execute transactions when predefined conditions are met, eliminating the need for intermediaries and reducing transaction costs [59].

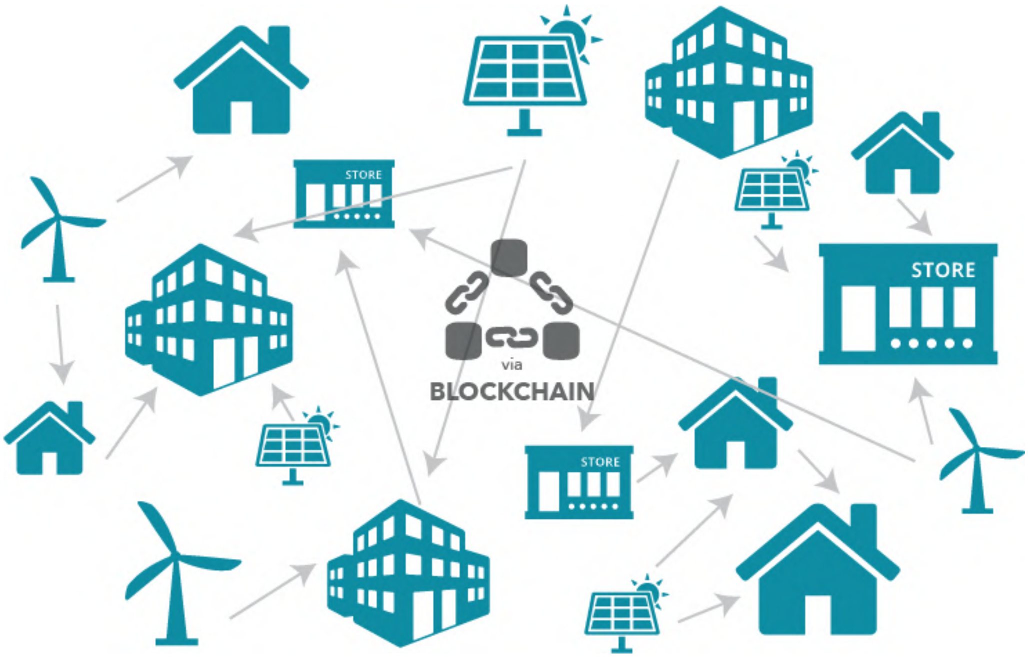

Figure 14: Representaion of Blockchain Energy trading [60]

This technological framework is particularly beneficial for distributed energy communities focused on sharing hydrogen storage equitably among households. By automating energy trades and cost distribution, smart contracts ensure that all transactions are transparent, efficient, and secure. Furthermore, they allow for the implementation of dynamic pricing models that reflect real-time supply and demand, as well as external market conditions, ensuring the competitiveness of hydrogen energy. Finally, it can be assumed that an easy-to-use interface of a capacity trading market through blockchain, is the most modern way of implementing shared hydrogen storage in ECs.

In the study outlined in [58], the authors establish the groundwork for P2P energy trading within a VPP framework, employing blockchain technology, specifically Ethereum-based smart contracts. This innovative architecture is designed to enhance energy security and transparency in energy exchanges among users. The system uses a public blockchain network to manage transactions via smart contracts, which support automated, auction-based bidding processes. This setup not only addresses cost and security issues but also optimizes financial transactions in P2P trading, ensuring that the platform can adapt and scale effectively across various VPP operations. The successful implementation of smart contracts in this context demonstrates their potential to streamline utility sharing in ECs, eliminating the need for intermediary "handshakers" or third-party organizations in decision-making processes.

2.4.2 Governance Framework for Hydrogen Storage Responsibility

Providing a complex mechanism for driving hydrogen storage integration is impossible without systematic monitoring and governance. Such systems demand an overhead for administration, which will be responsible for troubleshooting, maintenance, systemic resilience, and energy equality. Several frameworks have been applied toward sharing utilities, each with different characteristics, benefits and drawbacks. For the implementation of a hydrogen storage sharing system, a focus on simplicity must be given, as total knowledge of the mechanisms and policies can be overwhelming for its users. For this reason, two different governance frameworks are studied:

Balancing Responsible Party The role of a Balancing Responsible Party (BRP) in energy control is crucial, especially in the context of managing resources from distributed energy resources. A BRP is responsible for maintaining the balance between energy production and consumption within a specific grid or control area. **Demand response,** used to be the responsibility of grid owners which is nowadays subject to change. It involves overseeing multiple access points to the grid and ensuring that the total energy injected into it matches the energy taken out, considering trades between stakeholders and possible in- or exports to other control areas.

In the research presented in [61], the authors focus on the specific functions of BRPs within smart grid networks. By simulating various household types, they identify significant energy inefficiencies in certain households, underscoring the urgent need for effective demand response[9]. In this context, a BRP plays a crucial role in initiating changes in stakeholders' energy consumption patterns and behavioral habits. In the context of hydrogen capacity allocation, a BRP will oversee the operation of shared hydrogen storage infrastructure and will act as the central authority for managing energy consumption and coordinating demand response activities within the EC. Additionally, the BRP will be tasked with ensuring the seamless integration and maintenance of the shared hydrogen infrastructure, which will be vital for the community's energy system. This includes monitoring and managing the associated service costs.

Decentralized Governance Decentralizing governance and involving the community in the administration of shared hydrogen storage presents a transformative approach to community energy management. This idea empowers community members by granting them direct control and responsibility over the energy storage system, promoting a sense of ownership, accountability, and participation. Furthermore, it requires local decision-making, where policies and practices are tai-

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[9] Demand response is a utility management strategy that encourages consumers to alter their power usage in response to grid needs or economic signals, typically to reduce demand during peak usage times or enhance system reliability

lored to the needs and preferences of each EC, potentially leading to more efficient and sustainable energy usage. However, decentralization also requires a robust framework for coordination and conflict resolution, as well as a commitment from community members to actively participate in such processes. While decentralization can enhance community cohesion and resilience, it also poses challenges in terms of ensuring effective participation and maintaining consistent standards and practices across the community.

2.4.3 Market-Based Mechanisms for Trading Hydrogen Capacity

In the domain of facilitating hydrogen energy capacity transactions among EC households, two primary options stand out: token-based and monetary-based trading. Each approach offers a unique transaction facilitation mechanism, shaped by distinct operational, economic, and technological landscapes. Understanding the complexities of these models is crucial for policymakers aiming to identify the most efficient, fair, and sustainable method for conducting energy trades.

Token-Based Energy Trading: Token-based trading involves the use of digital tokens as a medium of exchange for hydrogen energy capacity within a community. These tokens are typically issued on a blockchain platform, in this case representing a certain unit of hydrogen capacity. The decentralized nature of blockchain ensures transparency, financial security and immutability of transactions. In [62], the author gives great insights into the introduction of a blockchain-based token economy for user-friendly transactions and bookkeeping. In these models, community members earn tokens by selling their unused hydrogen capacity surplus while other users give their tokens to buy additional capacity from the community's **Local Energy Market** (LEM). This option facilitates a circular economy model where the energy value remains within the EC ecosystem.

The token-based approach promotes a sense of community ownership and incentivizes participation in the energy network. It can also enable more granular and flexible energy transactions, as tokens can be divided into smaller units than conventional currency, allowing for precise energy trading [62]. Furthermore, this model supports the integration of smart contracts, automating the trading process based on predefined criteria and reducing the need for manual intervention.

Monetary-Based Energy Trading: Monetery-based trading, on the other hand, involves direct financial transactions using conventional currencies. In this model, individuals buy or sell hydrogen capacity with money, with prices typically determined by supply and demand dynamics within the community or in relation to external energy markets. This approach is more straightforward and may be easier for participants to understand and integrate into their existing financial practices and habits. This method most likely demands that a form of EC management is introduced to determine the fluctuating prices.

Monetary-based trading can offer greater liquidity and flexibility, as money is a universally accepted medium of exchange and can be used for various purposes beyond the energy ecosystem. However, it may also introduce challenges related to price volatility, regulatory compliance, and the need for secure payment processing systems. Additionally, the involvement of traditional financial institutions may increase transaction costs and potentially slow down the trading process.

2.5 Hydrogen for Heating in ECs

The transition towards utilizing hydrogen for heating in residential buildings can be crucial to decarbonizing urban energy systems. Given that this shift intersects with numerous aspects of infrastructure, it shall be considered for implementation only if it provides tangible benefits. To validate the advantages of this transition, a comprehensive examination of hydrogen production, distribution, and utilization for this process is undertaken. This analysis encompasses an evaluation of the efficiency, system costs, and environmental consequences associated with the deployment of hydrogen-based heating solutions.

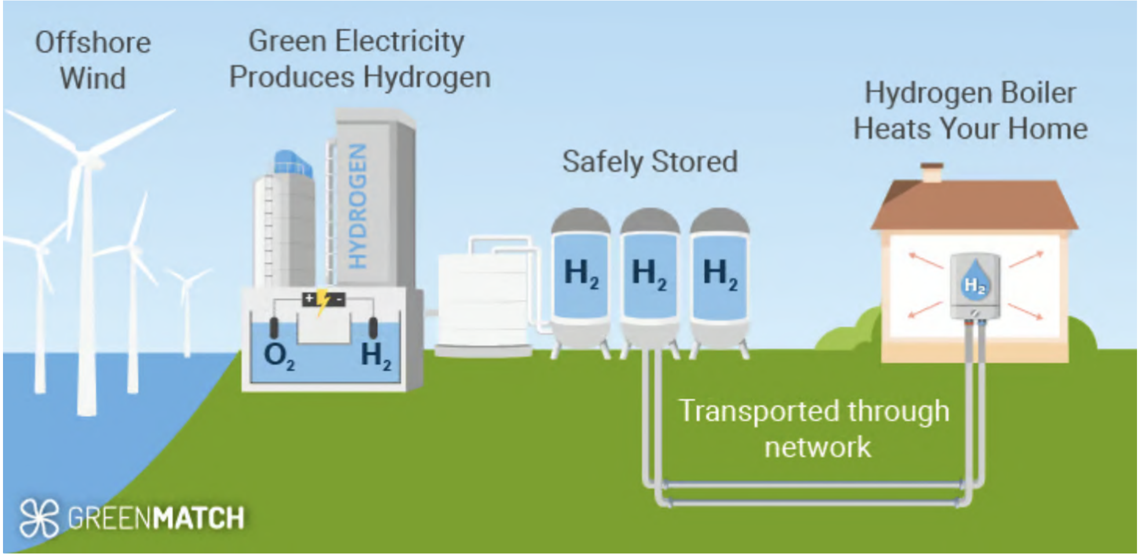

Figure 15: Greenmatch Green Hydrogen for Heating [63]

The process for obtaining hydrogen for heating is related to the P2G2P cycle discussed in 2.3. After the hydrogen is compressed inside a storage tank, a central EMS can regulate and distribute the compressed H2 in the pipelines of an EC. Existing natural gas networks may need significant upgrades to accommodate hydrogen's different physical properties, such as its lower energy density and higher leak propensity (**hydrogen embrittlement**[10]). This entails reinforcing or replacing pipelines, as well as retrofitting or replacing heating systems within buildings to ensure they are hydrogen-compatible. Transitioning to hydrogen heating, therefore, implies significant capital and operational costs, posing a notable challenge for its integration into urban and commercial settings. This shift requires extensive infrastructure modifications and substantial upfront costs for establishing hydrogen production, distribution, and utilization systems [64]. Such financial demands make hydrogen heating's large-scale adoption challenging, especially compared to alternatives like heat pumps and direct electrification, which are more cost-effective and readily implementable.

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[10] Hydrogen embrittlement of pipelines is the process where hydrogen atoms infiltrate metal, causing it to become brittle and susceptible to cracking, potentially leading to pipeline failure.

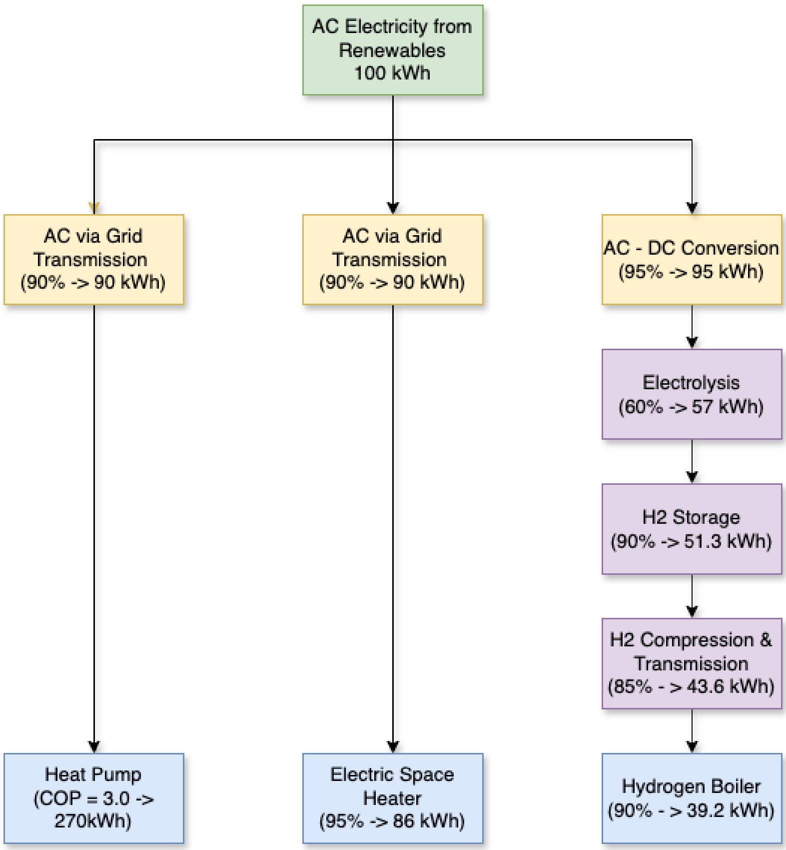

Figure 16: Flowchart 100kWh Example for Heating [65]

Hydrogen offers a versatile and clean alternative to fossil fuels, emitting only water vapor when combusted. However, the **efficiency** of hydrogen as a heating source is a subject of extensive debate [65]. The energy conversion process from electricity to hydrogen and back to heat—either through combustion in hydrogen-ready boilers or via fuel cells—incurs inherent energy losses as seen in the 100kWh example in Figure 16. Assuming an electrolyzer efficiency of 60% as seen in Section 2.3.5, the total efficiency of the system amounts to around 40%. This means that for 100kWh of input electricity, around 60kWh is lost during the conversion (to heat) process. The example of Figure 16 found in [65] explores two other options next to utilizing a hydrogen boiler for heating, specifically utilizing a heat pump and a large electric heater. The most important outtake has to deal with the heat pump implementation, which is given a realistic **Coefficient of Performance** (COP) equal to 3, meaning that these systems deliver three times more heat energy than the electricity provided.

Environmental considerations and the need for additional policies to drive its integration further complicate the narrative [66]. While hydrogen produced from renewable energy sources offers a low-carbon heating solution, the overall environmental impact depends on the life cycle emissions of hydrogen production, distribution, and use. The debate often centers around the carbon footprint of continuous electrolysis powered by non-renewable electricity sources versus greener alternatives.

Looking forward, the viability of hydrogen for heating will largely depend on advancements in technology, reductions in renewable energy costs, and the development of policies that support the hydrogen economy. Comparative technologies, such as heat pumps, which offer higher direct electricity-to-heat conversion efficiencies, currently represent a more immediate path to decarbonization. However, hydrogen's potential for high-density energy storage and versatility in application across sectors keeps it in the realm of viable long-term solutions for a sustainable energy future.

2.6 Summary and Implications for Future Research on ECs

In Section 2.6, the literature review is summarized, highlighting the critical role that shared hydrogen storage systems hold in enhancing the sustainability and resilience of ECs. After showcasing relevant examples of ECs with shared utilities, the importance of hydrogen for urban households is brought into focus, explaining how it represents a promising solution for long-term energy storage and management within urban settings. This is particularly relevant for urban households seeking sustainable and reliable energy sources that align with the broader goals of carbon neutrality and energy independence.

The exploration then shifts to a thorough examination of the Power-to-Gas-to-Power (P2G2P) cycle for hydrogen and its subsystems, representing the technological process that can facilitate the conversion of surplus renewable energy into green hydrogen, which can be stored and later converted back to electricity. The cycle is elaborated further by identifying the relevant efficiencies, costs, life spans, ramping times and different technologies of the respective subsystems.

After explaining the conversion process, the chapter transitions to the technical feasibility and economic viability of shared hydrogen storage systems. These systems are underlined as significant enhancers of energy security, optimizing the energy acquired from renewable resources and allowing for a more decentralized and democratic energy infrastructure. The examination extends to governance frameworks and market-based mechanisms that can facilitate the integration of shared hydrogen storage solutions into ECs. The role of blockchain technology in enabling transparent and efficient energy trading within communities is particularly emphasized.

Additionally, the use of hydrogen for heating in ECs is considered, acknowledging the challenges related to efficiency and infrastructure modifications alongside the potential of hydrogen to contribute to sustainable heating solutions. This is dependent on continuous technological advancements and the establishment of supportive policy frameworks.

In conclusion, this chapter argues that incorporating shared hydrogen storage systems is essential for advancing energy communities and a natural step forward. Such systems are essential for enhancing energy reliability, although several barriers impede their integration. Currently, the market lacks a universally applicable hydrogen storage solution that caters to the varied needs of ECs, highlighting the necessity for targeted research and development in a modular structure. This research should focus on developing adaptable and scalable hydrogen storage technologies tailored to diverse community sizes and requirements. Finally, given the relatively low efficiency of the complete P2G2P system, adding a local energy market implementation for energy capacity trading is essential for ensuring a sustainable urban energy landscape.

Additionally, the integration of hydrogen storage requires the development of comprehensive regulatory frameworks. Presently, specific policies governing the deployment and management of these systems are absent, necessitating policy interventions to facilitate technology adoption and ensure operational safety and efficiency. Thus, while the adoption of shared hydrogen storage systems represents a progressive strategy for energy communities, it demands significant research and policy formulation efforts.

3 Methodology

This chapter focuses on describing the steps undertaken to model an architecture suitable for sharing and monitoring utilities inside ECs. The architecture design is a product of a comprehensive analysis of relevant stakeholder energy requirements and the supporting infrastructure. Initially, in **Section** 3.1, a survey is conducted, significant towards acquiring anonymous energy data, identifying trends in energy consumption and towards acceptance on shared hydrogen storage. In **Section** 3.2, the survey is followed by an analysis of the obtained results, for the two rounds of interviewees that are identified. In **Section** 3.3, the chapter transitions to hydrogen for heating in urban settings, aiming to answer one of the research questions and ultimately determine whether hydrogen heating will be considered in the proposed architecture. In **Section** 3.4, the `Benchmark Model` is developed, facilitating hydrogen capacity calculations for energy community households. The proposed model is optimized for maximizing energy security and equipment longevity, acquiring insights from **Section** 2.3. This model is compared with the `Complex Model` of **Section** 3.5, which proposes a novel architectural framework for the digitalization of shared hydrogen storage within energy communities. After explaining the necessary modules of the architecture, several mechanisms and policies are built on the `Complex Model`, which is further optimized to maximize social welfare. Finally, in **Section** 3.6 a summary, encapsulating the key methodologies and findings, thereby providing a coherent overview of the research process, is provided.

Figure 17: Energy Community featuring Shared Hydrogen Storage (Render by Author)

3.1 Survey of Energy Communities on Shared Hydrogen Storage Adoption

In the pursuit of advancing toward sustainable and self-sufficient energy communities, understanding user trends and preferences becomes imperative. This section delves into a meticulously formulated survey aimed at acquiring anonymous energy data, clearing up the intricate dynamics of household energy usage and attitudes towards renewable energy technologies, specifically focusing on the role of **Shared Hydrogen Storage Systems** (SHSS). The survey, which can be found in Appendix A, encapsulated through questions Q1 to Q20, serves as a cornerstone for acquiring critical data to fuel the development of a methodology toward optimum SHSS capacity calculation for energy community needs.

By examining user energy consumption data, the survey initially shapes anonymous energy profiles and lays the groundwork for a nuanced understanding of consumer behavior. Additionally, it explores the community's readiness for advancing to greater energy sufficiency, acceptance of shared utilities and preferences on supporting control mechanisms. The insights garnered from these questions are instrumental in shaping the `Complex Model` of Section 3.5 and for formulating a community energy system that not only aligns with user preferences but also ensures reliability, safety, and efficiency. The anonymous energy profiles, developed for the purpose of the `Complex Model` can be found in Appendix C. The questions and their significance are elaborated below:

Table 11: Survey Questions

Question No.	Question Description	Question Goal
Q1	How many KWh on average does your household consume on a monthly basis?	To establish baseline energy usage, crucial for sizing and planning energy systems, including renewable sources and storage capacities.
Q2	Would you expect to consume more electricity during the weekdays or during the weekend?	To determine whether consumption is higher in weekdays or during weekends according to user input.
Q3	Do you notice any seasonal variation in your energy consumption?	To determine if higher consumption trends are noticed on a specific period
Q4	Are you aware of any subsidies or incentives for participating in an energy community or using renewable energy sources?	Assesses awareness of subsidies or incentives, indicating the effectiveness of existing policies in encouraging participation in energy communities or the adoption of renewable technologies.
Q5	Would you consider allowing a third party to optimize your consumption based on your preferences or handle energy management yourself?	Explores willingness to allow third-party optimization of energy consumption, shedding light on consumer trust in automated systems and preference for control over energy management
Q6	Can you identify specific needs or applications in your daily life that you believe a long-term storage solution should address?	Identifies specific needs or applications for long-term storage solutions, helping to tailor storage technologies to actual household demands
Q7	If you could prioritize the use of stored energy for specific purposes, what would be your top three priorities?	Aims to create a list that reveals the most important purposes for which green electricity should be used
Q8	Are there specific appliances or systems you would prioritize for backup power?	Focuses on prioritization for backup power, essential for resilience planning and ensuring continuity of key services during outages.

Q9	For how long would you like to be able to rely on your hydrogen storage solution as backup power?	Gauges expectations for the duration of reliance on hydrogen storage as backup power, critical for designing storage capacity to meet emergency needs
Q10	On a scale from 1 to 5, how important is it for your household to be part of a self-sufficient energy community?	Measures the importance placed on being part of a self-sufficient energy community, indicating community readiness and support for decentralized energy solutions.
Q11	On a scale of 1 to 5, how supportive are you of the idea of implementing hydrogen storage for long-term energy storage in our community?	Evaluates support for implementing hydrogen storage, reflecting community acceptance and potential uptake of this technology.
Q12	On a scale of 1 to 5, how well do you understand the process of converting surplus renewable energy into hydrogen for storage?	Assesses understanding of converting surplus renewable energy into hydrogen, indicating the level of public knowledge and potential educational needs
Q13	On a scale of 1 to 5, how confident are you in the reliability and stability of a hydrogen-based storage system?	Gauges confidence in the reliability of the hydrogen-based storage systems
Q14	On a scale of 1 to 5, how confident are you in the safety of a hydrogen-based storage system?	Assesses how confident the users are towards utilizing a hydrogen-based storage solution close to the energy community.
Q15	On a scale of 1 to 5, how reluctant are you to provide your energy consumption data to facilitate better communal energy handling?	Explores reluctance towards sharing energy consumption data, highlighting privacy concerns and the need for secure data handling mechanisms.
Q16	How much control would you like to have over the operation and settings of the hydrogen storage solution?	Asks about desired control over hydrogen storage operation, revealing preferences for automation versus manual control in energy systems
Q17	What are your primary concerns, if any, about the implementation of hydrogen storage in our community?	Identifies concerns about hydrogen storage implementation, providing insights into potential obstacles and areas needing clarification or reassurance.
Q18	Do you see value in involving the community in decisions related to the long-term storage solution to ensure it meets diverse needs? Would you rather have a third-party company to handle all decisions?	Queries the preferred approach to decision-making regarding storage solutions, indicating the desired level of community involvement versus third-party management
Q19	Would you be interested in participating in community initiatives or programs related to the implementation?	Assesses interest in participating in community initiatives or programs related to renewable energy implementation, suggesting potential for community engagement and support
Q20	Are there specific reliability features or performance guarantees that you would like to see?	Seeks input on desired reliability features or performance guarantees for the storage solution, highlighting consumer expectations and standards for technology performance

Together, these questions form a comprehensive survey for investigating the factors that influence the adoption of renewable energy technologies and the development of sustainable, self-sufficient energy communities featuring shared utilities. The insights gained will be instrumental in guiding policy, designing effective community energy systems, and accelerating the green energy transition. Finally, the acquired data will be used privately to identify trends, support calculations and assumptions and assist in answering the research questions of this paper, as defined in Section 1.2.

3.2 Analysis and Interpretation of Survey Results on Shared Energy Utility Trends

This section examines the survey data and findings derived from engaging with representatives of the Research and Development Team at the Greek Transmission System Operator[11] (TSO), IPTO[12], and from the Green Village EC in the Netherlands. The focus of the survey was on acquiring user energy data and on gauging the adoption of shared hydrogen storage systems. Insights related to energy consumption trends, preferences for energy usage, and perceptions concerning shared hydrogen storage implementations in ECs are collected and carefully analyzed. The survey was initially conducted in Greece and subsequently in the Netherlands. The gathered demographics are acquired after interviewing 15 members during the first round and 5 members during the second round, respectively. This section outlines the methodology employed, discusses the significant findings, and explores their implications for integrating hydrogen energy systems within ECs.

3.2.1 Respondent Demographics

For the first round of the survey, relevant stakeholders part of the Greek Transmission Systems Operator (TSO) were interviewed. Their input gave valuable insights into energy consumption trends and household occupancy in terms of members and their energy habits. Furthermore, technical discussions on the integration of hydrogen storage laid the path for a carefully designed architecture.

For the second round of the survey, residents of the Green Village EC located in Delft, The Netherlands provided their valuable input. The second round did not focus greatly on acquiring further technical data but on the contrary, aimed to obtain valuable insights for data privacy and systemic integration.

3.2.2 Energy Consumption Trends in Households

During the initial interview phase, representatives from IPTO provided their monthly energy consumption and household occupancy data. The results indicate an average monthly consumption (Q1) of 248.75 kWh and an average household occupancy of 2.25 members. Interviewees were queried about their peak energy usage periods, asking whether more energy was consumed during weekends or weekdays (Q2). The findings revealed that 57% of respondents consume more energy during weekends, 29% during weekdays, and 14% report similar energy usage across the week. To further delineate these trends, Figure 18 illustrates the answers to the 6th survey question, concerning the distribution of energy consumption across different applications.

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[11] A Transmission System Operator (TSO) is an organization responsible for the efficient and reliable transmission of electricity from generation plants via the power grid to regional or local electricity distribution operators.

[12] IPTO is the state-owned TSO of Greece.

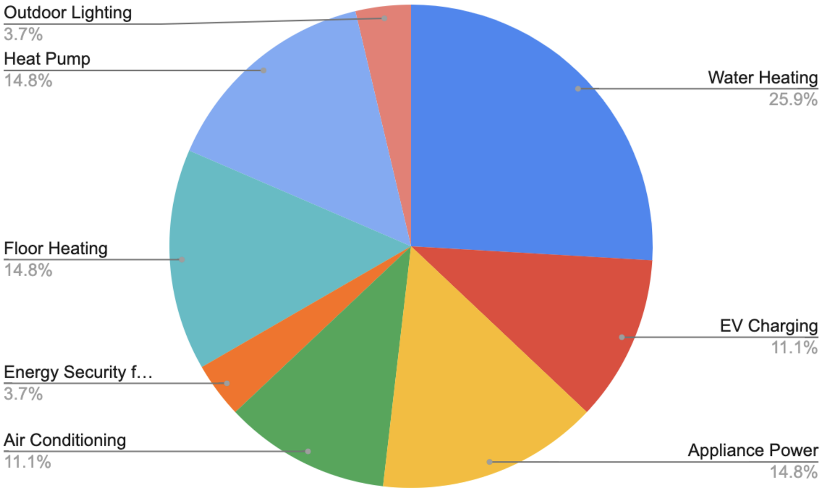


Figure 18: Energy Split for Various Applications - Survey Question 6 Answer

In analyzing IPTO's responses about energy applications, three top priorities emerged: **Water Heating**, **Charging of Electric Vehicles**, and **Air Conditioning**. These highlight the emphasis on essential daily needs and sustainable transportation. Regarding preferences for backup power allocation, **Powering of Appliances**, **Ensuring Water Heater Operation**, and **Air Conditioning** were identified as critical. These preferences demonstrate a concentrated effort to preserve food, ensure availability of heated water and management of indoor climates, thereby emphasizing the significance of **comfort** and **safety** during new implementations.

The consumption trends highlighted by these priorities were confirmed through responses to Q3. IPTO Representatives suggested that energy consumption peaks during the intense summer months and subsequently during the winter season, thereby validating the initial observations extracted from the survey data.

Concerning energy security (Q9), it was revealed that 65.4% of the interviewees desired a daily safety margin sufficient to meet demands in the event of a system fault. Conversely, the remaining 34.6% expressed a preference for a higher safety margin, adequate to sustain energy demands for up to a full day.

In the second round of the survey at the Green Village, technical results were challenging to obtain due to the residents' lack of access to their energy consumption data. Despite this limitation, outcomes from interviews and survey questions were compiled and analyzed. It is determined that energy consumption is higher during the weekdays, attributed to the majority of residents having the ability to work from home (Q2). This finding marks a notable variance from the results of the first round.

It was consistently reported that energy usage escalates during the winter months (Q3). Residents spend increased time indoors, utilizing heating systems to combat the colder weather, which contributes to higher energy consumption.

When queried about priority in energy applications(Q6-Q8), three main areas were emphasized: **Water Heating**, **Air Conditioning**, and **Powering of Appliances**. Secondary priorities included EV charging and Lighting. These energy applications are recognized with high energy consumption. Consequently, preferences for safety capacity margins (Q9) among the residents were split into two equal groups. One group favored a reserve capacity sufficient to address energy needs during a system fault, while the other group preferred a safety margin that would ensure a full day's worth of electricity coverage.

3.2.3 Preferences for Energy Management and Control

On the subject of energy management and control, the survey asked the interviewees questions regarding their preferences, specifically when it comes to managing energy by themselves or by allowing third-party organizations to optimize their energy consumption(Q5). Assuming an EMS is installed, providing control over the digitalized hydrogen capacity allocated to each household, the EC members can either set the system to utilize hydrogen-sourced electricity for specific applications or have a third-party organization automatically configure the assigned energy to specific uses such as water heating or EV charging.

On the first round of the interview, 61.6% of the representatives of the Greek TSO wished to personally manage their energy consumption to be more flexible and 38.4% wished to have a third-party organization to manage their hydrogen capacity based on their preferences. This answer is further enforced by Q15, which asked how reluctant the users would be towards sharing their consumption data to facilitate better communal energy handling. The answers did not allow for a clear-cut answer, as 30.8% were in the middle, with 23.1% leaning towards not wanting to share their energy data and 46.1% being fine with sharing their energy data.

In Q18, IPTO representatives were asked to choose between involving the community in decisions related to the shared hydrogen storage system or delegating management to a third-party company. The results indicated that 69.2% of the interviewees preferred that all decisions be managed internally within the community, with the assistance of an expert consultant. Conversely, 23.1% of the interviewees favored outsourcing all decision-making to a third-party company. The remaining 7.7% of respondents expressed a preference for a hybrid approach, combining elements of both options.

During the second round of consultations at Green Village, the EC residents consistently expressed a preference for managing their own energy consumption, rather than outsourcing this responsibility to a third-party organization. Notably, one resident strongly opposed the idea of sharing energy data with an external energy management organization. Such perspectives indicate a clear mandate for internal management of hydrogen capacities and preferences within the energy community itself.

The community's demands included enhanced involvement in decision-making processes and a deeper understanding of the hydrogen system's operation. There was a strong inclination towards restricting the distribution of energy data solely within the community boundaries, suggesting a model where the community administrator collaborates closely with an energy expert. This expert would be tasked with explaining the mechanisms by which hydrogen capacity allocation can effectively meet the residents' energy needs.

Moreover, the residents demonstrated a keen interest in both learning about and utilizing hydrogen energy. Consequently, organizing educational workshops and ensuring a comprehensive understanding of the hydrogen system emerged as essential responsibilities to be addressed by the community administration. This approach highlighted the community's commitment to both **autonomy** and **informed participation** in its energy management practices.

3.2.4 Preferences on Control of Shared Hydrogen Storage System

During the initial round of the survey, representatives from the Greek TSO were presented with technical inquiries concerning their preferences for system control of the shared hydrogen storage. This section included questions Q12, Q16, and Q19, which were designed to provide a comprehensive understanding of opinions on system control.

When IPTO participants were queried about their familiarity with the P2G2P process for hydrogen (Q12), it was observed that a substantial majority of the respondents were very familiar with the total process, as seen in Figure 19, indicating a high level of technical knowledge among the participants. Furthermore, various ideas on implementations were discussed with the majority wanting to control their allocated hydrogen capacity through a smart EMS that communicates with the other EMS of the EC. Through this way, the household users would indeed be able to control their energy share on the SHSS and facilitate energy transactions with the other community members.

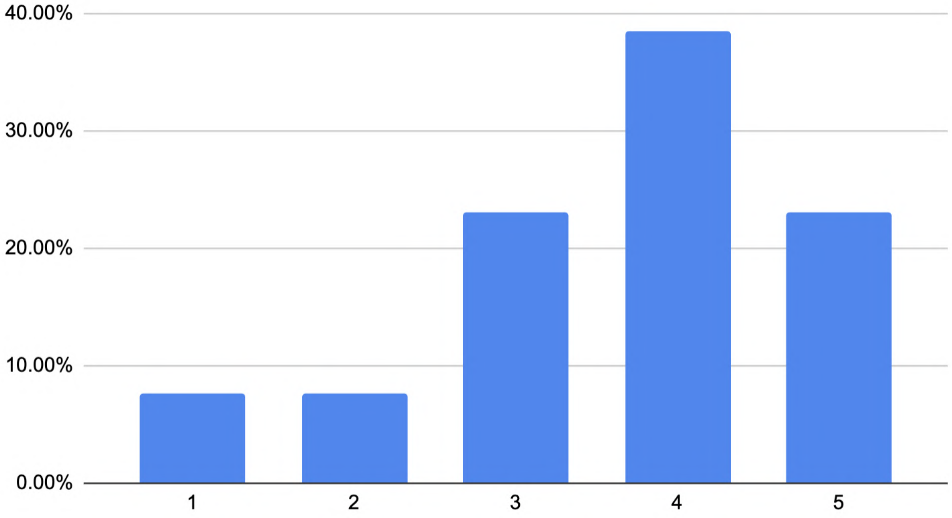


Figure 19: Q12: 1 Not Familiar - 5 Very Familiar

Additionally, when questioned about their preferences for the degree of control over the operation and settings of the hydrogen storage system (Q16), the majority expressed a preference for a configuration that allows for significant control (answers seen in Figure 20). This preference underscores the desire among stakeholders for an operational framework that permits active management and adjustment according to specific needs and circumstances. Such findings highlight the importance of designing systems that are not only efficient but also adaptable to the preferences and expertise of their operators.

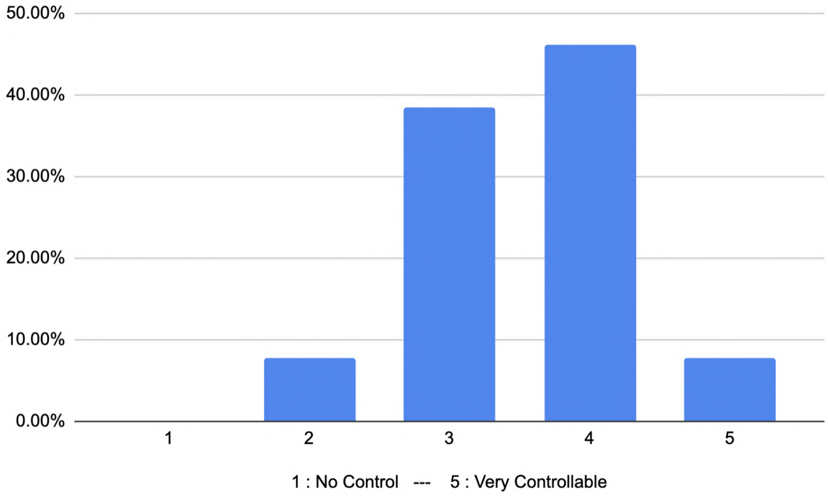


Figure 20: Q16: Preference for automation vs manual control

In the second round of the survey at the Green Village, residents provided feedback on their preferences for controlling the SHSS. While Q12 was omitted due to the residents' limited technical expertise, their contributions were nonetheless insightful regarding the integration of the system into their daily lives.

The residents of the Green Village expressed a strong preference for a system that allows substantial user control. Supporting this, the residents were keen on participating in workshops, where an expert alongside the EC administrator would educate them on the operation and capabilities of the system. The initiative to organize such workshops was met with enthusiasm from the community members, who were eager to learn and take an active role in managing their allocated hydrogen capacity. This response highlights the community's commitment to being involved in the management of their energy resources.

3.2.5 Integration, Data Privacy and Safety

During the initial survey round, representatives of IPTO provided substantial feedback on the integration of shared hydrogen storage in future ECs. Their responses were overwhelmingly supportive, reflecting a strong belief in the potential benefits of hydrogen technology for enhancing energy systems. Similarly, the residents of the Green Village were keen on the idea of utilizing shared hydrogen energy capacity for a more sustainable energy landscape.

The **importance** of hydrogen integration within energy communities (Q10) was strongly affirmed. The representatives of IPTO unanimously argued that hydrogen storage is crucial for meeting increasing energy demands and achieving environmental goals, facilitating a transition towards a more sustainable and decarbonized energy framework. The residents of the Green Village gave matching responses, additionally adding that hydrogen storage feels like a natural step forward, if executed correctly and with social welfare in mind.

Considering **supportiveness** towards implementing hydrogen for long-term energy storage (Q11), both the IPTO representatives and residents of the Green Village expressed a high level of commitment towards integrating hydrogen storage systems. Their enthusiasm indicated a readiness to actively engage in advancing these energy technologies, as long as no third parties are involved and provided that the system's interface is easy to use. The residents of the Green Village furthermore advised the provision of workshops by the EC administrator to familiarize themselves with the new technology implementation.

System reliability (Q13) was another area where IPTO representatives expressed strong confidence. They anticipated that hydrogen storage systems would significantly enhance energy system resilience, ensuring a consistent energy supply, especially during fluctuations caused by relying solely on renewable energy production. On the other hand, the residents of the Green Village were uncertain about what to expect given their limited technical knowledge on the subject.

As for **safety** (Q14), a high level of confidence was also expressed by the IPTO representatives concerning the safe implementation of hydrogen technologies. Emphasis was placed on the need for safety protocols, policies and cutting-edge monitoring systems. The importance of a comprehensive energy management strategy and system structure was underscored, indicating that with proper safety measures, the potential risks associated with hydrogen—such as its flammability and the challenges related to its pressurization—could be effectively mitigated. The residents of the Green Village shared the same thoughts, adding that the integration of shared hydrogen storage systems shall be commercially available only after smaller-scale systems have been tested in pilot sites.

Concerns (Q17) were primarily centered around safety. Despite high confidence in the safety measures and risk management strategies (Q14), the IPTO representatives acknowledged the inherent risks associated with hydrogen's flammability and material permeation, emphasizing the need for strict oversight. Finally, the residents of the Green Village stressed the importance of having an easy-to-use interface, thereby not requiring the administrator or a third party to operate it and facilitate energy transactions for them.

3.2.6 Discussion on Survey Findings

This chapter detailed an extensive survey conducted with stakeholders from both the Greek Transmission System Operator, IPTO, and the Green Village Energy Community in the Netherlands. The focus was on exploring the adoption potential and operational preferences regarding shared hydrogen storage systems within ECs as well as on acquiring anonymous energy consumption data.

Significant insights were revealed into energy consumption trends and household preferences in energy management. The 15 representatives from IPTO demonstrated an interest in independently managing energy utilities. They proposed high energy-consuming applications such as water heating, air conditioning, and electric vehicle charging for green hydrogen utilization. Their preferences indicate the importance of developing a modular hydrogen storage solution that offers user autonomy and energy flexibility.

Similarly, the (five) members of the Green Village EC expressed a preference for self-management of energy resources, underscoring the need for expert support to understand and utilize hydrogen-based systems. Concerns about data privacy, system safety, and the need for user-friendly interfaces were also highlighted, emphasizing the necessity for comprehensive planning in the implementation of hydrogen systems.

The findings suggest that the successful integration of hydrogen storage into energy communities requires alignment with user needs and preferences, therefore the importance of delivering a modular framework for sharing utilities, promoting easy user engagement, safety, and reliability is emphasized.

In summary, the enthusiastic and proactive engagement from the stakeholders provides a strong foundation for future advancements in hydrogen storage technology within energy communities, indicating that targeted research, policy-making, and community-focused strategies are crucial for realizing the potential of hydrogen in sustainable energy systems.

In terms of concluding remarks, it is worth noting that during the interview phase, the discussion with the interviewees could sometimes not be encapsulated in 20 questions. Insights on energy demand and habits on energy consumption were given from the perspective of living in a future energy community. Furthermore, alongside the preceding data, each participant was asked about the square meters of their household, which is an important piece of information utilized in Section 3.5.3 and Section 4.2.2. Processing these data points made it possible to develop several scenarios applicable to the `Complex Model`.

3.3 Assessing the Viability of Hydrogen for Urban Heating: A Methodological Approach

This section examines the feasibility of using green hydrogen for heating, both for space and water heating, within urban energy communities, referencing the findings of Section 2.5. The research question guiding this analysis is:

Is it feasible to facilitate H2 heating within the energy community annually?

Through a comprehensive examination of scholarly articles and industry reports, an overview is provided, highlighting the economic, environmental, and technical challenges associated with hydrogen as a heating solution for future urban settings. In addition, the methods used to signify the findings are shown and a conclusion aiming to answer the aforementioned research question is given.

3.3.1 Economic Viability and Efficiency

The economic implications of utilizing hydrogen for heating purposes have been a significant concern. It has been identified that hydrogen heating systems exhibit higher initial and operational costs compared to electric heat pumps, making them a less economically viable option [67], [68]. This financial aspect poses a substantial barrier to the widespread adoption of green hydrogen for heating in EC settings, especially when evaluated on an annual basis [64]. Even if incentives were to be given, the overall efficiency of converting surplus electricity to hydrogen which can supply heat to households is low enough (around 40%, found in Section 2.5) to be considered not viable [65]. In urban settings, water heating is predominantly facilitated by electric boilers, accounting for 20%, or natural gas, which comprises 40% of the market, thus serving as the primary source [69]. Although hydrogen could technically be employed for water heating, its lower efficiency necessitates a substantially greater energy requirement and a higher overall expense.

3.3.2 Environmental and Technical Challenges

The environmental impact and technical feasibility of hydrogen production, particularly green hydrogen produced through electrolysis, necessitate high running and maintenance costs and a high energy input, which is derived from DERs. This process, while aiming to produce clean fuel for heating, diverts significant renewable energy that could directly power heating systems and pumps which have a much higher efficiency, raising questions about the overall sustainability of such an approach [66], [67].

Furthermore, the infrastructure essential for the distribution and storage of hydrogen for heating presents substantial obstacles. The use of compressed green hydrogen for electricity provision during peak household demand periods entails greatly lower capital investments for infrastructure development than those required for also integrating heating solutions. Additionally, the adaptation of existing natural gas networks or the establishment of new pipelines tailored for hydrogen distribution necessitates extensive financial investments and poses engineering challenges. These include dealing with hydrogen's inherently low energy density and with mitigating the risk of metal embrittlement [68].

Moreover, the deployment of hydrogen-based heating systems introduces safety concerns among a significant proportion of homeowners. Despite rigorous engineering efforts to enhance system safety, the perception of risk associated with hydrogen heating remains a deterrent, with a preference for the perceived safety and higher efficiency of electric heating. This preference underscores the broader apprehension towards adopting hydrogen for residential heating.

3.3.3 Methods for Annual Feasibility Assessment

Addressing the core research question regarding the annual feasibility of hydrogen heating, it is observed that the lower efficiency and higher costs associated with hydrogen transmission and production, along with the extensive energy requirements for its production, present considerable obstacles. These factors complicate the potential of hydrogen to meet community heating demands consistently throughout the year [67], [68].

The considerations are enforced further when estimating the actual energy demands for heating of an EC, situated in Europe. Specifically, in [69] the combined energy used for space and water heating is found to equal 78.9% of the total energy a household in Europe consumes. The total energy share is shown in Figure 21.

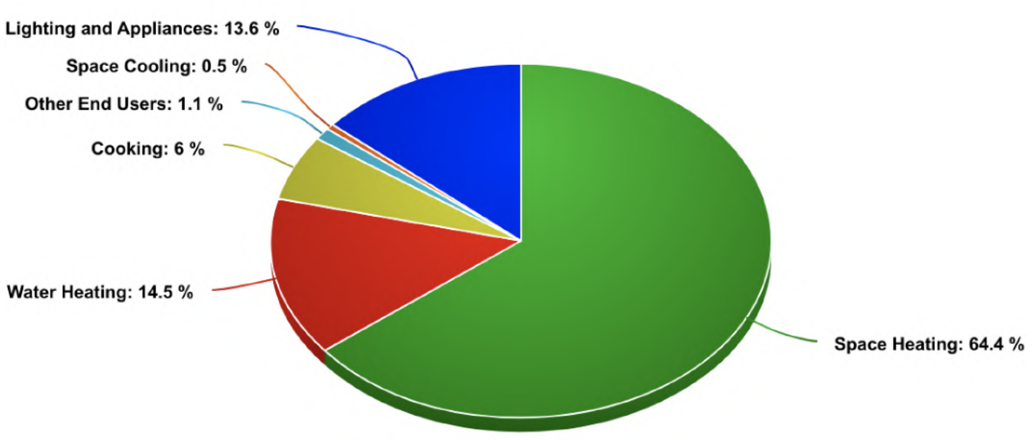


Figure 21: Energy Consumption in the residential sector by use, EU, 2021 [69]

In [70], it is specified that the average energy consumption per dwelling in the EU, equals 1.3 tonnes of oil equivalent (toe) per year. The figure of 1.3 toe/dwelling/year is a general average that reflects the energy consumption across the EU, taking into account the disparities between countries due to differences in climate, building characteristics, and energy usage patterns. If this amount of energy for heating were to be supplied through hydrogen, the following results would be obtained.

The total annual energy consumption in kWh is calculated as:

$$\text{Annual Energy Consumption} = 1.3 \times 11630 = 15119\,\text{kWh} \tag{1}$$

Considering 78.9% of this energy for heating, the annual energy required for heating is:

$$\text{Energy for Heating} = 15119 \times 0.789 = 11928.891\,\text{kWh} \tag{2}$$

The energy required for each heating system is calculated as follows:

$$\text{Hydrogen Energy Required} = \frac{11928.891}{0.4} = 29822.2275\,\text{kWh} \tag{3}$$

$$\text{Natural Gas Energy Required} = \frac{11928.891}{0.8} = 14911.11375\,\text{kWh} \tag{4}$$

$$\text{Heat Pump Energy Required} = \frac{11928.891}{3} = 3976.297\,\text{kWh} \tag{5}$$

The analysis reveals that electric heat pumps are significantly more efficient than both hydrogen and natural gas heating systems. Specifically, the use of heat pumps results in substantial energy savings and reduced energy consumption for heating purposes.

3.3.4 Hydrogen for Heating: Concluding Remarks and Discussion

In summary, the analysis reveals significant challenges associated with the economic viability, environmental impact, and technical feasibility of hydrogen as a primary fuel for annual community heating. While hydrogen may find application in specific sectors within the energy landscape, its role in urban heating systems appears limited when assessed on an annual basis. The comparative analysis based on the preceding calculations demonstrates that electric heat pumps can offer an **86.67%** efficiency gain (COP = 3.0) over hydrogen heating systems. This finding underscores the importance of adopting energy-efficient technologies, such as heat pumps, to meet household heating needs sustainably and cost-effectively. This examination does not undermine the potential contributions of hydrogen to a low-carbon future but underscores the need for continued research into enhancing its efficiency and reducing production costs. This would potentially render hydrogen a more viable option within a diversified urban energy solution framework.

This comprehensive assessment, based on the exploration of current literature and industry reports, provides a thorough understanding of the complexities involved in adopting hydrogen for urban heating. The final outtake confirms that using hydrogen for heating is not found reasonable and will not be considered as an option for the coming simulations of this paper. Future studies are encouraged to delve deeper into innovative strategies that could improve hydrogen's viability as part of the broader transition toward sustainable urban energy systems.

3.4 Optimal Sizing of Shared Hydrogen Tank Methodology

This section details the methodology for determining the optimal size of a shared hydrogen tank within an EC, drawing upon the findings from Section 2.3. The primary goal is to provide ECs with a sustainable energy storage solution that ensures adequate capacity over several months. This involves modeling the necessary algorithms to estimate energy demand and storage costs, with a particular focus on maximizing energy security and equipment longevity. This is especially relevant during periods of high energy demand. The overarching objective is to address the following research question:

How can the optimal size of a shared hydrogen tank be determined?

The determination of the hydrogen storage capacity hinges on the monthly energy consumption data of the energy community, comprising a fixed number of households. Each household is set to consume a fixed amount of kWh per month. This particular study extends over the winter season, spanning from October to March, highlighting the heightened demand for energy that is present during the winter season.

3.4.1 Development of the Benchmark Model for Hydrogen Tank Sizing

The methodology described in this section is useful for accurately determining the size of hydrogen infrastructure required for ECs. This section builds on existing literature to introduce the `Benchmark Model`, which lays the groundwork for dynamic optimization algorithms and models presented in Section 3.5.3.

This model, optimized for energy security and equipment longevity, accurately determines the necessary hydrogen capacity to meet ECs' consumption demands. In addition, it provides an estimation of storage infrastructure costs. Although it is theoretically possible to provide a total infrastructure cost, encapsulating also the costs of the electrolyzer stack, pipelines, compressors and fuel cells, it has been chosen not to, as technologies vary and depend on the specific EC configuration. Thus, the `Benchmark Model` calculates monthly energy requirements for a given EC in kWh of energy or kilograms of hydrogen, as well as the total necessary expenditures for storage infrastructure.

3.4.2 Methods for Calculating the Optimal Hydrogen Tank Size

The efficiencies concerning the Power-to-Gas-to-Power (P2G2P) cycle of the `Benchmark Model`, referencing the literature of Section 2.3 are the following:

Table 12: Benchmark Model - Composition of Total SHSS Efficiency

Efficiency Type	**Unit**	**2024 Efficiency Scenario**
(AC-DC or DC-DC) Conversion Losses	η_{conv}	95%
Electrolyzer Efficiency	η_{el}	60%
Hydrogen Transmission Losses	η_{trans}	92.6%
Hydrogen Storage Efficiency	η_{stor}	94%
Fuel Cell Efficiency	η_{FC}	60%
Total System Efficiency	η_{total}	**29.77%**

The overall P2G2P cycle efficiency is given by:

$$\eta_{total} = \eta_{conv} \times \eta_{el} \times \eta_{trans} \times \eta_{stor} \times \eta_{FC}, \tag{6}$$

where η_{trans} represents the hydrogen transmission efficiency:

$$\eta_{trans} = \eta_{comp} \times \eta_{decomp}. \tag{7}$$

With the total system efficiency (η_{total}) calculated, the total electricity demand (E_{total}) can be estimated using:

$$E_{total} = N_{households} \times N_{months} \times E_{monthly} \times H2_{coverage} \tag{8}$$

Equation 8 calculates the total energy demand in kWh for a set amount of households ($N_{households}$) and months (N_{months}). Alongside these two inputs, the monthly energy demand ($E_{monthly}$) is needed as well as the percentage of electricity demand that the hydrogen system has to cover ($H2_{coverage}$). The last component is necessary if the total electricity demand has to be **partially** covered by the SHSS. The total hydrogen demand is calculated as follows:

$$H2_{total} = \frac{E_{total}}{\eta_{total}} \tag{9}$$

$$H2_{safe} = H2_{total} \times N_{safety} \tag{10}$$

A safety margin (N_{safety}) is integrated into Equation 9 to maintain pressure inside the shared tank(s) and to enhance the reliability of the storage system under variable conditions. The energy requisite of Equation 10 is expressed in kWh and can be used to estimate the total energy capacity that needs to be reserved in H2 to substitute grid-sourced electricity. The required hydrogen mass, accounting for energy content per kilogram, is particularly useful for hydrogen storage calculations and is defined as follows:

$$Mass_{H2} = \frac{H2_{safe}}{33.33}, \tag{11}$$

where 33.33 equals the hydrogen energy content in kWh per kilogram and M_{H2} is the mass of hydrogen required. This concludes the sizing algorithm of the `Benchmark Model`, providing the groundwork for estimating the energy needs of hydrogen infrastructure for ECs. This model makes it possible to run different case studies, experimenting with different scales of energy communities, monthly consumptions of households and total system efficiencies.

3.4.3 Methods for Economic Analysis of Hydrogen Storage Tanks

An economic assessment is conducted to estimate the comprehensive cost of the hydrogen storage system through the `Benchmark Model`. The storage cost estimation, based on [71], [72], [73] and [74] encompasses the costs of the tank, installation, maintenance over a projected lifespan of **10 years**, and the initial procurement of hydrogen. In Table 13, the relevant costs alongside projections for scenarios of 2030 and 2050 found in [75], [71] and [76] are shown:

Table 13: Hydrogen Storage Costs for 2024, 2030, and 2050

Year	Tank Cost per kg	Installation Cost Fraction	Annual Maintenance Cost Fraction
2024	\$550	25%	2%
2030	\$350	20%	1.5%
2050	\$250	15%	1%

The equations outlining the cost calculations start by determining the storage tank cost as:

$$\texttt{Storage Tank Cost} = (\texttt{Hydrogen Mass Required}) \times (\texttt{TankCostPerLiter}) \tag{12}$$

Installation costs are calculated as a percentage of the tank cost, whereas maintenance costs are considered annually over the lifespan:

$$\texttt{Installation Cost} = (\texttt{Storage Tank Cost}) \times (\texttt{FractionInstallCost})) \tag{13}$$

$$\texttt{Maintenance Cost} = (\texttt{Storage Tank Cost} \times (\texttt{MaintCostPerYearPerc}) \times (\texttt{Lifespan}) \tag{14}$$

Finally, the total cost integrates all individual cost components of the system:

$$\texttt{Total Cost} = (\texttt{Storage Tank Cost}) + (\texttt{Installation Cost}) + (\texttt{Maintenance Cost}) \tag{15}$$

Equation 15 covers the costs of hydrogen storage assuming compressed hydrogen storage tanks are used and maintained for 10 years. The equation is used as an estimate for total expenditures. For the calculations of the `Benchmark Model`, Hydrogen Costs are equal to zero as it is assumed that H2 is acquired from surplus DER energy when the SHSS is not in its operation period.

3.4.4 Optimal Sizing of Hydrogen Storage: Concluding Remarks and Discussion

This section provides a step-by-step methodology on the important algorithms governing the `Benchmark Model`. The energy demand calculations consider efficiencies for several subsystems obtained in Section 2.3, resulting in a reasonable estimation of the total P2G2P system efficiency. As a result, the total system efficiency for the shared hydrogen infrastructure in the 2024 scenario equals **29.77%**. This value will be used in the various case studies of this thesis. It is important to highlight that alongside the P2G2P system efficiency, the G2P-only efficiency can be determined. When assuming that the SHSS is fully charged or when assuming that H_2 is externally supplied, the steps for acquiring hydrogen for electricity involve decompression (η_{decomp}, [52]) of stored compressed hydrogen and operation of the fuel cell (η_{FC}) infrastructure. This explains how the following expression is obtained:

$$\eta_{P2G} = \eta_{stor} \times \eta_{decomp} \times \eta_{FC}, \tag{16}$$

which results in a total of **55.27%** G2P system efficiency for 2024. If hydrogen production were to be centralized and then distributed to emerging ECs, the overall system would be more compact and efficient. This approach would enable multiple ECs to be interconnected through hydrogen, which could be produced at a central location and stored, potentially exploiting the abundant underground caverns, shown in Figure 7.

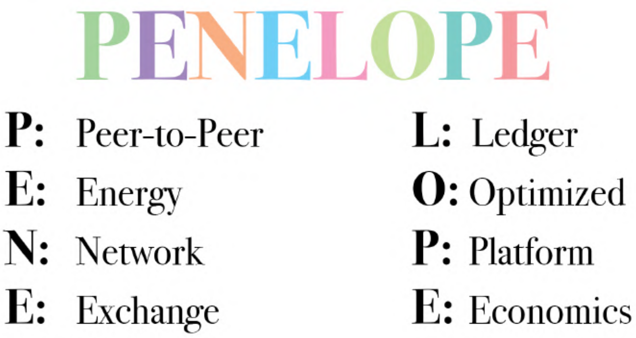
To address the research question and determine the optimal size of a shared hydrogen tank for a given EC, this methodology integrates technical energy and economic feasibility analyses. By applying these methods, a final hydrogen demand in kilograms can be calculated, along with an estimation of the total cost of the storage infrastructure. To validate the methodology and ensure the realism of the `Benchmark Model`, case studies and scenarios will be explored in Chapter 4.

In summary, this model not only provides current efficiency estimates but also allows for projections into the future, as seen in the efficiency and cost data for 2030 and 2050 (Tables 12 and 13). These projections help to assess the economic and energetic feasibility of the P2G2P cycle as technology advances.

It is important to note that the `Benchmark Model` does not account for the costs of electrolyzers, fuel cells, and pipelines in Equation 15. While it is possible to estimate these costs using literature references (such as those in Table 2), doing so would result in a rough estimate applicable only to a few specific EC configurations. Therefore, the `Benchmark Model` focuses solely on the costs associated with hydrogen storage and its maintenance over a defined lifespan. Finally, the model does not factor in the degradation of components over time, which could affect both economic and efficiency calculations.

3.5 Development of PENELOPE: An Architecture for Digitalization of Shared Utilities

The transition towards sustainable energy sources has highlighted the potential of hydrogen as a key player in future energy systems. Despite its promise, there has been a notable absence of a structured architecture designed for hydrogen capacity allocation and facilitation of buying and selling of hydrogen capacity within ECs. There have been energy market mechanisms that combined DERs and BESSs in ECs [77] but undeniably, hydrogen systems are only now being considered. Recognizing the need for a solution, the concept for "**PENELOPE**" is born. This proposed architecture is a tribute to the ingenuity and perseverance of Penelope from Homer's "Odyssey." Just as Penelope wove her tapestry with strategic foresight, the PENELOPE platform strategically weaves together technology and community, stimulating a sustainable future of fair hydrogen capacity allocation and energy exchange using smart contracts. By drawing on the symbolic resilience and wisdom of its namesake, PENELOPE aims to enable EC households to seamlessly integrate hydrogen in their energy landscape. In Figure 69, the acronym is explained:



PENELOPE

P: Peer-to-Peer
E: Energy
N: Network
E: Exchange
L: Ledger
O: Optimized
P: Platform
E: Economics

Figure 22: Penelope Architecture Acronym

- P (Peer-to-Peer): Emphasizes the decentralized nature of the platform, allowing individual users or households to interact directly with each other to buy or sell hydrogen storage capacity without intermediaries.
- E (Energy): At the core of the platform is the focus on energy—specifically hydrogen energy—indicating the type of commodity being exchanged in this peer-to-peer network.
- N (Network): Refers to the interconnected system of users, administration, infrastructure, and technology that facilitates the exchange of hydrogen energy, emphasizing the **collaborative** aspect of the platform.
- E (Exchange): Highlights the primary function of the platform, which is to enable blockchain-based trading (buying and selling) of hydrogen storage capacity among users.
- L (Ledger): Points to the use of blockchain technology as a secure and transparent ledger, recording all transactions to ensure trust and verifiability in the exchange process.
- O (Optimized): Suggests that the platform is designed for efficiency, using advanced algorithms and **smart contracts** to optimize the allocation of resources, pricing, and other operational aspects.
- P (Platform): The digital infrastructure that supports all activities related to the energy exchange, from user registration to transaction execution and beyond.
- E (Economics): Implies the study and application of economic principles within the platform, governing how resources are distributed, how prices are set, and how value is created and exchanged among participants.

With the acronym defined, the focus of this architecture is clearly shown. This architecture will be made to work alongside existing EC policies and mechanisms such as system administration, energy monitoring and maintenance. Additionally, this architecture is crucial for answering the following research question of this paper:

What mechanisms need to be designed to operate and integrate shared hydrogen storage within the community?

To answer this question, several modules are identified. After structuring the architecture's modules as seen in Figure 23, the defined mechanisms will be analyzed through several case studies. These modules are the foundations of the `Complex Model`, which is built considering the energy demand algorithms of the `Benchmark Model` from Section 3.4. The dynamic and modular nature of the `Complex Model` encapsulates the methods used in PENELOPE, ultimately aiming to answer the research question. The flowchart can be seen in greater detail in Appendix B.

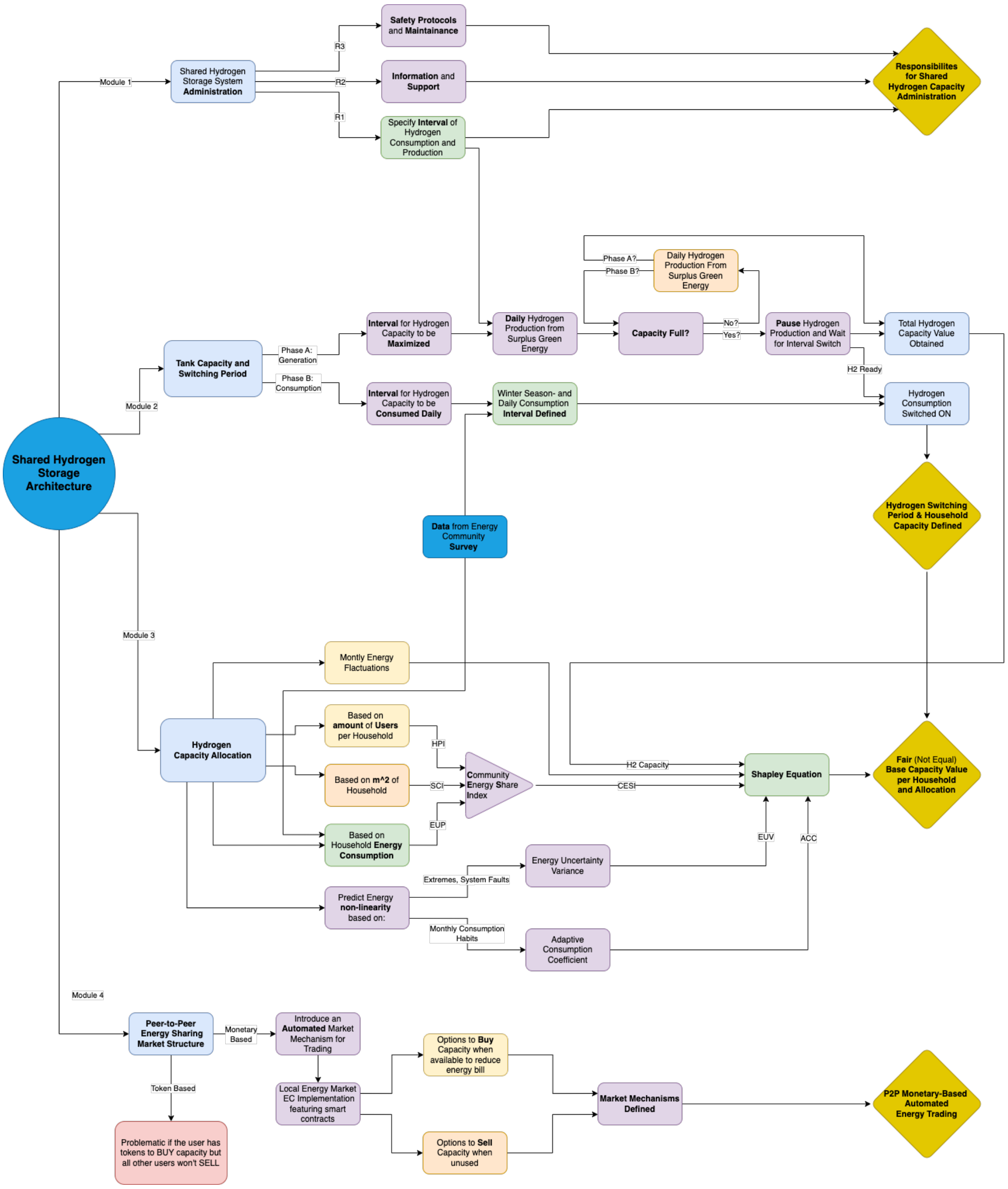


Figure 23: Flowchart of PENELOPE Architecture

The flowchart provided delineates the operational framework and the key modules of the PENELOPE architecture, which is designed to facilitate the integration of an SHSS within an EC and answer the defined research question. The flowchart outlines the intricate processes and mechanisms that necessarily govern aspects of the system. The architecture is designed so that it is applicable to emerging ECs and aims to help in adapting systemic hydrogen generation and consumption. Four modules are identified and explained in greater detail, ensuring that the foundations and links presented in Figure 23 are thoroughly understood.

3.5.1 Module 1: Responsibilities of Administration

The first module of PENELOPE, shown in Figure 24, focuses on the **Administration** of the SHSS, delineating the additional responsibilities assigned to the EC administrator. Within the framework of the PENELOPE architecture, the scope of duties for the EC administrator is expanded, aiming to enhance the integration of the shared hydrogen storage system. The EC administrator, who additionally obtains the role of the **SHSS Administrator**, is tasked with responding to inquiries regarding the operational mechanisms and capabilities of the system, alongside ensuring its functionality and adherence to the EC's norms.

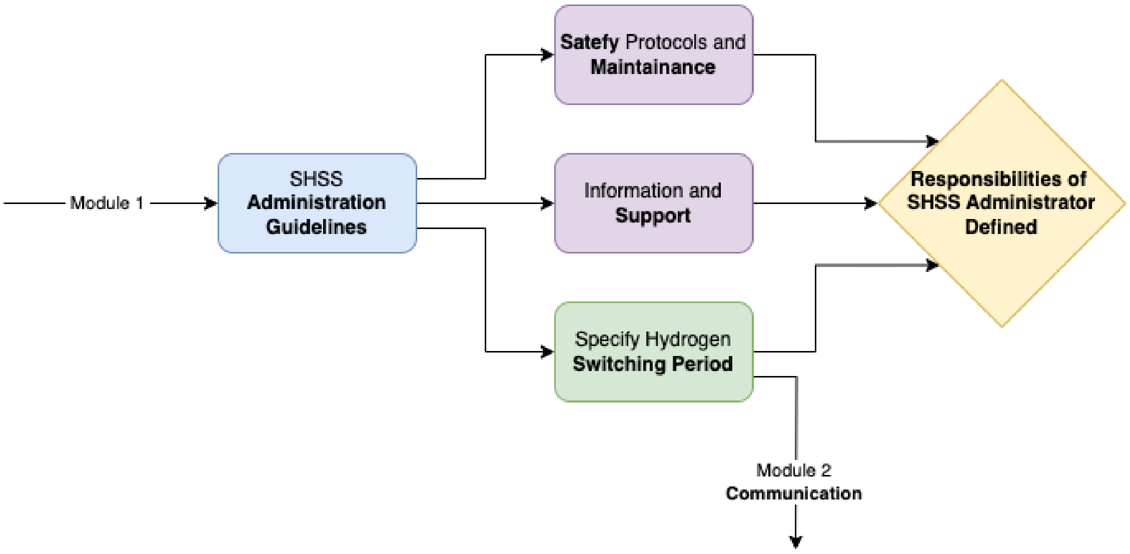


Figure 24: Module 1 from Penelope Flowchart

The responsibilities extended to the administrator encompass not only the **monitoring** of the system and ensuring its **safety** but also the coordination of **maintenance schedules** and the management of responses to system faults or related issues. By understanding the operation of the SHSS within the EC infrastructure, the administrator shall also be in a position to define a **safety margin of capacity**, ensuring that additional capacity is available in case of an internal or external system fault. This role is crucial for the maintenance of system reliability and efficiency. An efficient communication protocol is necessitated, enabling EC members to easily report concerns or seek information about the SHSS. Moreover, it is the responsibility of the administration to engage with designated third-party organizations for the resolution of technical problems, ensuring that such issues are addressed promptly and effectively. This structured approach underscores the critical role of the administration in maintaining the operational integrity and performance of the SHSS, through a framework that prioritizes accessibility, reliability and efficient problem resolution.

A vital responsibility for the administration is to deal with when the SHSS is switched ON and OFF from operation. As mentioned in 2.3.6, it is not possible to continuously operate a hydrogen generation plant without hurting systemic longevity. For a given period, which is defined as **Phase A**, the SHSS is getting charged from surplus energy provided by DERs. The delineation of Phase A is judiciously chosen to encompass the summer months, a time characterized by the generation of surplus energy from wind turbines and PV systems. This surplus energy, prevalent during peak hours over several hours, is strategically directed toward electrolyzers for the production of hydrogen. As the duration of Phase A advances, there is a cumulative increase in the volume of hydrogen that is compressed and stored within the communal tank. The integration of the SHSS into the EC households necessitates the deployment of an advanced EMS. This system is required to provide a digital representation of the shared H2 storage tank, illustrating the proportional share of the total capacity allocated to each household. This approach ensures that the integration of the SHSS is both accessible and reliable, facilitating efficient energy management between EC households without the need for third-party organizations for control, as decided by the survey findings shown in Section 3.2.

The transition to **Phase B**, a phase designated for the utilization of hydrogen to generate electricity daily, is at the discretion of the system administrator. The decision-making process regarding the specific daily intervals for the activation and deactivation of the SHSS is informed by load data sourced from household consumption patterns. For this paper, the survey of Section 3.1 is used to provide a tailored daily interval based on the energy needs of the asked users. This approach not only facilitates the engagement of each EC member with the system but also ensures its optimal use as necessitated by the community's energy requirements.

3.5.2 Module 2: Hydrogen Tank Capacity and Switching Period

The second module, entitled **Hydrogen Tank Capacity and Switching Period**, describes the processes associated with the production, compression, and storage of hydrogen within the SHSS. The second module is connected to Module 1, acquiring the specified switching period intervals from the administration. Furthermore, the daily intervals for system switching ON/OFF are necessary inputs, which for this paper are obtained through analysis of the survey results of Section 3.2. As explained in Section 3.5.1, the system operationalizes two distinct phases which can be seen in Figure 25:

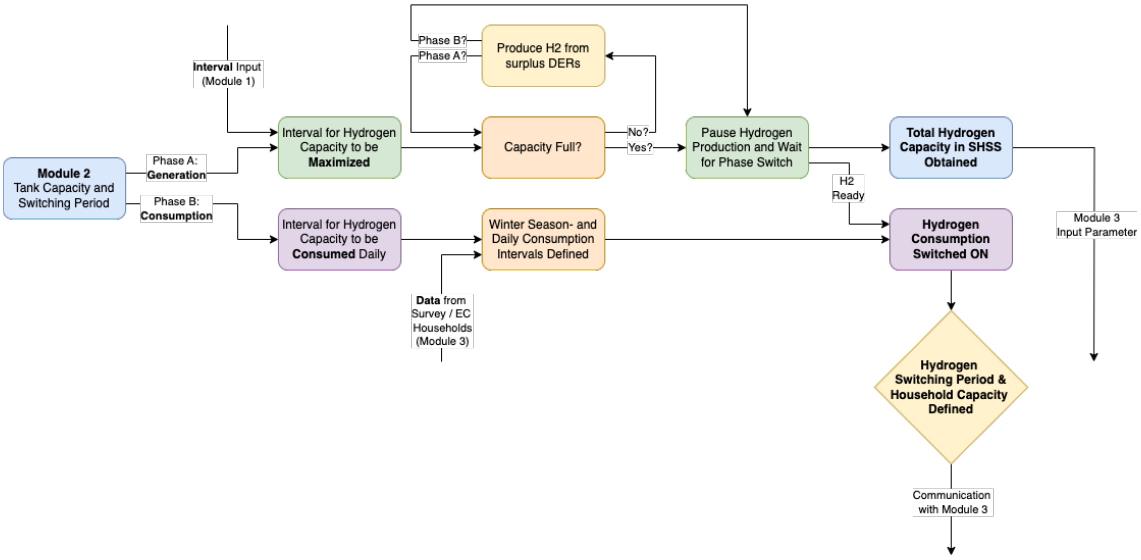


Figure 25: Module 2 from Penelope Flowchart

Phase A, typically coinciding with the summer months, is dedicated to maximizing the generation of green hydrogen utilizing surplus electricity. Upon the hydrogen storage reaching its capacity threshold, the system administrator is presented with the discretion to transition to Phase B, thereby initiating the daily consumption of the stored hydrogen. Alternatively, the transition to Phase B can be enacted before the attainment of maximum storage capacity, though this decision will invariably result in a reduced total H2 storage capacity and consequently, a diminished duration of green hydrogen availability for consumption. The beginning of Phase B necessitates the integration of the terminal hydrogen storage capacity value into the Capacity Allocation Algorithm of the `Complex Model`, as explained in Section 3.5.3 to optimize the distribution of capacity among the EC members. This module showcases the strategic flexibility embedded within the SHSS, allowing for modularity in the management of hydrogen production and consumption in alignment with storage capacity and energy demands.

3.5.3 Module 3: Hydrogen Capacity Allocation

The third module, **Hydrogen Capacity Allocation**, details the algorithms used to achieve a **fair** allocation of hydrogen storage capacity to each household. For this to be achieved, seasonal fluctuations within the winter period need to be identified, as well as algorithms and pragmatic parameters need to be combined to obtain a proper mechanism for hydrogen capacity allocation. These algorithms are all necessary components of the `Complex Model`, which is a more advanced version of the `Benchmark Model`, thereby **optimizing energy allocation and maximizing social welfare**.

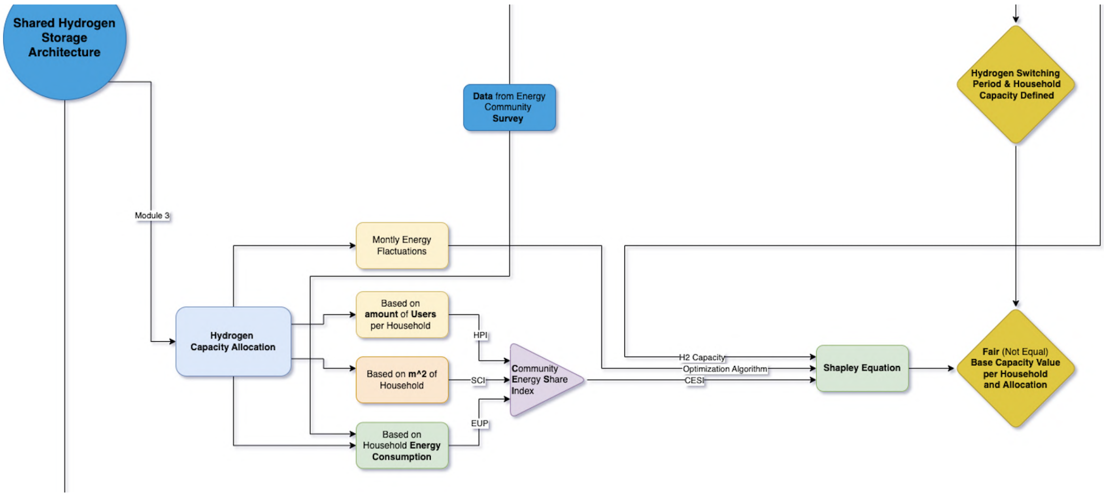


Figure 26: Module 3 from Penelope Flowchart

Utilizing the Shapley Equation for Hydrogen Capacity Allocation

As a foundation for the algorithm for fair capacity allocation of hydrogen among EC members, the seminal works of Lloyd Stowell Shapley are referenced. Awarded the Nobel Memorial Prize in Economic Sciences in 2012 for his "theory of stable allocations and the practice of market design", Shapley's groundbreaking methodology for fair resource allocation has paved the way for various applications, including the distribution of hydrogen capacity.

The *Shapley Value*, a principle from cooperative game theory, offers a methodological approach to distribute payoffs fairly among participants of a coalition based on their contributions. It is mathematically expressed as:

$$\phi_i(v) = \sum_{S \subseteq N \setminus \{i\}} \frac{|S|!(|N| - |S| - 1)!}{|N|!} (v(S \cup \{i\}) - v(S)), \tag{17}$$

where:

- N denotes the set of all participants (or community members, in this context).
- S represents any subset of N excluding participant i.
- v is a characteristic function that assigns a value to each coalition.
- $\phi_i(v)$ indicates the fair share of the total payoff for participant i, calculated through the Shapley value.

Through Equation 17, the fair share of hydrogen each community member is to receive is calculated, considering their contribution to the community's total hydrogen capacity. The employment of the Shapley value ensures an equitable distribution of resources, fair and proportional to individual contributions. However, to provide a scientific but also realistic algorithm, the Shapley equation needs to take into account additional components, thereby enhancing the accuracy of the results.

Community Energy Share Index

The **Community Energy Share Index** (CESI), as seen in Figure 26, is developed to serve as a comprehensive metric for evaluating household energy-related attributes within an energy community. It encompasses factors such as the number of household members as the **Household Participation Index** (HPI), the space of a household in square meters as the **Spatial Consumption Index** (SCI) and household energy usage as the **Energy Utilization Profile** (EUP). The following equation is used:

$$CESI = \left(0.33 \times \left(\frac{\text{df}\,[HPI]}{\text{max\_HPI}}\right) + 0.33 \times \left(\frac{\text{df}\,[SCI]}{\text{max\_SCI}}\right) + 0.33 \times \left(\frac{\text{df}\,[EUP]}{\text{max\_EUP}}\right)\right) \tag{18}$$

As seen in Equation 18, it is possible to assign different weights to the HPI, SCI and EUP respectively. Though it is possible to assign equal weights, Section 4.2.2 experiments with assigning different weights to the variables of Equation 18 to allocations, tailored to the specific EC. Data regarding the aforementioned parameters is obtained through the survey of Section 3.1 for the application of this paper. These parameters can be easily obtained for the emerging ECs of the future, thereby resulting in an easy-to-apply index. CESI quantifies the relative importance of each household in meeting the energy demands of the community, providing a basis for fair resource allocation. It involves a weighted aggregation of household attributes, where weights reflect their relative importance in energy provision. The weighted sum yields an anonymous CESI score for each household, representing its overall contribution to the community's energy pool. Higher CESI scores indicate greater energy significance within the community. Figure 27 illustrates the fluctuation in Shapley value that can occur assuming a case study of 10 households with different energy habits and needs. (different CESI)

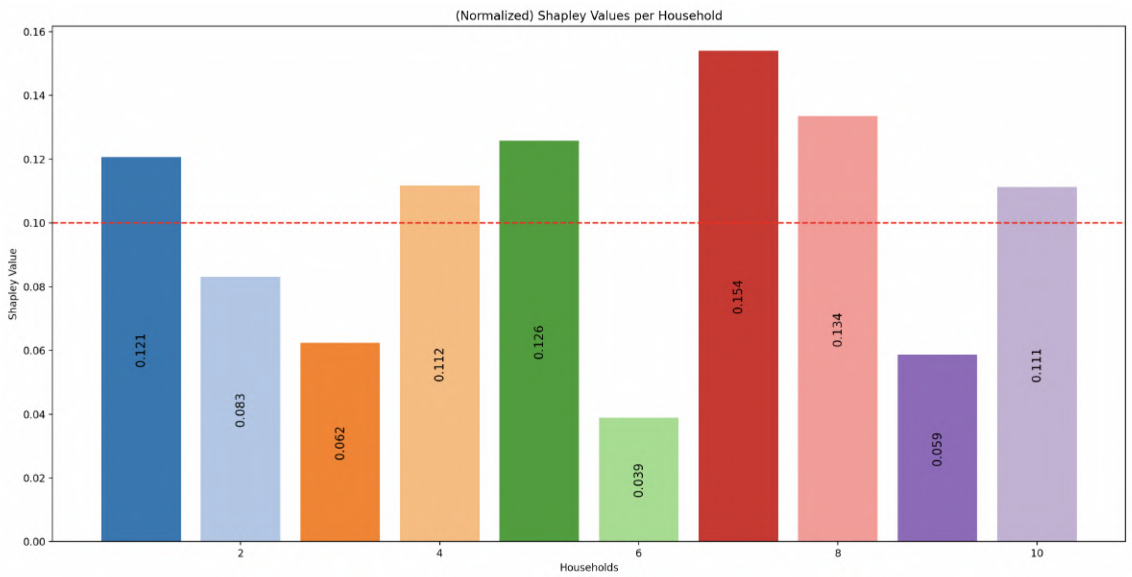


Figure 27: Shapley Values of Case Study 2, Section 4.2.2

In the context of hydrogen capacity allocation, CESI serves as a critical input for the Shapley value calculation. Each household's CESI score acts as a weight in determining their share of the hydrogen capacity allocation. By integrating CESI into the Shapley value calculation, the allocation process accounts for the varying contributions of households to the energy community. This integration contributes to a fair and realistic distribution of hydrogen capacity.

Assessing Monthly Energy Fluctuations to Optimize Dynamic Energy Allocation Strategies

In addition to considering CESI for the Shapley equation for hydrogen capacity allocation, another crucial factor that enhances the fairness and efficiency of allocation is the modeling of seasonal fluctuations in energy demand. The seasonal fluctuations in energy demand are a vital input parameter in the allocation algorithm, ensuring a more **dynamic**, responsive and realistic distribution of the total hydrogen capacity based on monthly consumption trends.

The energy demand tends to peak during the colder winter months, with January being the most energy-intensive, followed by February, December, March, November, and October. This pattern forms a ladder of energy demand intensity, where allocation priorities are higher in the more energy-intensive months and lower in the less energy-intensive ones.

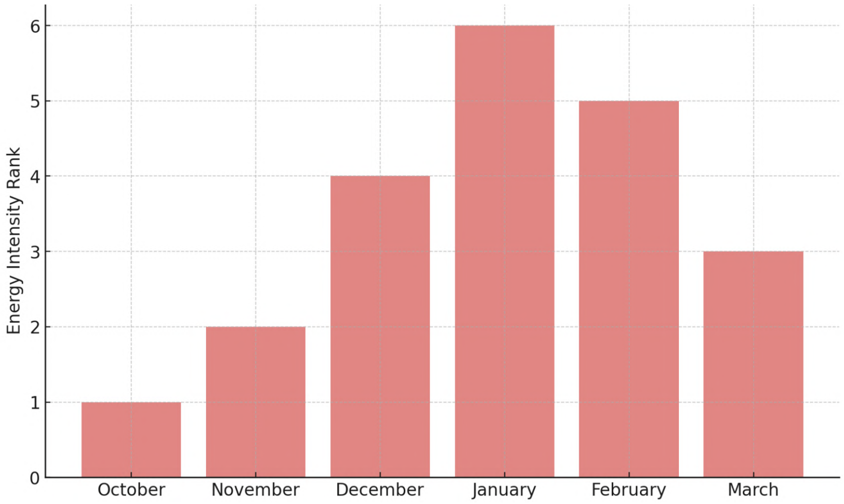


Figure 28: Energy Intensity of Winter Months

The data used to form Figure 28 of energy intensity between winter months is obtained through the Transparency Platform of ENTSO-E [78], which provides access to historical energy data per country and thus allows for these conclusions to be obtained. To acquire a reliable metric, historical monthly load data were collected, focused on the Netherlands, France, Spain and Greece. These data points were used to determine whether different European countries of the equator presented different energy consumption trends. An example is shown in Table 14, illustrating the energy trends for the winter months of 2022 and 2023 respectively:

Table 14: Monthly Energy Demand for Netherlands, France, Spain, Greece (2022 and 2023)

Country	Month	2022 Demand (MW)	2023 Demand (MW)
Netherlands	January	13333.70	12804.86
	December	13008.14	14219.95
	February	12728.95	12096.80
	November	12237.46	13711.00
	March	11270.55	11455.17

Continued on next page

Table 14 – *Continued from previous page*

Country	**Month**	**2022 Demand (MW)**	**2023 Demand (MW)**
	October	11084.88	12923.63
France	January	69361.65	62019.97
	February	62665.12	60526.76
	December	60638.79	57774.56
	March	56141.19	52954.86
	November	50520.18	52953.41
	October	42627.18	43249.11
Spain	January	28935.10	28082.67
	February	28471.93	28785.25
	March	27340.52	26097.13
	December	25944.21	26812.17
	November	25560.27	26075.13
	October	24547.17	24817.37
Greece	January	6375.68	5413.28
	March	6180.73	5098.04
	February	6095.33	5739.09
	December	5278.48	5446.78
	November	4832.65	4943.38
	October	4602.49	4899.66

By incorporating a seasonal ranking of energy demand into the allocation algorithm, households receive a dynamic and more realistic split of the total hydrogen capacity allocation. This approach optimizes resource utilization, ensuring that hydrogen capacity is allocated in accordance with the community's fluctuating energy needs throughout the winter season which for this paper is considered to start in October and end in March. The modular nature of the PENELOPE architecture allows for assigning different weights to each Phase B (winter) month, with the EC administrator deciding on the adjustments based on the particular EC.

Adaptive Consumption Coefficient

To introduce a non-linear progression and better simulate real-world variations in energy consumption among different households, a household-specific **Adaptive Consumption Coefficient** (ACC) is incorporated into the model. Each household is assigned a unique coefficient, which is calculated as follows:

$$ACC_i = 1 + 0.05 \times random\_uniform(0.8, 1.2) \tag{19}$$

where random_uniform$(0.8, 1.2)$ generates a random number between 0.8 and 1.2. This means that each household's ACC slightly varies. This factor is currently a **fixed** parameter, adding a slight discrepancy next to the expected values. As a future improvement, this parameter is set to scale based on the seasonal consumption pattern of the respective household. If a household consumes overall less energy than projected from the `Complex Model`, the ACC contribution for the following year will result in a slightly decreased capacity allocation.

Energy Uncertainty Variance

To further enhance the realism of the `Complex Model` and account for unpredictable variations in energy consumption, another parameter is added. This parameter, referred to as the **Energy**

Uncertainty Variance (EUV) introduces a small random variation into the energy allocation calculations, defined as:

$$EUV_i = 1 + \text{random\_uniform}(-0.05, 0.05) \tag{20}$$

where random_uniform$(-0.05, 0.05)$ generates a random number between -0.05 and 0.05. This means that the energy allocation for each household can fluctuate by up to ±5% due to random variations. This component reflects the uncertainty and variability in energy demand due to factors such as weather changes, unexpected events, or behavior changes.

Implementation of a Fair Hydrogen Capacity Algorithm

To acquire a model for fair capacity allocation of hydrogen in ECs, several algorithms had to be identified and combined within the `Complex Model`. The purpose of this implementation is to introduce a more dynamic and modular model for emerging ECs, which could be theoretically used to achieve fair capacity allocation, tailored for each EC. As the *Complex Model* optimizes allocation based on social welfare, it has to be adjustable by the SHSS administrator to seamlessly follow the evolution of the respective EC. To do this, the identified subsystems of Module 3, encapsulated in the `Complex Model`, are made to work together and will be tested in Section 4.2. In Figure 29, a flowchart showcasing all the subsystems of the `Complex Model` is shown. These enhancements provide a more responsive and equitable allocation mechanism, aligning with the principles of fair allocation and increasing efficiency and realism in the community energy management domain.

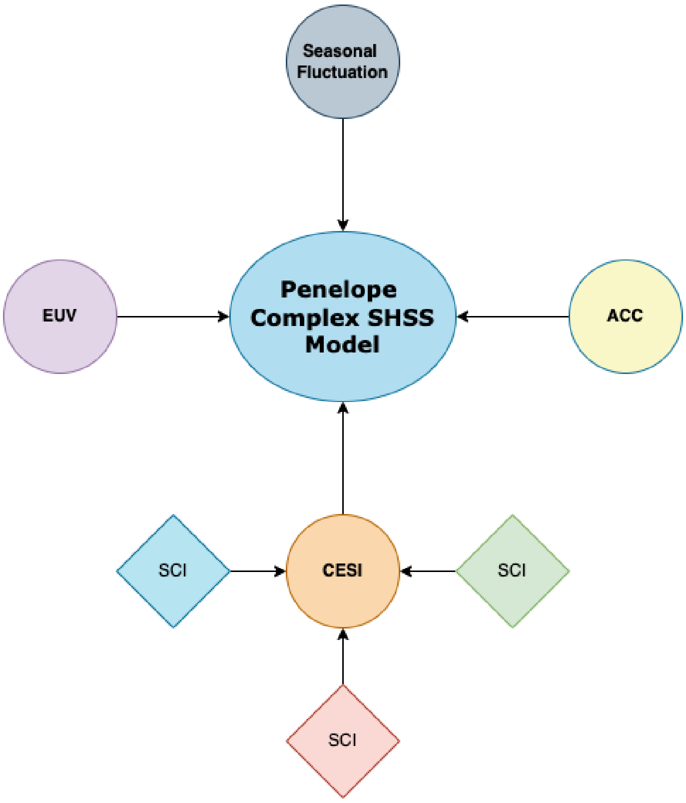


Figure 29: Complex Model Variables

3.5.4 Module 4: Peer-to-Peer Energy Sharing Market Structure

The fourth module introduces a monetary-based market mechanism for trading hydrogen capacity. For this thesis, this mechanism is initialized together with the `Complex Model`, making it possible for the simulated EC users to buy/sell capacity upon demand, therefore adjusting their energy needs and ultimately maximizing the social welfare of the community. Figure 30 shows the module in detail:

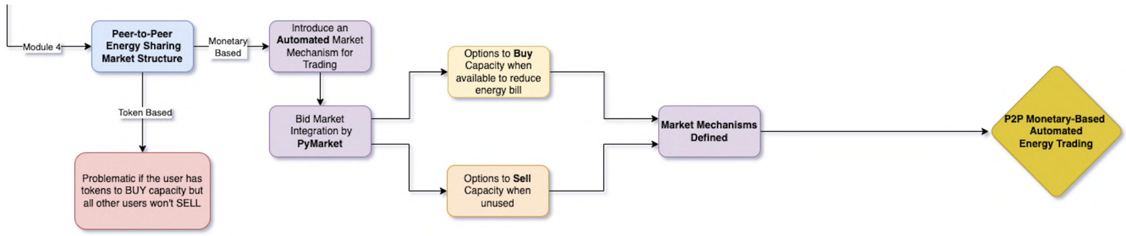


Figure 30: Module 4 from Penelope Flowchart

The ambition behind this implementation is to develop an easy-to-use platform that helps EC households to seamlessly integrate hydrogen into their energy landscape. This involves potentially purchasing additional hydrogen capacity when needed and selling excess capacity back to the community's local energy market. The system features the following market operations:

- **Dynamic Pricing and Trading Capacity:** The market's algorithm assigns prices based on households' energy usage profiles (EUP) and requested capacity volume. Households with higher EUP levels are prioritized, with varying ranges of trading capacities and prices per kWh based on the capacity availability in the market and the actions of the other households, simulating a real-world dynamic pricing mechanism. This setup ensures that prices reflect real-time supply and demand conditions, enabling effective resource allocation beyond the monthly allocation of the `Complex Model`.

- **Transaction Simulation:** The market simulation in this thesis involves a randomized process to determine whether each household buys or sells energy. All households of the EC participate in the LEM, meaning that once the LEM algorithm is initialized, it affects all EC households. This approach enables the simulation of continuous market transactions, ensuring that all household allocations are updated in real time. Trading capacities and detailed transaction records are also logged, providing the EC administrator with a comprehensive archive of market activities.

- **Smart Contract Simulation:** Smart contracts automate the execution of trades based on predefined conditions. In the simulations, this is represented by automatically logging transactions and adjusting trading capacities and prices without manual intervention. This reflects the efficiency and security benefits of smart contracts in managing decentralized energy transactions and aligns with the wishes discussed in Section 3.2, where stakeholders wished for a system that doesn't involve third-party enterprises for handling energy transactions.

- **Visualization and Analysis:** The system visualizes market outcomes using bar charts featuring the capacity transactions, distinguishing between buying and selling activities. Finally, the updated hydrogen capacity allocation after the LEM run can be showcased.

This paper will explore how a P2P system could facilitate the trading of hydrogen capacity within these local ECs. By adopting a P2P model, households can trade hydrogen capacity directly among themselves, promoting more sustainable and efficient resource use. The integration of such a system could significantly enhance energy flexibility and independence for community members. This approach aims to make green energy more accessible and cost-effective for all participants in future urban settings.

3.6 Summary and Implications

This chapter describes the chosen methods for developing a robust architecture tailored for the integration, management, and optimization of SHSS within ECs. Through detailed sections, ranging from survey design and analysis to advanced algorithmic modeling and optimization, the fundamental research questions of this paper have been addressed and elaborated on.

The chapter began by introducing a survey aimed at understanding user trends and preferences towards renewable energy technologies, particularly focusing on SHSSs. The survey featured two rounds of interviewees and provided valuable insights into energy consumption habits, preferences towards hydrogen storage, and energy management within ECs. Key findings from the survey, detailed in Section 3.2, highlighted the community's interest in managing their energy consumption independently and their concerns regarding data privacy and system safety. This information forms the basis for developing user-centric energy systems with modular architectures that align with the community's expectations and energy needs.

The chapter continues by addressing the first research question of this paper, considering calculations for optimal sizing of hydrogen infrastructure in ECs. After developing the so-called `Benchmark Model`, a comprehensive methodology details the necessary steps that need to be undertaken to acquire an expression for the optimal hydrogen storage tank size. The final answer is expressed in kilograms or kWhs of H2 required, which then have to be stored in large compressed hydrogen tanks. The `Benchmark Model` calculates the hydrogen energy requirements for a given set of parameters while also estimating the necessary expenditures to store the calculated amount. Though the research question is answered and the `Benchmark Model` is optimising energy calculations for equipment longevity and energy security, the algorithms remain to be tested in simulations to evaluate the feasible extends of each efficiency scenario.

Furthermore, the second research question of this chapter evaluates the viability of using hydrogen for urban heating, concluding that hydrogen heating is currently less economically and technically viable compared to other heating solutions like electric heat pumps. This analysis was crucial in refining the focus of the SHSS and its models to focus to electricity needs rather than also including heating, thereby optimizing resource allocation, reducing SHSS capacity needs and significantly increasing system efficiency.

One of the core components of this chapter is the **PENELOPE architecture**, a novel framework designed to facilitate the digitalization and management of shared hydrogen utilities within ECs. The PENELOPE architecture is introduced and proposes several subsystems, all built in the so-called `Complex Model`, facilitating the seamless integration of shared utilities, tradable energy capacity, fair energy allocation, and enhanced user engagement. It stands out as a decentralized modeling approach, eliminating the need for third-party intervention in controlling energy systems and reserves. Instead, it leverages advanced algorithms and smart contracts to enable P2P energy sharing and trading, thereby promoting autonomy and energy efficiency within the community. Several mechanisms make it possible to propose a complete architecture that answers the energy demands of future ECs in a user-engaging and energy-efficient manner. Although the mechanisms are displayed to provide a complete answer to the third research question, the ambition is to test the performance of the algorithms through several case studies and simulations, elaborated in Chapter 4.

To summarize, the PENELOPE architecture and subsequently the `Complex Model` constructed around it, are built upon four distinct modules:

1. Administration Responsibilities: Expands the role of the EC administrator to include monitoring, safety, maintenance, and managing of the SHSS. This ensures that the system operates smoothly and efficiently, with clear protocols for addressing issues and communicating with EC members. The administrator is also in charge of helping EC members to familiarize themselves with the control of the SHSS.
2. Hydrogen Tank Capacity and Switching Period: Defines the processes for hydrogen production, storage, and consumption. It introduces two operational phases—Phase A for hydrogen generation and Phase B for consumption—based on seasonal energy availability and demand. The EC administrator decides the span of each phase and the daily switching period, based on EC energy requirements.
3. Hydrogen Capacity Allocation: Employs the algorithms of the `Complex Model`, including the Shapley equation and several sub-components, to ensure fair allocation of hydrogen capacity among EC members. This module incorporates dynamic factors such as seasonal energy demand based on historical data, individual household profiles to optimize capacity allocation and maximize social welfare within the EC. Finally, two coefficient are introduced to express random fault events, energy under/over subscription and contribute to a more realistic hydrogen capacity allocation.
4. Peer-to-Peer Energy Sharing Market Structure: Establishes a P2P market mechanism for trading hydrogen capacity within the EC. This mechanism simulates the use of blockchain-based smart contracts to ensure rapid, secure, and transparent transactions, promoting energy flexibility and maximizing social welfare without the need for a third-party organization to manage energy transactions. The LEM is initialized through the `Complex Model` for all households and provides plots and logs that archive the transactions of hydrogen capacity.

Undeniably, there is significant potential for further improvement in the proposed architecture and developed models. By incorporating historical data of EC household consumption, the allocation algorithms can become more dynamic and precise in tailoring capacity allocation. Additionally, calculating the safety margin based on individual household demand rather than a fixed percentage of the total capacity would enhance the system's efficiency. Furthermore, exploring the concept of over-/undersubscribing daily hydrogen capacity allocation could offer superior optimization opportunities, albeit at the cost of requiring additional energy from the connected DERs.

4 Applications

After a thorough literature review on the recent trends revolving around sustainable housing and energy, it is clear that energy communities will significantly rely on sharing their utilities and strive to function as an energy-sustainable urban ecosystem. During the methods chapter, two models were developed to help optimally allocate hydrogen capacity among households of energy communities. In Section 3.5, the PENELOPE architecture is developed, featuring various modules to ensure seamless integration of shared hydrogen storage in energy communities. This chapter aims to test, compare and optimize the performance of the `Benchmark` and the `Complex Model`, based on the PENELOPE architecture, through a series of case studies. Ultimately, the goal is to answer the central research question of this thesis, namely:

When is the introduction of shared hydrogen storage a sustainable long-term storage solution for the ECs of the future?

To acquire an answer, this chapter starts by defining the first case study of this thesis in **Section 4.1** along with the necessary constraints, requirements and assumptions. The constraints, requirements and assumptions used in the so-called `Benchmark Model` of **Section 4.1** will be carried on for **Section 4.2**, where the `Complex Model`, will be tested and calibrated for the continuation of this thesis' simulations. In **Section 4.3**, case study 3 is introduced to compare the performance and limitations of the two models. In **Section 4.4**, a long-term sustainability and scalability analysis is conducted, discussing ECs of 2030 and 2050 based on the available literature, reflecting on advancements in technology and policy, ultimately leading to an easier and more sustainable introduction of SHSS in emerging ECs. This section initially considers the changes in total system efficiency which can be expected in 2030 and 2050, respectively. Then, by reflecting on the advancements in policy, an answer to the preceding research question will be given. Finally, in **Section 4.5**, a conclusion of **Chapter 4** is given, reflecting on the various case studies and the respective findings.

4.1 Case Study 1: Small EC in Urban Setting

This case study explores the dynamics of Shared Hydrogen Storage Systems in ECs under specified conditions concentrated in **Case Study 1** (CS1), featuring a small EC in an urban setting. The setup involves five energy-interconnected households, all located in the same building as illustrated in Figure 31. These energy-efficient households are connected to DERs and have access to energy obtained from accumulated hydrogen reserves, which is stored in compressed hydrogen tanks.

It is assumed that from April until the end of September, designated as **Phase A**, the SHSS converts surplus electricity to green hydrogen. During the remaining six winter months, referred to as **Phase B**, the shared hydrogen tank is assumed to be full and idle, ready to fulfill the energy needs of the interconnected households. The parameters of Case Study 1 are shown in Table 15.

Figure 31: Energy Community of Case Study 1 with 5 Households (Render by Author)

As defined in Section 2.3.6, a P2G2P system needs to have a predefined switching period. For this case study, the SHSS is switched ON daily from 17:00 to 23:30. This interval, determined based on the energy demands of the interviewees from Section 3.2, ensures equipment longevity and energy security during peak energy demand hours. This case study's primary focus is on evaluating the total system's performance and efficiency, using the developed `Benchmark Model`.

Case Study 1: Research Objective

The main objective of this case study is to acquire results from the `Benchmark Model`. Data will be collected by simulating the winter months of this scenario, based on the parameters of CS1. This includes energy consumption rates, efficiency measurements, calculations and operational time intervals. The simulation will replicate the winter conditions to assess system performance, energy consumption and efficiency accurately. Furthermore, the capital expenditures concerning storing the necessary H_2 of this case study will be included. The objectives of the case study are summarized:

1. Evaluate the feasibility and economic impact of using hydrogen to meet the energy demands of an EC.
2. Understand how changes in allocational efficiency impact overall energy requirement, demand and consumer benefit.

Case Study 1: Scenario Parameters and Assumptions

The parameters for the case study are summarized as follows:

Table 15: Case Study 1 Modelling Parameters

Parameter	Number	Unit	Notes
Household Num.	5	-	Households connected to the SHSS
Energy Consumption	248.75	kWh/Month	Average Monthly Electricity Consumption (from Section 3.2)
Months	6	-	Winter Months, Phase B (from Section 2.3.6)
System Efficiency	29.77	%	P2G2P System Efficiency (from Section 3.4.4)
H2 Coverage	60	%	Daily Energy to be supplied by SHSS
Switching Period	17:00 - 23:30	-	Daily Interval that SHSS is switched ON (from Section 3.2)

Additionally, the following set of assumptions governs the results of this case study:

1. The developed algorithms of the `Benchmark Model` consider that months only have 30 days.
2. The switching period duration is chosen to determine whether it's possible to solely rely on the hydrogen infrastructure during peak demand hours. Thus, it is assumed that a coverage of 60% of the total daily energy demand is enough to cover the needs at the specified interval.
3. Once the daily limit is surpassed or the switching period is over, the EMS switches consumption back to grid electricity.
4. Households have smart energy management systems and can allocate hydrogen-obtained electricity to any demanding or non-demanding application.
5. The household energy consumption is fixed, assuming that households have similar energy demands and pay similar energy bills with a fixed tariff, which returns funds to the household owners when the household energy consumption is lower than the approximation.
6. The interconnected households have a daily energy consumption budget that does not fluctuate through the days of the week.

Case Study 1: Identification of Constraints

The constraints for this case study include:

1. Technological: The system efficiency is set at **29.77%**, reflecting current technological limitations as seen in Section 2.3.
2. Environmental: Only winter months are considered to assess energy efficiency under peak demand scenarios. During the remaining months, the SHSS is set to charge until full.
3. Operational: Energy consumption periods are limited to peak hours between 17:00 and 23:30 daily. During Phase A, the SHSS is charging from surplus renewable energy. During Phase B, the SHSS is discharged daily according to the EC's needs.

4.1.1 Case Study 1: Fixed Capacity Allocation

In Figure 32, the SHSS is set up through the `Benchmark Model` to cover the **total** monthly electricity demand of the community households. With the H_2 coverage set to 100% and the rest of the parameters of Table 15, the EC would run entirely on accumulated H_2 reserves, therefore resulting in high energy demand due to the system's relatively low energy efficiency of **29.77%**. Specifically, if the necessary monthly energy were to be covered fully by the proposed SHSS, monthly energy demand would increase from 1243.75 kWh to 4595.30 kWh, translating to an increase of **3351.55 kWh** or **269.43%**.

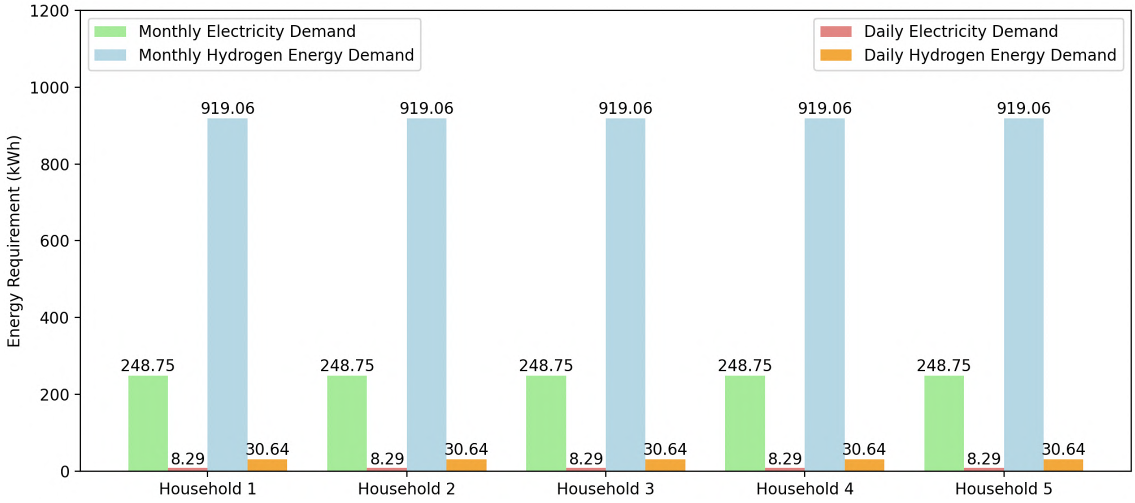


Figure 32: CS1 - Fixed Energy Allocation of Households (100% Coverage by SHSS)

Throughout this case study, each household of the urban EC takes in a **fixed allocation** of the total hydrogen capacity. This implies that H_2 capacity is **equally split**, even if the households have different energy requirements. For a monthly electricity demand of 248.75 kWh, the average electricity demand equals 8.29 kWh per day. To cover 100% of this demand with H_2, the SHSS of the `Benchmark Model` requires 30.64 kWh per household per day. Figure 32 is relevant to understanding that the addition of an SHSS currently has considerable energy requirements, in this case, an increase of **269.43%** from standard and is thus an employable option only when large amounts of surplus energy are accessible.

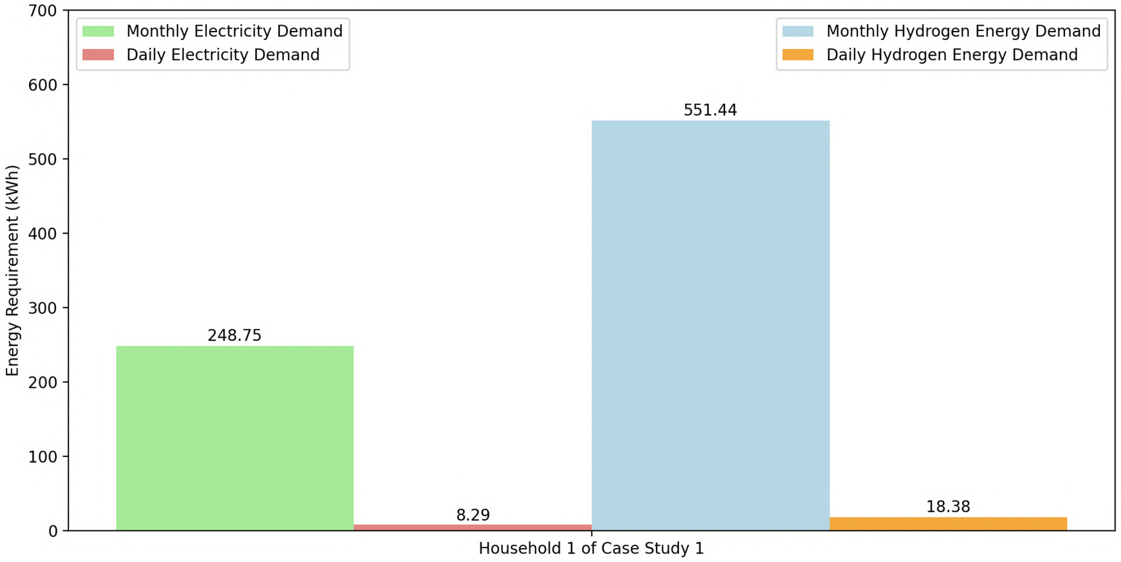


Figure 33: Case Study 1 - Fixed Energy Allocation of a Single Household (60% Coverage by SHSS)

In Figure 33, the energy requirements of a single household of CS1 are shown, aligning entirely with the parameters of Table 15. To cover **60%** of the monthly energy needs, a total of **551.44 kWh** are required from the SHSS. By adding the remaining 40% of grid-sourced electricity, monthly household energy demand increases to **650.94 kWh** (Equation 21). In terms of total energy requirements, a SHSS sized for this EC application is estimated to require **16543.08 kWh** of energy from DERs. This energy requirement, necessary to provide sustainable power to the EC households for the designated winter months, translates to **451.22 kilograms** of H_2 as seen in Figure 34, after incorporating the defined **10%** safety margin[13], which has to be stored and used throughout Phase B.

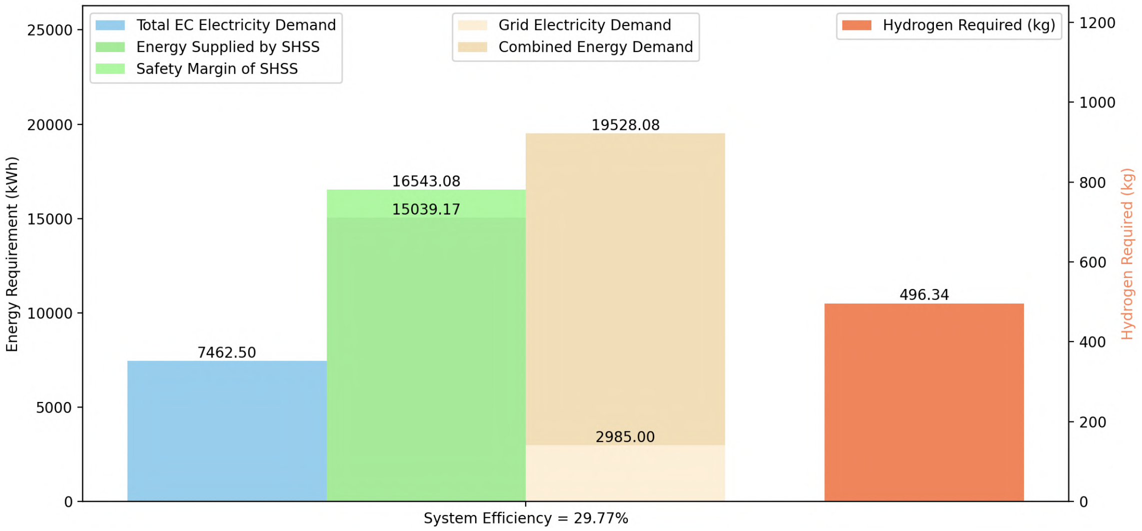


Figure 34: CS1 - Detailed Energy Demand and Necessary Hydrogen Volume

To store this amount of hydrogen and by assuming the 56.8-kilogram tanks of [51] are used, Figure 35, derived from running the `Benchmark Model`, details the necessary expenditures for storage infrastructure. Specifically, the total storage infrastructure cost for this case study is estimated at **$395832.83**, considering a maintenance span of 10 years. To store the necessary hydrogen capacity for Phase B, also accounting for the **10%** safety margin, a total of 9 H_2 tanks are required, alongside an electrolyzer stack and fuel cell systems. The cost of the latter systems is not considered as pricing fluctuates greatly among the different employable technologies as seen in Section 2.3.

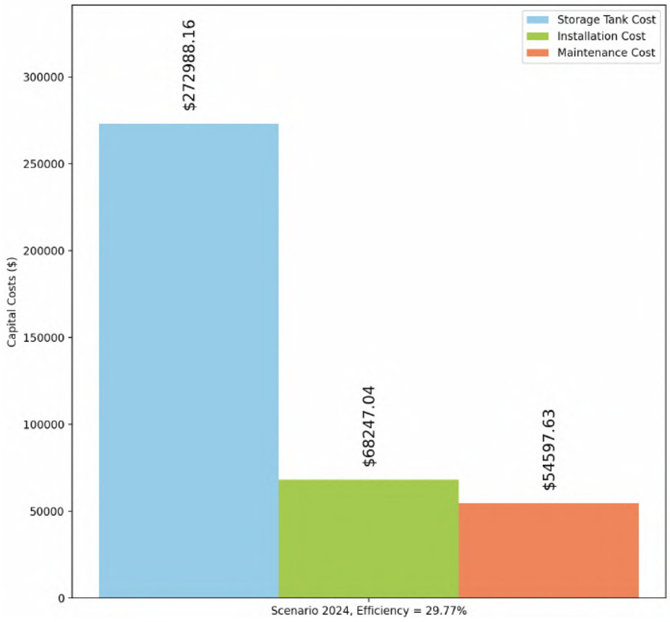


Figure 35: CS1 - Cost of Storage Infrastructure

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[13] The safety margin is necessary to ensure that there is always a reserve of hydrogen in the shared tank, preventing the pressure from dropping to critically low levels. This unused capacity acts as a buffer, maintaining the tank's integrity and operational efficiency. The 10% safety margin is a precautionary measure to accommodate unforeseen fluctuations in consumption and to guarantee a continuous supply of hydrogen throughout Phase B.

4.1.2 Case Study 1: Results and Discussion

The first case study results of this thesis employing the `Benchmark Model` suggest that the proposed SHSS in an urban EC can be favorable, particularly when there is a green energy surplus. The addition of such a LTS system can greatly alleviate part of the energy grid during high-demand hours. Ultimately, this system allows for routing excess electricity from DERs to an EC's shared hydrogen infrastructure, ensuring that renewable resources are not switched off and that there's no electricity shortage during peak hours. Switching from grid-sourced to tank-sourced electricity is increasingly relevant in modern households with smart systems and EVs, whose substantial energy demands will typically have to be covered by the grid.

Using the methods of Section 3.4, the Phase B electricity total calculated by the model for this EC amounted to **7462.5 kWh**. Implementing the proposed SHSS for **60%** of this demand translates to **16544.34 kWh** of energy required from the SHSS, as seen in Figure 33, increasing total energy demand to **19529.34 kWh**. The additional demand amounts to **9080.58 kWh**, leading to a **161.7%** increase from the standard case. If DERs cannot meet this energy requirement, the EC administrator can lower the H_2 coverage percentage or Phase B months.

This study evaluates the effectiveness of an SHSS in an urban setting with 5 households. The `Benchmark Model` conveys **fixed** energy capacity allocation among EC households and has no possibilities for local energy trading. Enabling energy trading within the community and adjusting allocations based on a household's parameters could further enhance energy independence and flexibility, resulting in overall higher social welfare and sustainability. Finally, to meet the demands of Table 15, **the capital expenditures of storage infrastructure are estimated at 400.000 dollars.** The necessary expenditures for the total SHSS, alongside resources to facilitate its digitalization and integration into energy communities, remain significant barriers that must be addressed to ensure the feasibility and efficiency of the proposed system.

In conclusion, the first case study illustrates that with current technology, an SHSS could contribute to the energy ecosystem of small urban communities, but its high infrastructure costs and relatively low efficiency make widespread implementation unlikely. **The methods of Section 3.4 are confirmed**, allowing for a wholesome answer to the first fundamental research question. With higher subsystem efficiencies, hydrogen has high prospects of becoming the main stakeholder of energy storage in decentralized grids. However, the primary challenges remain in the high initial costs and the overall system integration, which require strategic planning and investment to overcome.

The ambition is to develop the proposed energy-sharing algorithms to their fullest potential, ensuring they are ready for deployment when infrastructure costs become more affordable for widespread introduction in ECs. Achieving this goal requires implementing dynamic algorithms that account for diverse household energy profiles, enabling efficient and fair distribution of energy resources. Furthermore, facilitating local energy market transactions will be crucial in optimizing resource use and enhancing the flexibility and resilience of the community's energy landscape. Concurrently, these advancements are the digital groundwork for effectively sharing energy utilities in emerging ECs.

4.2 Case Study 2: Refinement and Calibration of the Dynamic Model

This section evaluates the performance of the `Complex Model` for shared hydrogen storage through a case study of 10 energy-interconnected households. Table 16 summarizes the parameters of this case and the dataset outlining the energy profile of each household can be found in Appendix C. The objective of the second case study, referred to as **Case Study 2** (CS2) is to present the performance and flexibility of the `Complex Model`, through the same assumptions and constraints of CS1.

The second objective of CS2 is to experiment and explain the discrepancies that can be obtained by adjusting the various parameters of this model. The obtained results are in the form of plots and are detrimental towards fine-tuning the parameters of the `Complex Model`, achieving better capacity allocation and higher social welfare. This calibration process tests the performance of the developed algorithms to effectively compare it with the `Benchmark Model`, which is optimized for equipment longevity and energy security. At the end of Section 4.2, the revised `Complex Model` and its various parameters will have been adjusted for maximized social welfare, sustainability and robust energy allocation.

Figure 36: Energy Community Render of Case Study 2 with 12 Households (By Author)

Table 16: Case Study 2 Modelling Parameters

Parameter	**Number**	**Unit**	**Notes**
Household Num.	10	-	Households connected to the SHSS
Household El. Consumption	248.75	kWh/Month	From 3.1: Average Monthly Consumption (from Section 3.2)
Months	6	-	Winter Months, Phase B (from Section 2.3.6)
System Efficiency	29.77	%	P2G2P System Efficiency (from Section 3.4.4
Energy By SHSS	60	%	Daily Energy to be supplied by SHSS
Switching Period	17:00 - 23:30	-	Daily Interval that SHSS is switched ON (from Section 3.2)

4.2.1 Degrees of Freedom in PENELOPE Architecture

Unlike the `Benchmark Model` developed in Section 3.4 and tested in Section 4.1, the `Complex Model` developed in Section 3.5 proposes a comprehensive framework, suitable for handling shared hydrogen storage processes within ECs without the need of a third-party organization. To achieve this, the `Complex Model` builds upon the `Benchmark Model` and introduces policies and a modular energy-sharing structure through the adjustment of its **Degrees of Freedom** (DOFs). These DOFs can be adjusted by the EC administrator to **achieve better capacity allocation, optimized for maximizing social welfare and energy flexibility** of the given EC.

The DOFs for this model concern the **Community Energy Share Index** (CESI) and its respective parameters (SCI, HPI, EUP), the **Energy Uncertainty Variance** (EUV) index, the **Adaptive Consumption Coefficient** (ACC), as well as the ability to adjust the energy intensity of the designated winter months. Adjusting these parameters aids in creating a personalized energy profile for an EC household, considering fair energy allocation algorithms. Demonstrating the flexibility obtained from the following DOFs and evaluating system performance are the two main objectives of CS2.

The **Degrees of Freedom** that will be explored and analyzed throughout Section 4.2 are the following:

1. Community Energy Share Index (CESI)
    - Spatial Consumption Index (SCI)
    - Household Participation Index (HPI)
    - Energy Utilization Profile (EUP)
2. Monthly Energy Intensity
3. Adaptive Consumption Coefficient (ACC)
4. Energy Uncertainty Variance (EUV)

4.2.2 Adjustment of CESI Parameters

This subsection explores the role of the **Community Energy Share Index** as the first adjustable DOF within the `Complex Model`. The section aims to experiment by modifying the weights of the three parameters within CESI, namely the EUR, SCI and HPI to showcase the discrepancy in monthly hydrogen capacity allocation across all households of this case study's EC. To achieve this, a baseline scenario (**Scenario 2A**) is defined, in which all three parameters have equal weights. After this, the weights are adjusted in scenarios **2B** and **2C**, and the results are discussed. The acquired final values of the CESI will be used in the refined `Complex Model` of the proposed architecture for acquiring the final Shapley values, which are seen in Figure 37.

The initial weights of the CESI parameters are set equal for the baseline scenario 2A. Two additional scenarios are chosen with their respective weight alterations shown in Table 17. The weight changes aim to demonstrate the flexibility and variability in systemic performance that can be achieved.

Table 17: Adjustment of CESI Parameters - Weight Distribution across Scenarios

Degrees of Freedom	**Scenario 2A**	**Scenario 2B**	**Scenario 2C**
Household Participation Index (HPI)	0.33	0.25	0.20
Spatial Consumption Index (SCI)	0.33	0.35	0.35
Energy Utilization Profile (EUP)	0.33	0.40	0.45

These parameters have to be configured by the respective EC administrator, to efficiently allocate energy based on the particular EC configuration. The CESI algorithm is based on Equation 17, as developed in Section 3.5.3. Furthermore, each scenario is tested using the standard `Complex Model` of Section 3.5 which calculates the CESI for each household and generates the corresponding monthly energy allocations. The rest of the parameters remain unchanged across Scenario 2A, 2B and 2C, to effectively compare the final results. In the end, the chosen weights of the respective parameters are implemented into the revised `Complex Model`, facilitating refined capacity allocation and higher social welfare.

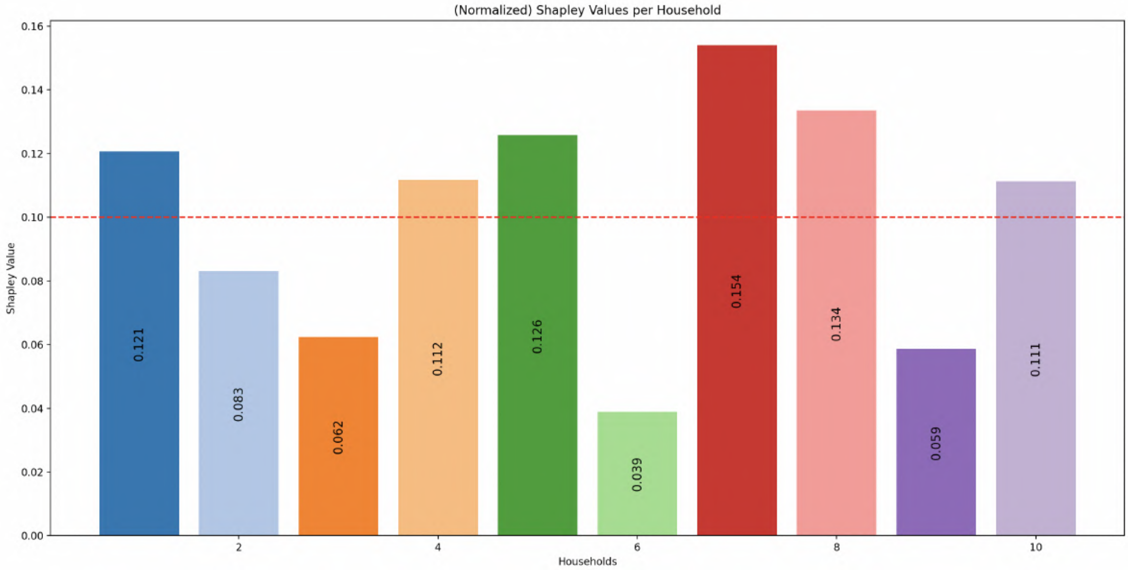
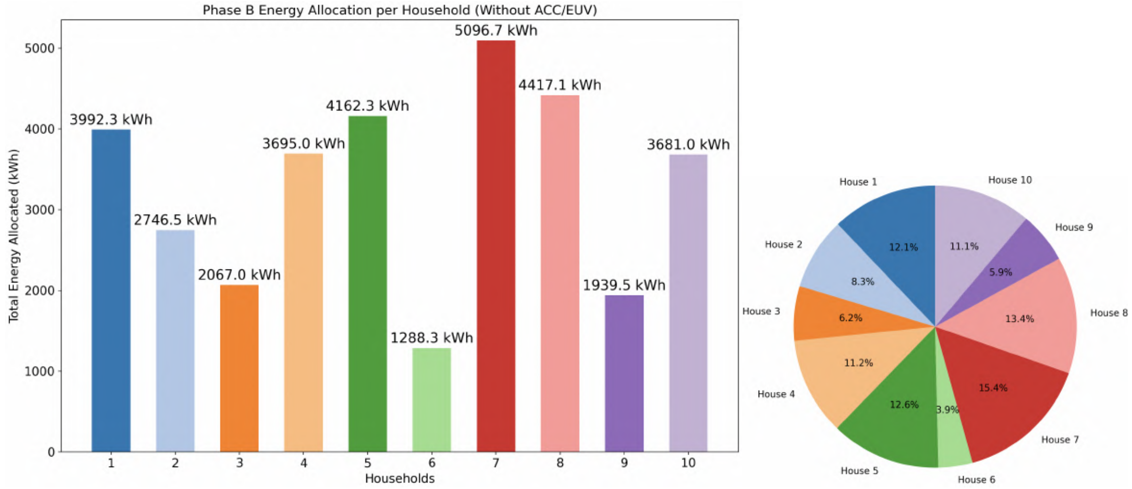


Figure 37: CS2 - Normalized Shapley Values of Scenario 2A

Simulation Results and Evaluation of Scenario 2A, 2B and 2C

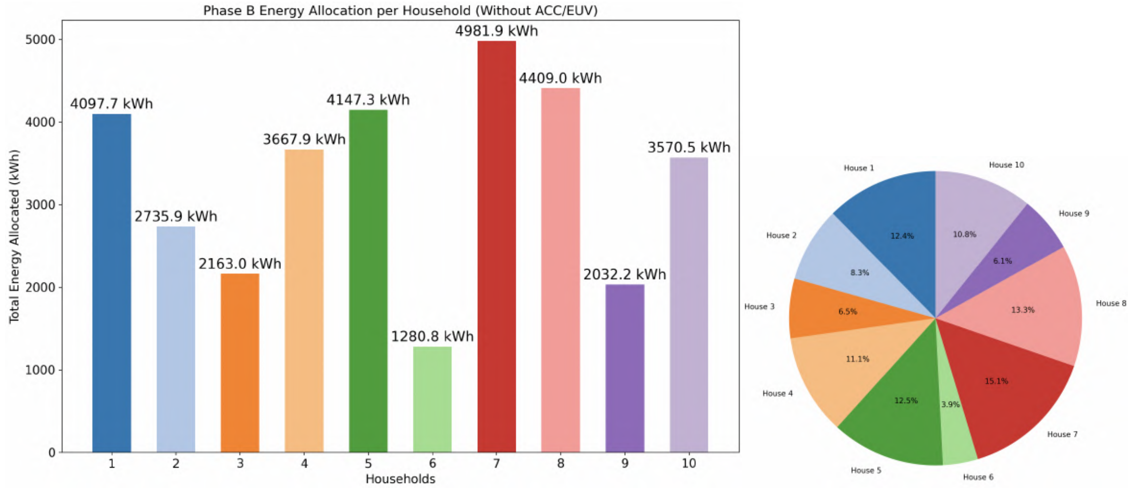
Scenario 2A (Baseline): Setting all weights to equal provides a baseline for comparison. This scenario demonstrates the distribution of hydrogen capacity allocation in kWh of energy, reflecting the equal influence of household members, household size, and energy usage patterns on the algorithm of the `Complex Model`. The results seen in Figures 38a and 38b concern the total energy that the SHSS has to allocate throughout the designated Phase B of CS2.



(a) Phase B Energy Allocation for Scenario 2A **(b)** Monthly Capacity Split

Figure 38: Scenario 2A: HPI = 0.33, SCI = 0.33, EUP = 0.33

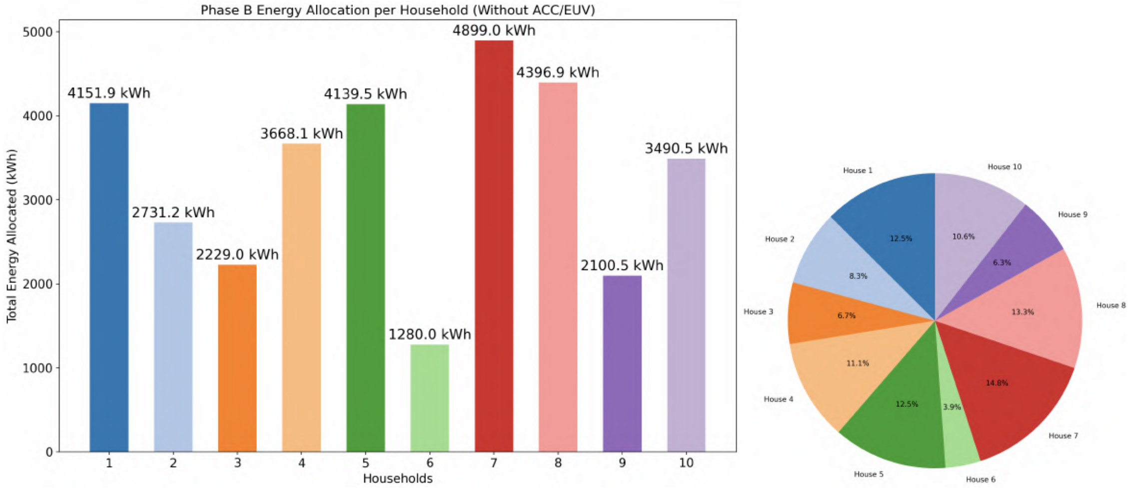
Scenario 2B: Increasing the weight of SCI and EUP while reducing HPI is argued to be more pragmatic- and usage-driven. In Figures 39a and 39b, the adjusted energy demand that the SHSS has to allocate is shown. Households **9** and **10** showcase the highest discrepancies from the baseline values, with a **4.75%** energy increase and **-3.00%** energy decrease, respectively.



(a) Phase B Energy Allocation for Scenario 2B **(b)** Monthly Capacity Split

Figure 39: Scenario 2B: HPI = 0.25, SCI = 0.35, EUP = 0.40

Scenario 2C: This scenario emphasizes energy utilization, as provided by the household owners to the administrator. The results, as shown in Figures 40a and 40b are the most promising in terms of ensuring equitable energy distribution, especially for households with high energy consumption. The higher weight on EUP seemingly aligns capacity allocation with actual usage patterns. Consequently, households **9** and **10** showcase the highest discrepancies, with a **8.28%** energy increase and **-5.18%** energy decrease, respectively.



(a) Phase B Energy Allocation for Scenario 2C **(b)** Monthly Capacity Split

Figure 40: Scenario 2C: HPI = 0.2, SCI = 0.35, EUP = 0.45

4.2.3 Proposed Weights for CESI and Concluding Remarks

Based on the results of the preceding scenarios, **Scenario 2C** (HPI 0.2, SCI 0.35, EUP 0.45) emerges as the chosen weighting scheme for CESI calculation. This scheme gives the highest priority to energy usage, reflecting the primary importance of actual energy consumption behavior in shared hydrogen storage capacity calculations. Household size in square meters is argued to be similarly important and is thus appropriately weighted.

The adjustment of CESI parameters to prioritize energy usage significantly improves the effectiveness and equity of hydrogen storage allocation. The proposed weights (HPI 0.2, SCI 0.35, EUP 0.45) offer a consumption-based focus that addresses the diverse household profiles of the EC of CS1, ensuring an appropriate energy distribution system. The modularity of the `Complex Model` allows for easy adjustment of the preceding parameters, ensuring that the capacity allocation algorithm can be easily modified according to the needs of the specific EC.

Future research could improve the CESI by introducing more parameters such as the tendency to buy-sell capacity within the LEM, V2G connectivity and access to privately owned BESSs. In any case, this section showed the change in performance that can be achieved by modifying the CESI weights. It is up to the EC administrator of the respective EC configuration to adjust these parameters, to better reflect on the energy needs of the EC and its respective users.

4.2.4 Monthly Weights Based on Energy Intensity

This section explores the model's ability to adjust the weights of the months of Phase B, based on monthly energy intensity. The `Complex Model` is run for the conditions defined in Table 16, further enhanced with the adjusted CESI parameters of **Scenario 2C**. Initially, equal weights are assigned to each winter month as a baseline scenario (**Scenario 2D**). Subsequently, the weights are adjusted in **Scenario 2E** to reflect the varying energy demands across different months, as found in Section 3.5.3. This adjustment aims to linearly optimize the energy allocation patterns by accounting for seasonal variations in energy demand.

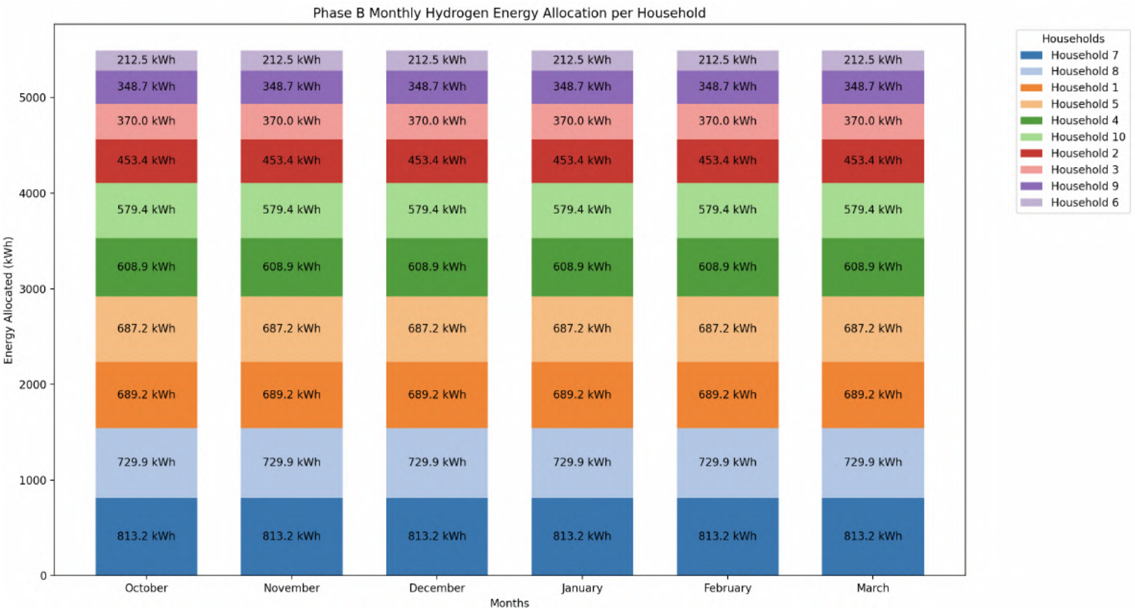


Figure 41: Energy Requirements of Scenario 2D throughout Phase B

Scenario 2D sets a baseline by using **equal weights for each winter month**, representing an even distribution of hydrogen capacity throughout each month of Phase B that the SHSS is in. The parameters of this DOF are set up in the `Complex Model` as follows:

```
self.monthly_weights = {
    'January': 0.166,
    'February': 0.166,
    'December': 0.166,
    'March': 0.166,
    'November': 0.166,
    'October': 0.166
}
```

In Figure 41, the monthly energy distribution that the SHSS has to provide is shown. The households within the EC of CS2 have different energy demands, which is reflected by the uneven total capacity split. By using equal monthly weights in this scenario, the monthly energy demand is equal across Phase B. For each Phase B month illustrated, each bar is viewed as a digital hydrogen tank representation, ranking the allocated capacities based on the highest quantity allocated.

In Figure 42, the energy requirements for the EC of CS2 are shown for December. For this scenario, the decision to choose December to showcase the EC's energy requirements is no different from the rest of the months. The left y-axis reflects the electricity demand for the different households and the right y-axis deals with the total energy requirement in kWh, necessary to run 60% of the defined monthly consumption through the SHSS.

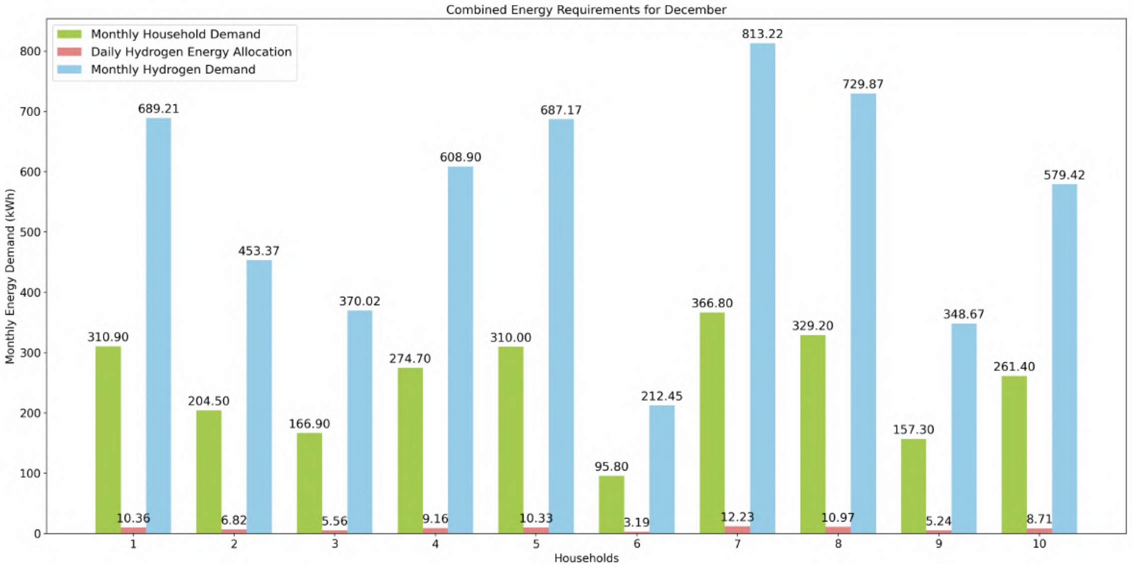


Figure 42: Scenario 2D - Energy Requirements of EC for December

In **Scenario 2D** it is assumed that each month has the same energy intensity, leading to uniform energy allocation through Phase B. The uniformity across the months is achieved as the algorithm multiplies each monthly weight with the total capacity stored in the SHSS, resulting in equal monthly allocation of the total capacity.

In **Scenario 2E**, the monthly weights are adjusted to better reflect the intensity rank found in Section 3.5.3. This setup is more realistic as it is the average result of the most energy-intensive months for four European countries: Netherlands, Spain, France and Greece. The historical data that were analyzed in Section 3.5.3 showed higher demands in colder months (January, February, December) and lower demands in milder months (October, November). Plots associated with this part of the research are shown in Appendix D.

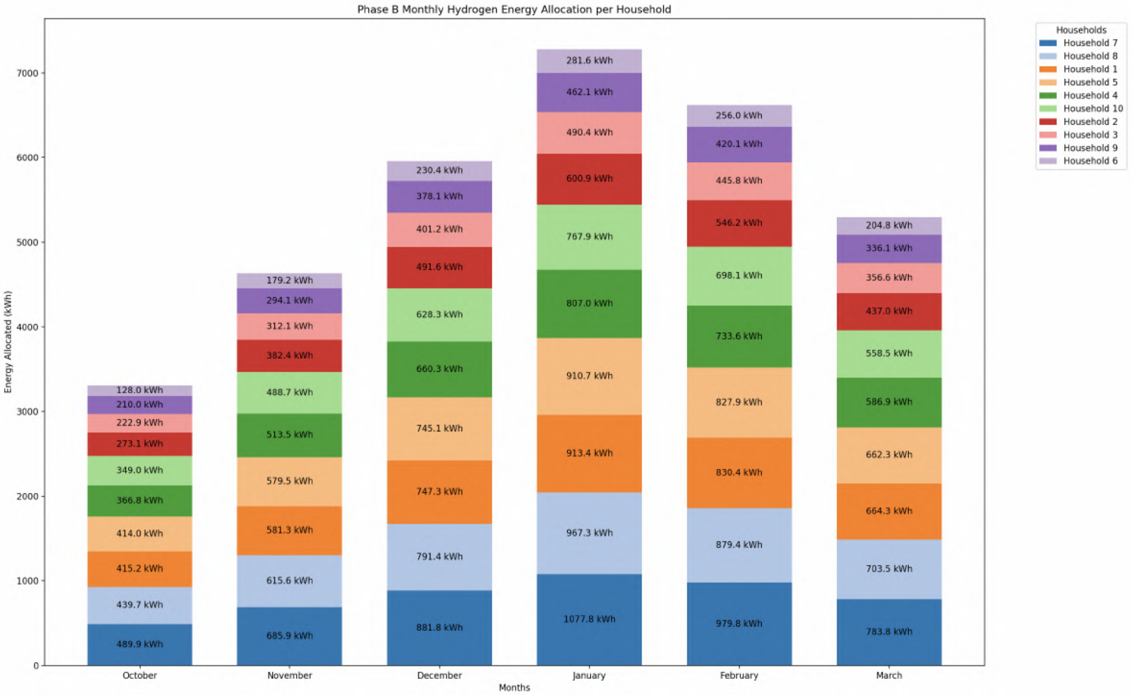


Figure 43: Scenario 2E - Energy Requirements of EC throughout Phase B

```
self.monthly_weights = {
    ’January’: 0.22,
    ’February’: 0.20,
    ’December’: 0.18,
    ’March’: 0.16,
    ’November’: 0.14,
    ’October’: 0.10
}
```

In Figure 43, the `Complex Model` is configured for the **adjusted monthly weights**, thereby providing a more realistic energy allocation. In Figure 44, the capacity allocation for December is shown, featuring **8.1%** overall higher energy demand in comparison to **Scenario 2D**, which can be argued as more realistic, given the fact that December is considered one of the coldest months of the winter season.

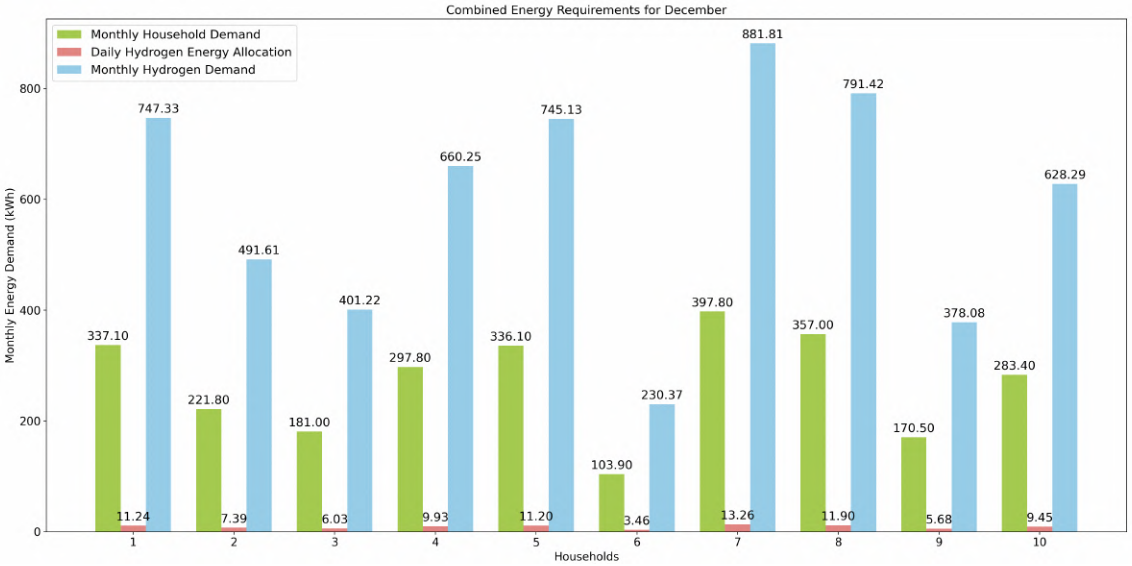


Figure 44: Scenario 2E - Energy Requirements of EC for December

4.2.5 Proposed Weights for Monthly Intensity and Concluding Remarks

Adjusting the monthly weights based on energy intensity significantly enhances the effectiveness of shared hydrogen storage allocation. The weights of **Scenario 2E** (January 0.22, February 0.20, December 0.18, March 0.16, November 0.14, October 0.10) provide a more accurate representation of seasonal energy needs. This approach ensures that capacity allocations are aligned with actual energy consumption patterns found in historical data.

For the continuation of this thesis, the `Complex Model` will be configured with the adjusted monthly weights of Scenario 2E, which contribute to an overall more realistic capacity allocation across the winter months. The modularity of PENELOPE allows the EC administrators to adjust the defined monthly weights annually, thereby resulting in higher accuracy of capacity allocation, influenced by historical and forecast data.

To further improve the `Complex Model`, the fluctuation of energy demand within the week can be modeled, referencing the survey findings of Section 3.2. The model can be made more advanced by monitoring consumption values within the EC, thereby dynamically changing the weights for each household. Finally, the addition of forecasting algorithms, useful for better seasonal capacity allocation but also to forecast the energy consumption of EC households, is seen as the next step towards improving this architecture.

4.2.6 Modeling the Effects of EUV and ACC Parameters on System Performance

This section explains the addition and influence of the two final parameters proposed for the algorithms of the `Complex Model`, namely: the **Energy Uncertainty Variance** and the **Adaptive Consumption Coefficient**. These parameters are introduced to enhance the realism and accuracy of energy consumption estimation within the diverse households that can take part in emerging ECs.

The EUV and ACC parameters are essential for modeling the non-linear behaviors of energy consumption. The EUV accounts for random fluctuations in energy demand due to unforeseen circumstances, while the ACC adjusts consumption based on user behavior. These additions help create a more dynamic and responsive energy allocation system.

Throughout Case Study 2, the `Complex Model` has been refined to consider the energy profiles of individual EC households (CESI) and to account for seasonality across the different winter months. This section adds the EUV and ACC to the refined `Complex Model`, providing a more realistic energy consumption estimation.

To visualize the influence of EUV and ACC on total energy demand, **Scenario 2E** is used as a baseline reference for comparison. The total energy that the SHSS has to supply during Phase B is split across the different households based on the refined DoFs. In Figure 45, the Phase B energy allocations without the proposed ACC and EUV can be seen, featuring the linearity of the hydrogen allocation algorithm.

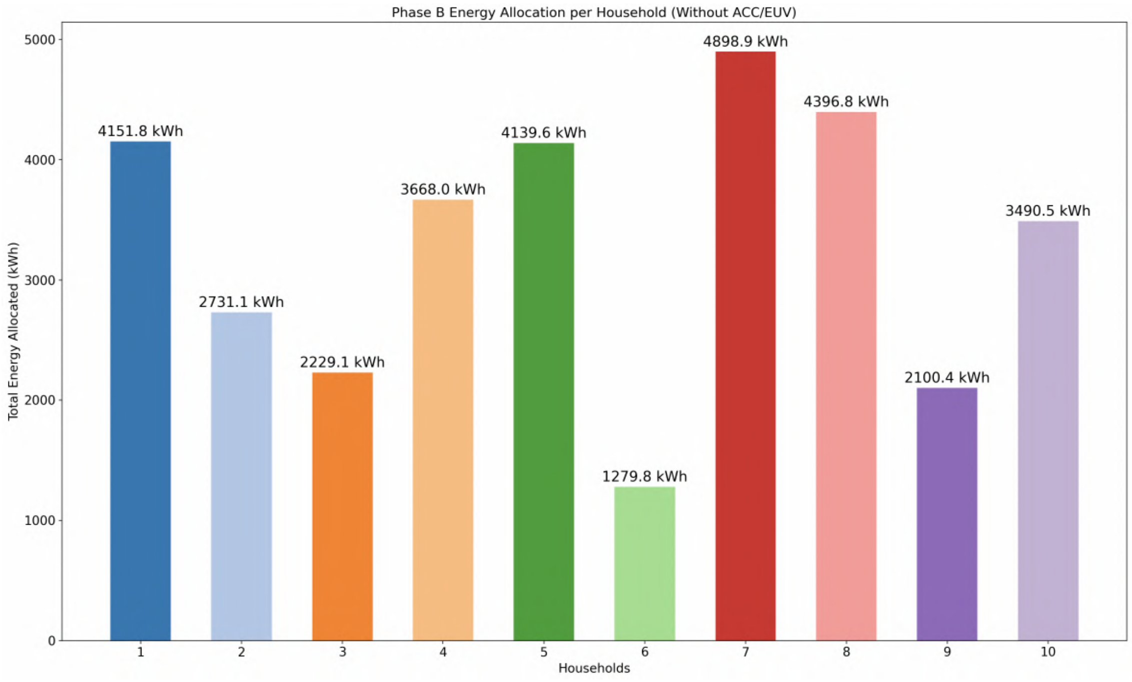


Figure 45: Scenario 2E - Energy Requirements of EC for December

In **Scenario 2F**, the EUV and ACC are modeled and compared against **Scenario 2E** to identify changes in how total household energy demand is affected.

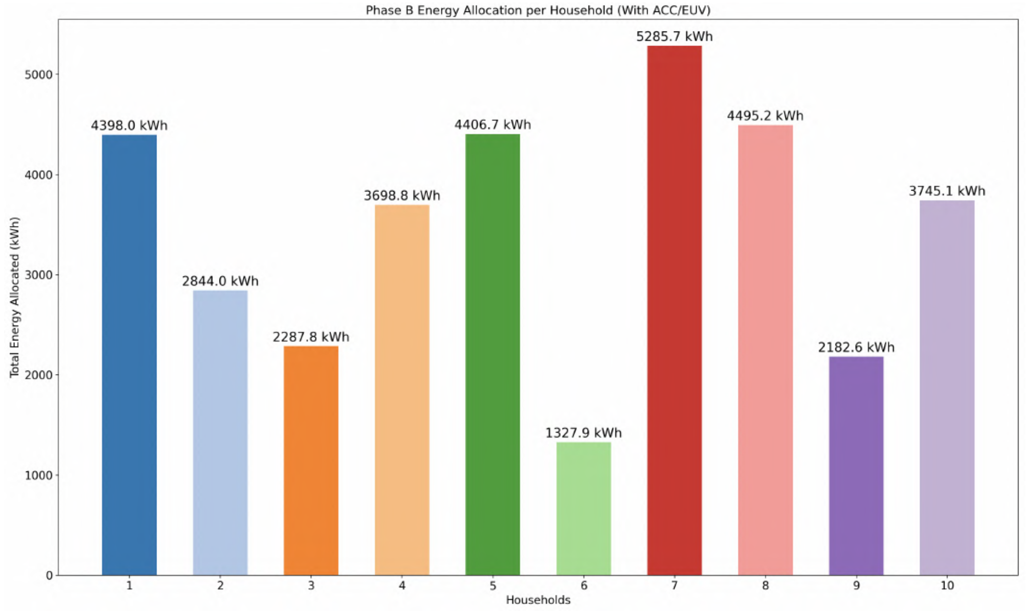


Figure 46: Scenario 2F - Energy Requirements of EC for December

In Figure 46, the allocations of each respective household of CS2 are compared showing an increase in SHSS energy demand as a result of the addition of the ACC and EUV parameters. The incorporation of EUV introduces a small random variation into the energy allocation calculations, reflecting the uncertainty and variability in energy demand due to factors such as weather changes, unexpected fault events, or behavior changes. The ACC, on the other hand, scales consumption based on user behavior, accounting for the unique energy usage patterns (CESI) of individual households. This dynamic adjustment ensures that the system can adapt to the actual consumption needs of the community more effectively. By comparing Figure 45 and 46, household 7 sees its total SHSS energy demand estimation increase by **7.9%** as the highest increase and household 4 sees an increase of **0.82%**.

4.2.7 Conclusions on the Implementation of EUV and ACC

The inclusion of the EUV and ACC parameters is crucial for modeling the non-linear behaviors of energy consumption within EC households. The Energy Uncertainty Variance variable accounts for emergency situations and unpredictable fluctuations in demand, which is a necessary inclusion for any realistic energy model. The Adaptive Consumption Coefficient variable scales consumption based on user behavior, providing a more accurate representation of individual household energy needs.

The modeling of these parameters enhances the flexibility and responsiveness of the `Complex Model`, allowing it to better accommodate the diverse consumption patterns of different households. This results in a more equitable and efficient allocation of shared hydrogen storage resources, ultimately contributing to higher social welfare and energy security within the community.

Future work could further refine these parameters by incorporating more detailed data on household energy usage patterns and external factors influencing demand. Additionally, the integration of advanced forecasting algorithms could improve the accuracy of seasonal capacity allocation and overall system performance.

4.2.8 Case Study 2: Results and Discussion

The scenarios of Case Study 2 demonstrated the effectiveness of the `Complex Model` in managing shared hydrogen storage capacity within an EC of 10 households. The refined `Complex Model` optimized energy allocation by incorporating several key parameters: the CESI, EUV and ACC. The results obtained in Scenarios 2A - 2F demonstrate the ability of the `Complex Model` to align energy distribution based on seasonal fluctuations and the different energy profiles of the specific EC households.

The results highlighted the importance of a dynamic approach to sharing energy utilities. In the end, the refined `Complex Model` allows for effectively creating EC household energy profiles through its algorithms. For the continuation of this thesis, the CESI parameters of **Scenario 2C** are chosen as they reflect an **energy-centered** approach for EC households. Scenarios 2D and 2E showcased the necessity for allocating more hydrogen capacity towards the colder Phase B months, resulting in more practical and realistic energy allocation. Finally, in **Scenario 2F** the parameters of ACC and EUV were implemented leading to an overall more reliable hydrogen capacity estimation. The results of the preceding scenarios are summarized in Table 18.

The `Complex Model`'s flexibility in adjusting to varying household energy demands and seasonal patterns marked a significant improvement over the fixed methods developed in the `Benchmark Model`. By incorporating and adjusting the preceding parameters in Section 4.2, the hydrogen energy-sharing landscape in urban settings becomes more straightforward, and sizing estimation is optimized. As the LEM implementation of the `Complex Model` does not currently have any DOFs, it is not featured in this case study. However, implementing a LEM structure, alongside a **refined** `Complex Model`, tailored to the specific EC requirements, certainly provides reliable calculation and control of shared energy utilities, albeit improving energy security and control. Such findings support the potential of shared hydrogen storage systems as a sustainable long-term solution for viable energy management in future ECs.

In conclusion, Case Study 2 demonstrated the effectiveness of the `Complex Model` in optimizing shared hydrogen storage within energy communities. The model's dynamic and responsive energy allocation capabilities offer a promising solution for enhancing efficiency and energy sustainability. Future improvements are possible thanks to the modularity of the PENELOPE architecture, which could involve integrating more detailed household energy usage data and advanced forecasting algorithms to refine the model's capacity allocation ability further. Finally, additional shared utilities can be added, such as sharing battery energy capacity, leading to a greater community-driven energy landscape.

Table 18: Complex Model - Change in Energy Demand Results across CS2 Scenarios

Households / Energy Demand [kWh]	**Household 1**	**Household 2**	**Household 3**	**Household 4**	**Household 5**	**Household 6**	**Household 7**	**Household 8**	**Household 9**	**Household 10**	**Scenarios**
Grid Electricity Demand	310.9	204.5	166.9	274.7	310	95.8	366.8	329.2	157.3	261.4	**Scenario 2C & 2D**
Hydrogen Energy Demand	689.21	453.37	370.02	608.9	687.17	212.45	813.22	729.87	348.67	579.42	
Total Energy Demand per Household	**4135.2**	**2720.4**	**2220**	**3653.4**	**4123.2**	**1275**	**4879.2**	**4379.4**	**2092.2**	**3476.4**	
Grid Electricity Demand	337.1	221.8	181	297.8	336.1	103.9	397.8	357	170.5	283.4	**Scenario 2E**
Hydrogen Energy Demand	747.33	491.61	401.22	660.25	745.13	230.37	881.81	791.42	378.08	628.29	
Total Energy Demand per Household	**4151.9**	**2731.2**	**2229**	**3668.1**	**4139.5**	**1280**	**4899**	**4396.9**	**2100.5**	**3490.5**	
Grid Electricity Demand	362.4	226.9	196.3	309.7	365.7	113	406.5	384.6	173.7	300.2	**Scenario 2F**
Hydrogen Energy Demand	788.81	499.34	421.22	673.36	760.15	231.88	924.13	856.9	387.18	643.6	
Total Energy Demand per Household	**4393.1**	**2851.7**	**2386.4**	**3867.6**	**4309.4**	**1351.2**	**5159**	**4717.4**	**2173.8**	**3597.7**	

4.3 Case Study 3: Comparison of SHSS Models

This case study evaluates the performance of the two models developed in this thesis, namely: the `Benchmark Model` and the **refined** `Complex Model`. **Case Study 3** (CS3) involves an energy community of six energy-interconnected modern households of different sizes featuring advanced energy management systems, allowing for the monitoring and enabling transactions of shared energy utilities, specifically hydrogen capacity. The households are of different sizes (different SCI) but are all located close to each other.

Figure 47: Energy Community Render of Case Study 3 (By Author)

The SHSS in CS3 is treated as an experimental addition to the EC's infrastructure. The objective of the EC administrator is to test the system's efficiency during two heavy winter months to understand the potential benefits and gather feedback from the residents. Infrastructure costs are not considered in this study; the focus is solely on the models' performance. The same assumptions and constraints as in CS1 are used.

Table 19: Case Study 3 Modelling Parameters

Parameter	Number	Unit	Notes
Household Num.	6	-	Households connected to the SHSS
Energy Consumption	248.75	kWh/Month	Average Monthly Electricity Consumption (from Section 3.2)
Months	2	-	January and February
System Efficiency	29.77	%	Total System Efficiency (from Section 3.4.4)
H2 Coverage	60	%	Daily Energy to be supplied by SHSS
Switching Period	17:00 - 23:30	-	Daily Interval that SHSS is switched ON (from Section 3.2)

Table 19 summarizes the modeling parameters for CS3. The `Benchmark Model` will be used to calculate hydrogen capacity based on **fixed** parameters, providing a baseline for comparison. Then, the `Complex Model` adjusts the allocated capacity to maximize social welfare and system performance. The energy profiles of the 6 households are anonymous entries from the survey results of Section 3.2 and can be found in Appendix C. Case Study 3 aims to compare the outputs of the two models to evaluate them based on social welfare and energy sustainability.

4.3.1 Case Study 3A: Using the Benchmark Model

This case study starts with the `Benchmark Model`, featuring fixed hydrogen capacity allocation for the 6 households. As seen in Figure 48, it is assumed that 248.75kWh is the monthly electricity demand of all households, translating to 8.29kWh of daily energy consumption. The SHSS of CS3 initially estimates that 551.44 kWh of hydrogen energy are necessary to cover 60% of a household's energy demand. This equates to a total household monthly energy demand $E_{combined}$ of:

$$E_{combined} = 248.75 * (1 - 0.6) + 551.44 = 99.5 + 551.44 = 650.94\text{kWh}, \tag{21}$$

where 99.5 kWh is the remaining (grid-sourced) electricity demand and 551.44 kWh, is energy allocated by the SHSS. **This translates to an increase in EC energy demand, from 1492.5 kWh to 3906.64 kWh, equal to 2414.14 kWh per month.**

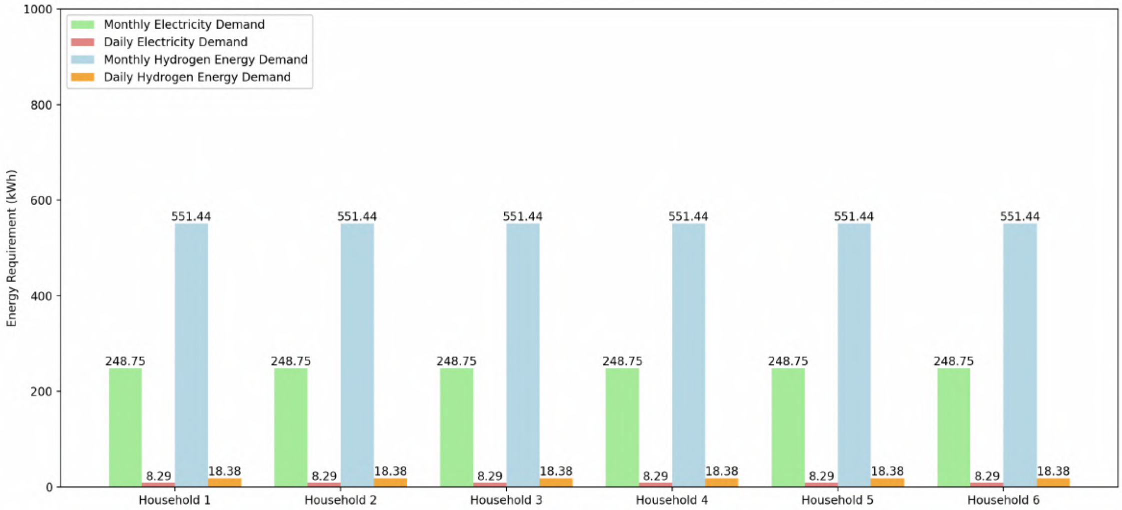


Figure 48: CS3A - Benchmark Model Monthly Energy Requirements

In Figure 49, the preceding calculations are shown for the span of Phase B, in this case study, January and February, respectively. The final values for the energy consumption of Phase B, are equal to **7811.23 kWh**, an increase of **161.68%**, aligning with the findings of Section 4.1.2.

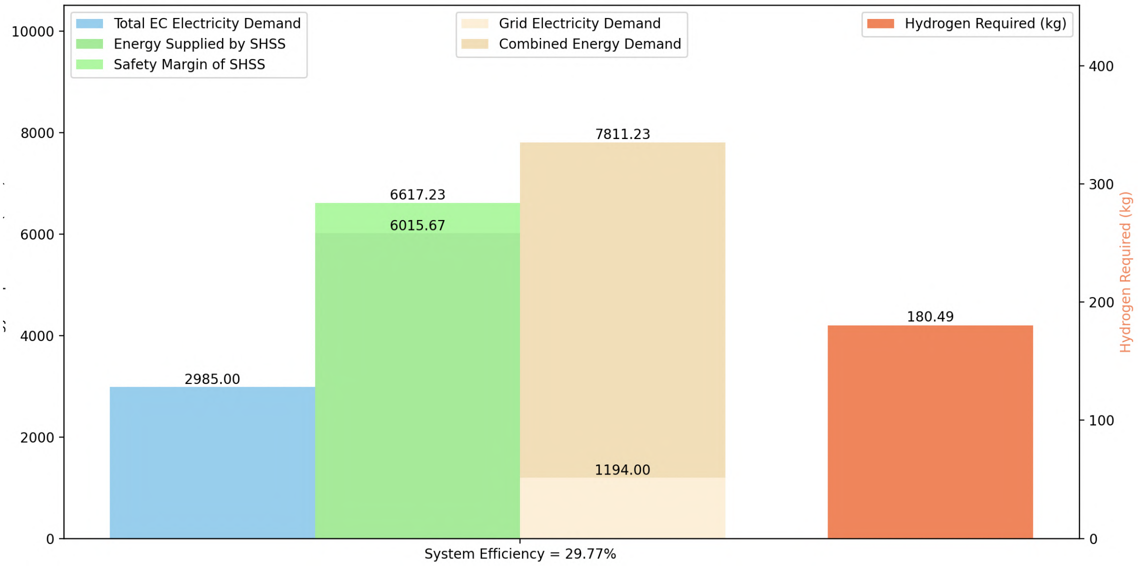


Figure 49: CS3A Benchmark Model Phase B Hydrogen Demand

4.3.2 Case Study 3B: Using the Complex Model

For the utilization of the `Complex Model`, additional parameters, including the CESI of the respective households and the months that the SHSS is switched to Phase B, are required. The `Complex Model` applies the supplementary parameters as explained in Section 4.2, allowing for a more dynamic, user-centered and responsive H_2 capacity allocation.

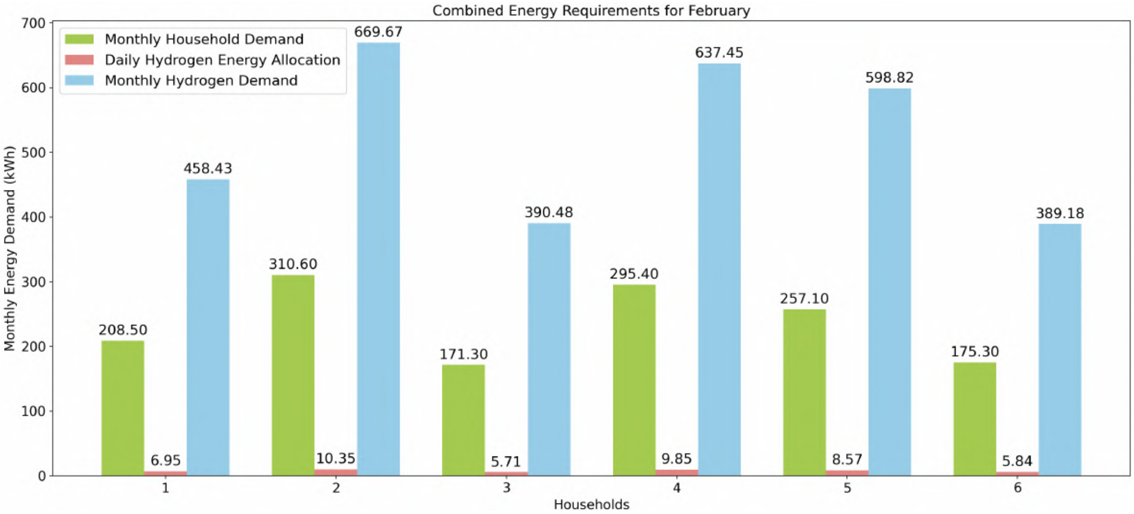
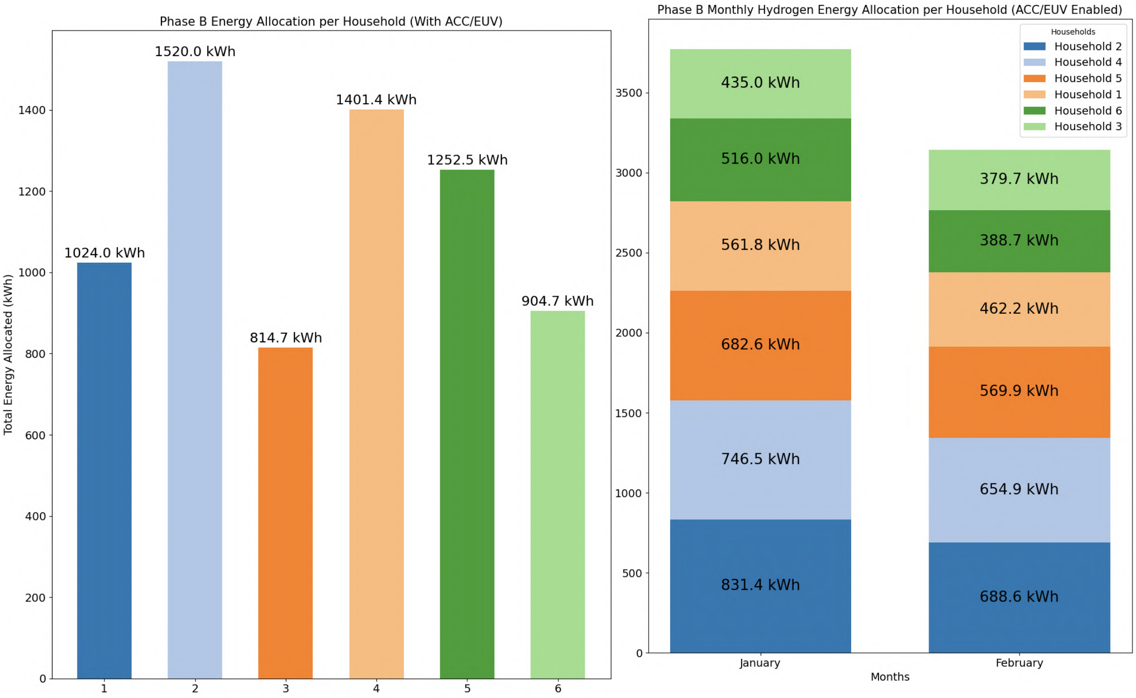


Figure 50: CS3B Complex Model Energy Requirements for February

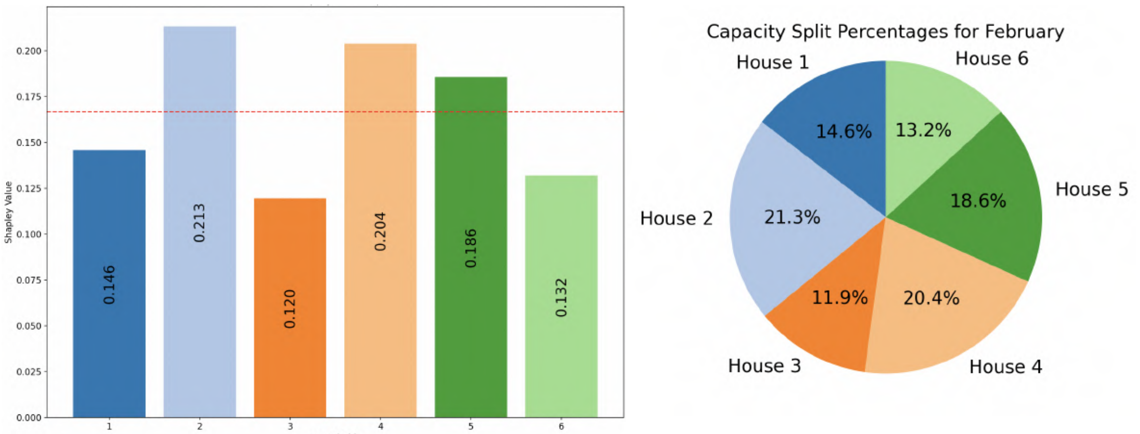
Figures 50 through 52 are the results of applying the `Complex Model` to the EC of CS3 during two critical winter months: January and February. The model delivers a more accurate electricity demand calculation, based on the household profiles (CESI, ACC and EUV) and intensity of the winter months. For this case study, the monthly weights of the `Complex Model` are set to 0.55 and 0.45 for January and February respectively. The total energy allocation can be seen in Figure 51a and Figure 51b.



(a) CS3B - Combined H_2 Allocations

(b) CS3B - Monthly H_2 Allocations per Household

Figure 51: CS3 - Total vs Monthly H_2 Capacity Allocations



(a) Shapley Values of CS3B Households

(b) CS3B - Hydrogen Capacity Split for February

Figure 52: CS3B - Total vs Monthly Capacity Allocation Plots

For the two months of this case study, the SHSS determines that to match the energy demand with the SHSS, an additional total of **6917** kWh are required. The combined energy requirement of the EC, taking into account the remainder of energy covered by the grid (40% grid sourced electricity equal to 1194 kWh from 2985 kWh, Figure 49) is equal to:

$$E_{total} = 6917 + 1194 = 8111\text{kWh} \tag{22}$$

$$dE_{total} = \frac{8111 - 2985}{2985} = 171.72\% \tag{23}$$

Equations 22 and 23 showcase the additional energy requirement of the EC of CS3B. The findings suggest **171.72%** energy increase compared to utilizing grid-sourced electricity and approximately a 10% energy increase compared to the `Benchmark Model` scenario of CS3A. The `Complex Model` demonstrates higher energy demand than the `Benchmark Model`, as intended, considering non-linear conditions such as energy under/over-subscription and unexpected extremes leading to higher monthly consumption. The findings of running the respective models in CS3A and CS3B are summarized in Table 20, which outlines the change in energy demand as a result of implementing shared hydrogen storage, specifically:

Table 20: CS3 - Comparison of Energy Demand based on Model Results

Energy Demand [kWh]	1 Month - SHSS Only		1 Month - Total Energy Demand		Phase B - Total Energy Demand	Change in Energy Demand
Grid Electricity	-		1492.5		2985	-
Benchmark Model	3308.64		3905.64		7811.28	4826.28 (161.68%)
Complex Model	**January** 3773.3	**February** 3143.7	**January** 4370.3	**February** 3740.7	8111	5126 (171.72%)

Examining the findings of Table 21 reveals that implementing a SHSS within an EC to meet peak hour energy demands would significantly boost the community's total energy consumption. Current technology limits the efficiency of subsystems, necessitating large-capacity solutions even for small, energy-efficient households. Thus, the introduction of a mechanism for buying and selling hydrogen capacity, such as the introduction of a blockchain-based LEM, is a logical and necessary enhancement that can exploit the advantages of shared hydrogen storage and combat the lack of high efficiency. By enabling the buying and selling of capacity, this approach would improve efficiency and encourage EC users to participate in a more sustainable energy system.

Case Study 3C: Energy Trading Example

In the real world, combining an advanced energy allocation model, encapsulated in the household's EMS, with the ability to rapidly buy/sell energy capacity based on demand fluctuations will make the green energy transition efficient and reliable. To showcase the potential of this setup, the `Complex Model` of the PENELOPE architecture allows for simulating trades of hydrogen capacity using smart contracts for a specific month and archives the transactions for bookkeeping purposes. The methods on which the local energy market is based are explained in Section 3.5.4.

Case Study 3 suggested that approximately 160% - 170% of additional energy is necessary to supply hydrogen-based electricity to the respective households during peak hours, assuming the parameters of Table 19. The `Complex Model` allowed for an accurate estimation of hydrogen capacity allocation, within a coalition, through advanced algorithms that aim to optimize allocations based on social welfare and energy security. To make the `Complex Model` - and the PENELOPE architecture on which the model is based - more robust and user-centered, the ability to facilitate blockchain-based energy trading between the households, is deemed necessary.

The algorithms encapsulated in the PENELOPE architecture allow for the simulation of a LEM environment with the LEM participants being the EC households. Each household can trade their allocated capacity within the energy market. In Figure 53, the results of the first round of energy transactions is illustrated. For this case study, energy transactions were fulfilled only once during the last day of January. Participants bought and sold allocated hydrogen capacity based on their respective needs, reflecting in realistic needs and choices. As can be seen, households 2 and 4 chose to buy additional capacity for February, resulting in energy demand of approximately 60 and 70 kWh, respectively. Hydrogen capacity was available for purchase as households 1,3,5 and 6 decided to sell part of their respective allocation.

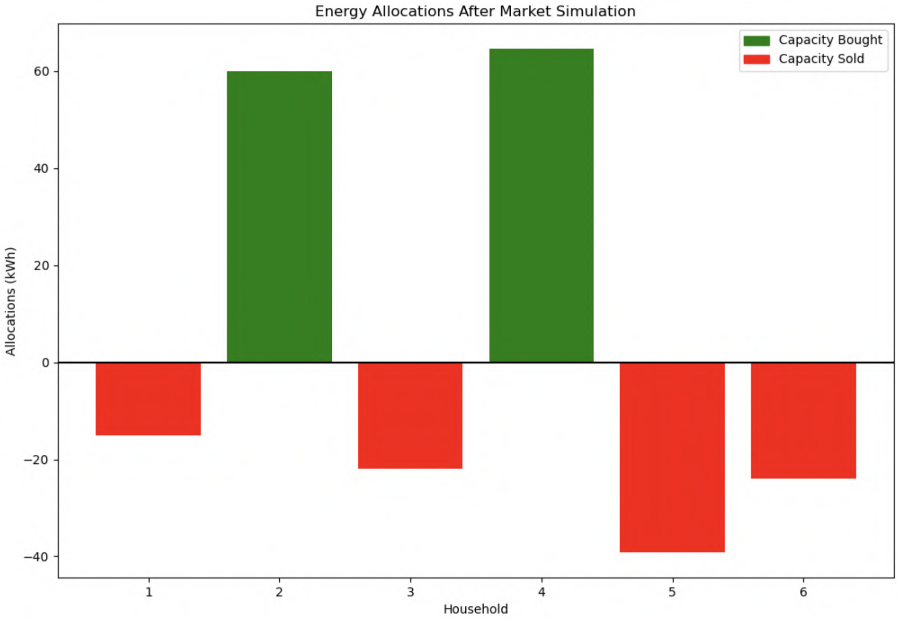


Figure 53: CS3C - Local Market Simulation Energy Transactions

The methodology behind the PENELOPE architecture ensures that enough purchasing capacity is available in the local energy market, utilizing part of the defined 10% safety margin if necessary and returning money to the households when more capacity is sold in the market than the demand allows for. Through this mechanism, social welfare within the community can be further increased as households can get money back if their allocated capacity is not utilized.

In Figure 54, the adjusted energy requirements for February are shown, highlighting how the first round of energy transactions influenced the monthly and total energy requirements of the EC. The transaction decisions are based on the ACC and EUP profiles of each household in CS3, which also influence the willingness-to-pay and willingness-to-sell prices. After running the market simulation within the `Complex Model`, similar graphs can be obtained and the changes in accumulated household capacity can be visualized in Figure 55a and Figure 55b for comparison.

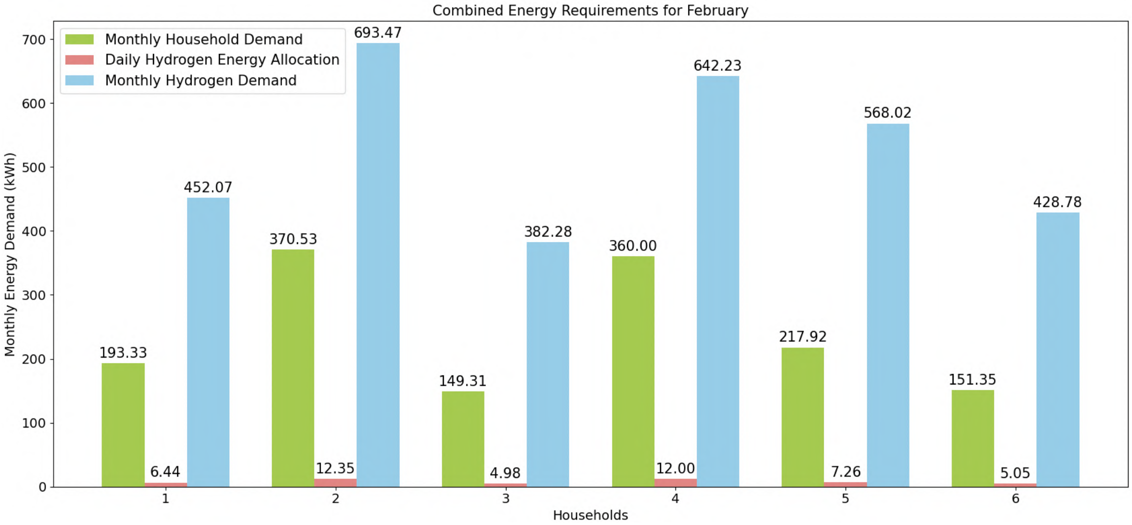
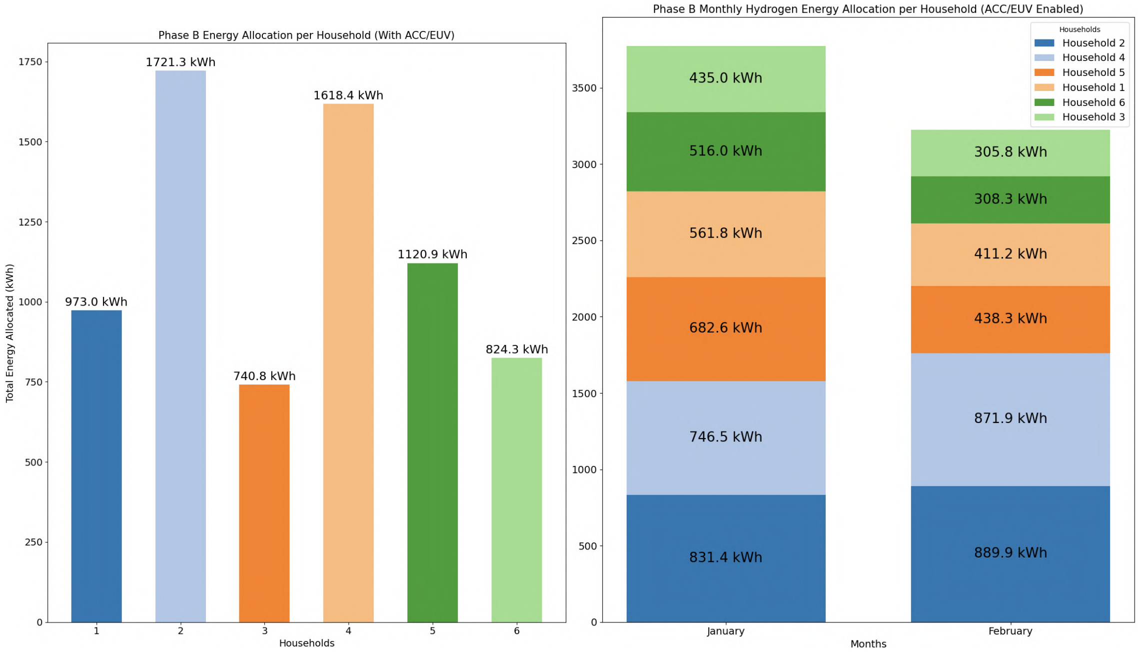


Figure 54: CS3C - Energy Requirements of February after Simulation

The objective of Case Study 3C has been to illustrate the functionality of a LEM implementation within an EC. The effectiveness of this sharing mechanism is underpinned by smart contracts, which facilitate rapid transactions and energy transparency. Additionally, the application of PENELOPE's monetary-based algorithm offers the advantage of reclaiming funds when allocated capacity remains unutilized, thereby enabling the reallocation of surplus hydrogen capacity to other applications.



(a) CS3C - Adjusted H_2 Allocations **(b)** CS3C - Hydrogen Capacity Split for Phase B

Figure 55: CS3C - After Market Simulation Energy Allocation Plots

4.3.3 Case Study 3: Results and Discussion

The findings from Case Study 3 illustrate the impact of the different modeling approaches on energy allocation and social welfare within an EC. As demonstrated, the `Benchmark Model` provided a straightforward allocation of hydrogen capacity based on fixed parameters, resulting in a significant increase in total energy demand by approximately **161.68%**. This model, while simple to implement, led to a substantial rise in the community's energy consumption, primarily due to the uniform distribution of resources without considering the specific needs and consumption patterns of individual households. This results in oversubscribed hydrogen capacity allocated to households with low energy consumption and potentially undersubscribed hydrogen capacity to larger, more energy-demanding households. The greatest disadvantage of the `Benchmark Model` lies in the disability to share energy capacity through smart contracts, resulting in lower social welfare, energy sustainability and sustainability.

In contrast, the `Complex Model` offered a more fine approach, dynamically adjusting hydrogen allocations based on various factors, including the CESI, ACC, and EUV coefficients. These methods, however, resulted in a **171.72%** increase in energy demand, 10% higher than the `Benchmark Model`. Still, it did so by better addressing the individual energy requirements of the households. The `Complex Model` allowed for a tailored energy distribution, which, although seemingly more resource-intensive, ultimately enhances the community's social welfare by optimizing energy use according to realistic energy needs and conditions. Moreover, showcasing the benefits of a local energy market (Case Study 3C), where households could trade excess hydrogen capacity, added a greater layer of energy flexibility and sustainability to the system. The market simulation of CS3C displayed the ability of households to adapt to fluctuating energy demands, by trading hydrogen capacity locally, thus reducing waste and improving overall system efficiency. The ability to trade energy not only provided a mechanism for more efficient resource use but also introduced economic benefits for the households involved, reinforcing the community's resilience and sustainability.

Overall, Case Study 3 highlights the advantages of employing a sophisticated model like the `Complex Model` within a smart energy community. While it demands higher computational resources and more complex management, the benefits of optimized energy distribution, enhanced social welfare, and opportunities for energy transactions justify the additional effort. The `Complex Model` demonstrated the aforementioned benefits without the need for a third-party organization, answering to the demands of the interviewees of Section 3.1 and to the third research question of this thesis. Future implementations could explore further refinements and additional parameters to the model, such as incorporating real-time data from household energy management systems to enable even more precise adjustments and transactions, potentially leading to a more sustainable and efficient energy ecosystem.

4.4 Case Study 4: Long-Term Sustainability and Scalability Analysis

This section examines the future integration of ECs with shared hydrogen storage systems, particularly focusing on three key elements: advancements in subsystem efficiency, overall system cost reduction, and the policy frameworks that support their implementation. The goal of this analysis is to evaluate how technological improvements and cost reductions can incentivize the adoption of SHSS in emerging energy communities. Two scenarios are examined in **Case Study 4 (CS4)**:

- **Case Study 4A (CS4A):** Energy communities of 2030.
- **Case Study 4B (CS4B):** Energy communities of 2050.

The first part of this analysis is encapsulated in Sections 4.4.1 and 4.4.3, focusing on technological advancements and cost projections for the 2030 and 2050 scenarios, respectively. The projected efficiencies will be used as an input to the `Complex Model`, and the results will be compared with present-day values obtained in Scenario 2E of Section 4.2.4. The section continues with an examination of relevant policy frameworks in Sections 4.4.2 and 4.4.4 for 2030 and 2050, respectively, documenting how policies and regulatory incentives can either facilitate or hinder the adoption of a SHSS in emerging ECs. The foremost objective is to approximate the most optimal time to integrate SHSS in ECs by weighing technological advancements, policy support, and economic feasibility. The central research question will be addressed by analyzing the alignment of these factors in Section 4.5.

Figure 56: Future of Energy Communities Example (Render By Author)

For Case Study 4, the parameters in Table 21 are used. These parameters incorporate the necessary inputs from the `Complex Model`, as determined in Section 4.2, with particular reference to findings from Scenario 2C (Household Participation Index, Spatial Consumption Index, Energy Utilization Profile) and Scenario 2E (Monthly Weights). The goal of this final case study is to estimate the appropriate time frame for introducing SHSS in ECs, considering subsystem efficiencies, cost factors, and policy frameworks. Through this, the section ultimately aims to provide an answer to the central research question posed in Chapter 1.

Table 21: Case Study 4 Modelling Parameters

Parameter	Number	Unit	Notes
Household Num.	10	-	SHSS Shareholders
Consumption	248.75	kWh/Month	-
Months	6	-	Winter Months, Phase B
Safety Margin	10	%	-
Energy By SHSS	60	%	Energy to be supplied by SHSS
Switching Period	17:00 - 23:30	-	SHSS running
HPI Weight	0.20	-	Household Participation Index
SCI Weight	0.35	-	Spatial Consumption Index
EUP Weight	0.45	-	Energy Utilization Profile
Monthly Weights	-	-	Same as Scenario 2E

4.4.1 Case Study 4A: Technological and Economic Analysis

By 2030, several milestones are set for the global energy landscape aiming to decarbonize the energy sector and transition towards CO_2-free electricity [79]. Significant advancements in green hydrogen production will be driven by infrastructure upgrades and ambitious sustainability goals set by several countries.

By 2030, the implementation of a P2G2P system in ECs will likely see significant advancements. Key technological improvements, particularly in electrolyzer efficiency, are anticipated. The current efficiency of around 60% could improve to 65-75%, driven by technological innovations in PEM- and Alkaline Electrolyzers. Ongoing research in [80] already reveals a working SOEC electrolyzer featuring 85% efficiency, which equates to 39 kWh of electricity per kilogram of green hydrogen produced. Such advancements are crucial as they enable more efficient hydrogen production from renewable energy sources, thus supporting a greener energy ecosystem. The lifespan of the mentioned technology is also expected to improve significantly, thus reducing costs and increasing sustainability further. However, the consensus is that until after 2030, this period will see great advancements in necessary technologies, but more towards the experimental and not in the commercial phase.

By 2030, fuel cell technology is also expected to experience notable advancements, further enhancing the feasibility and efficiency of hydrogen energy systems in ECs. Key improvements include increased efficiency in PEMFCs and SOFCs. PEMFCs are anticipated to achieve efficiencies up to 65%, while SOFCs could reach even higher efficiencies of 70-80%, driven by innovations in materials and manufacturing processes [39], [81]. These advancements will reduce the cost of hydrogen-based energy and increase the durability and lifespan of fuel cells, thereby enhancing their economic viability and sustainability.

Fuel cells and electrolyzers are undeniably the two least efficient components of the P2G2P cycle for hydrogen, as shown in Section 3.4. Consequently, improving the aforementioned efficiencies will make introducing an SHSS in ECs energy-efficient and sustainable. However, the high costs associated with the discussed electrolyzer and fuel cell technologies use rare materials, making their costs a significant barrier to widespread commercialization.

Referencing the methods for calculating the total system efficiency of Section 3.4 and the research of this section, it is possible to acquire expressions for the total system efficiency of the SHSS with updated forecast values.

$$\eta_{total} = \eta_{conv} \times \eta_{el} \times \eta_{trans} \times \eta_{stor} \times \eta_{FC}, \tag{24}$$

For 2030, a worst case, average case, and best case scenario are identified to showcase the discrepancy in expected total system efficiency change. The results are summarized in Table 22:

Table 22: Efficiency Scenario Comparison for SHSS in 2030

Efficiency Scenarios for 2030	**Unit**	**Worst Case Efficiencies**	**Average Case Efficiencies**	**Best Case Efficiencies**
Conversion Losses	η_{conv}	97%	97%	97%
Electrolyzer Efficiency	η_{el}	65%	75%	85%
Hydrogen Transmission Losses	η_{trans}	95%	95%	95%
Hydrogen Storage Efficiency	η_{stor}	96%	96%	96%
Fuel Cell Efficiency	η_{FC}	65%	70%	80%
Total System Efficiency	η_{total}	**37.38%**	**46.44%**	**60.16%**

The motivation for identifying three distinct cases of total system efficiency lies in the significant differences between the projected efficiency outcomes. The worst-case scenario predicts a **7.61%** improvement over present efficiency levels, while the average case anticipates a **16.67%** increase. In the best-case scenario, system efficiency could improve by **30.39%**. However, the best-case scenario is not deemed commercially feasible because it depends on SOEC technology currently under development, which also requires large quantities of surplus heat to operate efficiently. Although SOEC technology shows great potential, particularly when integrated with high-temperature industrial processes, infrastructure, even by 2030, is unlikely to provide the necessary surplus heat to support SOEC systems in urban environments. As a result, the best-case scenario remains speculative. To accurately assess the potential impacts of improved system efficiency on costs and sustainability, the `Complex Model` was applied on the average 2030 case, yielding the following results:

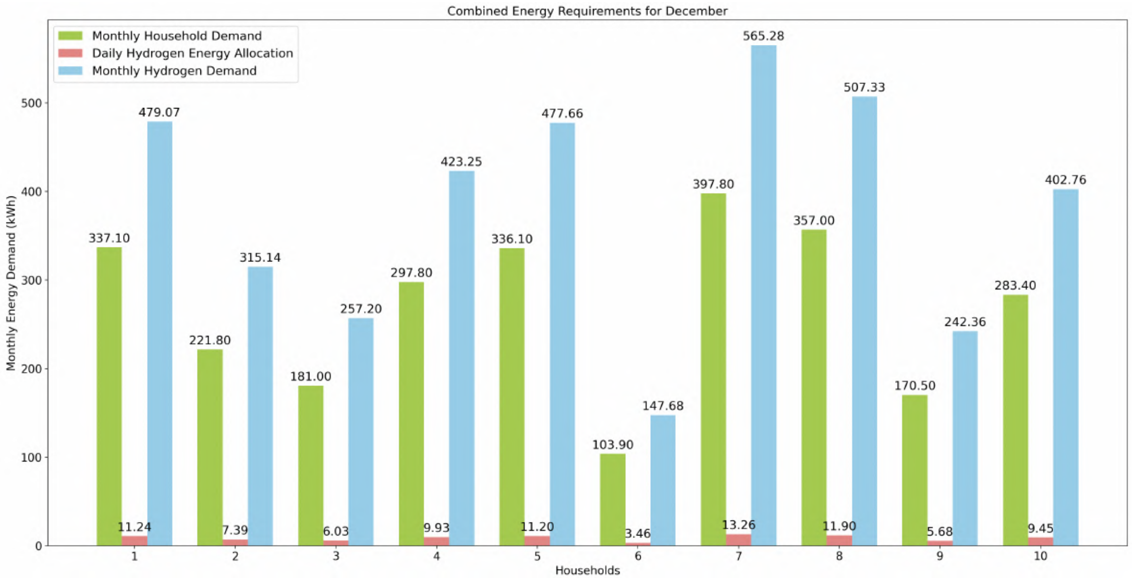


Figure 57: CS4A - Energy Requirements of December after Simulation

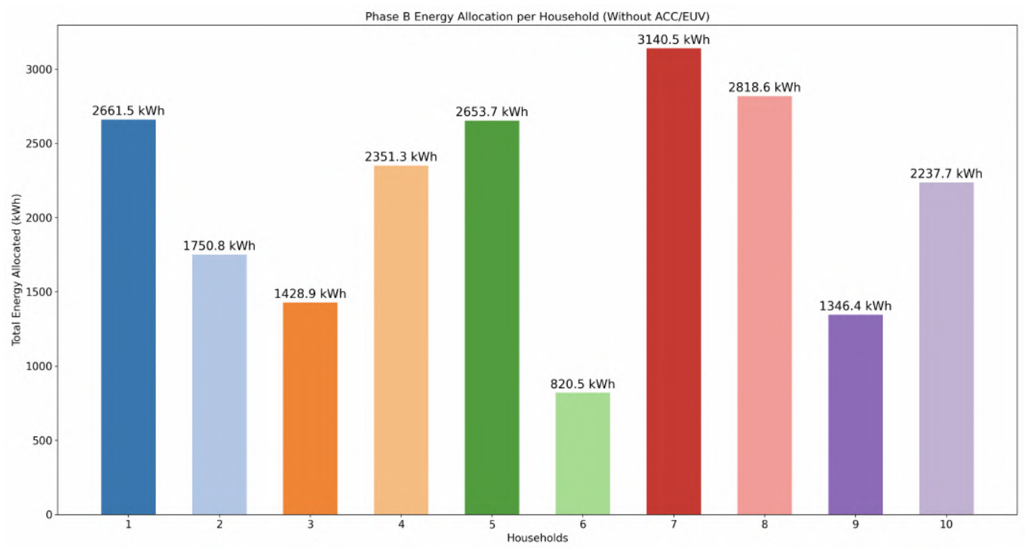


Figure 58: CS4A - Total Hydrogen Energy Requirements for Phase B

Plots concerning the average case scenario for 2030 are shown in Figures 57 - 59. Similar plots for worst-case and best-case efficiency can be found in Appendix D. To compare the results of the 2030 scenario, it is necessary to have linear results. Thus, the ACC and EUV coefficients are switched off, allowing Figures 57 and 58 to be compared with Figures 44 and 45, which feature present-day efficiency values obtained in Scenario 2E of Section 4.2.4. Table 23 compares the efficiency of the two scenarios.

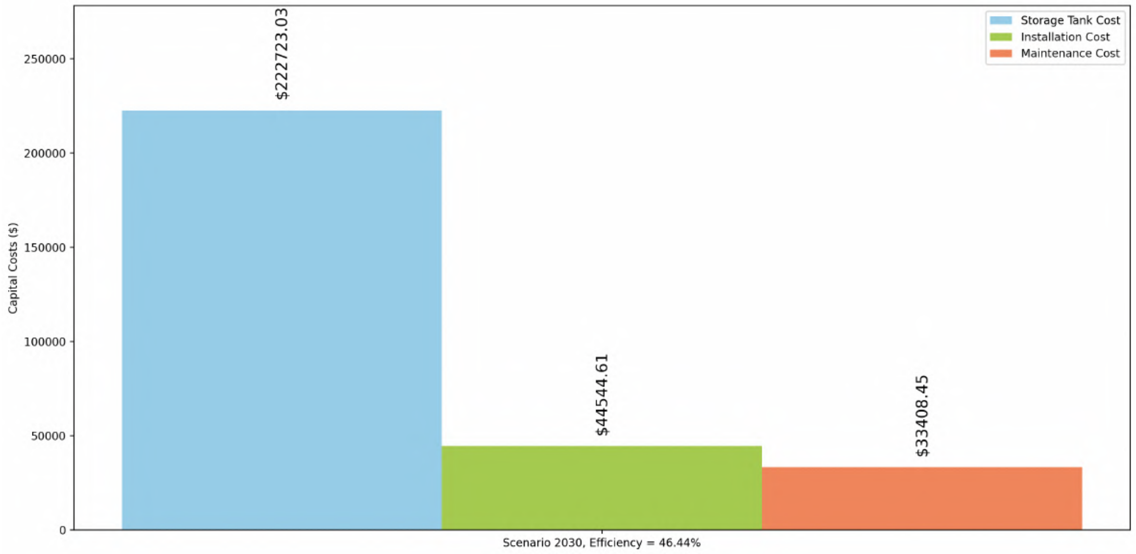


Figure 59: CS4A - Hydrogen Storage Costs Estimation for parameters of Table 21

Table 23: Comparison of 2024 (Green) vs 2030 (Blue) Efficiency Scenarios

Households / Energy Demand (kWh)	**Household 1**	**Household 2**	**Household 3**	**Household 4**	**Household 5**	**Household 6**	**Household 7**	**Household 8**	**Household 9**	**Household 10**
Grid Electricity Demand	337.1	221.8	181.0	297.8	336.1	103.9	397.8	357.0	170.5	283.4
Hydrogen Energy Demand	747.33	491.61	401.22	660.25	745.13	230.37	881.81	791.42	378.08	628.29
Total Energy Demand per Household (2024)	**4151.9**	**2731.2**	**2229.0**	**3668.1**	**4139.5**	**1280.0**	**4899.0**	**4396.9**	**2100.5**	**3490.5**
Grid Electricity Demand	337.1	221.8	181.0	297.8	336.1	103.9	397.8	357.0	170.5	283.4
Hydrogen Energy Demand	479.07	315.14	257.20	423.25	477.66	147.68	565.28	507.33	242.36	402.76
Total Energy Demand per Household (2030)	**2661.5**	**1750.8**	**1428.9**	**2351.3**	**2653.7**	**820.5**	**3140.5**	**2818.6**	**1346.4**	**2237.7**

4.4.2 Case Study 4A: Policy and Regulatory Considerations

By 2030, evolving policy frameworks will heavily influence the integration of Shared Hydrogen Storage Systems in ECs. Several key policies and regulations at the European Union and national levels will shape the deployment and adoption of hydrogen technologies to move away from fossil fuels and accelerate the transition towards CO_2-free electricity.

1. **European Union Hydrogen Strategy**

As part of the REPowerEU publication in May 2022, the EU outlines the potential of hydrogen and places targets of 40 GW of electrolyzer capacity by 2030. The ambition aligns with the Fit-for-55 plan, which calls for reducing greenhouse gas emissions within the EU by at least 55% by 2030 [82]. Furthermore, through the hydrogen public funding compass, the EU has created funding opportunities to incentivize hydrogen projects, thus paving the way for pilot projects where hydrogen storage systems are paired in existing infrastructure [83]. As hydrogen production technologies advance and pilot projects receive incentives, the main focus of hydrogen policies will prioritize industrial applications. Urban hydrogen deployment, by contrast, will remain a lower priority, with attention only shifting to urban settings after the ambitious goals for reduced emissions are met and policy frameworks for green hydrogen production and consumption are established.

2. **National Policies and Incentives**

Many EU countries, such as Germany, France, and the Netherlands, are implementing national hydrogen strategies that align with the EU's broader goals. These national policies include subsidies for renewable energy storage, particularly hydrogen, combined with grid and public transport modernization projects, which will also enable hydrogen to participate in demand response programs and local energy markets [84, 85]. Considering private transportation, several countries aim to decarbonize the sector by introducing incentives for FCEVs, which are recognized for their fast refueling times and ability to connect to the hydrogen grid. Though FCEVs are expected to become more popular by 2030, expensive materials and overall production costs estimate the widespread adoption of CO_2-free cars to occur closer in 2050 [75, 86].

3. **Private Sector Incentives**

Carbon pricing and Emissions Trading Systems (ETS) are expected to drive private investment in hydrogen infrastructure by 2030. The EU ETS will likely expand to include hydrogen storage systems, incentivizing companies to invest in such technologies and ultimately transforming private industries to be powered entirely by green energy. Additionally, tax breaks for investments in clean energy technologies will make the utilization of hydrogen for energy and storage a commercially feasible opportunity [87]. No information could be found regarding SHSS implementation and incentives, perhaps as a result of hydrogen only now starting to be considered for urban long-term storage. Finally, there haven't been any actions towards introducing a complete P2G2P hydrogen system for urban applications, thus few private sector incentives are expected, even by 2030.

4. **Safety and Regulatory Standards**

The International Organization for Standardization and the European Committee for Standardization are expected to update hydrogen safety standards, covering hydrogen storage, production, consumption, and transportation. These standards are critical for the safe operation of hydrogen, including its operation in SHSS, where storage safety and hydrogen purity will play a critical role [88]. To successfully implement hydrogen storage in ECs, safety frameworks have to be implemented, which will undeniably occur upon the introduction of pilot projects, featuring hydrogen storage for urban energy supply.

5. Local Energy Markets

By 2030, the development of decentralized, blockchain-based energy trading platforms will allow ECs to trade hydrogen as a commodity. These platforms will support real-time energy transactions, increasing the economic viability of SHSS while enabling more autonomy for ECs to transparently manage shared energy utilities [89].

4.4.3 Case Study 4B: Technological and Economic Analysis in 2050

By 2050, the energy landscape is expected to have undergone a substantial transformation towards carbon neutrality and sustainability, with renewable energy resources being the main urban energy supplier. Increasing fuel cell and electrolyzer efficiency, driven by technological advancements and combining these systems with surplus heat, will play a crucial role in the decarbonization of urban environments. Ambitious sustainability targets and infrastructure advancements will push green hydrogen to the forefront of energy systems. In addition, cities are likely to rely heavily on hydrogen as a clean energy carrier, combining V2G for urban and commercial applications to effectively and finally neutralize carbon emissions in these sectors.

One of the key technological shifts by 2050 is anticipated to be solid oxide electrolyzers, which have the potential to reach efficiencies of 85-90%, producing green hydrogen with as little as 35-37 kWh of electricity per kilogram of hydrogen [90]. These advancements in efficiency will be driven by innovations in materials, replacing rare and costly metals with more abundant alternatives, improving electrolyzer durability, and greatly increasing their lifespan compared to current systems. These technological efforts will drastically reduce hydrogen production costs, making green hydrogen a competitive alternative to fossil fuels in urban energy systems. Furthermore, by 2050, these electrolyzers will be integrated into Power-to-X (P2X) systems, where they will efficiently convert surplus renewable energy into hydrogen, enabling flexible energy storage and use across the city grid [91].

Fuel cells are also set to experience transformative advancements by 2050. PEMFCs are projected to achieve 70-75% efficiency, while SOFCs could exceed 80% efficiency in urban applications [92], [93]. These improvements, coupled with reduced material costs and longer operational lifespans, will increase the economic viability of fuel cells in both transportation and stationary power applications. As cities adopt fuel cells to power public transport and provide decentralized energy for buildings, the reduced cost per kilowatt-hour of hydrogen will make it a mainstream energy option. This will help cities reach the ambitious decarbonization targets and minimize greenhouse gas production.

In summary, the improvements in electrolyzer and fuel cell efficiency by 2050 will lead to the widespread adoption of hydrogen in urban energy systems. With electrolyzers capable of producing green hydrogen more efficiently and at lower costs and fuel cells providing more reliable power, cities will be better equipped to transition to sustainable energy ecosystems. However, while 2030 marks the beginning of large-scale pilot programs and infrastructure upgrades, 2050 will likely be the turning point where these technologies reach full commercial maturity and play an essential role in decarbonizing urban environments.

Based on the conducted research, it is possible to identify two efficiency scenarios for 2050. For this case study, the efficiency of the best case scenario is used in the `Complex Model`. The efficiency scenarios are summarized in 24.

Table 24: Efficiency Comparison for 2050

Efficiency Scenarios for 2050	**Unit**	**Worst Case Efficiencies**	**Best Case Efficiencies**
Conversion Losses	η_{conv}	98%	98%
Electrolyzer Efficiency	η_{el}	85%	90%
Hydrogen Transmission Losses	η_{trans}	96%	98%
Hydrogen Storage Efficiency	η_{stor}	96%	97%
Fuel Cell Efficiency	η_{FC}	70%	80%
Total System Efficiency	η_{total}	**53.74%**	**67.07%**

Plots concerning the best case scenario for 2050 are shown in Figures 60 - 62. Similar plots for the worst-case efficiency can be found in Appendix D. In correspondence to the 2030 scenario, the ACC and EUV coefficients are switched off to make the comparison of the 2024, 2030, and 2050 scenarios possible. In Figure 60, the monthly energy demand of the SHSS is effectively equal to the monthly electricity demand of the households. This change is a direct result of the significantly higher efficiencies of the electrolyzer and fuel cell technologies expected to come as these technologies mature further. By reflecting on the substantial increase in efficiency, it is clear that shared hydrogen storage systems will be commercially feasible after these developments occur, paving the way for energy-efficient and economically viable hydrogen energy systems.

In Figure 62, the storage costs across the three efficiency scenarios are compared. By reflecting on the graph, the decision to not provide commercially available SHSS in the current market is clear. For the current case study of 10 households, total storage costs, assuming a 10-year maintenance plan, are approximately 800 thousand dollars. The costs are expected to decrease to 300 thousand dollars by 2030 and to 140 thousand dollars by 2050. This translates to a **62%** and **82%** percent decrease in costs for the 2030 and 2050 scenarios, clearly portraying the benefits of higher efficiencies and advancements in infrastructure processes.

Upon acquiring the results from the `Complex Model`, Table 25 can be completed, including the energy demand of a shared hydrogen storage system with 2050 efficiencies.

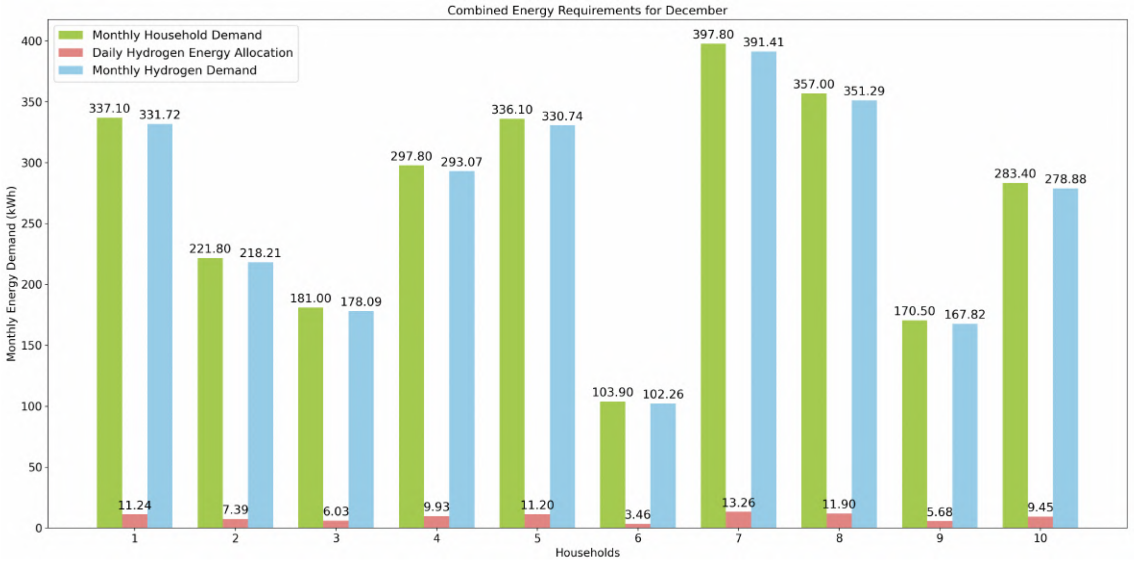


Figure 60: CS4B - Energy Requirements of December after Simulation

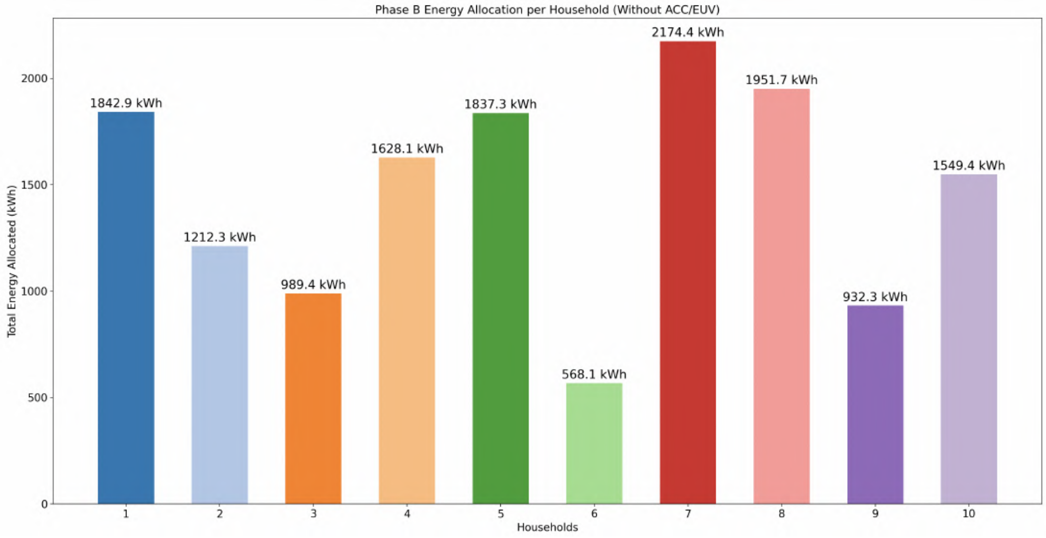


Figure 61: CS4B - Total Hydrogen Energy Requirements for Phase B

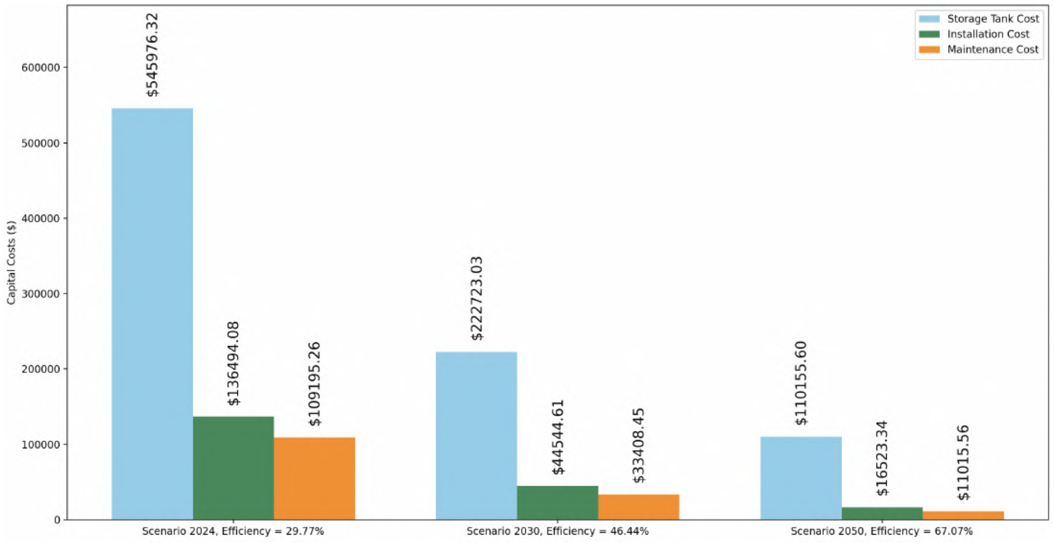


Figure 62: CS4B - Hydrogen Storage Costs Estimation for 2024, 2030, 2050 Scenarios

Table 25: Comparison of Energy Demand - 2024, 2030, 2050 Scenarios

Households / Energy Demand (kWh)	**Household 1**	**Household 2**	**Household 3**	**Household 4**	**Household 5**	**Household 6**	**Household 7**	**Household 8**	**Household 9**	**Household 10**
Grid Electricity Demand	337.1	221.8	181.0	297.8	336.1	103.9	397.8	357.0	170.5	283.4
Hydrogen Energy Demand	747.33	491.61	401.22	660.25	745.13	230.37	881.81	791.42	378.08	628.29
Total Energy Demand per Household (2024)	**4151.9**	**2731.2**	**2229.0**	**3668.1**	**4139.5**	**1280.0**	**4899.0**	**4396.9**	**2100.5**	**3490.5**
Grid Electricity Demand	337.1	221.8	181.0	297.8	336.1	103.9	397.8	357.0	170.5	283.4
Hydrogen Energy Demand	479.07	315.14	257.20	423.25	477.66	147.68	565.28	507.33	242.36	402.76
Total Energy Demand per Household (2030)	**2661.5**	**1750.8**	**1428.9**	**2351.3**	**2653.7**	**820.5**	**3140.5**	**2818.6**	**1346.4**	**2237.7**
Grid Electricity Demand	337.1	221.8	181.0	297.8	336.1	103.9	397.8	357.0	170.5	283.4
Hydrogen Energy Demand	331.72	218.21	178.09	293.07	330.74	102.26	391.41	351.29	167.82	278.88
Total Energy Demand per Household (2050)	**1842.9**	**1212.3**	**989.4**	**1628.1**	**1837.3**	**568.1**	**2174.4**	**1951.7**	**932.3**	**1549.4**

4.4.4 Case Study 4B: Policy and Regulatory Considerations

Global policy frameworks and ambitious hydrogen production targets will influence the long-term integration of Shared Hydrogen Storage Systems within ECs by 2050. As hydrogen becomes an essential part of the energy mix, several key policies and initiatives will accelerate its adoption, even in urban landscapes. The subsystems of the P2G2P cycle for hydrogen will have been optimized for stationary urban energy use, allowing the connection of hydrogen-enabled energy communities to hydrogen hubs and FCEVs.

1. EU Climate Neutrality Goals and Hydrogen Integration

By 2050, the European Union aims to achieve carbon neutrality through its NET-Zero 2050 program, with renewable hydrogen playing a critical role in decarbonizing hard-to-abate sectors such as transportation, heavy industry, and energy storage. The EU Hydrogen Strategy outlines the use of hydrogen in 23-24% of the EU's total energy mix by 2050, contributing to energy security and emissions reductions. Investments in large-scale electrolyzer capacity and hydrogen storage infrastructure will be paramount to enabling this transition [94, 95].

The EU envisions a global hydrogen market by 2050, facilitating energy trading with partner countries. Green Hydrogen Partnerships will support the import and export of renewable hydrogen, while hydrogen blending in existing gas infrastructure will offer an early method to integrate hydrogen into energy grids. The EU aims to consequently establish a liquid hydrogen market by ensuring price signals and introducing clear rules for third-party access to hydrogen infrastructure. Finally, hydrogen trading by sea will play an essential role in securing green energy supply to partner European countries [96, 97]. By 2050, it is safe to assume that a complete policy mix will be in place, confirming safe hydrogen energy consumption for urban household usage.

2. Financing and Investment Initiatives

The EU estimates that cumulative investments in renewable hydrogen production could reach €470 billion by 2050. The European Hydrogen Bank, launched as part of the REPowerEU initiative, will support these investments by facilitating cost-efficient hydrogen trading and production. The bank is expected to connect hydrogen supply and demand, while other mechanisms like the EU's ETS Innovation Fund will offer financing for clean hydrogen projects [98, 94].

Private sector investments and initiatives are set to greatly increase, with leading energy and industrial companies forming strategic alliances and partnerships to co-develop hydrogen technologies. It is argued that only when these giant companies shift their interest towards exploiting the hydrogen energy market will nations completely stop relying on fossil fuels and energy. By 2050, advancements in hydrogen infrastructure and subsystem efficiency will certainly allow for complete hydrogen storage systems to be introduced, providing a cost-effective storage solution with considerable benefits to battery energy storage.

3. Regulatory Framework and Safety Standards

Ensuring the safe deployment of hydrogen technologies is crucial by 2050. Regulatory frameworks for hydrogen safety, transport, and storage will continue to evolve. The Clean Hydrogen Partnership will play a critical role in advancing hydrogen safety standards and certification schemes for renewable hydrogen. Furthermore, innovations in hydrogen production and storage will lead to stricter safety regulations, especially as hydrogen becomes a key component of residential and industrial energy supply [97, 99].

4. Decentralized Energy Markets and Hydrogen in Energy Communities

By 2050, decentralized energy markets will be common market participants, effectively buying and selling renewable energy capacity to cover their energy needs. Hydrogen storage will likely be integrated for long-term energy storage in ECs of the future, working alongside BESS and contributing to a completely carbon-neutral energy supply. Blockchain-based trading platforms will facilitate real-time hydrogen transactions, allowing ECs to efficiently manage hydrogen reserves. Following sustainable housing and V2G connectivity, shared hydrogen storage systems are likely to be another essential participant in the decentralized energy market, with ECs being the general standard for energy sharing in the urban sector.

4.4.5 Case Study 4: Research Question Answer and Summary

This case study considers the refined `Complex Model` developed throughout Section 4.2 to assess its performance in two scenarios, a 2030 and a 2050 case study. For these two scenarios, the projected subsystem efficiencies are estimated, and an outlook on policy advancements is made. The objective of this case study is to consider advancements in policy, energy efficiency, and reductions in total system cost to determine when the introduction of a SHSS in emerging ECs can be a sustainable long-term storage solution, therefore answering the central research question.

Considering the 2030 scenario, three efficiency cases were derived from reliable literature forecasts. The worst case resulted in an efficiency of 37.38%, a 7.61% increase from present values, and the average case resulted in an efficiency of 46.44%, showing a 16.67% increase in present-day efficiency. Finally, the best-case scenario resulted in 60.16% efficiency, an improvement of 30.39% over present-day values. The best-case efficiency scenario was considered unreasonable as it required technology that is not yet commercially available and the addition of large amounts of heat, currently only available in industrial areas. Therefore, the average case efficiency scenario was used as an input to the `Complex Model`, demonstrating a significantly better energy-sustainable system that could become commercially available. Still, the relatively high infrastructure costs and necessary rare materials make the proposed system difficult for widespread placement. Looking at the anticipated policy mix associated with hydrogen, it seems that several ambitious goals are set, led by various incentives for higher hydrogen production and consumption. However, it seems that these policies strive to achieve the decarbonization of the industrial sector and overall higher penetration of DERs and hydrogen to the energy grid. As there are no mentions of hydrogen storage systems being incentivized for urban landscapes, it is concluded that policy support won't be mature enough to incentivize commercial placement of SHSS in emerging ECs, but only finance pilot projects to study and optimize hydrogen storage systems further.

By 2050, the subsystems of the P2G2P cycle for hydrogen will be optimized further, with pioneering technologies such as solid-oxide electrolyzers and fuel cells becoming the new norm for hydrogen production and consumption. Alongside the rest of the subsystem efficiencies improving, the total SHSS efficiency is expected to rise from 29.77% to anywhere between 53.74% - 67.1%. This increase in efficiency paired with decreased marginally lower costs for storage (Figure 62, can lead to shared hydrogen storage systems becoming the standard for sustainable energy in urban ecosystems. In terms of policy, it is anticipated that the ambitious goals of 2030 will be met, resulting in a clear policy mix for green hydrogen utilization in urban settings. These policies will consider safety, maintenance, administration, and support, ensuring that hydrogen storage systems will be a viable replacement for BESS.

Optimal Timing for Introduction The central research question of this thesis—When is the introduction of shared hydrogen storage a sustainable long-term storage solution for the ECs of the future?—can be addressed by analyzing current and projected technological, economic, and policy developments. Based on the preceding analysis, **the 2035 to 2040 time frame emerges as a reasonable launch window for the commercial integration of shared hydrogen storage systems into ECs.**

By this period, major corporations in the energy and automotive sectors will likely have shifted significant investments toward hydrogen technologies, helping drive down production and storage costs. Additionally, policy frameworks regulating hydrogen use, safety, and energy security will be fully established, supported by decentralized, blockchain-based energy markets that enable efficient trading of hydrogen capacity within ECs. Finally, the introduction of more and more FCEVs will steadily incentivize household owners to participate in V2G operations.

4.5 Chapter 4 Summary and Discussion

This chapter has examined multiple case studies featuring energy communities of different sizes, with shared hydrogen storage facilitating long-term energy storage. Through these cases, the feasibility, scalability and optimal timing for SHSS implementation in emerging ECs has been addressed.

In the first case study, the `Benchmark Model` was validated, which is optimized for equipment longevity and energy security. By evaluating the results of the case study, the calculations behind acquiring a total system efficiency and allocating hydrogen capacity to the EC households has verified the expected operation of the `Benchmark Model`. The results of the first case study conclude that though the addition of a SHSS can be a sustainable solution towards alleviating the energy grid during peak hours, it requires 161.68% more energy compared to grid-sourced electricity. As a result, such a system shall only be considered if large amounts of surplus DER energy are available, to mitigate shutting renewables of because of overcapacity limits.

In the second case study, the *Complex Model* was refined by calibrating its degrees of freedom. Adjustments in the CESI algorithm, the addition of the ACC and EUV coefficients, and the incorporation of changes in monthly energy demand through historical data led to a more precise capacity allocation for EC households. Through the aforementioned methods, each EC household has a different energy profile, therefore receiving tailored hydrogen capacity allocations.

In case study three, the performance of the two models was compared in energy efficiency and capacity allocation strategy. The `Complex Model` demonstrated 10% higher energy demand than the *Benchmark Model*, leading to a more energy-consuming shared hydrogen storage system. The function of the local energy market implementation was also tested, showcasing how blockchain-based transactions can be simulated in an effort to maximize social welfare and allow greater energy flexibility among EC users.

In case study four, the `Complex Model` was used to speculate the energy requirements of ECs of 2030 and 2050, respectively. By conducting a thorough research, several efficiency scenarios were identified. For 2030, present-day SHSS efficiency of 29.77% could increase from 37% to 60%, with the average case efficiency being equal to 46.44%, substantially increasing the prospects of SHSS as a commercially viable long-term storage solution. By 2050, P2G2P hydrogen system efficiency is expected to climb 53%-67%, driven by advancements in electrolyzer and fuel cell efficiency.

The analysis of case study four continues by considering policy and infrastructure advancements, in an effort to acquire an expression on when is the right time-frame for introduction a shared hydrogen storage system as a sustainable long term storage solution for emerging ECs. After the preceding research, the expected window for the commercial implementation of SHSS in urban landscapes lies after 2035, specifically from 2035 to 2040. By then technology advancements and several policies will be in place, allowing for complete hydrogen storage systems to be launched in emerging ECs.

5 Conclusion

In this section, the overall conclusion is formulated by answering the central research question: **When is the introduction of shared hydrogen storage a sustainable long-term storage solution for energy communities of the future?** This thesis set out to explore the integration of shared hydrogen storage systems and blockchain-based energy transactions within energy communities. To provide an answer to the main research question, three fundamental sub-questions were formulated. The answers to the sub-questions are initially discussed, paving the way for a comprehensive answer to the central research question.

How can the optimal size for a shared hydrogen tank be determined?

In Section 2.3 of the literature review, the complexity of a hydrogen-based P2G2P system was discussed, detailing the necessary subsystems for creating a shared hydrogen storage system for urban settings. The subsystem efficiencies, costs, and respective lifespans were provided, followed by various technologies that could be considered. In Section 3.4, the `Benchmark Model` was developed, providing algorithms that ensured optimized sizing based on energy security and equipment longevity. Considering present-day values, a PEM electrolyzer, PEM fuel cell, and compressed H_2 tank storage were chosen, leading to a total system efficiency of **29.77%**. The `Benchmark Model` can estimate hydrogen capacity requirements based on input parameters and furthermore facilitates storage cost calculations. The model is tested in Sections 4.1 and 4.3, showcasing proper operation and realistic results. In the end, it is found that the developed model can facilitate realistic sizing and cost calculations, but also revealed that such a system would be very energy demanding and largely inefficient with today's infrastructure.

Is it possible to facilitate hydrogen heating within the energy community on an annual basis?

In Section 2.5, the potential of using hydrogen to provide heating in urban settings was researched. Through the flowchart of Figure 16, it is clear that this option, as compared to other options for heating households, is energy inefficient and poses significant complexities and dangers. In Section 3.3, the potential for using hydrogen for heating was approached in terms of economic, environmental and technical viability and efficiency. The comparative analysis based on the preceding calculations demonstrated that electric heat pumps could offer an 86.67% efficiency gain (COP = 3.0) over hydrogen heating systems, making them the preferred means for household heating. Ultimately, the analysis determined heat pumps to be safer, less complex, and more energy efficient than hydrogen-based heaters. Thus, hydrogen for heating was not considered in the energy calculations of the developed models.

What mechanisms need to be designed to operate and integrate shared hydrogen storage within the community?

In Section 3.5, the PENELOPE architecture was designed, providing all the necessary mechanisms to ensure proper integration of shared hydrogen storage systems in ECs. The architecture realizes four distinct modules, namely: Administration, Hydrogen Tank Capacity and Switching Period, Hydrogen Capacity Allocation, and P2P Energy Sharing Market Structure. These modules ensure that EC administrator responsibilities are updated to match the hydrogen storage system needs and introduce a local energy market structure featuring smart contracts, allowing for rapid hydrogen capacity exchange between the EC households. Furthermore, the `Complex Model` was developed, allocating hydrogen capacity to maximize social welfare. To achieve this, historical energy data were processed, and energy profiles for the respective households were created. The complexities of the model allow for fair hydrogen capacity allocation, which is tested in the simulations of Chapter 4. Specifically, in Section 4.2, the modularity of the `Complex Model` is shown, tailoring its respective parameters and weights to match the energy-centered approach of this thesis. After calibrating the `Complex Model`, Section 4.3 compares the `Benchmark` and `Complex` Models. In the end, the `Complex Model's` proper operation is verified upon delivering realistic results, specifically **10%** higher than those of the `Benchmark Model`, as seen in Table 20. This is reasoned due to the nonlinearity of the `Complex Model`, oversubscribing hydrogen allocations to take into consideration faults and out-of-the-ordinary household energy behaviors. Finally, in Section 4.3.2, the LEM implementation of the model is showcased, consequently verifying its correct operation. Thus, it is possible to conclude that the optimization done by the modular PENELOPE architecture and its respective `Complex Model` effectively maximizes social welfare and provides the foundations for a sustainable energy sharing mechanism within urban landscapes.

When is the introduction of shared hydrogen storage a sustainable long-term storage solution for energy communities of the future?

In Section 4.4, the potential of shared hydrogen storage is explored through two future scenarios. These scenarios discussed how potential technological advancements could lead to lower costs and commercially feasible shared hydrogen storage implementations. Furthermore, policy advancements have been considered, hoping to determine when the placement of shared hydrogen storage systems will be treated as the norm rather than a pilot project.

In the 2030 scenario, the projected total system efficiency for a SHSS increases, driven by advancements in electrolyzer and fuel cell efficiency. Specifically, the present day system efficiency of **29.77%** can potentially increase to **46.44%**. Even higher efficiencies are possible as shown in Table 23, but it is unreasonable to consider them commercially available in urban settings by 2030. Overall, with the forecast higher efficiency, the SHSS implementation becomes feasible in terms of energy demand, however the high total system costs remain significant barriers. Considering policy advancements, ambitious decarbonization goals are issued for 2030 in national levels, however a focus on the industrial sector is given. It is likely that during that time, hydrogen storage systems will still be in the pilot-project-phase, helping the introduction of new policies to ensure urban safety and feasibility. In the 2050 scenario, efficiency is projected to increase further to **67.1%**, driven by the commercial introduction of solid oxide electrolyzers and fuel cell systems. By that time, the ambitious decarbonization goals of 2030 will be met and a push to decarbonize sectors beyond industry will be in place. Fuel cell electric vehicles and public transportation will have replaced other less sustainable transportation methods. In addition, vehicle-to-grid connectivity will further enhance the efficiency of hydrogen storage systems, even in urban settings, allowing for safely considering hydrogen, as a sustainable long-term storage solution. With the introduction of new electrolyzer and fuel cell technologies, using common materials instead of rare ones, it is safe to assume that all-in-one hydrogen storage system will be commercially available, even for urban ecosystems.

To provide an answer to the central research question, it seems unreasonable to anticipate a commercial shared hydrogen storage system before 2035. Though decentralized, blockchain-based energy markets and advanced energy management systems can already facilitate hydrogen storage, the immature policies won't be ready, and total system costs will still be significant. **The window from 2035 until 2040 seems to be a reasonable estimation for when shared hydrogen storage systems will leave the pilot-project era and can launch as commercially feasible entities.**

6 Reflection and Recommendations

6.1 Reflection

Although the innovative PENELOPE architecture encapsulates a modular and realistic methodology, capable of fair capacity allocation and rapid energy transactions through smart contracts, it is not yet complete. The algorithms of the `Complex Model` can be equipped with additional variables and conditions to enhance equitable capacity allocation among EC users. These variables include historical seasonal energy data for better monthly energy allocation and forecast energy data to change the allocated capacity real-time. The potential of including battery energy storage systems in the architecture could further enhance energy efficiency and energy supply when the hydrogen storage subsystems are ramping-up or ramping-down. Finally, the architecture could benefit from the introduction of a artificial intelligence algorithm, capable of tailored hydrogen capacity allocation based on household energy habits.

In terms of limitations, the `Complex Model` currently allocates hydrogen capacity to households over a monthly basis, though the resolution could be made smaller, therefore greatly considering the energy habits of the household owners. Specifically, the algorithm could allocate more capacity during the weekdays if the household users are working from home or allocate zero energy if the household owners are away. Another limitation has to deal with the simulation of the local energy market. The current algorithm bases willingness-to-buy capacity solely on the EUP of each household, meaning that households with higher energy consumption get prioritized for buying hydrogen capacity that is available on the local energy market. A fairer algorithm could make the LEM more realistic, improving social welfare further and ensuring equal rights in the handling of shared capacity.

6.2 Recommendations

This thesis presents an architecture that addresses the integration of a shared hydrogen storage system within an energy community. The following recommendations outline key areas for future research and improvements:

1. **Explore change in system usage and logistics if the SHSS were to generate hydrogen even during Phase B:** Currently, two phases are identified. Phase A is the hydrogen generation phase, typically operating for half the year, to generate hydrogen from surplus renewable energy. During Phase B, compressed hydrogen is employed for the EC needs. However, generating hydrogen during the hydrogen consumption phase B could lead to significantly different logistics, efficiencies and necessary policies.

2. **Create a more realistic local energy market algorithm:** The current local energy market algorithm, as implemented in the PENELOPE framework, uses a static allocation system based on a household's Energy Utilization Profile (EUP). While this ensures a degree of fairness, it falls short in responding dynamically to fluctuating energy demands and supply levels, particularly in energy communities with significant variability in renewable energy generation. Future research should focus on developing a dynamic, real-time pricing model integrated into the algorithm. This model would adjust hydrogen pricing and capacity allocation based on real-time data inputs such as renewable energy availability, overall community demand, and individual household consumption patterns.

3. **Consider more parameters for the community energy share index:** The Community Energy Share Index (CESI) is a crucial component of the current model, but it is limited by the

number of parameters considered. Future research could incorporate additional factors, such as seasonal and real-time household energy data, to better reflect fluctuations in energy demand. This could also involve integrating behavioral data from households to optimize energy distribution dynamically. By expanding the CESI algorithm, it is sure that hydrogen capacity allocation can be made even more precise and fair for the entire EC ecosystem. To reach this milestone, the need for another survey is advised, to determine the willingness of the household owners towards sharing their energy data within the community management.

4. **Determine more effective ways to make the model non-linear:** The current model utilizes a largely linear approach, which may not fully capture the complexities of energy consumption and storage behaviors in ECs. Future studies should investigate additional non-linear methods that can accommodate variations in energy demand caused by factors such as weather, user behavior, and unforeseen technical issues. Incorporating artificial intelligence algorithms alonside the methods of this thesis could lead to more scientific non-linear algorithms and an even more precise capacity calculation and allocation model.

5. **Incorporate all relevant subsystem costs within the P2G2P hydrogen cycle:** While the models developed in this thesis enable the calculation of compressed hydrogen storage costs, a comprehensive cost analysis of the entire SHSS was not included due to the diverse range of available technologies and subsystems with varying capacities. An optimization algorithm could be developed to determine the optimal capacities for each subsystem, including electrolyzers, compressors, fuel cells, and necessary infrastructure. This would provide a holistic and precise evaluation of the total system costs, accounting for the various technological configurations that might be implemented.

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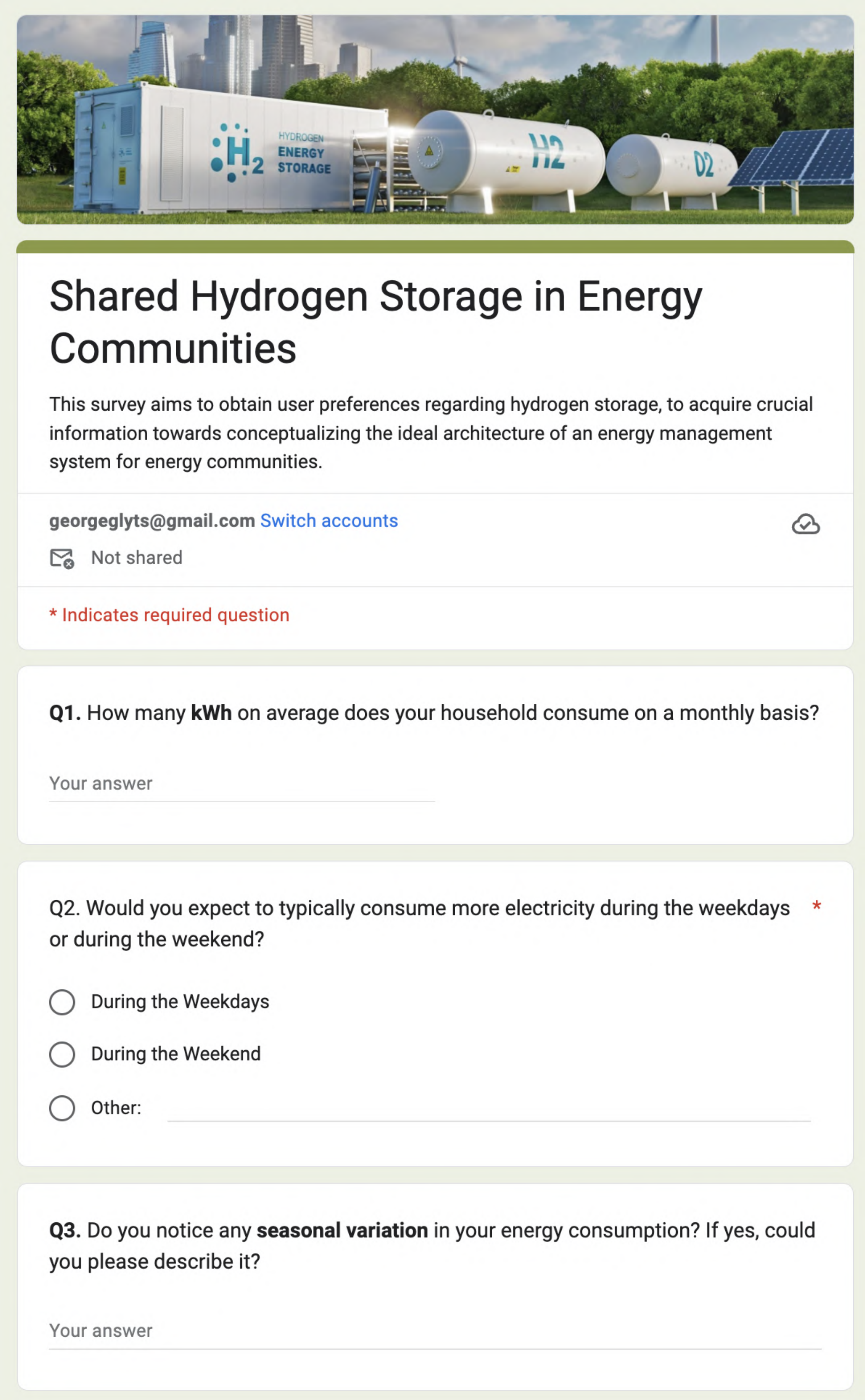
7 Appendix A: The Energy Community Survey



Shared Hydrogen Storage in Energy Communities

This survey aims to obtain user preferences regarding hydrogen storage, to acquire crucial information towards conceptualizing the ideal architecture of an energy management system for energy communities.

georgeglyts@gmail.com Switch accounts

Not shared

* Indicates required question

Q1. How many **kWh** on average does your household consume on a monthly basis?

Your answer

Q2. Would you expect to typically consume more electricity during the weekdays or during the weekend? *

○ During the Weekdays

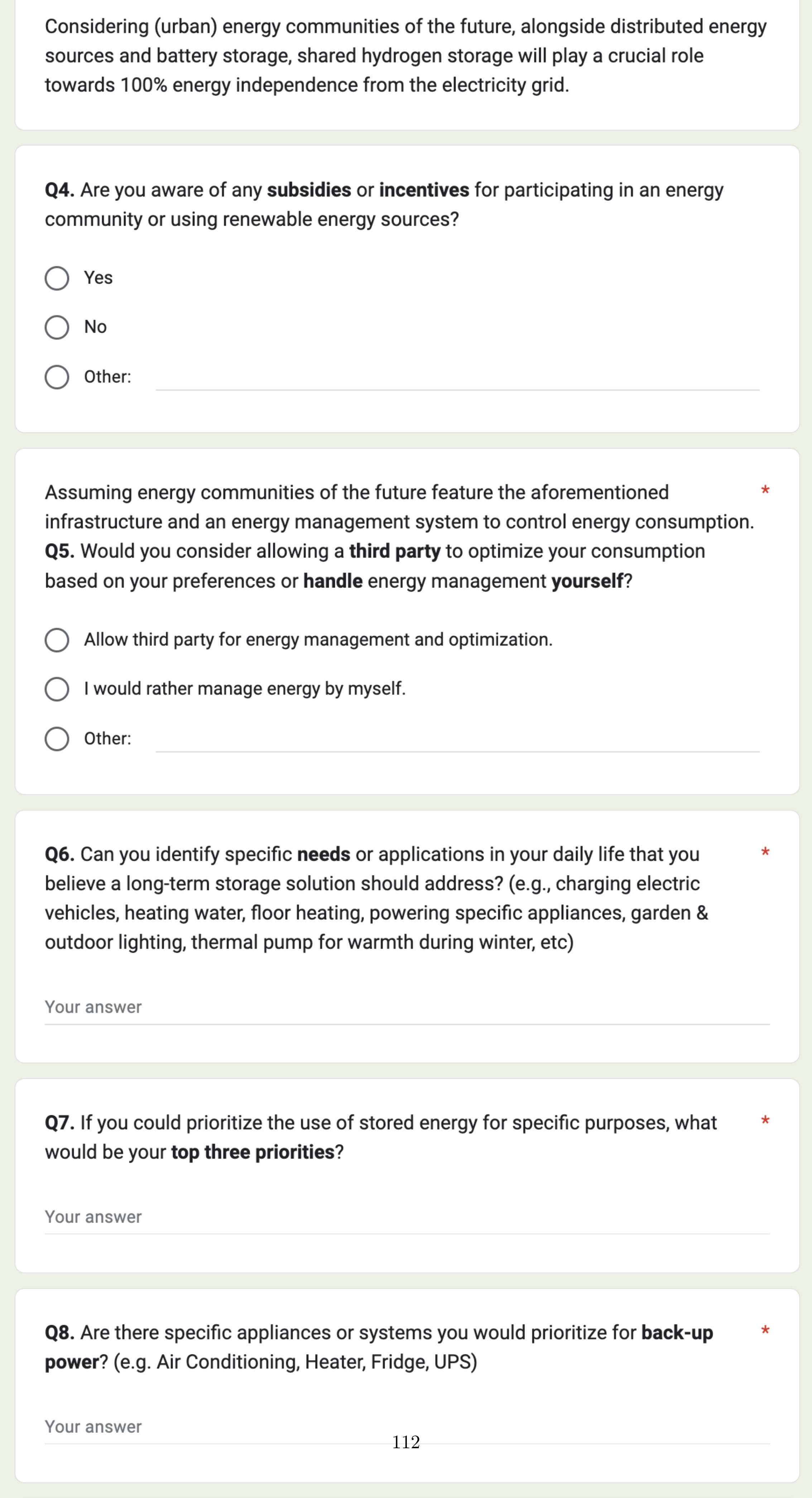
○ During the Weekend

○ Other:

Q3. Do you notice any **seasonal variation** in your energy consumption? If yes, could you please describe it?

Your answer

Figure 63: Survey of Energy Communities on Shared Hydrogen Storage Adoption P1



Considering (urban) energy communities of the future, alongside distributed energy sources and battery storage, shared hydrogen storage will play a crucial role towards 100% energy independence from the electricity grid.

Q4. Are you aware of any **subsidies** or **incentives** for participating in an energy community or using renewable energy sources?

○ Yes

○ No

○ Other: ______

Assuming energy communities of the future feature the aforementioned infrastructure and an energy management system to control energy consumption. **Q5.** Would you consider allowing a **third party** to optimize your consumption based on your preferences or **handle** energy management **yourself**? *

○ Allow third party for energy management and optimization.

○ I would rather manage energy by myself.

○ Other: ______

Q6. Can you identify specific **needs** or applications in your daily life that you believe a long-term storage solution should address? (e.g., charging electric vehicles, heating water, floor heating, powering specific appliances, garden & outdoor lighting, thermal pump for warmth during winter, etc) *

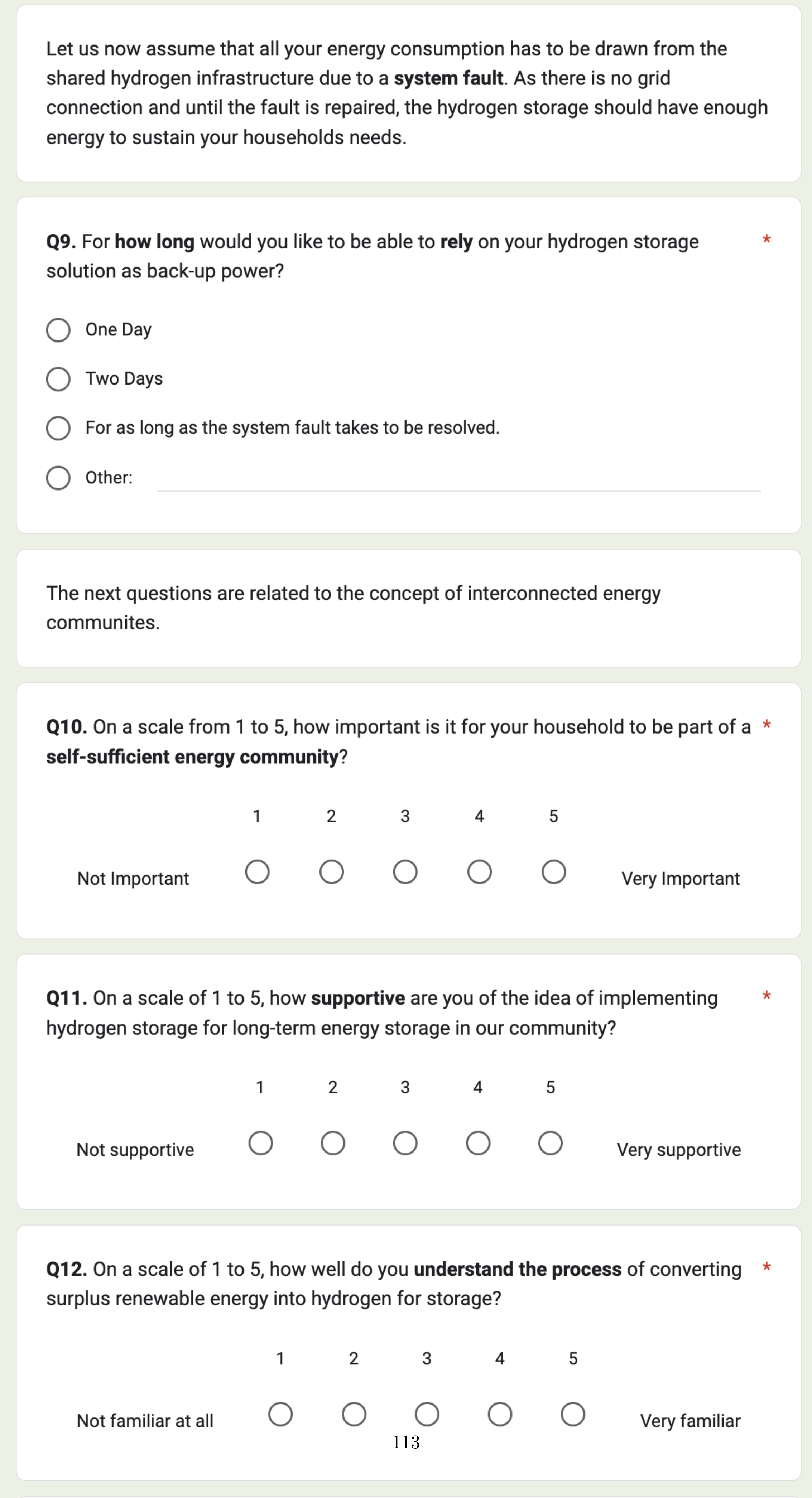
Your answer

Q7. If you could prioritize the use of stored energy for specific purposes, what would be your **top three priorities**? *

Your answer

Q8. Are there specific appliances or systems you would prioritize for **back-up power**? (e.g. Air Conditioning, Heater, Fridge, UPS) *

Your answer



Let us now assume that all your energy consumption has to be drawn from the shared hydrogen infrastructure due to a **system fault**. As there is no grid connection and until the fault is repaired, the hydrogen storage should have enough energy to sustain your households needs.

Q9. For **how long** would you like to be able to **rely** on your hydrogen storage solution as back-up power? *

○ One Day

○ Two Days

○ For as long as the system fault takes to be resolved.

○ Other: ____________________

The next questions are related to the concept of interconnected energy communites.

Q10. On a scale from 1 to 5, how important is it for your household to be part of a **self-sufficient energy community**? *

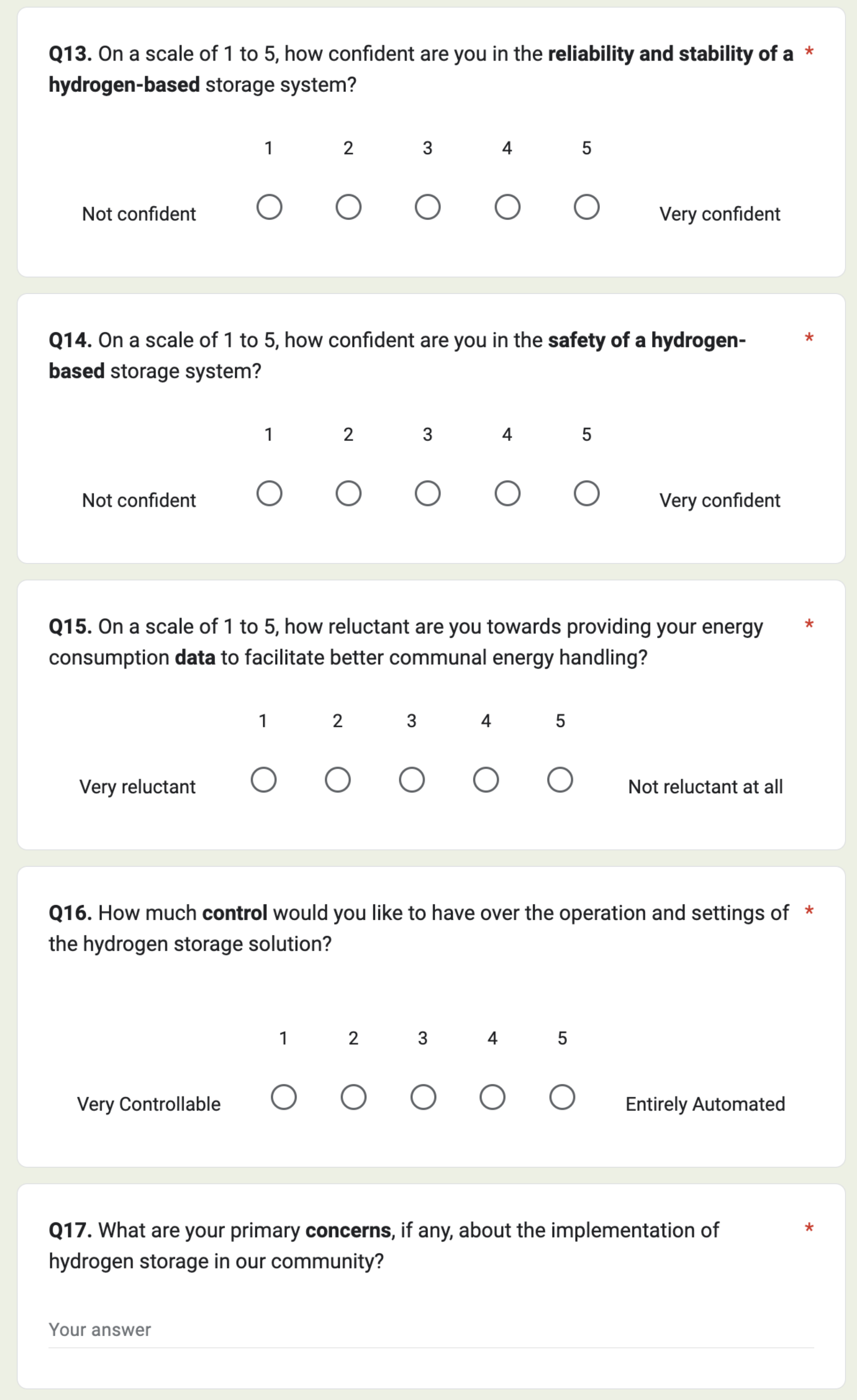
	1	2	3	4	5	
Not Important	○	○	○	○	○	Very Important

Q11. On a scale of 1 to 5, how **supportive** are you of the idea of implementing hydrogen storage for long-term energy storage in our community? *

	1	2	3	4	5	
Not supportive	○	○	○	○	○	Very supportive

Q12. On a scale of 1 to 5, how well do you **understand the process** of converting surplus renewable energy into hydrogen for storage? *

	1	2	3	4	5	
Not familiar at all	○	○	○	○	○	Very familiar



Q13. On a scale of 1 to 5, how confident are you in the **reliability and stability of a hydrogen-based** storage system? *

	1	2	3	4	5	
Not confident	○	○	○	○	○	Very confident

Q14. On a scale of 1 to 5, how confident are you in the **safety of a hydrogen-based** storage system? *

	1	2	3	4	5	
Not confident	○	○	○	○	○	Very confident

Q15. On a scale of 1 to 5, how reluctant are you towards providing your energy consumption **data** to facilitate better communal energy handling? *

	1	2	3	4	5	
Very reluctant	○	○	○	○	○	Not reluctant at all

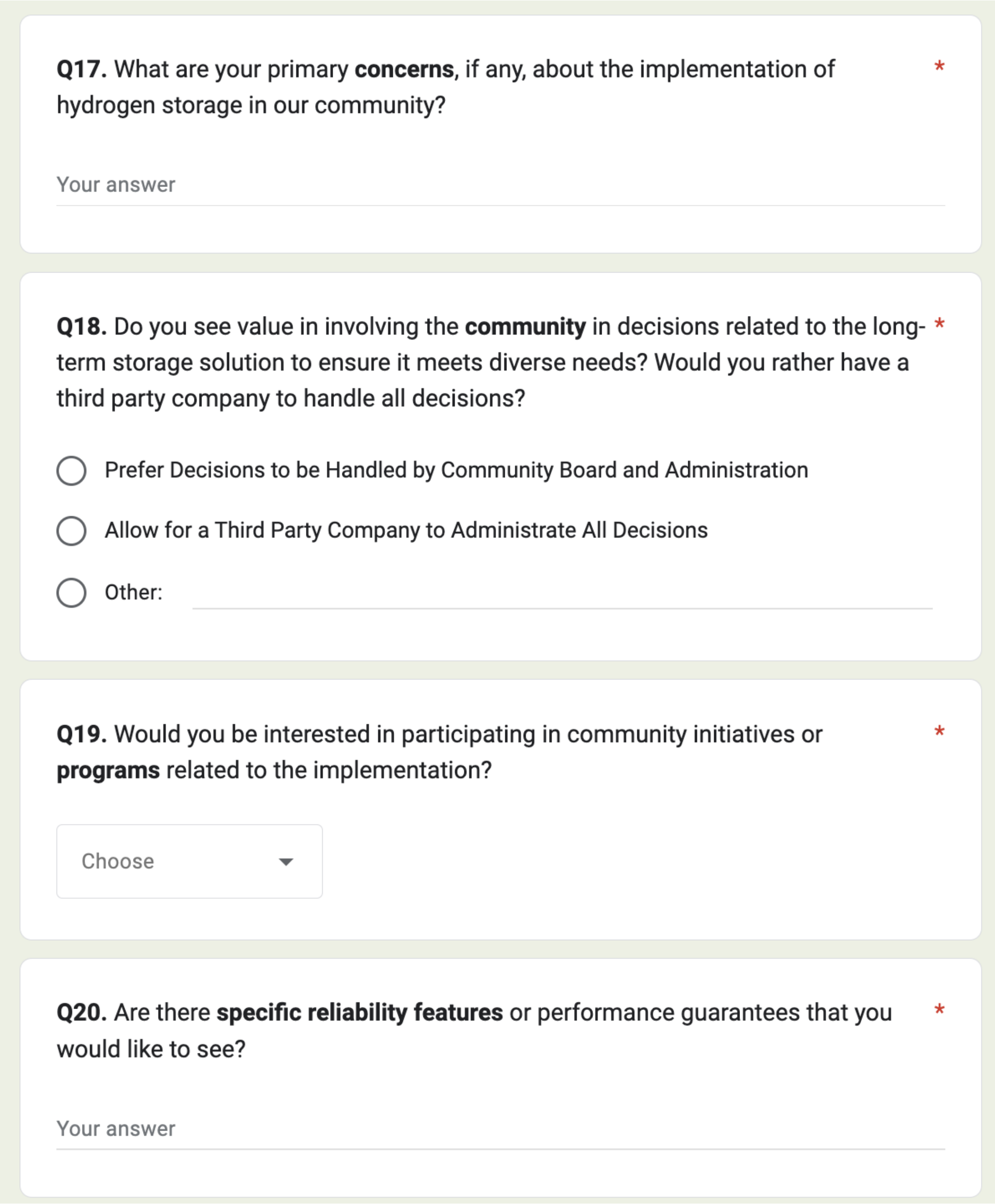
Q16. How much **control** would you like to have over the operation and settings of the hydrogen storage solution? *

	1	2	3	4	5	
Very Controllable	○	○	○	○	○	Entirely Automated

Q17. What are your primary **concerns**, if any, about the implementation of hydrogen storage in our community? *

Your answer

Figure 66: Survey of Energy Communities on Shared Hydrogen Storage Adoption P4



Q17. What are your primary **concerns**, if any, about the implementation of hydrogen storage in our community? *

Your answer

Q18. Do you see value in involving the **community** in decisions related to the long-term storage solution to ensure it meets diverse needs? Would you rather have a third party company to handle all decisions? *

○ Prefer Decisions to be Handled by Community Board and Administration

○ Allow for a Third Party Company to Administrate All Decisions

○ Other:

Q19. Would you be interested in participating in community initiatives or **programs** related to the implementation? *

Q20. Are there **specific reliability features** or performance guarantees that you would like to see? *

Your answer

Figure 67: Survey of Energy Communities on Shared Hydrogen Storage Adoption P5

8 Appendix B: Penelope Flowchart

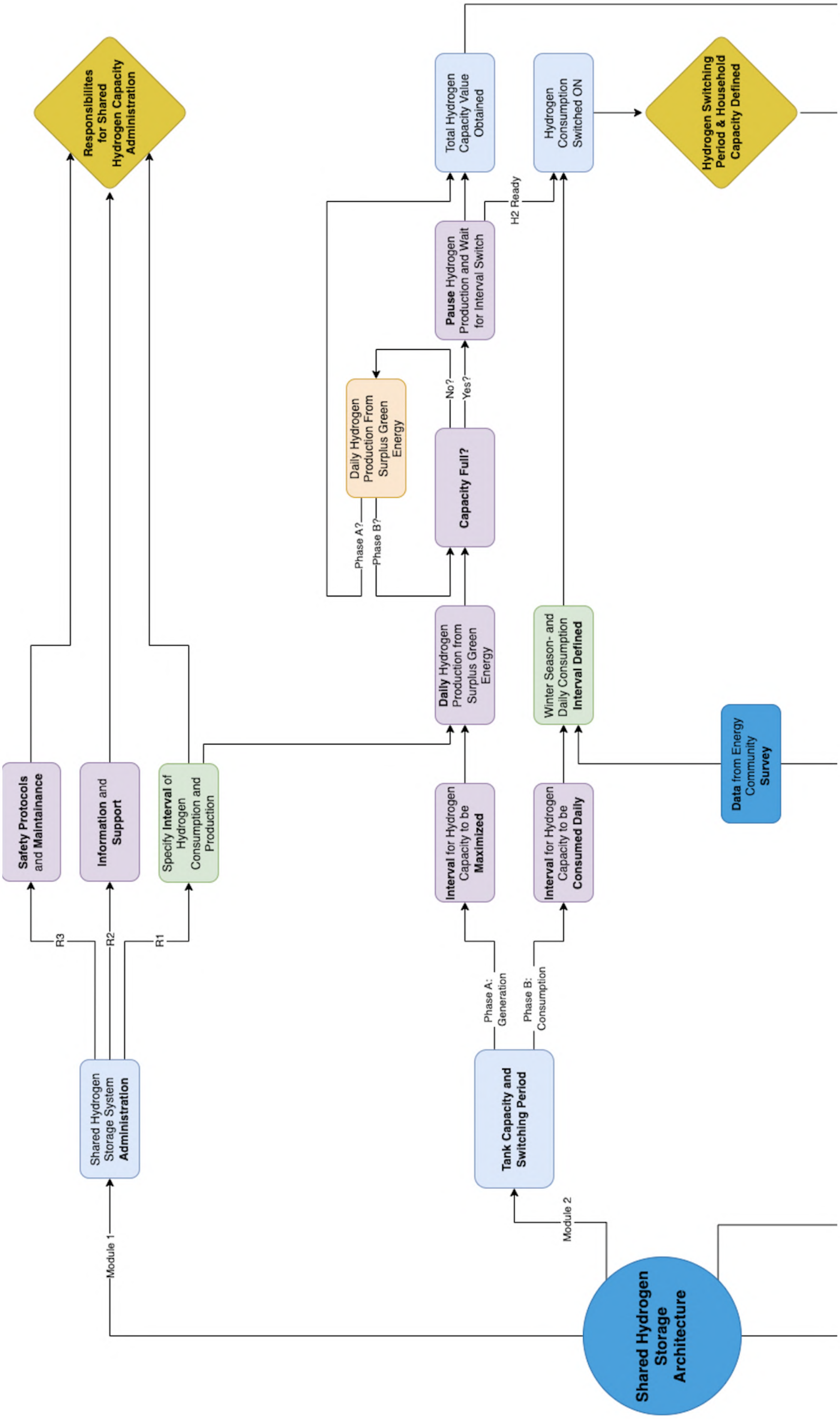


Figure 68: Penelope Flowchart Module 1 & 2

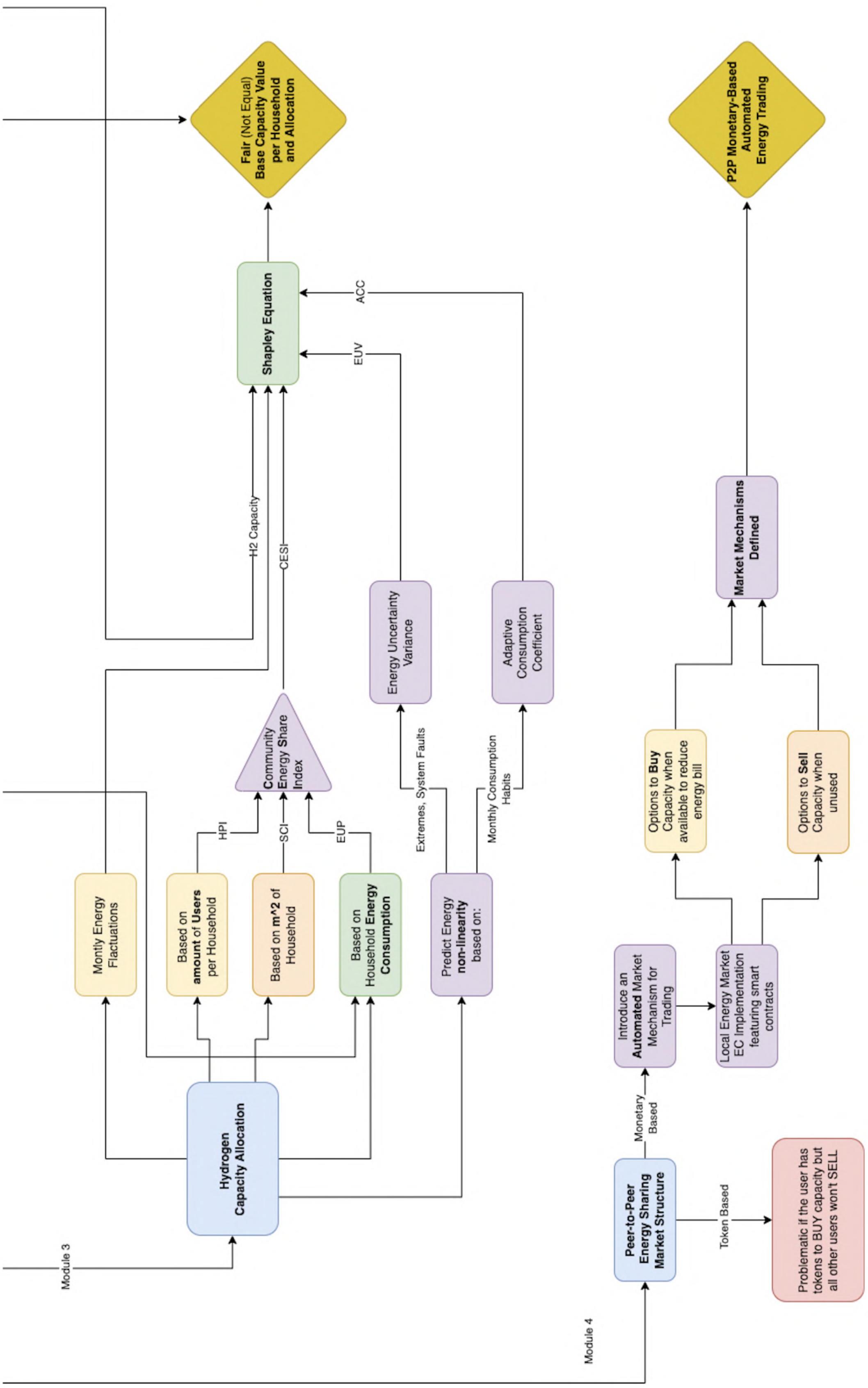


Figure 69: Penelope Flowchart Module 3 & 4

9 Appendix C: Datasets of Case Studies

The Community Energy Share Index (CESI) algorithm of the `Complex Model` is calculating the Shapley values of each respective household based on the following parameters:

- Household Participation Index
- Spatial Consumption Index
- Energy Utilization Profile

The values from Tables 26 - 28 stem from the survey participants, which have been asked to provide information regarding the amount of people in their household, the square meters of the house and the scale of energy consumption from 1 (least) to 3 (highest).

Table 26: CESI 1

Household Num.	HPI	SCI	EUP
1	3	80	2
2	4	170	3
3	2	50	2
4	4	105	3
5	3	100	3

Table 27: CESI 2

Household Num.	HPI	SCI	EUP
1	2	170	3
2	2	90	2
3	1	60	2
4	3	85	3
5	3	140	3
6	1	35	1
7	4	200	3
8	3	170	3
9	1	45	2
10	3	150	2

Table 28: CESI 3

Household Num.	HPI	SCI	EUP
1	3	80	2
2	4	120	3
3	2	55	2
4	4	105	3
5	2	110	3
6	2	75	2

10 Appendix D: Additional Plots

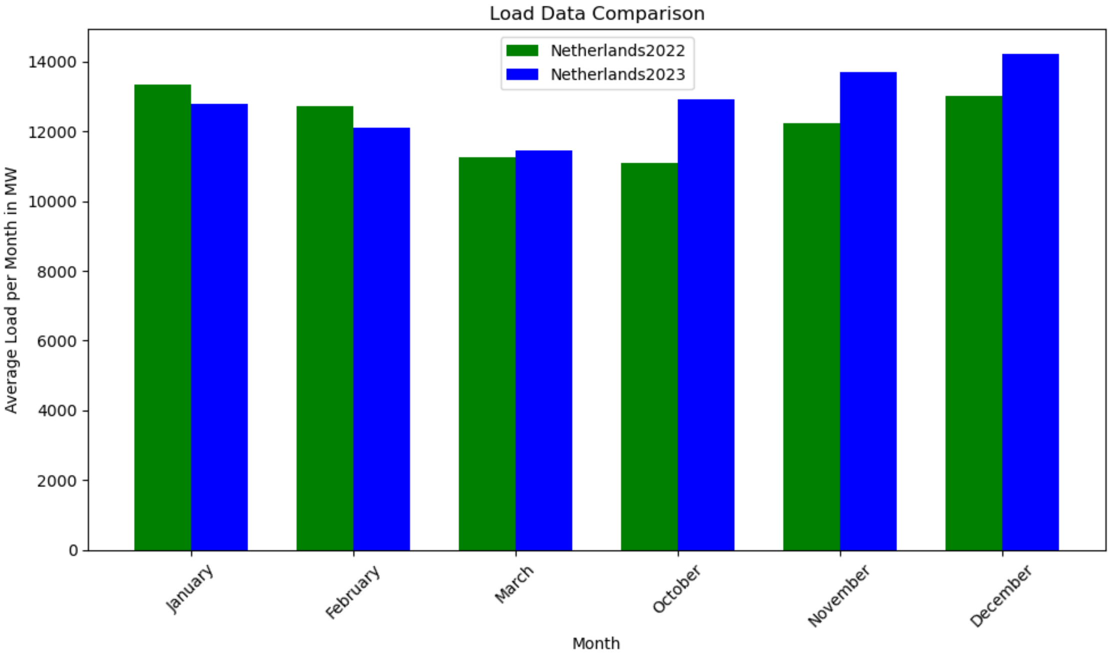


Figure 70: NL Monthly Energy Comparison

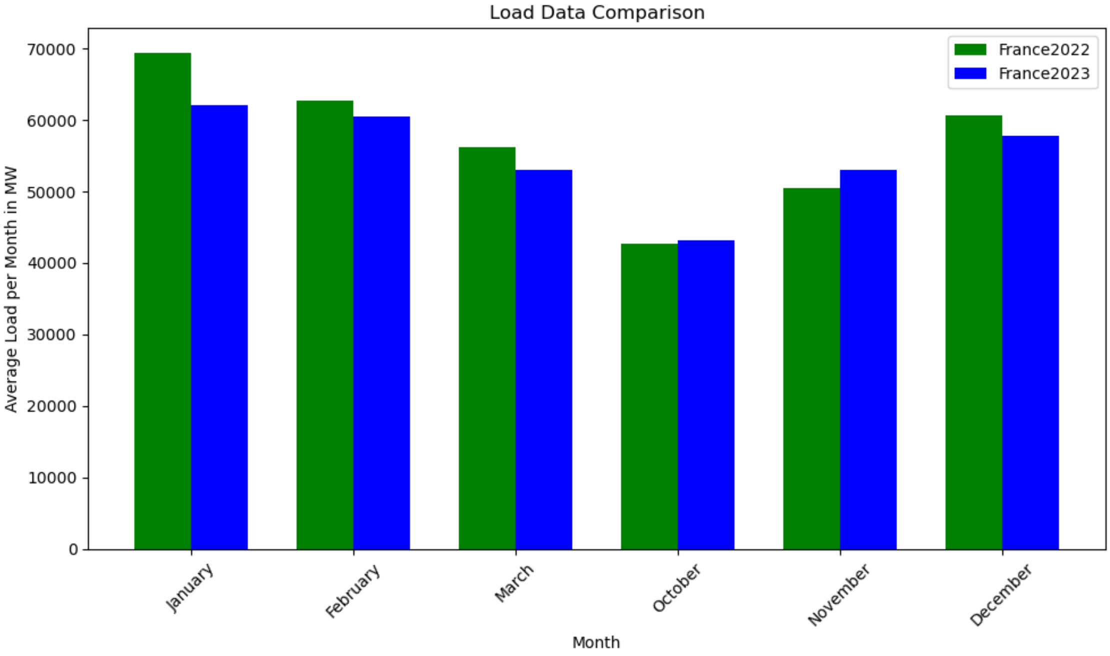


Figure 71: FR Monthly Energy Comparison

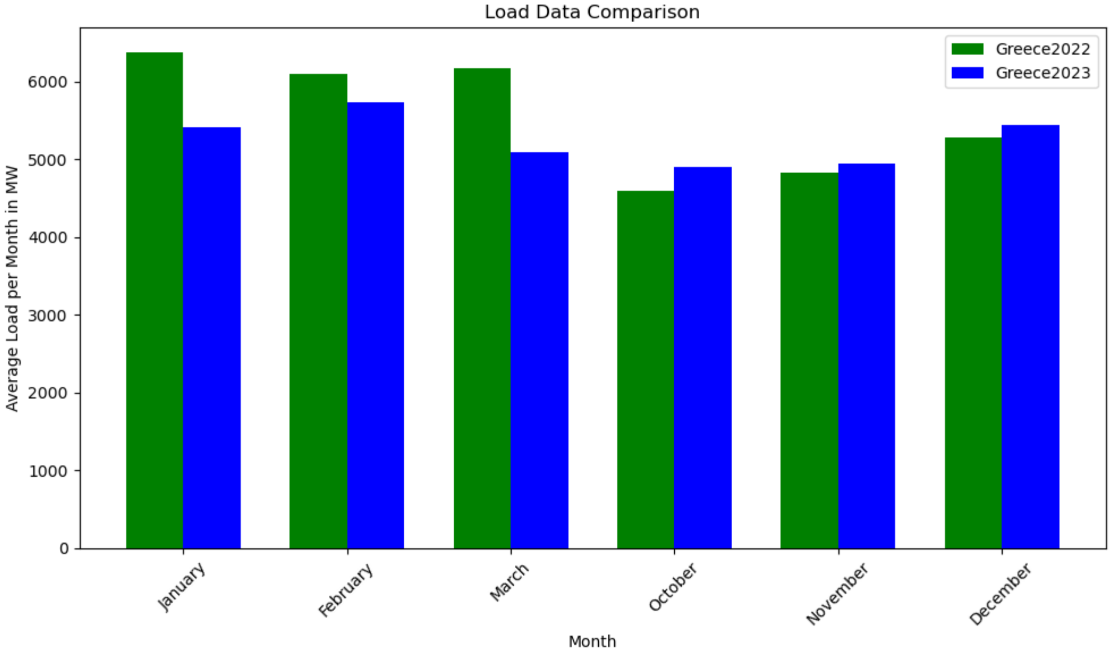


Figure 72: GR Monthly Energy Comparison

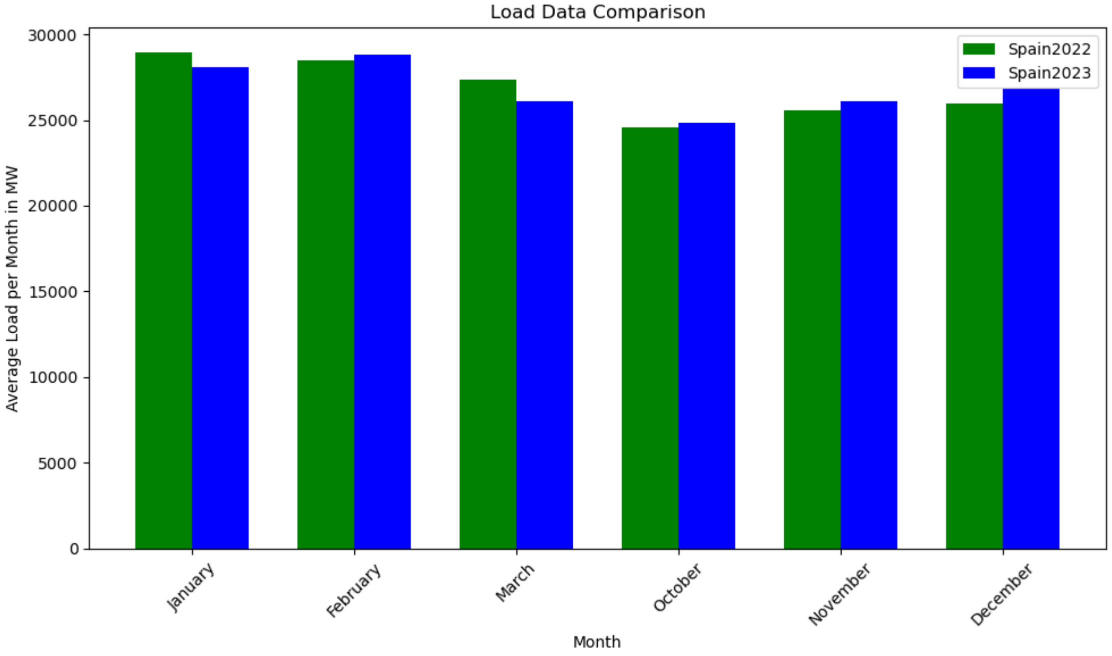


Figure 73: SP Monthly Energy Comparison