# Technological Framework to assess the implementation of Power to Hydrogen

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- Aditya Purohit

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# Summary

Context:

The current EU member states have set targets to reduce annual greenhouse emissions for 2021-2030. Sixty per cent of EU emissions include sectors like buildings, agriculture, non-ETS industry and waste. Much research cannot be found to reduce emissions in the buildings, houses and community-based scenarios. Therefore, this research focuses on developing an innovative model to make the community a hundred per cent reliant on renewable energy sources. Renewable energy produces power variably depending upon external conditions. At times, the variability of renewable energy cannot be fed into the power grid due to network constraints or low demand leading to curtailment of the energy or selling the energy at zero marginal price. Therefore, the curtailment of energy and its intermittency is the biggest barrier in delaying the transition towards a hundred per cent of renewable power into the power systems. Robust energy storage technology is required to integrate with an intelligent control system to increase the penetration of renewable energy into the energy mix. To meet this requirement, "Green Hydrogen" produced can contribute to energy security by providing another energy carrier with different supply chains, producers, and markets, diversifying the energy mix, and improving the system's resilience. To produce hydrogen, power to hydrogen technology is an innovative solution, and a framework needs to be developed to integrate this technology in the community using Industry 4.0.

Research Question:

For this, the main research question to be answered is:

***"What could be the technical model to implement Power to Hydrogen technology in the subcommunities that could be used by the government or private parties?"***

Research Methodology:

To answer the research question, exploratory literature research was carried out to understand the basics of the technology and the technological barriers associated with it. The technology is nascent and the implementation of power to hydrogen in a community-based scenario has various options, elements, components, and decisions to choose from while making the selection. Therefore, to make complex decisions multi-criteria decision making was carried out to rank or choose between the alternatives. The case study analysed found out that these are the following selections that need to be made to implement the technology.

These are :

a) To select the electrolyzer
b) To make a decision whether to construct new hydrogen infrastructure or use the existing natural gas pipeline and not invest in hydrogen-pipeline infrastructure or to use the existing natural gas pipeline before the hydrogen-pipeline infrastructure is developed
c) To select digital 4.0 technology(blockchain or digital twin) for smooth energy trading in the sub-communities

The selections for the electrolyzers and digital 4.0 technology was made using weighted sum method which is one of the methods of multi criteria decision making. The selection criteria parameters were weighted using the literature as it has enough data on the subject. The decision to construct new hydrogen infrastructure or not was done using an Analytical hierarchical process as literature research was not enough to come to a conclusion that which criteria parameters must be weighted more than others to make a decision. Structured survey method to compose and analyze complex decision makings based on mathematics and psychology was carried out to make the decision. The survey was carried out which involves institutes like municipality, academia and industry that were identified as key participants of this study.

Conclusion:

The main objective of the research was to develop a technical model for implementing Hydrogen technology in community-based scenarios. Based on literature study and survey conducted the thesis proposes the future using hydrogen technology in community based scenarios. The technology processes are discussed in detail, and the current technological barriers associated with technology are understood. Then, recommendations are provided to overcome the barriers associated with it. For example, after analysing different electrolysers using the weighted sum method, PEM electrolysers are selected according to the parameters needed to implement in a community. In the same way, recommendations using the Analytical Hierarchical process on how hydrogen transportation is feasible currently and in the future is discussed. Then what government policies are in place and whether the policies align well to foster hydrogen deployment in a community-based scenario is studied.

# Chapter 1: Introduction and Research Methodology

## 1.1 Introduction

There have been targets set to reduce annual carbon emissions for the years 2021-2030, according to existing EU member state legislation. Sixty per cent of total domestic EU emissions include the sectors like transport, non-ETS industry, building, agriculture, and waste. Therefore, to achieve a net reduction of 55% in greenhouse gas emissions by 2030 and climate neutrality by 2050, efforts must be made to increase the share of renewables in individual buildings and homes. ("Effort Sharing 2021-2030: Targets and Flexibilities" 2016). The Netherlands is one of the countries to sign up for this agreement and has set up a Dutch climate policy to reduce greenhouse gas emissions("IPCC — Intergovernmental Panel on Climate Change" n.d.).

For years, the energy system in the community has focussed on centralized fossil-based energy production and distribution due to its availability and lower price. However, the energy system is slowly transforming into a renewable-based system, as fossil fuels are exhaustive. In addition, the Netherlands needs to meet the legislation requirements of EU member states ("IPCC — Intergovernmental Panel on Climate Change" n.d.). Over the years, renewable energy technology has matured, resulting in lower prices, making energy more abundant (van der Roest Jos Boere 2017a). However, making the community buildings self-sufficient in energy using renewable power has many challenges to face. Renewable energy produces power variably depending upon external conditions. For example, solar irradiation varies over the day, making varied solar power depending upon the time. In the same way, wind energy produced varies depending on the area's wind speed on a particular day. At times, the variability of renewable energy cannot be fed into the power grid due to network constraints or low demand leading to curtailment of the energy or selling the energy at zero marginal price ("IRENA" 2019). The most significant challenge to the transition to 100 percent renewable energy in power networks is energy curtailment and its intermittency. However, because renewable energy generation has become a national goal for the country, integrating them with traditional energy systems for large-scale energy storage systems is critical to overcoming renewable resource variability. (Ghaib and Ben-Fares 2018). Therefore, to overcome the fluctuation of renewable energy, traditional storage technologies such as batteries, pumped-hydro, mechanical, and others are utilised to balance electricity demand and increase system flexibility in the present context. Using conventional storage systems has its own merits but is not environmentally friendly, has small-scale storage capacity, and has a shorter duration. These constraints highlight the need for a novel approach to energy storage in order to meet the European Union's aim.(Dawood, Shafiullah, and Anda 2020).

Therefore, to balance the supply and demand of power, we need an innovative technique of storing renewable energy that is storable, transportable, and usable. Furthermore, to improve the penetration of Renewable Energy into the energy mix, durable energy storage technology must be integrated with an intelligent control system.

## 1.2 Research Gap

Delivering low-carbon storage solutions is the new wave of interest if the aim is to achieve a climate-neutral energy supply. Oil price shocks, rising oil demand, and air pollution all fuel the search for a low-carbon storage option. To achieve this need, renewable-energy-derived "Green Hydrogen" is the best option for a totally sustainable energy transition. Green hydrogen can assist in energy security by diversifying the energy mix and boosting system resilience by offering carriers of energy with various supply chains, suppliers, and markets. In addition, hydrogen produces no emissions other than water when used in the fuel cell , which helps to reduce pollution. As a result, a new interest has emerged, centred on providing low carbon solutions as well as the benefits that green hydrogen can bring. The drivers for green hydrogen, which has gained interest to use as storage fuel, includes:

1. Low variable renewable energy cost: Green hydrogen is produced from water electrolysis which requires electricity. As a result, the cost of electricity to create hydrogen is the key cost driver. However, the cost of electricity generated by solar photovoltaics and onshore wind energy farms has dropped dramatically during the last years. Producing green hydrogen is becoming more cost-effective as the cost of solar and wind energy falls.

2. Advantages for the power system: As the use of renewable energy grows in various markets, the energy grid must become more flexible. By reacting to electric costs, the electrolysis used to make green hydrogen can ramp up or down to compensate for fluctuations in renewable energy generation.

3. Government objective for net-zero: The target set by the European Union to reach the net-zero emission target has been made to gain interest in renewable storage energy like green hydrogen.

4. Broader use of hydrogen: Hydrogen is used in a variety of fields. Hydrogen, for example, had previously sparked interest as a fuel for fuel cell electric vehicles. In contrast, the conversion of hydrogen to other products and energy carriers, like synthetic liquids, methanol, and ammonia, has sparked new interest. Also, the industry has invested in research and development aimed to produce hydrogen and reduce emission targets. These applications could boost future hydrogen demand and provide synergies to reduce costs in the green hydrogen value chain.

5. Technologies ready for commercialization: Many elements used in the technology of the hydrogen value chain have previously been tested on a small scale and are ready for commercialization.

6. Interest of various stakeholders: Interest in hydrogen is currently prevalent in both private and public parties as a result of the factors described above. Steelmakers, chemical businesses, aircraft manufacturers, shipowners, energy users, numerous jurisdictions, and governments intending to utilize renewable resources are among them. (“Irena: Green Hydrogen: A Guide to Policy Making” n.d.)

The drivers discussed have caught the eyes of the stakeholders to invest in the field of renewable storage energy and specifically in “Green Hydrogen.” The industrial players have heavily invested in producing hydrogen to reduce their emissions and play an active role in the reduction target. However, the buildings, commercial spaces, and households are the second-largest energy users in the Netherlands (Detz, R. J., Lenzmann, F. O., Sijm, J. P. M., & Weeda, M. n.d.). Therefore, we need to focus on power to hydrogen usage in a community-based scenario to reach the targets.

Current research includes models to integrate hydrogen storage with variable renewable energy in the buildings. However, while doing the literature survey, it was observed that there were few intricacies and gaps. For example, the model developed uses power to hydrogen storage with renewable energy but still uses fossil fuel-based heat and power plants if hydrogen storage cannot meet the electricity demand (Pietro Elia Campana Eva Thorin 2020; Dawood, Shafiullah, and Anda 2020; Wang et al. 2019a). Also, the literature talks about the use of power to hydrogen technology in one building or for a small community having a few houses(sub-community). However, to meet the demand for 100 per cent renewable energy, there should be a transition from using fossil fuel to other forms of renewable energy. Furthermore, there is no integration between the buildings or sub-community to meet the demand and supply of energy. The integration requires the use of Industry 4.0 technology to trade energy between the buildings or subcommunity. Therefore, a digitized system should be in place to integrate the buildings/ sub-communities using one hundred per cent of their source as renewable power to balance the demand and supply of heat and electricity.

Renewable hydrogen has the advantage of being stored for long seasonal periods. Therefore if the community produces excess hydrogen and does not require it for their consumption, hydrogen can be traded to fulfil the demand of the other community. Therefore, there is an opportunity to use a centralized or decentralized system to collect real-time excess renewable energy from the crowdsourcing within the precinct or surrounding areas to identify cheap renewable energy in real-time and supply it to needed communities. The development of the Internet of Things and Power to power technology can support the implementation of energy trading in smart microgrids (Sikorski, Haughton, and Kraft 2017). Therefore more research is needed to understand which technology in Industry 4.0 will be best suited to help the demand and supply of hydrogen. Each technology’s pros and cons will be measured and weighed against alternative means, and then a conclusion will be made to select the most feasible solution.

## 1.3 Research questions

For achieving the primary goal of the research, the following research questions need to be answered:

Main Research question:

***What could be the technical model to implement Power to Hydrogen technology in the subcommunities that could be used by the government or private parties?***

To answer the main question, the following sub-questions will be answered.

Sub research question:

a) What are different "Power to X" technologies?

- What is Power to Hydrogen technology?
- What processes are involved in Power to Hydrogen technology?
- What is the current status and barriers associated with different Power to Hydrogen processes?

b) Does the Dutch government have a strategic roadmap for Hydrogen deployment?

- What technical barriers exist that hinders the deployment of hydrogen technology?
- Are there any policies in place to foster the deployment of Hydrogen?

c) What technological model will be feasible to implement Power to Hydrogen in the community?

- What is the prevalent Industry 4.0 technology in the market?
- What are the current use cases of implementing Industry 4.0 technologies in the renewable energy scenario?
- From the models studied, what Industry 4.0 technology would be feasible to implement the Power to hydrogen technology in a community-based scenario?

## 1.4 Research Methodology

The first step to answer the research question involves an exploartory research approach. The implementation of power to hydrogen technology has various uncertainties associated with it. Therefore, the exploratory research will help to understand the basics of the technology and investigate the technical issues that are not properly defined in the literature. The literature has been organized into three steps to generate the framework and its application in the case study.

Step 1: Literature study

Exploratory research was carried out in this article using the observation method as the primary research, and descriptive method as the secondary research called the desk research. The observation method helped to analyze the behaviour of enterprises, and the desk research made it possible to perform a descriptive analysis of the enterprises and energy sector. The analysis of the text was based on reports from various companies and annual reports of energy companies. Additionally, material published in the articles in the specialist journalist on the websites were analyzed. Critical content analysis was performed as part of the source study, and the existing data were analyzed. Also, an analysis of data contained in official reports of EU institutions was carried out.

The literature survey was started by reading a yearly report published by “The International Renewable Energy Agency” (IRENA); titled “Renewable Power -to-Hydrogen - Innovation Landscape Brief” where I understood the basics of Power to Hydrogen technology, the current processes involved in the technologies, the barriers for its implementation and, the countries starting their pilot projects in Power to Hydrogen. Then, a scoping review was conducted and relevant findings were identified using: ‘structure search’, and ’snowball technique search’. First keywords like ‘Power to Hydrogen’ OR ‘Power to X’ were used in the search. Additionally, the search was further refined in two parts: a) from the year 2010 to 2015 and b) 2015 onwards. Part a) was done to understand if earlier the research gaps have been addressed. Part b) was done because the topic focuses on the deployment of the next decade.

In the next step the documents were screened based on their titles, abstract, introduction and conclusion. Also, at the same time a snowballing search was conducted for each paper (checking forward and backward citation tracking of the identified articles). The search criteria included keywords like “Power-to-Hydrogen” OR “Power-to-X”, and the time range was set between 2015 and 2021. The search resulted in 311 articles that had these words in their title, abstract or as keywords. To further narrow down the investigation, a subject area filter was put on, i.e. only “Energy” and “Business, Management and Accounting” and “Engineering” were chosen. Additionally, secondary research was used to analyze the external literature on digitization and innovation in the industry to answer the 3rd sub question.

Step 2: Surveys to collect data to help selecting the alternatives being evaluated and data analysis

Implementation of Power to Hydrogen in a community-based scenario being at a nascent stage has various options, elements, components, and decisions to choose from while making the selection. Therefore, in the case study, MCDM analysis is used wherever needed. Considering multiple criteria, there are various ways through which the selection criteria parameter is weighted. If enough data is available in the literature or research is already done on a particular subject, the weighting of criteria can be done by referring to data from the literature. Otherwise, the criteria are weighted using literature and preparing questionnaires by taking the surveys of the experts in that field to weigh the selection criteria.

The survey method was used because the literature research is not enough to come to a conclusion that which criteria parameters must be weighted more than others to make a decision. It is a structured survey method to compose and analyze complex decision makings based on mathematics and psychology.

The stakeholder’s opinion to weigh the selection parameters in order to select from the alternatives was done by pairwise comparison scale to express the importance of one parameter over the other.

| Explanation | Numeric Values |
|---|---|
| If Option A and Option B are equally important : Mark/Insert → | 1 |
| If Option A is moderately more important than Option B : Mark/Insert → | 3 |
| If Option A is strongly more important than Option B : Mark/Insert → | 5 |
| If Option A is very strongly more important than Option B : Mark/Insert → | 7 |
| If Option A is extremely more important than Option B : Mark/Insert → | 9 |
| Use even numbers for intermediate judgements | 2, 4, 6, 8 |

Figure: Saaty Comparison scale

For example, Given Options A & B, their relative importance can be judged as shown below:

a) If the option ‘Build Protective Structures’ in column A is strongly more important than the option ‘Improve Building Design’ in column B, then mark 5 on the left hand side.
b) If the option ‘Retreat' in column B is extremely more important than the option ‘Improve Building Design’ in column A, then mark 9 on the right hand side.

| A Options | Extremely | | Very Strongly | | Strongly | | Moderately | | Equally | | Moderately | | Strongly | | Very Strongly | | Extremely | B Options |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Build Protective Structures | 9 | 8 | 7 | 6 | X | 4 | 3 | 2 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | Improve Building Design |
| Improve Building Design | 9 | 8 | 7 | 6 | 5 | 4 | 3 | 2 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | X | Retreat |

In a multi-criteria decision-making process in Chapter 3, criterion parameters will be weighted according to the survey results that involve institutes like municipality, academia and industry that were identified as key participants of this study. Then the data collected from the survey was used to make decisions to foster the implementation of power to hydrogen technology

Step 3: Research outcomes

The last step involves the conclusion and recommendations to implement the technology.

Next, I present a brief overview of the approach and methods used to respond to each sub-question.

Table 1. Approach and method to answer the research questions

| **Question** | **Method** | **Research tasks** |
|---|---|---|
| What are different "Power to X" technologies?<br>● What is Power to Hydrogen technology ?<br>● What processes are involved in Power to Hydrogen technology?<br>● What is the current status and barriers associated with different Power to Hydrogen processes? | Desk Research<br><br>The question will be answered by reviewing papers, reports and literature. Each topic will be discussed in detail. | The power to hydrogen process will be studied in detail.<br><br>The basics of the technology will be understood, which will be the foundation to answering the following research questions.<br><br>The technology maturation of each process will help to understand what improvements are needed to use it commercially or is it ready to use it commercially. |
| Does the Dutch government have a strategic roadmap for the Hydrogen deployment?<br>● What technical barriers exist that hinders the deployment of hydrogen technology?<br>● Are there any policies in place to foster the deployment of Hydrogen? | Desk Research<br><br>The question will be answered by reviewing papers, reports and literature. Each topic will be discussed in detail.<br><br>Survey<br><br>It involves a complex decision-making process that requires analysis to elicit stakeholders' opinions on how the most difficult phase of hydrogen redistribution can be solved. | The research question will answer the current technology used in power to hydrogen and the barriers that hinder the use of improved technology answered in the first research question.<br><br>Current policies the government put in place will be studied.<br><br>What policies could be in place to bridge the gap between the use of current technology in government programs and the improved technology(answered in the first question) to foster the deployment of hydrogen used, if any. |

| | | |
|---|---|---|
| What technological model will be feasible to implement Power to Hydrogen in the community?<br>● What are the prevalent Industry 4.0 technology in the market?<br>● What are the current use cases of implementing Industry 4.0 technologies in the renewable energy scenario?<br>● From the models studied, what Industry 4.0 technology would be feasible to implement the Power to hydrogen technology in a community based scenario? | Desk Research<br><br>The question will be answered by reviewing papers, reports and literature. | Current technical models that exist in literature will be studied and pros and cons of each model will be analysed.<br><br>The analysis will help to know which technology is feasible presently. |

## 1.5 Scope

The scope of this study is defined by the categories in which it is conducted.

a) Model Development: The literature includes various technological models and frameworks in Power to Hydrogen technology. Also, the literature consists of the study of Industry 4.0 technologies and the methods/approaches for the application and feasibility to use in Power to Hydrogen technology.

b) Country: The study emphasizes its application to the Netherlands as the governmental and technical policies regarding the Netherlands were studied .

c) Process: The process of producing hydrogen can come from different roots and through various methods. The process under consideration will be arrived at using literature survey by using article acquisition tools which will involve terms like “Power to Fuel”, “Power to Gas”, where “Fuel” and “Gas” for this study is H2 specifically.

# Chapter 2: Framework development and implementation

## 2.1 Framework development to implement a nascent technology

Traditionally, it was believed that new inventions and their implementation cannot be planned but requires flexibility and free-thinking as the technology is uncertain due to limited, random data and knowledge. But as this approach was used, a lot of perspiration was required to balance the new technology and its implementation. Therefore, any innovative technology management requires a combination of structure and flexibility to deploy all the elements for the implementation of the technology successfully. Hence, any new technology goes through a cycle known as the innovation life cycle, and the figure below depicts the components present in the cycle. (Du Preez and Louw 2008)

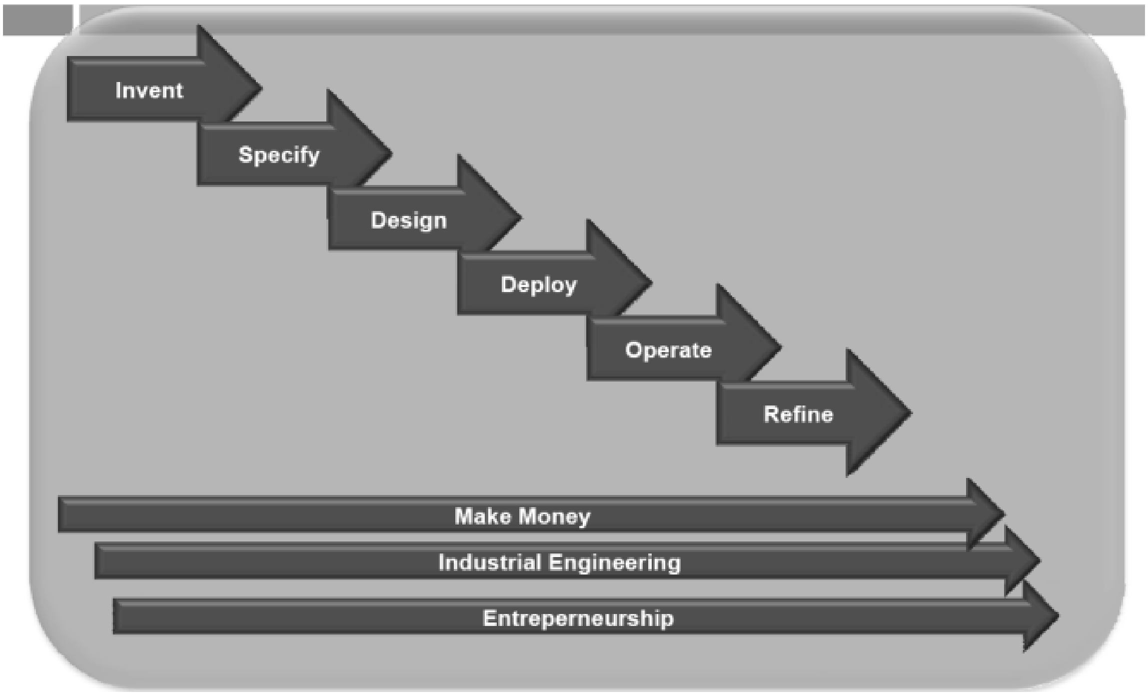


Figure 1: Innovation life cycle process(Du Preez and Louw 2008)

The figure shows all the steps that innovation goes through in its life cycle. Comparing power to hydrogen technology and the innovation life cycle, the technology is not mature enough to implement in the community-based scenario. Though the power to hydrogen technology is already implemented in industries and the technology is currently in use, the technology has passed the invention and specifying phase. Also, the thesis focuses on developing a technological framework for implementing power to hydrogen in the community; therefore how the technology will be designed and deployed will be the focus of the study. Operation and refinement are out of the scope of the thesis study because the implementation is proposed and not operated.

### 2.1.1 The system design/definition phase of the technology

Designing a system is an innovative process, and methods are required to support the exploration and identification of alternative designs to meet the requirements revealed by the literature survey, opportunity space and use of context. In a typical design of a system, there are three stages: the early stage, design mature stage and design completion stage. In the early stage, the design estimates will be primarily qualitative and where the design aspects are task completion. As the technology matures, the design estimates become more quantitative, and the estimates' confidence will improve. Finally, when the design has reached the completion stage, modelling studies or human in the loop evaluations can estimate the workload of critical phases or elements of the system. (“Read ‘Human-System Integration in the System Development Process: A New Look’ at NAP.edu” n.d.)

Therefore the system design is the process of defining the components, interfaces, data and modules for a system to satisfy specified requirements. In this process, systems are created or altered along with models, methodologies, practices and processes used to develop them. The activities in the system design/definition phase consist of system-level technical requirements and top-level system designs.(“System Design and Development” 2013a)

System-level technical requirements are the foundation of system design to develop and implement the technology. In contrast, a top-level system comes under the government and represents how the technology can be implemented with acceptable risk. The main reason to develop a top-level system is to provide the technical foundation to plan and implement the new technology. Designing the top-level system design can help meet people’s needs and also get to know what barriers and enablers are present which can hinder the implementation. (“System Design and Development” 2013b)

Therefore, the system design phase describes the user needs and provides data to meet legal restrictions, adhere to rules and regulations and integrate the systems effectively to implement the technology. The technology might be nascent, and there may be no single sustainable solution to implementing the technology. There might be various variables to consider, like the performance of various technologies in implementing the technology, social and environmental impacts and economic factors that need to be balanced and assessed. Therefore, in the early stage, the technology can have several alternatives to foster the implementation of the technology. The decisions made while defining the system can affect the number of potential solutions, the technical maturity of the potential solutions, system evolution, phasing, evolution and cost. This makes the system design phase sometimes a multi-criteria decision making problem where there could be more than one possible solution. (Ren and Toniolo 2018)

### 2.1.2 The system deployment and implementation phase of the technology

The core activities to design and deploy the technology includes developing system-level technical requirements and top-level system designs to assess and evaluate the design's ability to implement the technology. The importance of system-level technical requirements and top-level system designs is discussed in the system design/definition phase. Ideally, the system technical requirements and top-level system designs are developed to draft and develop experiment or prototype systems to clarify, confirm and discover user requirements. The prototyping systems are instrumental in validating the critical technologies needed to meet the technology implementation are sufficiently mature and meet the existing requirement. Once the prototype is established, the system requirements exist and continuously evolve in the implementation life cycle. (Blanchard and Fabrycky 2010)

After prototyping, the system is frequently updated as new needs are understood or the environment in the system works changes. Therefore, to make changes, there should be a foundation to change processes within the project. This is known as traceability. Traceability will help trace back the system components and requirements and make the changes effective that will be difficult to evaluate if the system is not structured and organised. Traceability provides two-directional flow requirements to manage the project carefully, accompanied by a well-organised foundation. ("System Design and Development" 2013b)

To summarise, for the implementation of new technology, there are two phases:

a) System design/definition phase
b) System deployment/ implementation phase

System design phase activities include developing system-level technical requirements and top-level system designs. This phase helps to define the components, data system, interfaces and modules to satisfy particular requirements. The system deployment phase uses the technology definition, processes, models, and methodologies defined in the system design phase to create or alter the system processes.

## 2.2 Use of framework to implement Power to hydrogen technology in community-based scenario

To implement new technology like power to hydrogen in the community-based scenario, there are two steps.

1) Step 1: System design/definition phase of the technology
2) Step 2: System deployment/implementation phase of the technology

The first step refers to the system design/definition phase and consists of two activities which are system-level technical requirement and top-level system as discussed above. These two activities can be defined by two stages:

a) Stage 1: System-level technical requirement stage
b) Stage 2: Top-level system stage

The second step refers to the system deployment/implementation phase which has one activity to implement the technology and in our case, it is to implement the power to hydrogen technology in a community-based scenario. Therefore, it is the last activity in the framework which can be defined by the stage:

c) Stage 3: Assessment and Evaluation phase

Stage 1 involves the activities of system-level technical requirements, which is the foundation of system design. The basics of the technology and the definition of components, data systems, interfaces and modules are discussed. As discussed earlier in the system design phase that there are 3 stages of a system: the early stage, design mature stage and design completion stage. The implementation of the power to hydrogen system is in the early stage. Therefore the design estimates are mainly qualitative, and the main task of the thesis is to complete the implementation. As the technology becomes mature, the estimates will become more quantitative, and estimates in the design will improve. Stage 2 involves the activities of the top-level system, which provides the technical foundation to implement the new technology. Stage 2 helps to understand the technical barriers which hinder the implementation of power to hydrogen technology and provide potential solutions to overcome the problem. This involves choosing between a set of possible solutions for a problem and is therefore known as the alternative prioritization phase. Also, the government policies are discussed to understand whether it aligns with solutions provided and create a robust foundation to deploy the technology in terms of performance, cost, schedule and risk.

The next step is the system deployment/implementation phase, where the input from the first step (system design/definition phase) are used as foundations to develop the system and implement the technology in the community. This is known as Assessment and Evaluation phase, where prototyping or experimenting systems are developed to implement the technology and confirm whether key technologies used are mature enough to meet the existing requirement. Defining the implementation in stages makes it easy for the system to trace(Traceability) back the problem. Changes can be made in the processes or components of the technology which would have been challenging to evaluate if the system was not structured and organised.

### 2.2.1 Assessment and Selection Criteria

The framework depicted in three stages should be conducted on a case by case study studying a particular region as the data and knowledge is uncertain. The framework can be used for a particular region to understand the complexities and variables that define the system of the region.

Step 1: System design/definition phase

Stage 1: System-level requirement

The system definition phase defines the power to hydrogen technology and the current technologies used to produce hydrogen. The activities involve establishing a list of alternative power to hydrogen generation systems through electrolyzers(Alkaline, Polymer Electrolyte Membrane(PEM), Anion exchange membrane(AEM), Solid oxide) and creating an assessment criteria system for the selection. Then the performances will be compared among the alternatives. The selection criteria for selecting the electrolyzers are efficiency, durability, cost of the electrolyzer and maturity of the technology.

Stage 2: Top-level system

In multi-criteria decision making, there could be a possibility that there could be more than one solution that can be employed among different alternatives. It is not possible that the best solution has absolute performance, but it should move towards the ideal situation. But, the current studies having uncertain data of alternative solutions, the evaluation and assessment of the performance of alternatives become important for selecting hydrogen production technology with better sustainability. Therefore, there will be difficulty in differentiating the alternatives that are similar in real-life applications. Therefore, there could be more than one solution, which is the case in selecting the membrane. The activities involved are to understand the technological barriers in power to hydrogen technology and determine the best to worst methods to overcome the technological barriers and provide recommendations among the alternatives. The selection criteria involve research and development to use the current technology, its application in the industry and the alignment with the governmental policy to use the technology.

Step 2: System deployment/ implementation phase

Stage 3: Assessment and Evaluation Phase

The first two stages help to create the foundation for developing a technological framework to implement power to hydrogen in the community. The first activity in stage 3 involves determining the loopholes in the current research and defining the expected future of the sub-community using power to hydrogen technology considering various parameters. Then to digitize the technology, various Industry 4.0 technologies are assessed and the technology is selected. The assessed technology is then evaluated in performance and validated. The selection criteria considered for stage 3 are current research in the field of power to hydrogen technology, maturity of current Industry 4.0 technology and the challenges in implementing the technology.

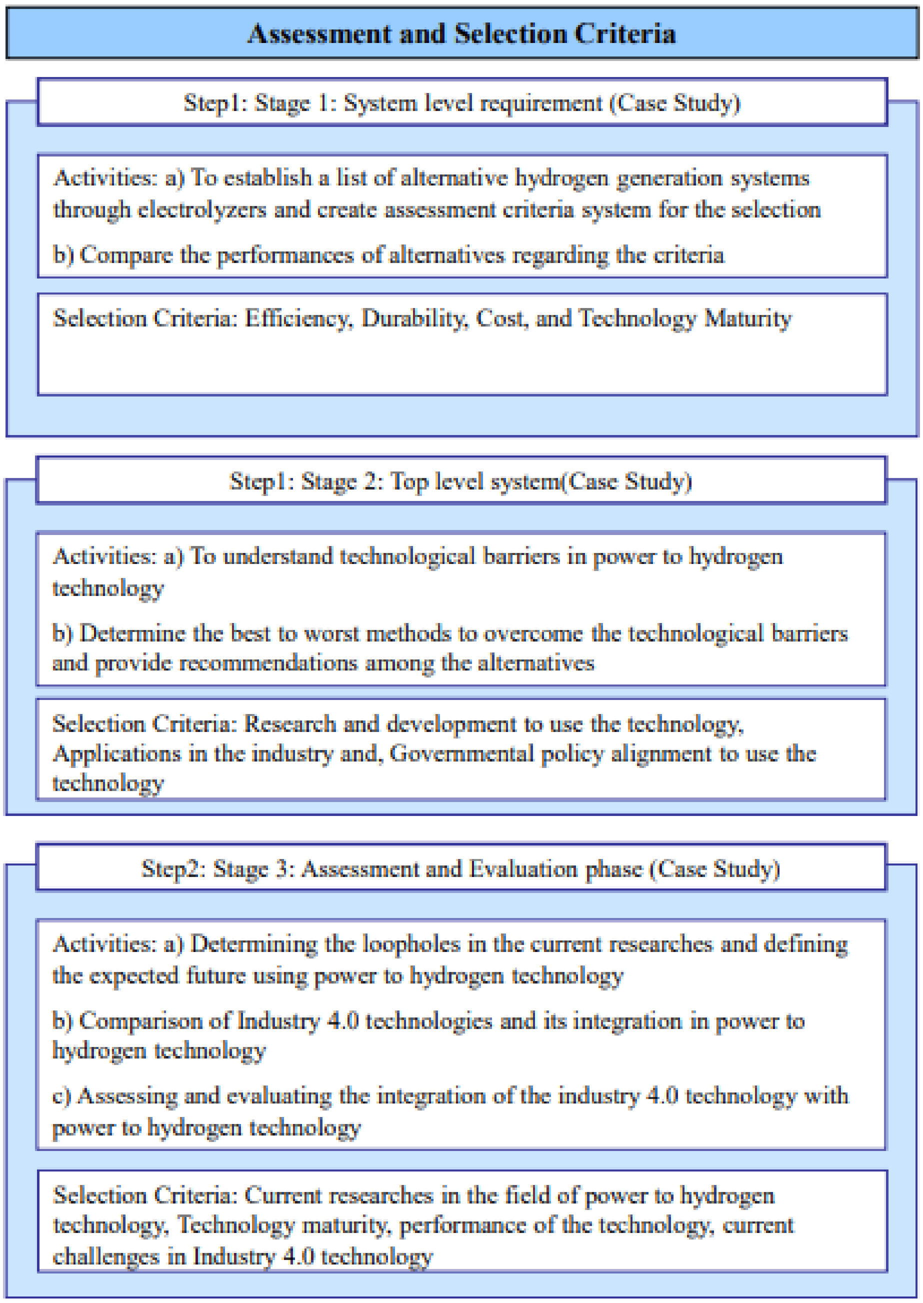


Figure 2: Assessment and Selection Criteria

### 2.2.2 Multi-criteria decision making(MCDM) analysis in selecting between the alternatives being evaluated

Multi-criteria decision making is a method that needs to be considered to rank or choose between alternatives that need to be evaluated. Implementation of Power to Hydrogen in a community-based scenario being at a nascent stage has various options, elements, components, and decisions to choose from while making the selection. Therefore, in the case study, MCDM analysis is used wherever needed.

MCDM involves four key components,

a) Ranking or choosing between the alternatives
b) Selection criteria through which alternatives need to be evaluated or compared
c) The weights represent the relative importance of criteria
d) Decision-makers whose preferences needs to be represented

Considering multiple criteria, there are various ways through which the selection criteria parameter is weighted. If enough data is available in the literature or research is already done on a particular subject, the weighting of criteria can be done by referring to data from the literature. Otherwise, the criteria are weighted using literature and preparing questionnaires by taking the surveys of the experts in that field to weigh the selection criteria.

There are various methods used in MCDM and one of them is the weighted sum model which is used to score the alternatives according to its rating on each criterion. It is a common-sense approach where each alternative's performance is evaluated in terms of their rating across the criteria. It involves:

a) Weighting the criteria to reflect the relative importance (where weights sum to 1)
b) Scoring each alternative according to its rating on each criterion

Each alternative's overall performance across the criteria is aggregated via a linear equation to produce a total score and alternatives are ranked by their total scores.
Stage 1 and Stage 3 uses a weighted sum model approach because it requires evaluating a number of alternatives in terms of a number of decision criteria and has good literature data to weigh its criteria parameters.

Other methods include the Analytical hierarchical process(AHP) which is used in Stage 2. This method is used in stage 2 because the literature research is not enough to come to a conclusion that which criteria parameters must be weighted more than others to make a decision. It is a structured survey method to compose and analyze complex decision makings based on mathematics and psychology. In this method, a goal is set at the top of an upside-down hierarchy with criteria derived to reach goal structure at the second level, sub-criteria (if any) at the third level and alternatives at the lowest level. Pairwise comparison is carried out starting from the lowest level in which each criterion contribution to achieving the level above is assessed. There is a 9 level numerical scale that is commonly used to evaluate the intensity of the importance of the criteria with 1 indicating equal importance, 5 indicating strong importance and 9 indicating an extremely important relation. The process is evaluated using pairwise comparison between selection parameters in which the criteria and alternatives are quantified with respect to the goal.

### 2.2.3 Research Methodology to implement Power to Hydrogen technology in a community-based scenario

The research methodology is developed using the three stages shown in Figure 3. The methodology uses a multicriteria decision-making process in each stage to choose or rank the alternatives in the system or processes. There are various multicriteria decision-making methods, and many times, different methods are used in the same kind of problem. For example, the same problem uses Analytical Hierarchical Process(AHP) and TOPSIS to choose or rank the alternatives. Also, sometimes combinations of both are used for selection problems. So, the question arises which decision-making method to use while choosing or ranking from the alternatives?

The AHP takes two alternatives at a time and compares their criteria, which is known as a comparison matrix. By doing so, the AHP finds out the best among the alternatives. Every criterion needs some weightage to choose the best alternative. Hence, a matrix is created, which is a long process. For example, if there are 60 alternatives to choose from, the number of comparison matrices would become (60C2 + 1), making the calculation lengthy. In the case of TOPSIS, all the alternatives will be taken at a time as alternatives, and the alternatives will be given a score on the basis of selection criteria which is known as decision matrix. Using the TOPSIS method's decision matrix, we can find the best alternative. The calculation becomes less as we find the best alternative from the decision matrix. (Syed Abou Iltaf Hussain 2016; Syed Abou Iltaf Hussain, Uttam Kumar Mandal, Shubhajit Kulavi 2017; Hussain, Mondal, and Mandal 2018)

The problem encountered using TOPSIS, or other MCDM methods is computing the weightage of selection criteria, which requires various ways like AHP, fuzzy performance programming, cross-entropy etc. As discussed above, the weightage of criteria can be computed by forming a comparison matrix for the selection criteria and following the steps of AHP. We can use different MCDM to solve the same problem, but using decision-making methods other than AHP requires computation that depends on AHP. Some other methods can be used, but weight computation requires AHP, making it irrelevant to use another method again for the same step. (Wan and Dong 2021; Hussain, Mandal, and Mondal 2018)

The experiment conducted to compare different MCDM methods found that other methods like TOPSIS and PROMENTHEE were superior in accuracy to make the right choices if there are many criteria(Widianta et al. 2018). But, when there were fewer selection criteria (less than or equal to 10), AHP showed similar results to other decision-making methods. Therefore, with the implementation of hydrogen technology being in its nascent stage, the selection criteria identified were less than 10, which makes the use of AHP relevant for this case.

The research methodology developed in Figure 3 will be used to implement power to hydrogen technology in community-based scenarios. The three stages are defined earlier to implement the new technology are:

- Stage 1: System-Level requirements
- Stage 2: Top-level requirements
- Stage3: Assessment and Evaluation Phase

The first stage starts with identifying and defining components, interfaces, and systems in the new technology. Then, main systems and critical processes are identified. The main systems and critical processes identified and defined have various alternative components, interfaces and subsystems to choose and make decisions. This requires using a multicriteria decision-making process to select or rank the alternatives in the system. Select weighted sum method or analytical hierarchical process will be used depending on if there is enough literature data available to quantify the selection criteria of the system. In the end, the data will be analyzed and a decision will be made.

Therefore, the first stage starts with identifying and defining the components, interfaces and systems in hydrogen technology using literature study. Then, the process is understood, and the critical process is identified to convert power to hydrogen. The electrolyzer process was identified as a critical step requiring ranking or selecting different types of electrolyzers using a multi-criteria decision-making method. The selection will be based on assessment criteria identified for selecting the electrolyzer which is efficiency, durability, cost and technology maturity. The selection will be made using a weighted sum method as it has enough literature data to weigh the assessment parameters. Finally, the stage ends with a selection of electrolyzers.

The second stage starts with identifying technological barriers that hinder the implementation of the technology. Then, a multicriteria decision process will be used to select or rank the alternatives that foster the implementation of the technology or process. Finally, data will be analyzed to make the decision.

Therefore, the second stage starts with identifying the technological barriers in implementing power to hydrogen technology using literature study. Then the main technological barrier in implementing power to hydrogen technology is identified. It was identified that hydrogen transportation is the main technological barrier, and ranking or selection needs to be made from various methods to transport hydrogen using a multi-criteria decision-making process. A decision needs to be made whether to construct a new hydrogen infrastructure or use the existing natural gas pipeline and not invest in hydrogen-pipeline infrastructure or use the existing natural gas pipeline before the hydrogen-pipeline infrastructure is developed. This required an analytical hierarchical process for the selection because the literature survey was not possible to weigh the selection criteria parameter. Therefore, data were collected using the survey and then it was analyzed to rank the choices to transport the hydrogen.

In the third stage, using the selection made in stage 1 and stage 2, the new technology will be implemented. While implementing the new technology, new technologies or components need to be integrated, which requires selecting or ranking the technologies using multicriteria decision making. After the selection and implementation, the technology will be assessed and evaluated to understand the feasibility of using the technology.

Therefore, the third stage starts with proposing how the expected future will look like using power to hydrogen technology using the selection made in stage 1 and stage 2. Also, the literature study found that hydrogen technology requires the integration of various technologies, including the implementation of digitization technology and the implementation of smart grid technology and its architecture. Currently, two digitization technologies: Blockchain or Digital Twin, are prominent for energy trading and require selection between the two. Therefore, using a weighted sum method, blockchain technology was selected for energy trading. Then, energy system using blockchain and smart grid technology was evaluated and assessed. Finally, key challenges to using the technology and its future outlook were discussed.

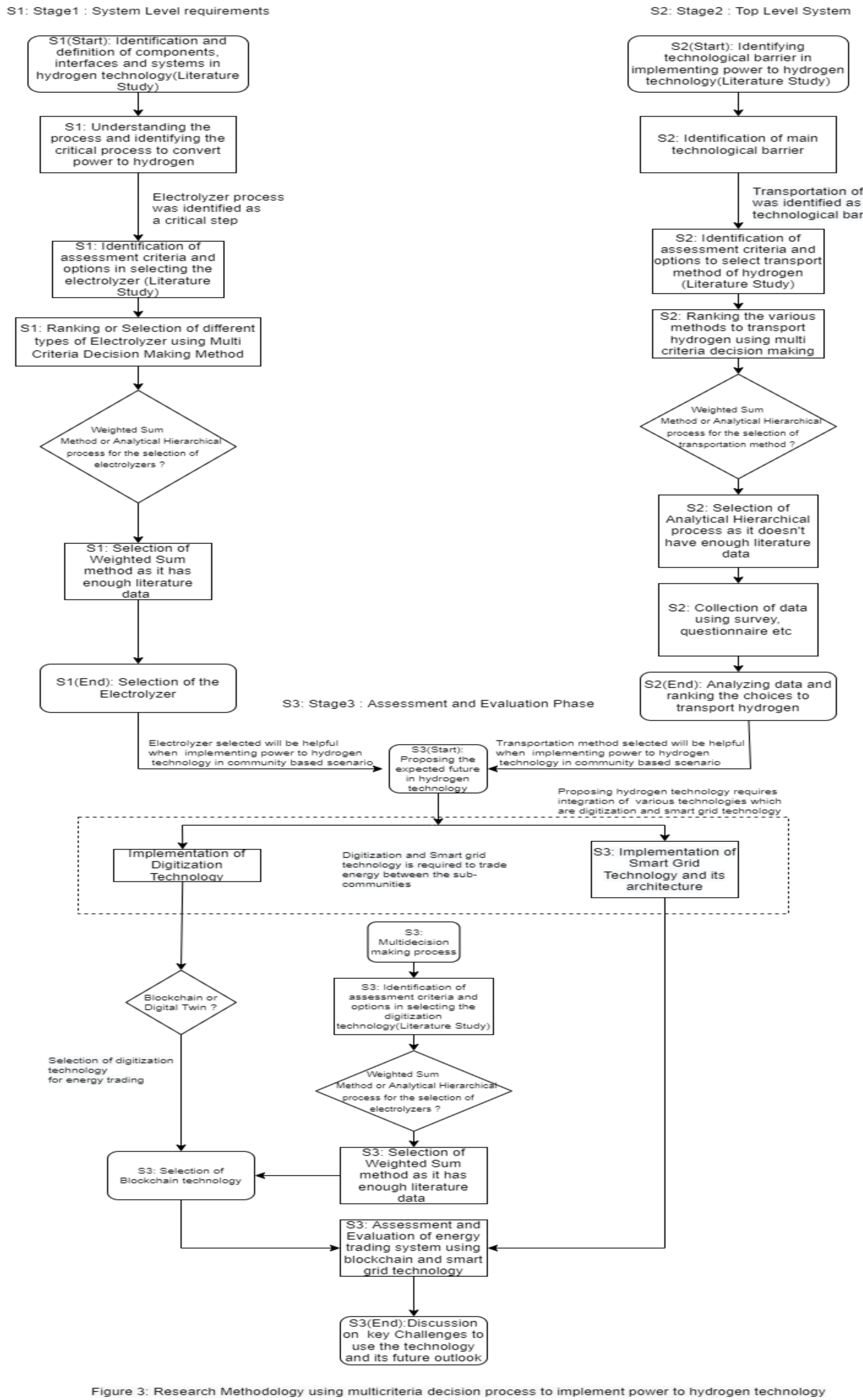


Figure 3: Research Methodology using multicriteria decision process to implement power to hydrogen technology

# Chapter 3: Use of the Framework to implement Power to Hydrogen technology in community-based scenario

## 3.1 Stage 1: System-Level requirements

### 3.1.1 Sustainable Energy Systems: The Present and The Future

Over the years, to heat the buildings, we have moved from wood to coal, then to oil, and now we frequently use gas. However, these materials are still burned in boilers to produce heat. In addition, to process the heat, companies need significant amounts of steam created in broilers. Coal, oil, and gas are also used as feedstocks to create metals such as iron and steel, as well as polymers, nylon, and artificial fertilisers. (van der Roest Jos Boere 2017b)

Old-fashioned steam engines with generators are still used to generate electricity. In addition, the gas turbine is utilised in conjunction with the steam turbine to produce efficient electricity for industrial steam production. Over the last century, the energy system has remained mostly unchanged. Based on fossil fuels such as gas, oil and coal, the system is powered by energy conversion technologies such as gas turbines, IC engines, steam turbines, boilers and generators. However, these energies are not renewable, and the energy system in the future has to be more sustainable as these resources deplete (van der Roest Jos Boere 2017b). Therefore, there is a transition to renewable energy, and in the future, the energy consumption will become all-electric. Buildings and households will be far more energy-efficient, with renewable heat sources, heat pumps, and efficient storage used for heating and cooling. Heating and cooling of houses, transportation, feedstock, and steam in the industrial, as well as power and light, will all be electric.

Renewable technology is advancing to make buildings self-sufficient in energy using renewable power. Energy must come from sustainable energy sources to make society sustainable, which is not an issue because solar radiation and wind are abundant. Sustainable energy is converted to electricity using essential energy conversion technologies, which has been done for a long time using hydro and geothermal power. However, now, it is increasingly done through wind and solar. Generally, hydroelectricity remains the cheapest form of electricity production. As technology progresses, it is believed that combining sun and wind in regions where both are abundant would be the most cost-effective way to generate electricity. Places like India, Mexico, Brazil, China, parts of Africa, Morocco, and the United States will produce electricity for 2 to 3 US cents per kWh. As the technology will mature, it will result in lower prices, making the energy more abundant. (“Lazard’s Levelised Cost of Energy Analysis (version 10.0)” n.d.)

### 3.1.2 Hydrogen as a renewable energy

Providing communities and buildings with clean and affordable energy and water comes with enormous challenges. The methods for producing clean energy are becoming more and more inexpensive, but environmental challenges have to be met. The production of energy from the sun, wind and water varies depending on the location and the time. For example, solar irradiation varies over the day, making varied solar power depending upon the time. In the same way, wind energy produced varies depending on the area's wind speed on a particular day. At times, the variability of renewable energy cannot be fed into the power grid due to network constraints or low demand leading to curtailment of the energy or selling the energy at zero marginal price (International Renewable Energy Agency IRENA 2019). The curtailment of energy and its intermittency is the most significant barrier in delaying the transition towards a hundred per cent of renewable power into the power systems. To overcome the variability of renewable sources, there should be a system to store, transport the energy over distance and time. Therefore, to overcome the variability of renewable energy, conventional storage systems like batteries, mechanical and hydro pumps are used to balance electricity demand and increase system flexibility. Using conventional storage systems has its own merits but is not environmentally friendly, has small-scale storage capacity, and has a shorter duration (Dawood, Shafiullah, and Anda 2019).

One of the methods involves utilising power to pump water into the reservoir. The water is then made to run down the turbine, which generates energy, whenever electricity is required. Therefore, transferring electricity to gravitational or potential energy and then back to electricity. However, this conversion storage technique does not allow transporting energy from one continent to another. Therefore, one of the ways to convert and transport electricity over long distances is to convert it into fuel and that fuel is hydrogen.(van der Roest Jos Boere 2017a)

### 3.1.3 Power to Hydrogen

Hydrogen is produced from the excess power from renewable energy that can be produced by electrolysis. Electrolysis is a process that uses electricity to split water into hydrogen and oxygen. Hydrogen is stored as a fuel and will be used when there is a need for electricity via a fuel cell, which cannot be fulfilled by renewable energy("RENEWABLE POWER-TO-HYDROGEN" 2019). This increases the power system flexibility and helps to decarbonise the overall economy. Therefore the power to hydrogen is a possible way to consume excessive electric power and meet the potential hydrogen demand. Furthermore, power to hydrogen can consume excessive power production from renewable energy and produce hydrogen at low cost and by a clean process using clean energy(Wang et al. 2019b).

Converting variable renewable energy sources to hydrogen via electrolysis provides benefits to power sector transformation in several ways :

- It helps in reducing variable renewable energy curtailment.
- It provides long term energy storage.
- It provides grid-balancing services via the electrolyser.
- The clean hydrogen as a fuel can be used in other sectors
- The renewable power can be transported as hydrogen over long distances.

The main components used in converting power to hydrogen and hydrogen back to power are:

a) Electrolyser
b) Storage tank for hydrogen
c) Fuel cell

The production of hydrogen and the use of hydrogen to generate electricity are two separate processes. Hydrogen is created by electrolyzing water, and subsequently fuel cells are used to generate electricity from the chemical energy stored in hydrogen(Luo et al. 2015). The type of electrolyte material used in electrolysers and fuel cells is classified as Alkaline, Polymer Electrolyte Membrane(PEM), Anion Exchange Membrane(AEM), and solid oxide.

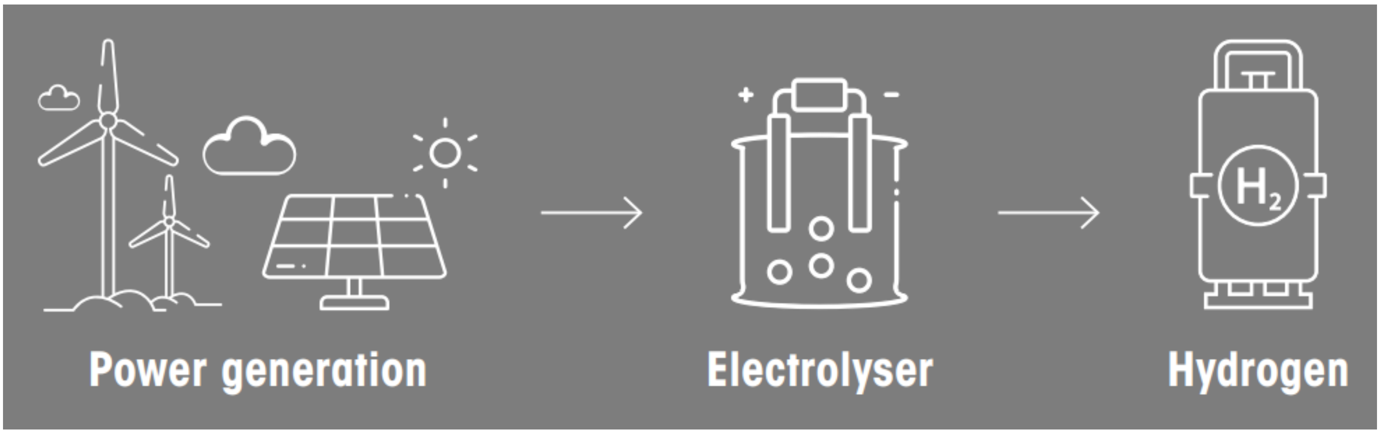


Figure 4. Power to hydrogen(International Renewable Energy Agency IRENA 2019)

A detailed description of the parts used in Power to Hydrogen will be done in the next section.

### 3.1.4 The Process

The process involved in Power to Hydrogen technology is simple, and the technology to implement is available today. The technology consists of three stages: production of hydrogen, storage of hydrogen and generation of power using hydrogen.

When surplus or peak power is available from the building/subcommunity, it is used to make hydrogen. Hydrogen is produced using the electrolysis method, where the power supply splits the water into hydrogen and oxygen. The splitting is done by the electrochemical device known as water electrolysers by the passage of an electric current. The system is fed with purified water using a pump. At the electrodes, water is split into oxygen and hydrogen, with ions such as OH- or H+ crossing a liquid or solid membrane electrolyte. The membrane is in charge of keeping oxygen and hydrogen gases apart and preventing them from mixing. Although the basic idea has remained the same, there have been technological advancements based on electrochemical, physical, and chemical factors. Electrolysers are currently split into four primary technologies based on the temperature of operation and the electrolyte used, leading in the use of various materials and components. These four types are:

a) Alkaline
b) Polymer Electrolyte Membrane(PEM)
c) Anion exchange membrane(AEM)
d) Solid oxide

There isn't a single electrolyzer device that outperforms the other electrolyzer. Therefore, electrolyzers must be designed with trade-offs in mind, as each technology has its own set of issues, ranging from crucial materials to durability, maturity, and performance.

Table 2. Characterisation of 4 types of electrolysers(Syed Abou Iltaf Hussain, Uttam Kumar Mandal, Shubhajit Kulavi 2017; International Renewable Energy Agency IRENA 2019)

| | Alkaline | PEM | AEM | Solid Oxide |
|---|---|---|---|---|
| Operating Temperature | Seventy to ninety degreeC | Fifty to eighty degreeC | Forty to sixty degreeC | Seven hundred to eight hundred fifty degreeC |
| Working | The electrolyser is simple in design and has a simple stack design. Therefore, the manufacturing of alkaline electrolyser is relatively simple.<br><br>Alkaline electrolysers use harsh environments which use high concentration KOH as electrolytes. | They use an advanced architecture that allows them to achieve higher efficiency than alkaline.<br><br>It uses perfluorosulfonic acid (PFSA membrane), which is mechanically and chemically robust. | This is a newer technology with limited deployment. It combines the benefits of a simple and efficient PEM design and an alkaline electrolyser, which creates a less toxic environment. | These work at a high temperature, which enables favourable kinetics that allows for lower electricity demand, cheaper nickel electrodes, and part of the separation energy is provided using heat. |
| Technology maturity | Commercial - They are reliable, sturdy and reach a high lifetime of above 30 years. | They have reached near-term commercialisation, but they are far away from large megawatt stack units as a concept. In addition, the lifetime characteristics of large | Demonstration- It is the latest technology with limited deployment. Technology still needs advancement. | Demonstration- Technology still needs to be matured and is currently deployed at KW - scale. |

| | | | | |
|---|---|---|---|---|
| | | scale megawatt PEM stacks and reliability still need to be verified. | | |
| Advantages | It has cheaper catalysts with respect to platinum metal group based catalysts used in PEM electrolysis.<br><br>It has high durability due to the lower dissolution of anodic catalysts.<br><br>It has high gas purity due to lower gas diffusivity in alkaline electrolytes. | It can operate at high current densities, which result in reduced operational cost.<br><br>The PEM electrolyser has low ohmic losses.<br><br>The PEM has a low gas crossover rate which results in high product gas purity. | AEM electrolysis combines the benefit of PEM and alkaline systems. It uses a non-noble catalyst used in alkaline electrolysis and achieves comparable energy densities and efficiencies to PEM electrolysis. | It works at high temperatures, which enhances kinetics and thermodynamics, lowering energy demand and low capital cost. |
| Disadvantage | Corrosive electrolyte and slow dynamics. | Due to the use of noble metals it has a high cost. | Under ramping or shutdown, thermochemical cycling causes rapid degradation and a shorter lifetime.<br><br>It also has to deal with contaminant sources from piping and sealing, as well as high differential pressure, and electrode contamination | It has mechanically unstable electrodes. Also, it has safety issues due to improper sealing. |

| | | | | |
|---|---|---|---|---|
| | | | from silica used as sealants. | |
| Challenges | To improve durability and reliability. | To reduce noble metal utilisation. | It suffers from a short lifetime, therefore, requires validation for dependability, durability and long term operation. | The mechanism employed in thermal cycling suffers the most damage as a result of the high operating temperature, and the system must be present to cool down in the event of dynamic operation.<br>Also, implementing at a large scale requires large cells, which need to be validated for use. Another contamination and sealing concept needs to be improved. |
| Efficiency | 60 - 70 per cent | 65 - 80 per cent | Upto 100 per cent | Upto 100 per cent |

The production of green hydrogen depends on the performance of the electrolyser, and the performance depends on three factors that are related to each other.

a) Efficiency
b) Durability
c) Cost of Electrolyser

These three dimensions are interdependent and improving one results in a decrease in the performance of the other. Therefore, tradeoffs have to be made according to the needs and select the electrolyser for our application.

For example, if the application requires more durability, then a thicker membrane is used, which is mechanically more robust. However, this, in turn, increases the resistance to transport charges leading to a decrease in inefficiency. Therefore, as the durability of the electrolyser increases, it has a lower cost contribution from the investment component, but lower efficiency cost results in a higher cost of operation. Therefore, to have a positive cost value of the system, a high durable electrolyser cannot be used as it will result in higher operating costs and in the same way, if efficiency is increased, it will lead to a high initial investment. (“IRENA” 2019)

### 3.1.4.1 Selection of the Electrolyser using Weighted Sum Method

The above detailed comparison using the literature research came to the conclusion that the selection parameters to select the electrolyzer includes Efficiency, Durability, Cost and Technology maturity.

Therefore, the criterion weight, the Levels and criterion score are defined for each selection criterion.

Table 3. Weighted sum model for selecting the electrolyzer

| **Criterion** | **Criterion weight** | **Level** | **Criterion Score** |
|---|---|---|---|
| Efficiency | 0.3 | Low | 20 |
| | | Moderate | 60 |
| | | High | 100 |
| | | | |
| Durability | 0.2 | Low | 0 |
| | | Moderate | 50 |
| | | High | 100 |
| | | | |
| Cost | 0.3 | High | 20 |
| | | Medium | 50 |
| | | Low | 100 |
| | | | |
| Technology Maturity | 0.2 | Not Matured | 20 |
| | | Matured | 100 |

In our application, electrolysers will be coupled to PV and wind energy in our application, which generally operates for fewer than 2000 hours per year, making capital cost an important aspect to address.Also, efficiency of electrolyser plays an important role to convert power to hydrogen completely. Durability may be less of a problem with such limited hours. Therefore, Efficiency and cost are given equal criterion weights and more than durability and technology maturity.

The criterion score for efficiency is defined using the actual efficiency of the electrolyzer and others are equally divided according to their respective levels.

Table 4: The rating criteria

| | Efficiency(0.3) | Durability(0.2) | Cost(0.3) | Technology Maturity(0.2) | Total score |
|---|---|---|---|---|---|
| Alkaline | Moderate | Low | Low | Matured | 68 |
| **PEM** | **Moderate** | **High** | **Moderate** | **Matured** | **73** |
| Solid Oxide | High | Low | High | Not matured | 40 |
| AEM | High | Low | High | Not matured | 40 |

The four types of electrolyser available which are compared above, Alkaline is an old technology that has lower efficiency though robust but has its disadvantages. They have slow dynamics and use corrosive electrolysis, which makes it less likely to be used.

PEM is moderately efficient, and the technology has matured to be used commercially. Therefore, they have a low cost of operation and a moderate investment cost as it uses expensive noble metal catalysts. On the other hand, while solid oxide and AEM have an efficiency of up to 100%, they are now only used in the lab and must take a significant step ahead to be used on a broad scale. In addition, the technological curve has not reached the stage where it can be used commercially. Therefore, the cost of investment is high.

Applying ratings on four criteria generates their total scores as shown below for example in case of PEM electrolyzer:

PEM total score: (0.3*60)+ (0.2*100) + (0.3*50) + (0.2*100) = 73

This is the best score out of all the electrolyzers. Therefore, PEM electrolysers will be the best-suited option as it is technologically matured and commercially available with moderate efficiency. In addition, it has a low cost of operation and moderate cost of investment.

Hydrogen is produced in a gaseous state, which is light and has a low energy density per volume. To obtain high energy density per volume, it must be compressed and maintained in a concentrated state. Storage under pressure in composite tanks or steel with pressures of 350-700 bar is the preferred method for power generation applications. Many renewable-energy based hydrogen storage systems will benefit from simple high-temperature hydrogen compression. This is a rather simple technology, and more modern storage systems with substantially higher energy density are projected to become accessible in the future. Underground storage is also an option for storing high-volume storage capacity. Underground storage caverns formed of salt domes have been used to store natural gas for many years, and some companies are also using similar structures to store hydrogen. This, however, is reliant on the availability of adequate underground geological features. This type of storage facility is required to sustain the hydrogen economy.(Breeze 2018)

After the storage, hydrogen can be converted in several ways. It may be consumed in the same way as natural gas, although the combustion temperature is normally higher. Gas turbines, gas-fired boilers, and piston engines can be adapted to use fuel as hydrogen. Adapting combustion engines to generate hydrogen for power is possible today, and it provides a small-scale adoption approach. Hydrogen fuel cells are projected to become the primary source of energy in the future. (Breeze 2018)

Oxygen and hydrogen combine in an electrochemical process to produce electricity in a hydrogen fuel cell. Heat and water vapour are the byproducts, making hydrogen fuel cells promising for reducing carbon emissions. The market for hydrogen fuel reached USD 865.1 million in 2018, and it is predicted to grow at a rapid rate to USD 49.12 billion by 2026. There are already pilot projects in the process, such as Hanwha Energy's hydrogen fuel cell power plant at Daesan Industrial Complex in Korea, which is the world's largest plant in terms of capacity (114 fuel cells) and power output capacity (400,000 MWh per year). To achieve a near-zero waste operation, the power plant employs extremely efficient microfilters installed in the fuel cells. Pollutants such as sulphur oxide, nitrogen oxide, and air dust are prevented from contaminating the electrochemical reaction that generates energy in fuel cells. (FuelCellsWorks 2020)

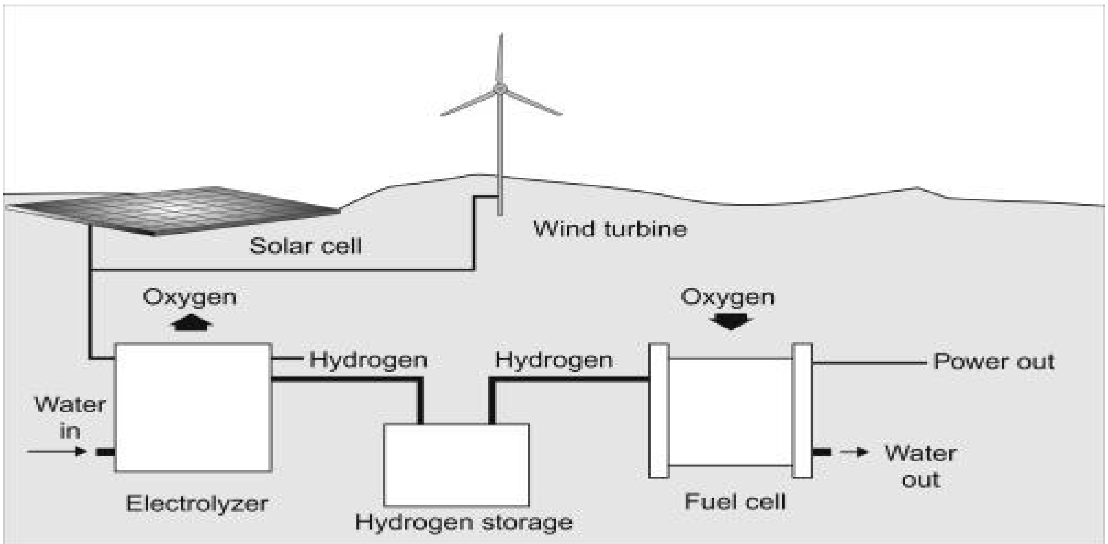


Figure 5. Simple Hydrogen Energy Storage System(Breeze 2018)

### 3.1.5 Power to Hydrogen Demonstration Projects

Germany is leading the way in the area of power to hydrogen technology. With strong dedication and backing from the government and high-tech firms, it generates a major amount of its electricity from solar and wind. The German Energy Agency (Deutsche Energie-Agentur GmbH, DENA) introduced their Power to Hydrogen platform in 2011 and has made substantial progress in stabilising the variable power supply. In Germany, there are now over 30 active power to hydrogen pilot projects with approximately total electrolysis capacity of 25 MW. Installing an electrolyser to produce hydrogen as an alternative has yielded positive outcomes in the projects. According to the German electrical distribution system, hydrogen from power to hydrogen (4-7.5 euro per kg) is cost-competitive to hydrogen supplied to refuelling stations (9.5 euro per kg). ("Power-to-Gas: Electrolyzers as an Alternative to Network Expansion – An Example from a Distribution System Operator" 2018)

Japan is the first country to develop a basic hydrogen policy as well as concrete measures to transition to a hydrogen society. However, the country's land availability and natural resources are limited. As a result, hydrogen import is critical to Japan's plan. According to the action plan, The Japanese Ministry of Economy, Trade, and Industry has set aims for hydrogen production at USD 3.3 per kg by 2030. ("Green Hydrogen Cost Reduction" n.d.)

The Netherlands is in the early phases of establishing a strong position in the hydrogen market. In March 2020, the Ministry of Economic Affairs submitted the government with a hydrogen plan. The strategy document goes into detail about the need of building a hydrogen economy, its role in the energy transition, and the hydrogen market's policy agenda. According to the government, a truly sustainable electricity generation in 2050 will require hydrogen to account for at least 30% and up to 50% of total energy use. The government wants to connect energy-related clusters by 2030 in order to expand electrolytic hydrogen production. Through the Main Energy Infrastructure Program, the government will determine the specific sites of electrolysers in conjunction with industry specialists. ("Green Hydrogen Cost Reduction" n.d.)

The scale of projects to date is quite small, and many concerns should be answered before power to hydrogen can take a significant share of the energy market. These includes:

a) The availability of cheap renewable power.
b) The need for low capital costs of electrolysers.
c) To improve the efficiency of electrolysers as the share of power to hydrogen technology increases.
d) To improve the feasibility of high-pressure electrolysers

These questions can be answered by using the learning curve theory. According to a study, the cost reduction potential for green hydrogen is higher and will come sooner than expected. This study was done to check the feasibility of starting a hydrogen economy in the port of Rotterdam (Jens 2020). The learning curve starts with slowly accumulating small steps at first followed by larger steps and then successively smaller ones at later. The technology is maturing at a faster rate and a fast and low cost road to carbon neutrality will reach sooner than 2050. Therefore, as the technology will be understood better, the researchers will dedicate themselves to overcome the barriers in power to hydrogen technology.

## 3.2 Stage 2: Top level system

### 3.2.1 Technological Barriers

There is a mismatch between supply of hydrogen and its demand, therefore hydrogen distribution technologies and infrastructure are critical for expanding the size of the market. The energy density per volume of hydrogen is relatively low, and the energy required for liquifying hydrogen is exceptionally high. As a result, the most difficult phase of hydrogen redistribution will be storage and transportation, which will be the focus of the discussion. ("Production, Storage, Fuel Stations of Hydrogen and Its Utilization in Automotive Applications-a Review" 2017)

There are various ways through which hydrogen can be transported, which includes:

a) Cryogenic liquid tanker for medium to large stations.
b) Hydrogen pressurised in tube trailers for small stations and early markets, and
c) Gas pipelines for the large stations and mature market.

However, each of these modes of transportation has its own set of drawbacks, like cost of operation is high to move large quantities, inefficient liquid liquefaction, and expensive time and capital costs for pipeline installation. The cost of construction can vary significantly with the estimation that it will currently cost around 10 to 20 per cent more than the construction of a natural gas pipeline with a lifetime of 50 years. (Ronevich et al. 2021)

The existing natural gas pipelines are already well established, and before the infrastructure is developed for hydrogen pipelines, a strategy needs to be placed for developing hydrogen infrastructure. As the hydrogen infrastructure develops, existing natural gas pipelines can be combined to supplement the new pipelines. However, these still come with difficulties to use hydrogen transportation in the existing pipelines of natural gas. Natural gas pipes are generally made of ferritic stainless steel, with a minor amount of plastic and wrought or cast iron. Using these pipes for hydrogen transport can result in hydrogen embrittlement, blistering, and fracture, especially when dealing with high-pressure hydrogen gases. ("Production, Storage, Fuel Stations of Hydrogen and Its Utilization in Automotive Applications-a Review" 2017)

As a result, one of the conceivable transportation methods in many aspects is to mix hydrogen with natural gas and use existing natural gas pipelines. Altfeld and Pinchbeck indicated in 2013 that a 10% hydrogen combination in natural gas is achievable, depending on the requirements in different places(Altfeld K 2013). As a result, it was suggested that a case-by-case analysis is required to determine what percentage range of hydrogen concentration with natural gas is possible. It was shown that hydrogen concentrations of 5 to 15 per cent pose no substantial concerns to public safety, household appliances or existing natural gas pipelines in the delivery of renewables to market. (Melaina, Antonia, and Penev 2013).

The best way is to install new pipelines for hydrogen. However, because investors are unwilling to invest in new facilities due to the uncertainty of natural gas depletion, promoting hydrogen transportation using existing natural gas pipelines is crucial. If it is possible to turn a natural gas pipeline into a hydrogen pipeline (by coating it, for example), this could assist investors in building good pipeline networks, which would boost hydrogen transportation.

Therefore, this is a complex decision-making process that requires analysis to elicit stakeholders' opinions on how the most difficult phase of hydrogen redistribution can be solved.
There could be three ways to transport hydrogen and choose from to grow the distribution sector of hydrogen which are:

a) To develop new hydrogen infrastructure and not use the existing pipeline
b) To use the existing natural gas pipeline before the hydrogen-pipeline infrastructure is developed
c) To only use the existing natural gas pipeline and not invest in hydrogen-pipeline infrastructure

Goal: How can hydrogen be redistributed?

Criteria: Four criteria were chosen in the AHP evaluation:

These are:

1) Research and Development of the technology: It refers to how much more time, cost and research is needed to develop and use the technology. For example, if a technology requires less research and development to implement the technology then it is a positive sign and requires less time, cost and research to use the technology.

2) Application of technology in the industry: It refers to legal, institutional, technical, human, social and political resources that should exist to implement the technology.

3) Government policy alignment to use the technology: It refers to actions, decisions and strategies by the government to foster or not foster the use of the technology.

4) Cost to use the technology: It refers to the cost of designing, implementing and maintaining an adaption action. The action should be economically feasible.

Adaption to the transport of hydrogen is complex as it involves considering various parameters such as research and development of the technology, widespread usage application in the industry, government policies and cost of developing the infrastructure. Therefore, it requires Analytical Hierarchical Process to make the decision from the following options.

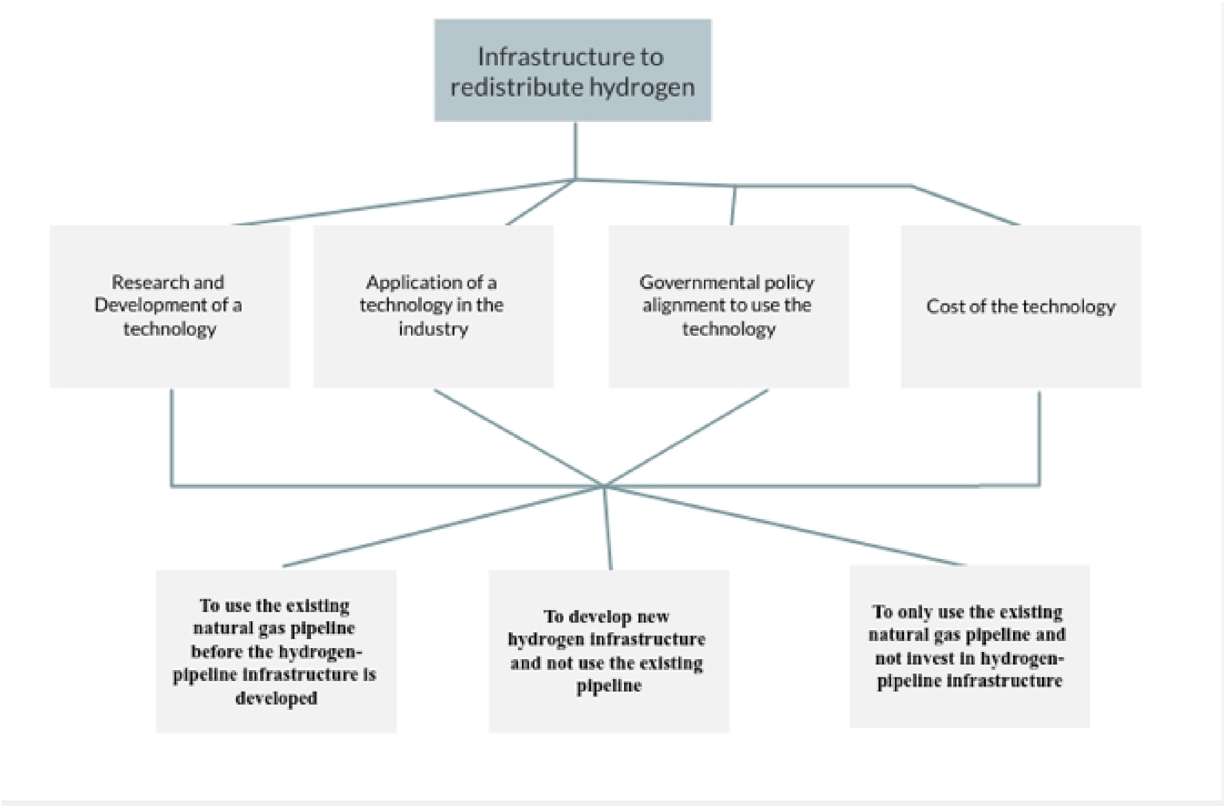


Figure 6. Analytical Hierarchical Process

The four criterion parameters will be weighted according to the survey results that involve institutes like municipality, academia and industry that were identified as key participants of this study.

The survey included 19 participants in which 27.8 percent were from Municipality, 44.4 percent were from Academia, 27.8 percent from Industry. 21.2 percent percentage had experience in the field of Power to Hydrogen and 26.3 percent sustainable energy. Also, 68.4 percent hold the degree of master's and above and 31.6 percent hold the bachelors degree bachelor's.

Table 5: Criterion Weights using the survey (From Survey and normalised pairwise comparison matrix)

| Criterion | Weights |
|---|---|
| Research and development of technology | 0.11 |
| Application of technology in the industry | 0.24 |
| Government policy alignment to use the technology | 0.28 |
| Cost of the technology | 0.37 |

Table 6: Criterion Rating

| **Criterion** | **Criterion weight** | **Level** | **Criterion Score** |
|---|---|---|---|
| Research and development of technology | | High | 20 |
| | | Medium | 50 |
| | | Low | 100 |
| | | | |
| Application of technology in the industry | | Low | 20 |
| | | Medium | 50 |
| | | High | 100 |
| | | | |
| Government policy alignment to use the technology | | Low | 20 |
| | | Medium | 50 |
| | | High | 100 |
| | | | |
| Cost of the technology | | Low | 20 |
| | | Medium | 50 |
| | | High | 100 |

Table 7: The rating criteria

| | Research and development of technology | Application of technology in the industry | Government policy alignment to use the technology | Cost of the technology | Total Score |
|---|---|---|---|---|---|
| To develop new hydrogen infrastructure and not use the existing pipeline | High | Low | Medium | High | 58 |
| **To use the existing natural gas pipeline before the hydrogen-pipeline infrastructure is developed** | **Medium** | **Medium** | **High** | **Medium** | **64** |
| To only use the existing natural gas pipeline and not invest in hydrogen-pipeline infrastructure | Low | High | Low | Low | 48 |

Therefore, for the following reasons, adding hydrogen to the natural gas pipeline is an appropriate short-term solution:

a) It is physically viable to add roughly 10 per cent to natural gas pipelines with negligible igniting hazards, no additional leakage concerns, and no increased pipeline fatigue.
b) Transportation of hydrogen will be cost-effective, and it can be considered an alternate mode of transportation until the early market development phase of hydrogen transport develops.
c) The public already accepts the transportation of flammable gas, and operating such cases will be essential to understand the future utilisation of the existing natural gas pipelines.

On this basis, transporting hydrogen through existing gas pipes will serve as a temporary measure. However, pure hydrogen needs to be separated from natural gas. The techniques for separating hydrogen from natural gas and their feasibility will be discussed in the next section.

### 3.2.2 Purification Methods

Separation methods for separating hydrogen from low-concentration mixture sources suited for hydrogen-enriched natural gas (HENG) at low temperatures have not been properly studied. As a result, it's critical to create low-cost, high-efficiency separating techniques to separate low concentrated hydrogen from natural gas. There are a variety of technologies that may be used to obtain pure hydrogen in a cheap and efficient manner.

Membranes:

Membrane technology has been employed in natural gas sweetening, hydrogen recovery from ammonia purge gas, and carbon capture for decades. Membrane technique for hydrogen recovery from $CH_4$ is primarily designed for mixtures with high hydrogen concentrations (more than 50%) in order to obtain pure hydrogen products (>= 99.99 percent) at high temperatures. To separate hydrogen from natural gas, researchers have looked into a variety of membranes, including dense metallic membranes, porous inorganic membranes, metal-organic framework membranes, and polymeric membranes. Among these, porous inorganic membranes and dense metallic membranes were the closest for industrialising hydrogen separation. However, the membranes effectively separated a mixture with a concentration of more than 50%, which is insufficient for separating hydrogen gas pipes. (Melaina, Antonia, and Penev 2013)

Sorbents:

Hydrogen purification via pressure swing adsorption (PSA) technology is the first large-scale application for purifying hydrogen. It is a well-known technology in the industry, and most scientists are focused on increasing the PSA technology's performance. The most often utilized adsorbents for hydrogen purification are activated carbons and zeolites. However, it was found that it is difficult to recover hydrogen and achieve high purity using activated carbon. However, 99.99 per cent can be easily obtained through PSA technology via zeolites as the adsorbent. Also, zeolites were shown to remove numerous contaminants from hydrogen, including $CO_2$, CO, $H_2O$, $N_2$, and others. These processes are generally for separating high concentrated hydrogen from methane. Companies have proven to increase hydrogen recovery from 87 percent to 95 percent using a three-stage PSA process: with two adsorption columns designed to treat lower hydrogen supply gas in the third stage of PSA. However, no study has yet been published with the specific goal of obtaining low concentration hydrogen from methane. (Hu et al. 2020)

This technique can be used, but there are two difficulties to address when using PSA technology to overcome low hydrogen concentrations from methane. First, because methane concentrations are high, more frequent regeneration adsorption regeneration cycles are required, resulting in higher total costs. Second, recovering hydrogen involves the recovery of main constituents at low pressure. As a result, massive recompression expenditures will be required for future transport. Also, PSA requires a large facility to function.

Hydrogen pump:

Electrochemical separation is used by the hydrogen pump to capture and pressurise hydrogen from bulk methane mixtures. In this process, the oxidation process is driven by electric potential, which is achieved by employing voltage to split H2 to H+ at a proton-conducting anode.  Then the H+ is transported through the proton-conducting membrane, and then protons are reassociated to hydrogen at another proton-conducting cathode. Although the hydrogen pump technique has promise, it is not yet suitable for large-scale industrial use.(Hu et al. 2020)

Solvents:

Solvents are not as effective as membranes and adsorbents to separate hydrogen and methane. Because most solvents have weak interactions with methane and hydrogen, using them has been a tremendous difficulty in recent decades. Furthermore, acceptable absorbents must have a low solvent power for hydrogen and a high solvent power for methane to achieve significant methane selectivity over hydrogen. As a result, using a high solvent power may result in significant hydrogen loss, making hydrogen regeneration from rich absorbents more challenging. Additionally, utilising absorbents with poor methane compatibility may compromise the purity of the end products. The use of solvents to separate hydrogen and methane is not beneficial to the industry since it requires a large amount of energy to optimise the operating conditions, which is not economically possible. (Hu et al. 2020)

Cryogenic Separation:

Cryogenic technology is a technology that is commercialised for separating gas and mainly hydrogen and methane. The purity of hydrogen from the process is 90 to 98 per cent having a feed gas hydrogen composition of 30 to 80 per cent (Rufford et al. 2012). Though it is widely used in the industry, the technology is costly and energy-intensive. The cryogenics must be large-scale facilities downstream of the hydrogen/methane transmission process to make it economical. Using this technology have few technical concerns that are addressed below:

a) At high pressure and low temperature, the hydrogen and methane mixture generates methane clathrate, which could clog the processing pipelines(Eslamimanesh et al. 2013).
b) The insulation employed in diffraction columns and liquified gas containers has a significant impact on the process's energy and cost efficiency.(F. Zhang et al. 2016).

### 3.2.2.1 Selection of Membrane

After understanding each purification method, two methods are possible to implement at a large scale due to seeing its large-scale application in the industry.

a) Sorbents
b) Cryogenic Separation

To tackle the disadvantages of separating low amounts of hydrogen from natural gas, an integrated membrane adsorption process may be utilised to create high purity hydrogen to overcome the problems in sorbents. However, the technology will come at a high cost in terms of recompression, which will be necessary for transportation.

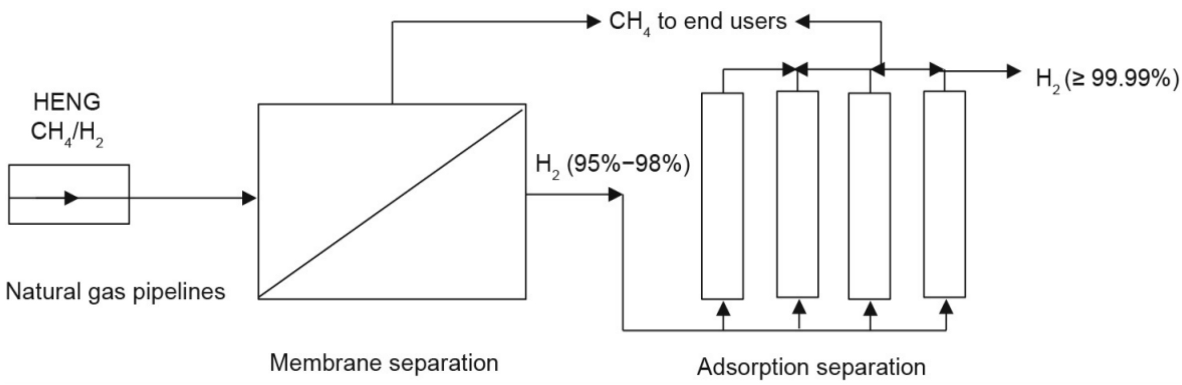


Figure 7. Integrated membrane-adsorption process for the separation of hydrogen from methane(Hu et al. 2020)

Cryogenic separation is already a commercialized technique that is used to separate methane and hydrogen mixture. Also, when installed on a large scale, the process becomes economically feasible to use. But, it has some technical issues that need to be taken care of during the functionality of the processes as discussed above. Hybrid systems, which mix membrane and cryogenic systems to reduce the cryogenic process's land and economic footprints, have also been devised to improve the technology. When a large amount of liquefied natural gas is required, the procedure is advantageous(Baker 2002).

## 3.2.3 Other Barriers

There are still barriers discussed for the technology, but it is pretty evident that the development of the technologies will contribute to the widespread use of Power to Hydrogen technology. Other than technological barriers, there are other barriers that need to be focused to ensure large scale deployment of power to hydrogen technology which are the availability of water and regulations from the government.

#### 3.2.3.1 Availability of water for electrolysis

Water is essential for hydrogen generation and electrolysis, and there is always a mismatch between renewable energy supply and clean water availability. For example, areas where solar power is ample often indicate poor availability of water. As a result, either energy transmission or water transportation will be needed in the region.  Therefore, a trade-off must be made between the transmission of power and the transport of water and hydrogen on a cost-benefit basis.(Reitenbach et al. 2015; Hu et al. 2020)

#### 3.2.3.2 Governmental impact

Regulations are a major factor that needs to be considered while implementing new technology. For example, different countries may have different views on the same technology. If we take China, hydrogen is classified as a dangerous chemical which makes the hydrogen refill station operate in chemical plant areas or far away from urban areas. This makes large scale deployment of the technology not possible. This is still a big question, and there is uncertainty whether the situation can be changed soon. However, on June 14, 2019, the International Energy Agency (IEA) released a special report on hydrogen for the G20 summit, which was followed by a joint statement from Japan's Ministry of Economy, Trade and Industry, the European Commission Directorate-General for Energy, and the US Department of Energy to promote hydrogen and fuel cell development. This will expedite the deployment of the technology, with the possibility of hydrogen deregulation in some aspects. (Reitenbach et al. 2015)

### 3.2.4 Policies

Previously, the interest to support hydrogen was triggered by oil supply shocks that shifted away from oil and increased energy security. This has caused most of the policies to emphasise hydrogen-based vehicles and refuelling stations. But, as the focus is on net-zero emissions and renewable technology becoming cheap, the focus has diverted to other sectors. Promoting hydrogen in various disciplines necessitates a unified policy approach, with national government plans serving as the basis. It takes a shared set of long-term visions from industry and government to implement policies that will benefit national conditions. Sound governance structures and supporting legislation will remove roadblocks to hydrogen expansion. (“Irena: Green Hydrogen: A Guide to Policy Making” n.d.)

A growing number of governments have implemented hydrogen policies and initiatives in recent years. It implies that there is a rapid increase in the ambition to recognise the objectives of the Paris Agreement. Green hydrogen plays a critical part in achieving the goal of zero greenhouse gas emissions from the power sector. In 2020, eight jurisdictions worldwide had announced hydrogen strategies, including the Netherlands, and ten more are expected in 2021. The strategies resulted from investments in the energy industry in the 1970s, which allowed for the advancement of hydrogen technology processes through close collaboration between public and private actors. Partnerships have aided progress, resulting in vision statements and roadmaps to pave the way for developing clear plans and policy measures for the long term. (“Irena: Green Hydrogen: A Guide to Policy Making” n.d.)

The European Union has the most ambitious green hydrogen programmes, with a goal of 40 gigawatt by 2030. This is supported by national targets from France, Germany, Netherlands, Portugal and Spain. The targets are 6.5, 5, 3-4 gigawatt, respectively. The EU policy also sets a volume production objective of 10 million tonnes of hydrogen per year. Only, EU, Chile and Australia have set specific electrolysis targets. Other options, such as providing incentives for domestic electrolyzer production, direct subsidies, feed-in tariffs, convertible and conditioned loans, and auctions, have been limited in the declared policies, which could impede the implementation of green hydrogen. Furthermore, green hydrogen generation necessitates increased renewable electricity generation, requiring additional investment in renewable power generation manufacturing capacity. The absence of policies to increase renewable electricity generation and hydrogen production can impede the growth in the hydrogen sector. (“Irena: Green Hydrogen: A Guide to Policy Making” n.d.)

#### 3.2.4.1 Policy agenda and vision for the future in the Netherlands

The strategic plan proposed by the Dutch government is in line with the National Climate Agreement's hydrogen commitments and illustrates that progress is being made. Because of its advantageous location, ports, and huge gas storage and grid capacity, the government has created the view that the Netherlands will operate as an energy centre in the future. In the coastal districts of the Netherlands, production can also take place utilising massive electrolysers or production units with CCS. In addition, smaller-scale production sites will also be built to increase output.

The government's main concern is establishing a clean hydrogen distribution network, which is a difficult task. Demand, supply, storage, and infrastructure all need to be built, and they are all intertwined. For the companies which will be market players of zero-carbon hydrogen as an energy carrier, it will be critical for them to know the estimate of future quantities and costs for hydrogen. Moreover, they should know the production capacity and should have insights into demand trends. Therefore, a system should be in place to integrate one hundred per cent of their source as renewable power to balance the demand and supply of electricity.

The development and dimensioning of infrastructure networks to meet the demand and supply of electricity requires the significant influence of government policy at the start and in the development phase. Introducing a new energy carrier is a complex journey that will take decades, and government support will steer and guide the process. Therefore, to meet the supply and demand, a centralised or decentralised system should be in place to collect real-time excess renewable energy from different areas to identify cheap renewable energy in real-time and supply to the needed regions. Development of the Internet of Things and Power to power technology can support energy trading in smart microgrids (Sikorski, Janusz J., Joy Haughton, and Markus Kraft 2017). Therefore, more research is needed to understand which technology in Industry 4.0 will be best suited to help the demand and supply of hydrogen, which will be discussed in Chapter 4.

In the first phase of development, the government is planning to focus on reducing costs of clean hydrogen production and the government sights that upscaling the production plants is a key way to do so. In the later phase, the transport will add value in the long term, and then storage infrastructure needs to be created to prepare for the potential realisation of green hydrogen.In conclusion, Dutch policy will work on the technical frontier to scale up the process through a variety of policy frameworks that can support ambitious objectives.

#### 3.2.4.2 Use of existing gas grid and safety

As discussed in the technological barriers, hydrogen transportation is a challenge, and using existing gas grids until the new infrastructure is in place is one option that aligns well with the government's policy agenda. The hydrogen supply chain will develop in the network sector, like natural gas and power, which will require developing a new gas infrastructure for hydrogen. But as the new infrastructure is developed, the government emphasizes using part of the existing gas grid to transport the hydrogen. In the Netherlands, the government will collaborate with national network operators and firms Gasunie and TenneT to know which conditions will be part of the gas grid and can carry and deliver hydrogen. In addition, the procedure will include regional network operators and network firms. Along with this, new infrastructure development will also take place to be the potential hub function for the neighbouring countries.(van Economische Zaken en Klimaat 2020)

Safety is a must when it comes to building supply infrastructure. At this time, the risk of using hydrogen is not considered to be greater than the risk of using conventional fossil fuels. But, As new hydrogen sources and applications are developed, more investigation and observation of the technology will be done to understand the magnitude and effective control of dangers. International and European principles and standards will be used to apply the safety laws. The Netherlands initiated the four-year Hydrogen Safety Innovation Program, which is public-private cooperation, in 2020. It will entail collaboration between network operators, the government, research institutes, emergency services, and businesses. The initiative will identify hydrogen-related safety concerns and recommend regulations and agreements that will allow these concerns to be effectively handled.(van Economische Zaken en Klimaat 2020)

#### 3.2.4.3 Scale-up green hydrogen

Currently, green hydrogen is produced on a small scale, making it more expensive than other alternatives. As discussed before, the barrier to reducing production costs lies in scaling up the green hydrogen production. This aligns with the various national and international studies that show that cost savings of around 50 to 60 per cent is possible in the next ten years. To achieve such a cost reduction, massive scaling up is required in the international market to scale up to several MW to GW scale by 2030. The policies to achieve scaling up will allow industrialised manufacturing and yield economies of scale. Moreover, innovation is key to lower costs and leading to higher energy efficiency. To scale up the process, the National Climate Agreement aims to scale up the electrolysis by 500 MW of installed capacity by 2025 and 3-4 GW of installed capacity by 2030. As the production scales up, the cost of green hydrogen is expected to fall, but at the moment, we see a significant operating cost gap. The government provides monetary assistance schemes for research to expand and deploy zero carbon hydrogen. Also, the government considers other options to scale up and reduce costs by linking the development of offshore wind energy and hydrogen through a blending obligation.(van Economische Zaken en Klimaat 2020)

In summary, the paper has discussed the Power to Hydrogen Technology, the barriers associated with the technology and the recommendations to overcome the barriers and deploy the technology at a faster rate. Also, the government understands the need to support hydrogen and the policies and vision set by them aligns to foster the development of hydrogen in the country. These drivers have caught the eyes of the stakeholders to invest in the field of renewable storage energy and specifically in “Green Hydrogen.” The industrial players are investing heavily in producing hydrogen to reduce their emissions and play an active role in the emissions reduction targets. But, the buildings, commercial spaces, and households are the second-largest energy users in the Netherlands (Detz, R. J., Lenzmann, F. O., Sijm, J. P. M., & Weeda, n.d.). Therefore, to reach the targets set by the European Union, implementation of hydrogen technology is vital in a community-based scenario.

## 3.3 Stage 3: Assessment and Evaluation phase

### 3.3.1 Current research in the Hydrogen Technology

Current research includes models to integrate hydrogen storage with variable renewable energy in the buildings. But, while doing the literature survey, I observed a few intricacies and gaps. The model developed uses power for hydrogen storage with renewable energy but still uses fossil fuel-based heat and power plants if hydrogen storage cannot meet the electricity demand (Pietro Elia Campana Eva Thorin 2020; Dawood, Shafiullah, and Anda 2020; Wang et al. 2019a). Also, the literature talks about the use of PtoH2 technology in one building or for a small community having a few houses(sub-community). There is no integration between the buildings or sub-community to meet the demand and supply of energy. Therefore, a system should be in place to integrate the buildings/ sub-communities using one hundred per cent of their source as renewable power to balance the demand and supply of heat and electricity.

The increased use of intermittent renewable energy sources to generate electricity suggests that the energy system need more flexibility. The energy storage solutions like Power to Hydrogen help to maintain a balance between supply and demand while also helps in increasing the system's flexibility. After learning about the drivers of green hydrogen, I looked into how renewable energy resources could be used on a regional scale that wasn't limited to the Netherlands. Specific region was not selected because at the start of the literature survey it was important to understand the application of the technology around the world to improve the knowledge in the energy storage field.

In a study, Power to gas storage interacts with a large-scale rooftop PV systems and is integrated to the regional energy system dominated by power and heat plants.It looks at the impact of storage systems on combined power and heat plants production planning as well as the system's flexibility. The system uses the Mixed Integer Linear programming method to model and optimizes the product's cost. Various effects are considered in the model, such as C02 emissions and power import into the regional system.The model was tested using several scenarios, and the results showed that the suggested storage system could cut marginal emissions and power imports by 53%. However, due to their low efficiency, fuel cells are unable to contribute considerably to power regeneration from stored energy. Therefore, 70 per cent of the year's Power still needs to be imported to the optimized system. Therefore, there is a need for a supply of hydrogen from the outside and to be traded to fulfil the demand of other communities. (Pietro Elia Campana Eva Thorin 2020)

One researcher proposed a remote community stand-alone microgrid(SAM) system to identify the viability of using a hundred per cent renewable energy-based system with hydrogen-battery energy storage in Western Australia (WA). In WA, there are isolated stand-alone power grids that are apart from the state's main utility grid. This place was chosen because decarbonizing the energy supply by locally produced, clean, and sustainable renewable power is critical for clean future energy. Therefore, this research considers a remote region in the North West of Western Australia. Using the SAM system, 100% renewable power based scenario were designed, modelled, and evaluated. Three cases were investigated: a battery-based, a hydrogen-based and hybrid combination of battery and hydrogen-based renewable energy storage systems and then reviewed and analyzed with each other. The evaluation demonstrated that hybrid battery hydrogen-based systems are a promising approach for reaching a hundred per cent renewable power based SAM systems. The demonstration revealed that the hybrid system has the least net present cost and Cost of Energy for the project lifetime of 25 years. Also, it uses less extra energy than battery-based systems, and a six-year payback period makes the system highly attractive and cost-effective for renewable energy systems. (Dawood, Shafiullah, and Anda 2020)

A proposal was presented in the Netherlands in which produced locally renewable power is partly stored and converted as heat and hydrogen, alongside rainwater collection, storage, filtration, and utilisation. To build an energy balance and perform a techno-economic analysis, a model is created. According to the simulation, an 8.7 MWp solar park combined with rainwater collection and solar energy can supply 900 homes for a year with 20 TJ and half of the water requirement via an underground heat energy storage system, as well as 90 tonnes of hydrogen.The estimated production costs for heat (26 €/GJ) and hydrogen (8.7 €/kg) are lower than the current selling prices of 34 €/GJ and 10 €/kg, respectively, making the system more affordable (Roest et al. 2020). These findings make it possible to deliver all of these services to the neighbourhood using hydrogen storage and solar power. But, the paper does not talk about trading hydrogen and transportation between the communities, which will be researched in the next section.

### 3.3.2 Expected Future using the Hydrogen Technology

All the roofs and houses of the buildings have solar panels that will produce electricity and are equipped with a rainwater harvesting system. The houses will be well insulated and perfectly ventilated, and there will be no longer a need for lots of energy for heating and cooling. The houses will be surrounded by electrical devices, including intelligent LED lighting, robots, drones, cameras and 3-D printers. The Internet of Things will be well established, which will enable us to operate the devices remotely. As a result, the devices will be more efficient, and the internet of things will make the devices use it more efficiently and economically. (van der Roest Jos Boere 2017a)

To understand the framework, a model architecture is considered. The model will have many small communities, and each small community will consist of 50-100 people in which they will be staying in housings forming around 25-50 neighbouring households. Each small community of 25-50 neighbouring households will be known as a sub-community. Therefore a region or city will have clusters of sub-communities interlinked via grids. The sub-community will have batteries and flywheels to store short term fluctuations from renewable energy and supply the electricity to meet the peak demands. When the electricity is cheap and in surplus, electrolysers will make hydrogen from renewable power. Then the hydrogen can be fed into the hydrogen pipe network, or the fuel cells will convert hydrogen to electricity whenever a structural electricity shortfall occurs. (Ledwaba et al. 2021a)

The sub-community will have its hydrogen storage unit, which will convert to electricity via fuel cells when it is not possible to supply from solar or wind energy. The sub-community strives to be self-reliant to meet its demand for electricity via renewable sources and hydrogen storage. But, sometimes, a sub-community is not self-sufficient to fulfil the energy demand using their renewable energy and hydrogen storage. Therefore, a sub-community will trade electricity to meet its power demand from other sub-communities having a decentralized system.

The electricity demand is often dispersed over large areas, and centralized generation stations and high voltage handle energy supply. Connecting new sub-communities to a centralised grid is difficult due to topological and topographical challenges. As a result, the proposed architecture should attempt to allow universal electrification by forming a series of interconnected microgrids employing renewable energy generation sources (Ledwaba et al. 2021b). Electricity demand involves efficient demand response management (DRM) methods, as well as external assistance from other subcommunities. As a result, in order to use information and communication technology in the energy revolution, there should be two way flow of data and energy. To handle the energy demand of the sub-communities, a smart grid system is crucial. A smart grid will be helpful to understand the demand and supply of energy and trade excess electricity between the subcommunities. Also, in the Industry 4.0 era, the development of Industry 4.0, which includes blockchain technology, digital twins, Internet of things, together with the power to technology using a distributed ledger technology, can offer support for initial proof of concept to implement decentralized energy trading in smart microgrids (Sikorski, Haughton, and Kraft 2017)

The hydrogen storage capacity of a subcommunity has limited storage. Sometimes, there is an overproduction of hydrogen that cannot be stored in the hydrogen tanks. Therefore, the network of pipelines is connected to a large centralised scale hydrogen storage complex where the hydrogen can be stored in compressed form. Therefore, centralised hydrogen storage will help store surplus energy and avoid the variability of energy production via renewable sources of energy.

From electricity to hydrogen

The electricity will be produced in the buildings using solar cells or wind energy, which will be set up everywhere and integrated into everything. Solar panels will be everywhere, on walls and roofs, solar cells into roof tiles, windows, bridges, roads, solar cell paint, windows frames and doors. As there is the transition to renewable energy, more and more houses will be equipped with solar panels, and there will be a huge surplus of electricity production. There will be batteries to store electricity at night. Though the batteries will absorb part of surplus electricity, the remaining power has to be absorbed somewhere in the system. This will be done by converting to hydrogen, which is an easier way to store than electricity. The hydrogen will be converted to electricity using fuel cells. Stationary fuel cells will be set up that will provide a robust electricity system. The produced hydrogen will be sorted in a decentralised manner, and hydrogen networks will be used, meaning the use of natural gas networks and hydrogen pipelines to transport the surplus renewable energy.

From hydrogen to electricity

The surplus electricity is stored in batteries or converted into hydrogen. But renewable sources like solar energy cannot provide sufficient electricity all the time, for example, at night and during the day in the winter. Therefore, the standalone microgrid can draw electricity from the neighbourhood community or produce extra electricity using fuel cells by converting hydrogen into electricity.

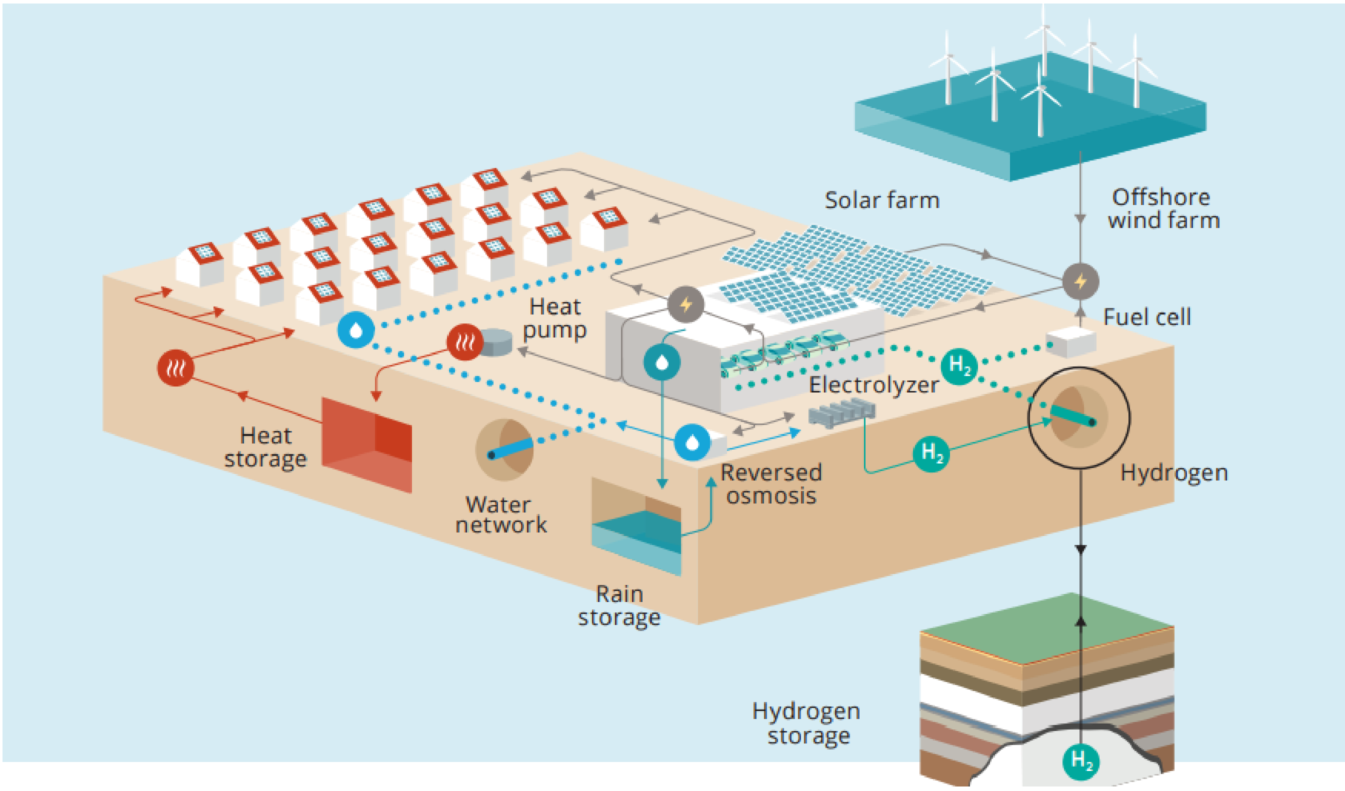


Figure 8. Model of a sub-community(van der Roest Jos Boere 2017a)

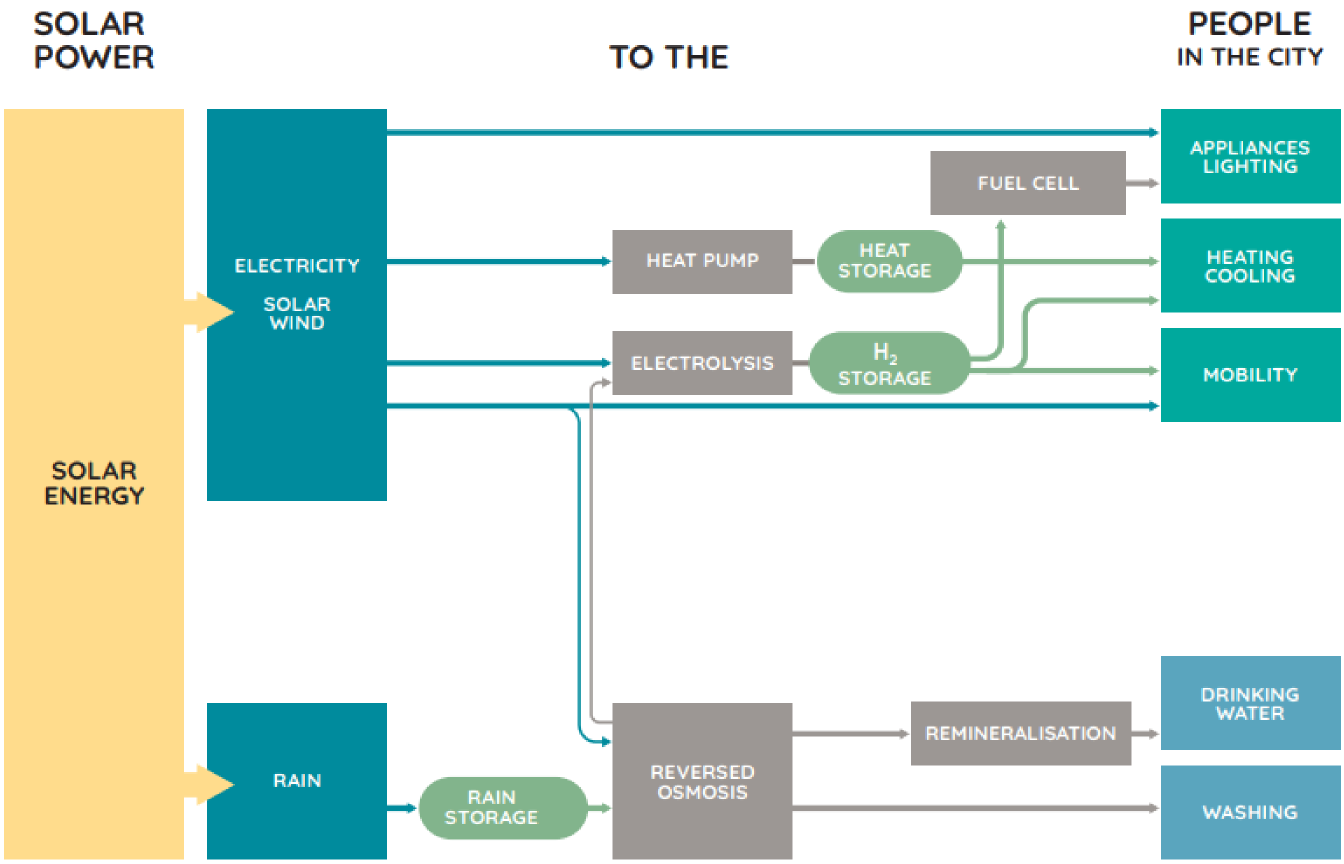


Figure 9. Power generation and utilization flowchart in a sub-community(van der Roest Jos Boere 2017a)

### 3.3.3 Smart Grids

Allowing sub-communities to become self-sufficient by developing renewable, self-generating facilities will increase energy supply reliability, stimulate economic growth, and minimise economic disparities.However, this necessitates preliminary research as a foundation for the development of a secure energy marketplace for larger smart microgrid systems. As a result, a secure energy trading system must be integrated into the smart grid system to ensure the safety and confidentiality of consumer data. A modern microgrid will be connected to a subcommunity's energy unit conversion; an integrated energy system solution consisting of a localised grouping of distributed power generation with storage and numerous electrical loads (Dawood, Shafiullah, and Anda 2019). It can be one controlled entity or grid, either standalone or connected to an existing utility grid.Renewable energy penetration, demand side management , and microgrid integration are all driving factors in the development of microgrids (Barbato and Capone 2014). However, due to isolated or remote sites, connecting the microgrid to the utility grid is not always practicable. A standalone microgrid(SAM) answers the power supply challenges (Vivas et al. 2018).

A stand-alone microgrid(SAM: A smart microgrid) is a self-contained energy system that serves distinct geographical regions like residential buildings, business centres, hospitals or neighbourhoods. Within a microgrid, one or more types of energy systems like wind turbines,solar panels or combined power and heat generators produce its energy. Also, many microgrids have power storage, for example batteries. The microgrid can operate independently. This helps them supply power when there is an outage of power in the central grid due to storms or other calamities. While microgrids can operate independently, they are usually not connected to the central grid. The two functions have a symbiotic relationship as long as the central grid operates normally. Also, the microgrid is an intelligent system. It's the system's brain, and it's in charge of carefully controlling the generators, batteries and nearby building power systems. To fulfil the energy targets, the controller coordinates different resources. It's a software-based technology that allows the controller to control energy supply in a variety of ways. The controller, for example, can monitor real-time changes in electricity pricing on the central grid. If t he price is low at any moment, it may opt to buy power from the central grid to service a sub-community rather than using renewable power. Renewable sources like PV and wind energy are used to produce hydrogen. When the grid power price goes up later in the day, the fuel cells can convert hydrogen to power rather than use grid power. The microgrid's resources working together through intricate algorithms generate a greater whole than the sum of its parts. hey push the system to levels of efficiency that no one could achieve on their own, and the orchestration operates in a self-contained manner. (Wood 2020)

The advantages of using the microgrids are:

- It will reduce transmission and transformer losses
- It will provide more independence from big power suppliers
- The smart grid will act as a backup system
- It has an intelligently controlled power supply
- The power generation is using renewable energy sources

A SAM network is a power network with no active power coupling lines to other parts of the main networks. It is remarkably smaller than the main network and does not incorporate high voltage power lines. This type of power supply is used for supplying energy to a specific region or for the industrial power supplies of large businesses. The SAM functions in a particular region or a subcommunity. There should be a system in place to manage the demand and supply of energy in other subcommunities. s a result, mining operations, as well as inter-and intra-community energy trading transactions, must be controlled by a base station known as a community node. To enable for information exchanges at a high level of network architecture, the base station device must be a high-power Industrial Internet of Things device with more computation power and storage resources. (Ledwaba et al. 2021b).

To ease trading between subcommunities, each neighbourhood will be turned into a single node based on municipal demarcation zones. These zone nodes will be able to trade with one another. If the sub-community has a supply shortage or surplus, the edge controller node will send a transaction request to the local microgrid network. The sub-community will have a distinct identity on the distributed ledger technology network and the wallets and smart contracts processing abilities. The controller would make buying from other microgrid nodes easier based on the energy available and current price of the market. The families would be able to supplement to satisfy immediate energy needs, allowing the microgrid to keep a stable, constant supply. The electrical energy produced will not be wasted, and a monetary incentive for energy trading, will make the microgrid more inclined to contribute to a community-wide generation and supply network. The community smart microgrid distributed ledger technology would be a ideal fit for a permission public ledger structure.(Ledwaba et al. 2021b) This will make it simple to join and transact amongst nodes within a neighbourhood network while blocking outsiders from joining the ledger(Mahmood and Wahab, n.d.).

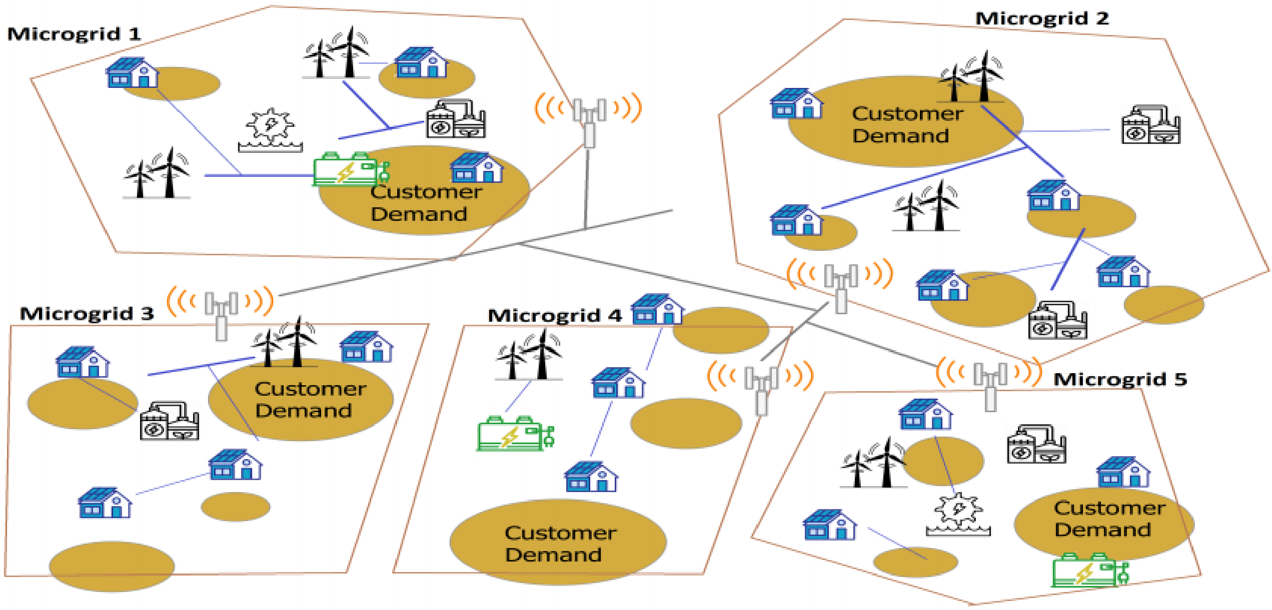


Figure 10. Distributed ledger technology-enabled microgrid system interlinking different subcommunities(Ledwaba et al. 2021b)

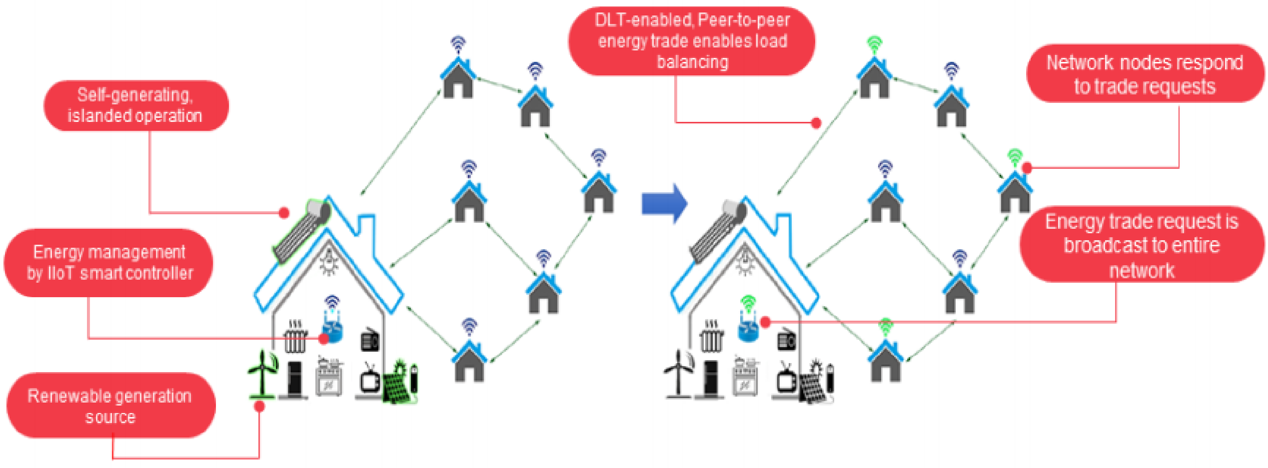


Figure 11. Microgrid system in a sub-community(Ledwaba et al. 2021b)

In order to support the sharing of electrical energy, a secure energy marketplace with real-time pricing must be built in a smart microgrid. There should be sufficient facilities that need to be implemented to ensure marketplace honesty which include:

- Users are selling available resources.
- The seller fully owns the resources.
- The protection of users is taken care of in any energy trade transactions.

SAM is a great place to start when switching from fossil-fuelled to renewable base energy power systems. The SAM is a low-voltage power system that provides power to a small region. It comprises a local power generation system with load needs that operate off-grid or in isolated mode. If transitioning to a hundred per cent renewable SAM system, centralized or decentralized storage systems and power generation are used to meet the energy need. SAM is a practical and viable approach for using renewable energy resources by reducing the problem of renewable energy's intermittency (Vivas et al. 2018). The proper sizing of system components to make the system efficient, dependable, and minimising capital expenditures is a SAM system's major difficulty. To optimise the performance of hybrid systems, an appropriate management strategy is required.The advancements in AI and Industry 4.0 make it possible to optimise SAM operations without depending on long-term data on weather forecasts (Dawoud, Lin, and Okba 2018).According to available research, SAM has a high proportion of renewable energy penetration. Hybrid renewable energy storage systems can be more dependable, cost-effective, and long-term than 100% fossil-fuel-based SAM(Shafiullah 2016).Many countries, including Bangladesh, South Africa, India, and Australia, are investigating how to establish microgrid-based power systems that are both efficient and robust for rural and island communities (Shoeb and Shafiullah 2018; Ali, Shafiullah, and Urmee 2018).

In conclusion, a stand-alone microgrid is an intelligent system that has the function to track power prices on the smart central grid and decide whether to buy the power from other subcommunities or produce its energy through its own renewable sources or produce energy from hydrogen. The base station will be a central brain with high processing and memory resources which will orchestrate to manage the energy supply in different ways and transport electricity through grids.

### 3.3.4 Digitization, Industry 4.0, Blockchain, Digital Twins as elements to manage processes in Energy Trading

Fundamentally, the smart microgrid must meet numerous architectural goals as it is a highly critical and regulated application space. Therefore, to manage the processes of smooth energy trading, digitization is key to reducing operating costs and increasing the efficiency of the processes. Digitization has already exceeded the traditional productivity improvement ranges from 3 to 5 per cent per year with cost potential improvement of above 25 per cent. The digital advances have increased the useful life of energy plants by 30 per cent.The activation of prosumers in the energy trading market is possible thanks to new technology, blockchain, and intelligent networks. Furthermore, digitization will help reduce energy consumption and boost energy efficiency, both of which the European Union is battling to achieve a clean air package and will have a good impact on environmental protection.(Borowski 2021b)

The system is a tightly regulated application environment that should prevent malicious actors out of the grid. However, there should be adequate security mechanisms, and it should enable defence methods against " unauthorised penetration, access or use of physical and cyber assets(Greer et al. 2014) . At all levels of the network, grid operations should protect client transactions and personal details. The method should also ensure that routine grid operations are not disrupted. According to the Smart Grid Security Guidelines, smart grid security methods should ensure that:

- A high level of availability is given the utmost importance.
- There is information integrity, and confidentiality of customer is protected(Committee and The Smart Grid Interoperability Panel–Smart Grid Cybersecurity Committee 2014)

Digitization contributes to increasing the level of security, efficiency, availability and durability of energy systems. The technologies that collect and analyze data have allowed increasing energy efficiency. The data are processed into useful information using data analysis technologies such as artificial intelligence algorithms and then sent to devices that can influence physical changes to optimize energy consumption (Rot et al. 2020). The research for these technologies concerns digitization, digital twins, and the latest solutions used in the energy sector. These technologies are already in different sectors, such as the aviation industry, but for the energy sector, these are innovative solutions.

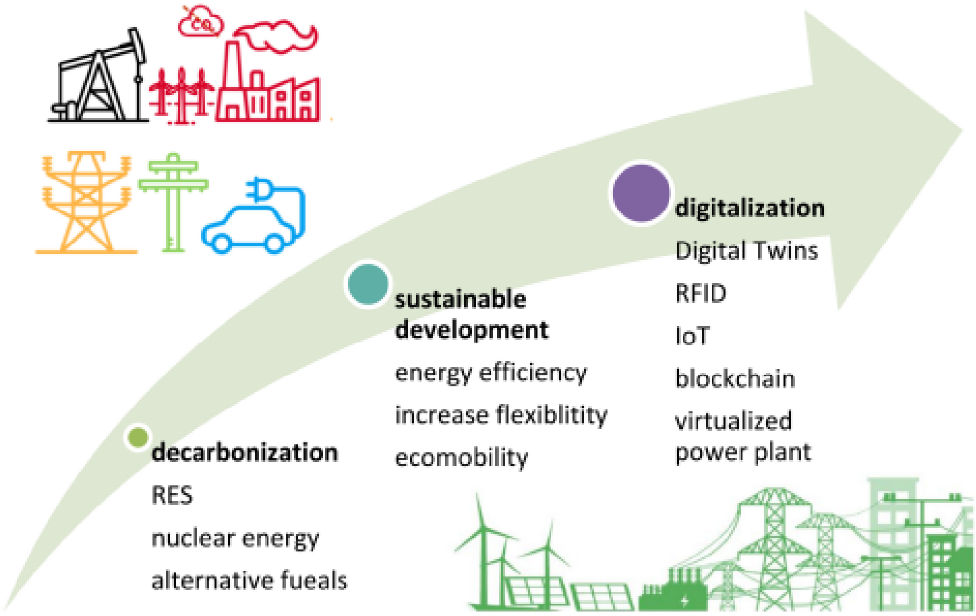


Figure 12. The direction of energy sector development(Borowski 2021b)

Industry 4.0 is a new phase of the industrial revolution that focuses on interconnectivity, automation, machine learning, real-time data, the Internet of Things, blockchain technology, and advanced digital manufacturing technologies (Hernes, n.d.). The technology is radically changing industrial production and increasingly blurring the lines between physical and digital manufacturing systems. To make the system intelligent, it should focus on fully integrated processes where information flows through operations and generate real-time feedback to support decision making. In such an environment, intelligent sensors and machine to machine communication, big data analytics, cloud computing, and artificial intelligence are very popular.

#### 3.3.4.1 Digitization in Energy Sector

Digitisation supports the energy sector based on Industry 4.0, including the Internet of things, machine to machine technology, and machine learning. The main components of the machine to machine technology include radio frequency identification, cellular, sensors or Wi-Fi link, and process control systems, which are important for automating and optimising the processes. Also, the autonomous data processing software programmed to aid a network device to interpret data and make decisions can trigger programmed, automated actions in the energy sector.(Borowski 2021a)

Traditionally, a centralized energy flow system is followed where energy flows in one direction from centralized generation to end-users.However, increasing access to renewable energy sources and rapid, open connections to everything (peer to peer) has paved the path for a multiple directional energy network between central grids and distributed prosumers (Chaudhuri 2021). Furthermore, Digital systems integrate various energy sources that will be increasingly used to manage energy distribution by monitoring and controlling its production and demand. Finally, the application of the Artificial Intelligence algorithm enables effective and efficient management of transmission and energy production in the ecosystem of thousands of producers and prosumers (Andersen, Lee, and Henriksen 2020). To strengthen the integration of energy trading services: digitization and decentralization are the key factors to enable the achievement.

An extensive discussion will be carried out to present how digitization and decentralization can help in energy trading.

### 3.3.4.2 Importance of Blockchain in the Energy Trading system

The use of Artificial intelligence, innovative machine learning processes, big data, Internet of Things(IoT), and distributed ledger technology(DLT) are known in the scientific community as the blockchain. Currently, a centralized system is followed where there is interaction with the central authority and consensus of central processing or trusted controller is required. This takes time and bottlenecks the flow of data. The DLT can improve the processes that use databases. DLT can play a significant role in energy trading, peer to peer trade, microgrids, and local demand response. This is a breakthrough technology where a peer to peer network can be created where nodes have to reach consensus and chain accepted blocks. Among all its existing applications of the technology, decentralized storage systems are one of its main applications. (Benisi, Aminian, and Javadi 2020)

Advanced smart grid technologies enable trade surplus energy from distributed renewable energy sources with peer-to-peer energy trading. Blockchain technology can provide innovative solutions that enable consumers and end-users to play an active role in the energy market and maintain liquidity by selling assets. Also, many scientific studies have been written on the use of blockchain technology in peer to peer networks, energy trade, and microgrid demand response programs. Blockchain is the new combination of data flow, energy flow and business flow on the DLT platform. The technology guarantees security and allows even the sale of micro amounts of energy between prosumers. It enables the automation of transactions within the power grid and monitors prosumers' energy consumption and production. The scheme of microgrids is shown using blockchain technology.(X. Zhang et al. 2021)

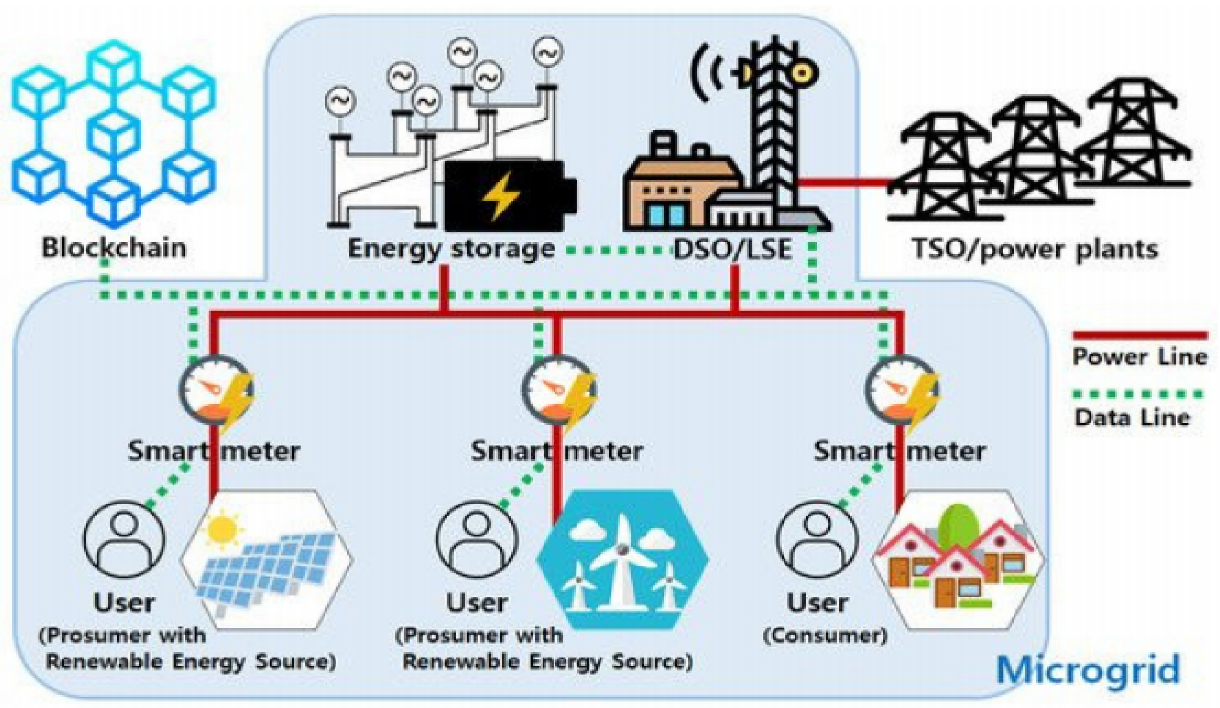


Figure 13. Information data flow using blockchain in microgrid scheme on energy market(Son et al. 2020)

The dynamic development of distributed generation, including renewable energy sources connected to the distribution grid, will significantly impact the role and functioning of distribution system operators. The transmission system transmits electricity from the power plant through the transmission line, supports optimal management, and promotes reliable system operation. According to a research from Eurelectric, DSO coordination of marketplaces may provide significant benefits to consumers in peer-to-peer platforms offering access to the wholesale energy market. ("EURELECTRIC Launches Expert Discussion Platform on Blockchain" 2017).

Blockchain is one of the solutions by using a machine learning approach to manage energy in renewable microgrids. The next technology that has brought a digital revolution in building smart grids, managing renewable energy and distributed generation is the digital twin, which will be discussed next.

#### 3.3.4.3 Importance of Digital- Twin in the Energy Trading system

Digital twin technology creates a virtual machine or production line simulation capable of mimicking the use and behaviour of the actual machine or production line in real-time. Using the model, it is possible to check strength issues, material fatigue, forces, and stresses, all mechanical engineering. The model simulates the natural user environment of the machine and work process. The simulation can help see how the equipment works and control the equipment maintained by engineers. The technology uses a combination of machine learning, artificial intelligence, and software analysis on data collected in production plants to create digital simulation models. It can allow for continuous updation when individual parameters of the process or operating condition of the given device change(Bevilacqua et al. 2020; Cigniti Technologies 2019). The technology creates a detailed and dynamic simulation if there is access to a larger amount of data. The twin can be used to simulate the operation of a piece of equipment or production line before any decision is made. This will help to save costs and reduce the risk associated with expensive investments. Digital twins is an important technology for design installations and systems, as simulation helps in research and conducted analysis. The idea of a digital twin engine with its mechanical elements is presented below:

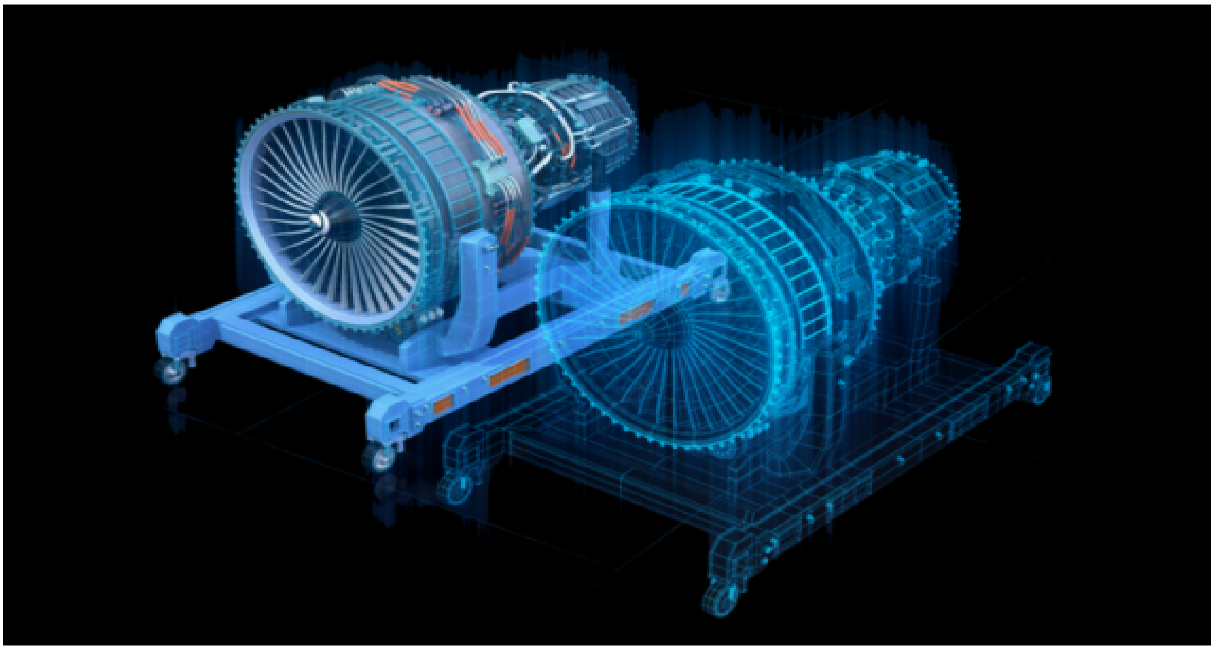

Figure 14. Real object and digital-twin model("Digital Twins as a New IoT Milestone: How Do They Work?" 2019)

Digital Twin technologies in the energy sector can enable the development and maintenance of smart grids equipped with high tech sensors and machine learning models for increased efficiency and monitoring. As discussed, the smart grid enables prosumers to make informed, strategic decisions and mitigate vulnerabilities and risk factors by updating the data regularly. The combination of cyber-physical systems, cloud computing, and intelligent industrial solution in digital twin technology becomes the foundation for smart grid deployment, renewable energy management, better integration and efficient transmission. The technology uses a network of sensors in the energy infrastructure, which allows for better monitoring of demand-supply of energy and effectively manages its transmission (Cigniti Technologies 2019). Additionally, sensors in the network enable the maintenance of the network by monitoring its element, for example, the level of corrosion. The virtual model created based on obtained current data from the existing grid reduces the time and cost of designing new installations. After processing with AI algorithms, the collection of large, time-varying, and diverse datasets can yield conclusions about future improvements and user anticipated features.

### 3.3.4.4 Use of Blockchain in the Smart Grid Versus Use of Digital Twin: Which is better?

The literature research of Blockchain and Digital Twin helped to know the selection criteria which is required to select the technology in Smart Grid. The selection criteria parameters are Current researches in the field of technology, their technology maturity, the performance of the technology, current challenges in the technology.

Table 8. Weighted sum model for selecting the technology for Smart Grid

| **Criterion** | **Criterion weight** | **Level** | **Criterion Score** |
|---|---|---|---|
| Current researches | 0.25 | Low | 20 |
| | | Medium | 50 |
| | | High | 100 |
| | | | |
| Performance of the technology | 0.25 | Not known | 0 |
| | | Medium | 50 |
| | | High | 100 |
| | | | |
| Current Challenges | 0.25 | Many | 40 |
| | | Few | 80 |
| | | | |
| | | | |
| Technology Maturity | 0.25 | Not Matured | 20 |
| | | Matured | 100 |

Each criterion is equally important and should overcome the criterion problem to implement the technology. Therefore, the criterion weight is equally distributed among the parameters. The criterion score provided is self-explanatory depending upon the levels defined.

Table 9: The rating criteria

| | Current researches | Technology Maturity | Performance of the technology | Current Challenges | Total Score |
|---|---|---|---|---|---|
| **Blockchain** | **High** | **Matured** | **Medium** | **Few** | **82.5** |
| Digital Twin | Medium | Not Matured | Not known | Many | 37.5 |

Digital Twin is the concept of creating virtual replicas of the physical object and synchronising data between the physical and virtual object to monitor, simulate and optimise the physical object(Hou et al. 2020). The technology is realised due to the possibility of real-time data processing and constantly updating the state of facilities and processes. But, the technology is currently at a nascent stage, and the technologies associated with it require advancement. The advancement of enabling technologies such as 5G development, Internet of Things standardisation, artificial intelligence algorithm, and the use of blockchain 3.0 technology is only a matter of time before the industry moves to the digital twin approach. The popularity of technology will grow as innovative factory trends unfold. Also, global efforts and government policy are leaning towards developing technology to better harness industrial energy efficiency and saving energy. Therefore, the technology needs more research and development and holds a promising future for developing digital twin energy-saving systems in the industry(Teng et al. 2021).

Blockchain technology has been successful and is used as the basis for digital transactions in areas such as trading, cryptocurrency, stock trading, and many other scenarios where the technologies' unique features have allowed for groundbreaking solutions(Maesa, Di Francesco Maesa, and Mori 2020). Therefore, blockchain can enable a more efficient, dynamic, reliable and sustainable electrical system. Power Systems can provide energy in response to demand at the right time, right place, at low cost and with the lowest emissions("Digitalization and Energy – Analysis - IEA" n.d.). The technology offers solutions to electricity and heat consumers at a large scale and an individual level. In the future, the integration of blockchain in microgrids will probably improve the quality of energy and proper operation in power systems. The machine learning approach to managing energy in renewable microgrids by creating models is one of the solutions provided by the technology.

Therefore, applying ratings on criteria generates total scores for Blockchain as 82.5 which is the best choice available between the two.

### 3.3.5 When Blockchain meets Smart Grid

The traditional power grids distribute constant energy supply to a region without knowing the consumption. As a result, the region experiences excess power wastage while the region that requires energy runs out. It does not take into account the demands and needs of consumers when it comes to electricity. The grid should be operated and managed efficiently in order to maximise the likelihood of electricity utilisation and distribution. Therefore, a smart grid having an advanced network system and communication can distribute flexible loads by sensing customer demands. (Dorri et al. 2019).

An efficient demand response management(DRM) system associated with the smart grid plays an essential role in balancing demand and supply of energy. As previously stated, it is possible that renewable energy sources will not be sufficient to meet consumer expectations. Therefore, to fulfil the low electricity supply, the electricity is managed by a demand system. The DRM system continuously checks power distribution regulation based on the region's demands.(Li et al. 2015). Deep learning and machine learning approaches are used to improve the system's intelligence, efficiency, and responsiveness. The system works well if a sub-community has a demand less than the energy generated by the microgrid (Apostolopoulos, Tsiropoulou, and Papavassiliou 2021). Otherwise, the region can experience a shortage which can cause a shortage of electricity. As a result, hydrogen storage or energy trading from different subcommunities is critical in creating energy at the consumer end to deal with the scenario. The subcommunities using renewable energy can store, produce, and share power supplies via the smart grid and share it with other consumers who need the energy.

Challenges in Energy Trading:

Energy Trading is a practical option to meet the energy demand and supply, but it has limitations mentioned below(Kumari et al. 2020):

- Trust Management: It is essential to have faith in a third party who can keep the seller and buyer's energy trading promises.
- Safety: The buying and selling of buyers and sellers should be broadcast securely and should safeguard it from cyber attacks such as privacy breaches, impersonation attacks, Sybil attacks, and data modification attacks.
- Transparency: There is a lack of transparency in the centralized system. Therefore, whatever energy needs to be traded by the prosumer, and whatever selling price has been set by the authorised nodes, the bid price should be available to everyone.

These challenges can be addressed by incorporating blockchain in Energy Trading, and the next section describes its integration.

### 3.3.5.1 Blockchain Integration in Energy Trading System

Blockchain ensures the security and integrity of block transactions by containing a chain of immutable blocks based on smart contracts and consensus methods. There are various fields in a block which are (Jindal et al. 2020):

a) The hash value of the current block: Block-hash
b) The hash value of the previous block: Previous block-hash
c) System for tracking transactions: Timestamp
d) For authenticating the transaction process, a random number is created: Nonce, and
e) The hash value of all transactions in the block: Merkel.

A block's transactions and data are immutable, which means they can't be changed.

Blockchain is a distributed ledger that safeguards consumers' trust by preventing single point failure. In Energy trading, trust is built between nodes by executing smart contracts that allow transactions to take place without the use of an intermediary or centralised nodes. A smart contract is a self-executing programme language written in programming software such as Go and Solidity. Purchasers store energy obtained from renewables and start an energy sell request through block transactions in blockchain-based Energy Markets. Each participant has a full copy of the energy trade transactions on the blockchain system. Every participant has an updated transaction value that is maintained by the integrity of energy trading transactions. The integrity of the transaction is taken care of by consensus algorithms. The consensus mechanism ensures that the data of buyers and sellers is revised in each registered member's ledger copy. Smart contracts manage and monitor the node's behaviour as well as the energy trading process. Therefore, smart contracts and blockchain offer complete transparency and a fantastic tool for trading energy. (Kumari et al. 2020)

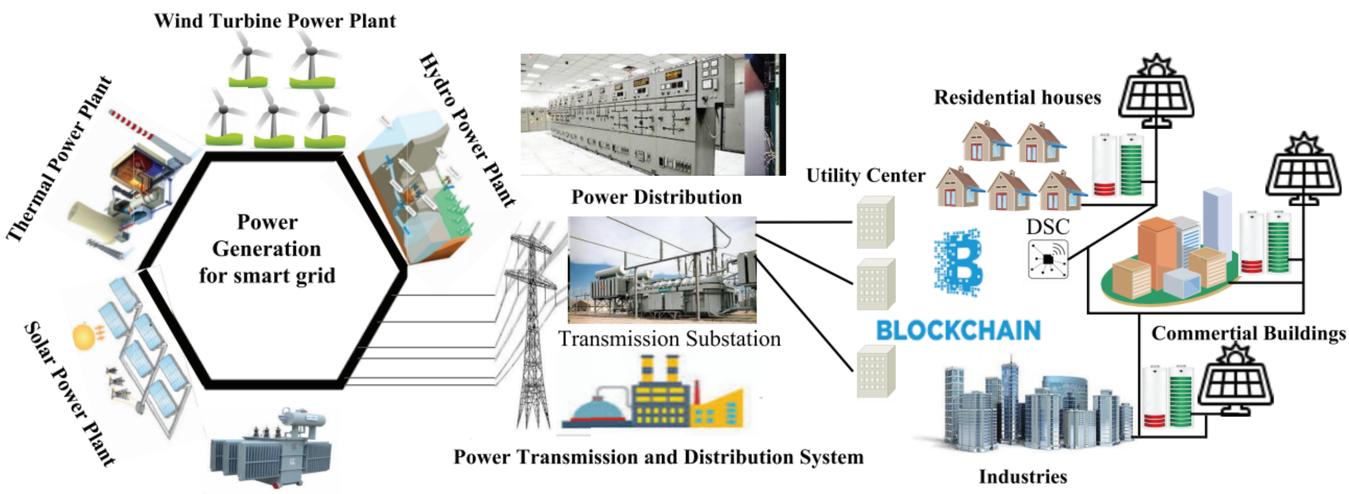


Figure 15. Secure Energy Trading System Using Blockchain(Kumari et al. 2020)

Energy trading system workflow:

To empower Energy trading using Blockchain technology, it should first have a microgrid consisting of consumers such as commercial buildings and housings, and producers such as buildings or houses connected to renewable energy, storage devices like hydrogen and grid. In our case, these all components are present in a sub-community. The consumers must have a device or a system to join the blockchain as a node. It should also build a blockchain system that connects producer and consumer nodes, and create a group of controller nodes that provide producer nodes the right to produce power and sell it to consumer nodes via the blockchain. In the Energy Trading Transactions, every node in the system is classified as a consumer and a producer. The producer nodes post the selling price for their energy assets, and the consumer nodes can look at the pricing and choose one that meets their needs, as well as offer to perform transactions using ET currencies. (Kumari et al. 2020)

The detailed ET process steps are discussed below(Kumari et al. 2020):

a) Energy trading request: A producer who wishes to sell its energy requires permission from an authority to sell the energy. The energy produced at the producer node can sell its assets, but they don’t have permission to sell it. Therefore, a controller node authorizes the producer node to sell the power to all the consumer nodes in the system by sending the service request. Then the controller node accepts the request, and the consumers can see the price published by the producer in the system. If the consumer wants to buy the energy, it can then request it for their consumption. The figure down below shows the flowchart of energy trading requests in a private blockchain system.

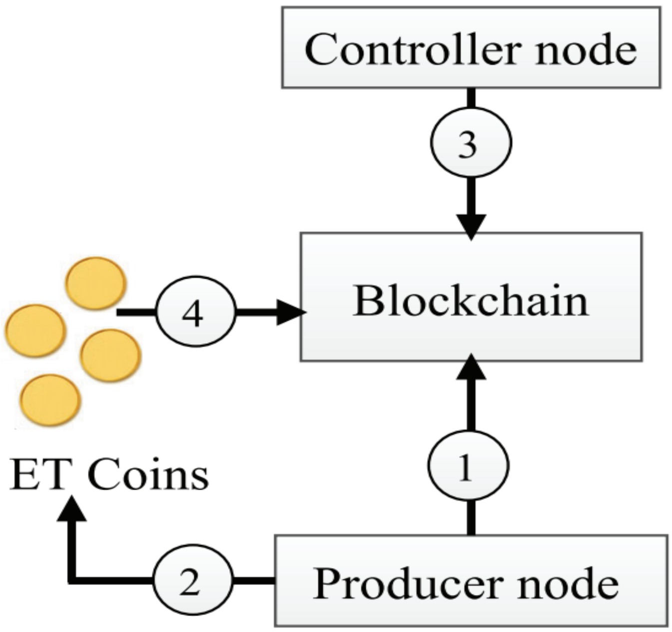


Figure 16. Request for Energy Trading

b) Purchasing coins from a controller node: Participating in Energy Trading requires the buyer to have a cryptocurrency in their blockchain wallet, such as ETcoins (a unit of ETcoin equals, for example, Euros/Rupees). If the consumer wants to buy the Etcoins, it should purchase it from the controller node. The currencies are then kept on a secure blockchain ledger. Any customer who wants to participate in ET transactions must buy it from the controller and update the ledger with the new value.

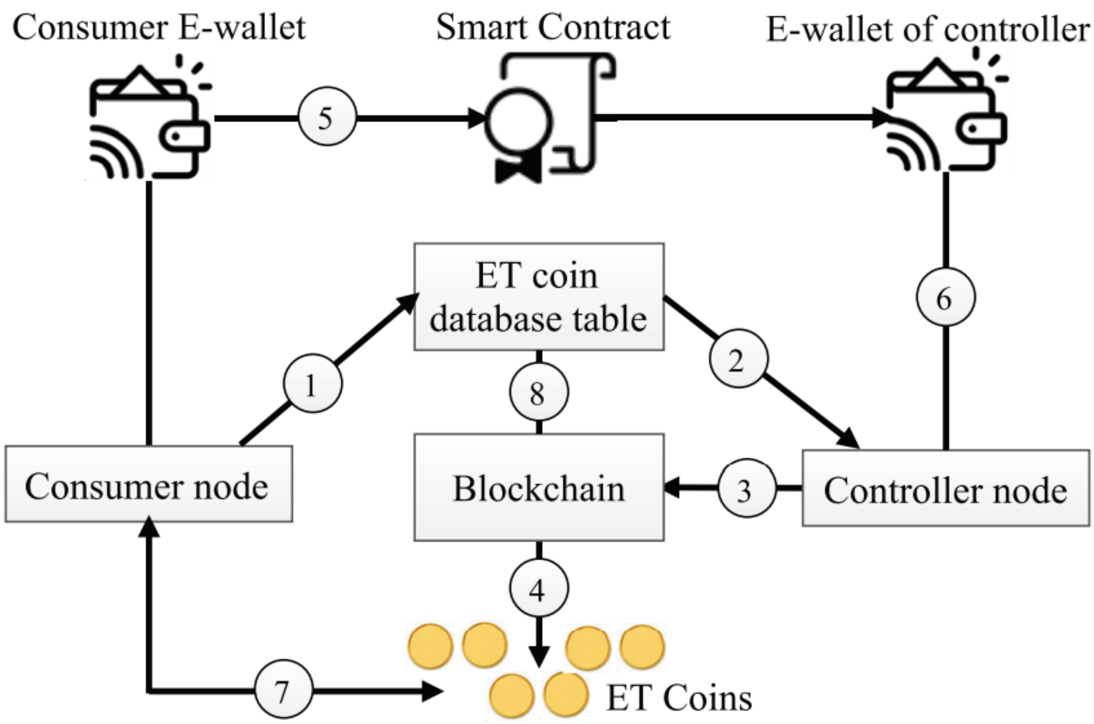


Figure 17. Purchasing coins from the controller node

c) Matching Energy Trading prices: The buyer dynamically posts its energy prices once the seller publishes their energy selling price within the network. The controller node then matches the purchasing and selling prices and keeps track of the matching prices. For example, consider the table below, which shows six nodes in a network. The producer node N1 posts his selling price as 5 Etcoins per kWh of energy on a certain day. Only two consumer nodes prices, N4 and N6, match the producer's sell price. As a result, only N4 and N6 can take part in the priority transaction, giving a higher price than the seller. Different price matching mechanisms can be applied, like auction matching, stable matching, and dynamic pricing matching, which can be applied depending upon the situation.

| SellerID | SellPrice (INR per kWh) | Energy to Sell (In kWh) | BuyPrice (INR per kWh) | BuyerID | Matched Transaction | Status | Remarks |
|---|---|---|---|---|---|---|---|
| N1 | 5 | 4 | 3.5 | N2 | ✗ | - | BP $<$ SP |
| N1 | 5 | 4 | 4 | N3 | ✗ | - | BP $<$ SP |
| N1 | 5 | 4 | 6 | N4 | ✓ | Successful | BP $>=$ SP |
| N1 | 5 | 4 | 3 | N5 | ✗ | - | BP $<$ SP |
| N1 | 5 | 4 | 5.5 | N6 | ✓ | - | BP $>=$ SP |
| N2 | 6.5 | 4.5 | 7.5 | N1 | ✓ | Successful | BP $>=$ SP |
| N2 | 6.5 | 4.5 | 4 | N3 | ✗ | - | BP $<$ SP |
| N2 | 6.5 | 4.5 | 6 | N4 | ✓ | - | BP $>=$ SP |
| N2 | 6.5 | 4.5 | 3 | N5 | ✗ | - | BP $<$ SP |
| N2 | 6.5 | 4.5 | 5.5 | N6 | ✓ | - | BP $>=$ SP |
| …<br>…<br>… | …<br>…<br>… | …<br>…<br>… | …<br>…<br>… | …<br>…<br>… | …<br>…<br>… | …<br>…<br>… | …<br>…<br>… |
| N6 | 4 | 3 | 7.5 | N1 | ✓ | Successful | BP $>=$ SP |
| N6 | 4 | 3 | 3.5 | N2 | ✗ | - | BP $<$ SP |
| N6 | 4 | 3 | 4 | N3 | ✓ | - | BP $>=$ SP |
| N6 | 4 | 3 | 6 | N4 | ✓ | - | BP $>=$ SP |
| N6 | 4 | 3 | 3 | N5 | ✗ | - | BP $<$ SP |

BP: Buy Price, SP:Selling Price

Figure 18. Example of Matching Energy Trading Prices

The establishment of consumer data protection rules is the responsibility of regulatory agencies. According to the EU's consumer data policy, the consumers and prosumers in the blockchain system should be identified in order to account for their liabilities. However, in the meantime, consumer's sensitive information, like the prices decided between the consumer and prosumer within the smart contract recorded in the ledger, must stay confidential. Data from various users are recorded in shared ledgers and solutions need to be found to protect information privacy and security. Additionally, to protect the users, the smart contract's need to be integrated with legal codes and conduct to comply with the law. For this, address fuzzification, data hiding and route hiding techniques are required.

- Address Fuzzification: This approach generates anonymous addresses to protect the blockchain users' real addresses. Each ET transaction generates a new pseudonym address to safeguard the privacy and security of the user.

- Data hiding: The basic idea is to hide the user and energy data in large data set so that no one misuses it. Therefore, data masking is employed to hide actual energy consumption.

- Route hiding: The system is vulnerable to attackers getting some private information from the consumer and prosumer based on routing messages. Therefore, the routing allocation scheme, like garlic routing, protects the parties' private information from hackers.

d) Transaction Creation and Settlement: The proposed system's privacy and security are ensured by transactions recorded in the blockchain ledger and carried out via various consensus techniques. If a consumer requests energy, the request is passed to the seller node, and the controller node validates the request if the customer has enough ETcoins. The process of execution of settlement is shown down below.

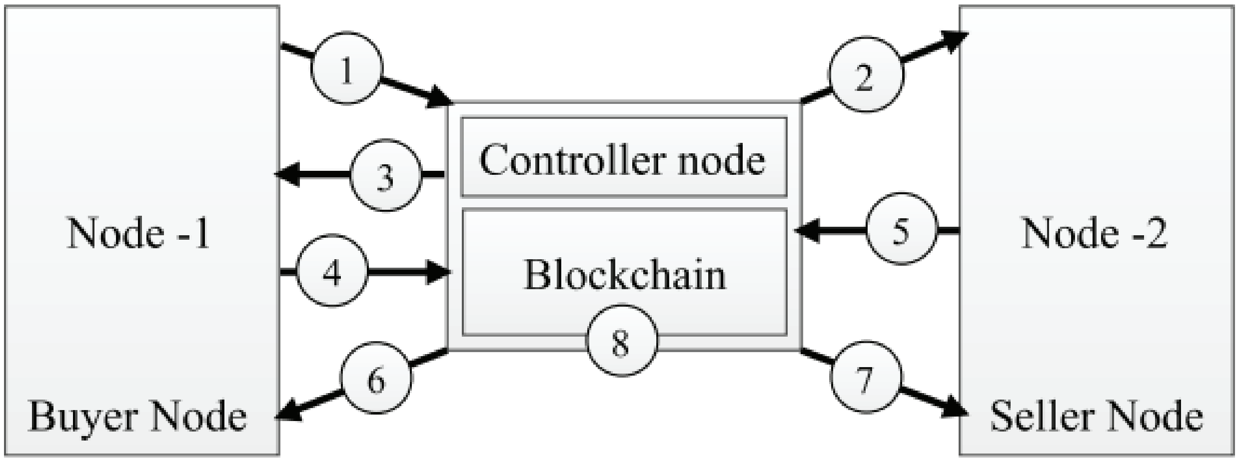


Figure 19. Transaction Creation and Settlement

### 3.3.5.2 Smart Grid Architecture

To achieve a robust and efficient operation, designing a robust communication network infrastructure is important. There are multiple smart architecture models, but they all follow a multilayered structure. There are three main layers (Qarabash, Sabry, and Qarabash 2020):

a) The power system layer, which is analogous to the old power grid, is responsible for producing and delivering electricity to customers.
b) The communication layer offers interconnection between all parts of system components by collecting data from end-user interfaces and sensors to transmit them to data centres and vice versa.
c) The application layer is where data is processed to control and monitor signals. They're also used for automatic metre reading, demand management, and fraud and misuse detection. In the figure below, the three levels are depicted.

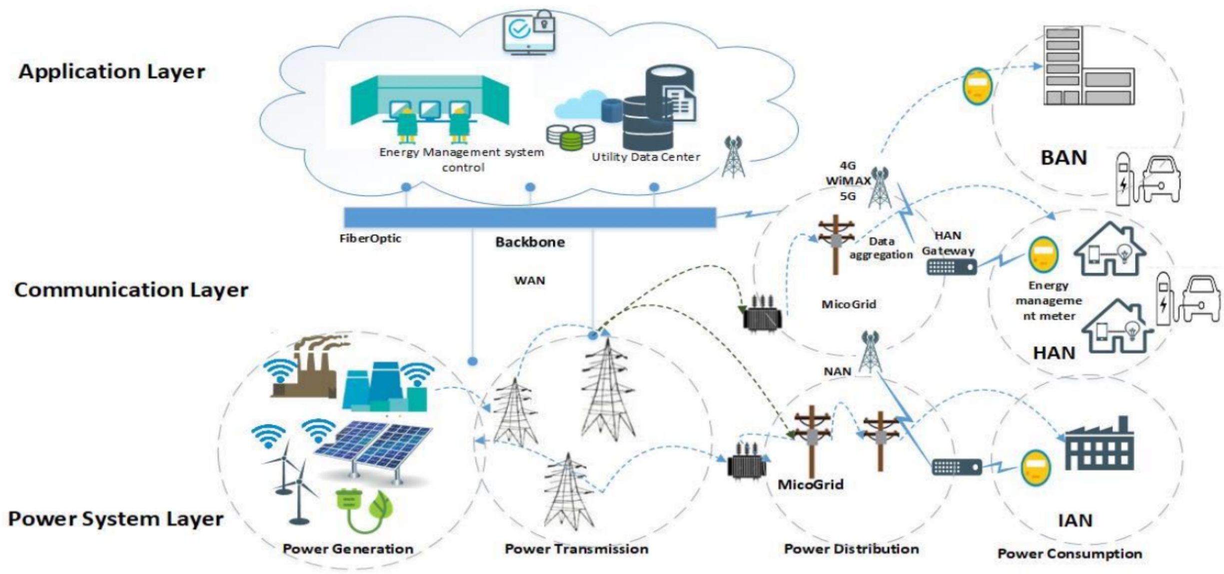


Figure 20. Smart Grid Architecture(Qarabash, Sabry, and Qarabash 2020)

The Smart Grid is based on the utilisation of a variety of networks that vary in location and size, such as:

a) Smart devices and appliances are connected to a smart metre within the home via the Home Area Network (HAN). They have a small range and can communicate reliably at low data rates. Therefore, it has low implementation costs and energy consumption. Therefore, in the sub-community, HAN will connect the smart devices and appliances to a smart meter inside the home.
b) The Building Area Network (BAN) is similar to the Home Area Network (HAN), except it spans a larger area and can be made up of numerous smaller networks. Therefore, BAN will connect the homes within a sub-community.
c) The Industry Area Network (IAN) is similar to the Business Area Network (BAN), but it is more complicated and focuses on industries and factories.
d) The Neighbourhood Area Network (NAN) connects HANs, BANs, and IANs to the WAN, allowing for the collection of metering data from thousands of smart metres. These have a broader range of

applications and faster data speeds. This network will connect all the sub-communities and ensure trade of energy between them.

e) NANs use a wide area network (WAN) to send electricity reports to the main control centre. They need a high data rate and a vast range of coverage. Optical networks are a frequent mode of communication.

#### 3.3.5.3 Evaluating the performance of the workflow

This section assesses the performance of the proposed secure energy trading system. A set number of member nodes, which are residential homes with computer systems, are participating in secure Energy Trading on a private blockchain platform to evaluate the performance. The controller node was then recognized as having all of the necessary system setups, and then administration rights were granted to it. The system's remaining nodes are called participating nodes. A typical node can be a consumer or prosumer node to perform the transaction. The framework is tested and deployed in Chandigarh, India. For evaluating, 100 homes were considered with PV solar panels having electricity generation capacity of 5KWh per day. The connected network area, such as the neighbourhood area network (NAN), consists of ten 20,000-kilowatt-hour power transmission stations. Therefore to validate the proposed framework, core functions of the secure energy trading system were implemented using the firm language like Ethereum (TestNet version). The network comprises three entities: the controller, prosumer and consumer node. (Kumari et al. 2020)

Computation Time:

The standard addition operation, the method for block processing, and the data appended take 1 ms, 2.7 ms, and 0.5 ms in the system, respectively. The computation time from node one to node two is the addition of computation time in node one and computation time in node two. The computation time noted for node one was 16.5 ms. Therefore, the total time of computation is 33 ms. Additionally, when the key transfer and block preparation durations increase for a growing number of transactions, the computation time increases.

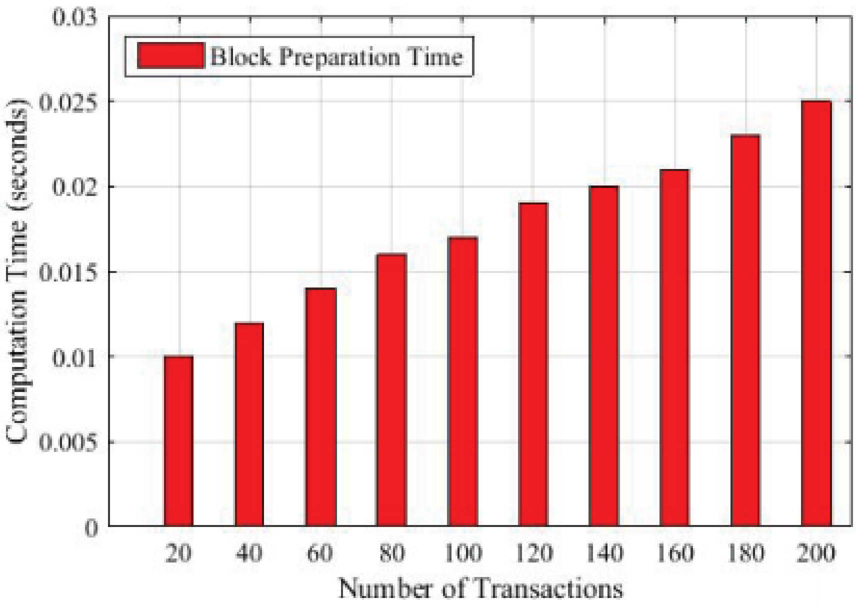

Figure 21. Block preparation vs Number of Transactions(Kumari et al. 2020)

To understand if the performance has improved, the framework was compared with the traditional energy trading system. The traditional trading system provides centralized authentication, whereas the smart energy trading system provides decentralized authentication and validation in the smart grid environment. The decentralized system provides complete safety and privacy to the data and energy and provides real-time execution of transactions faster than the traditional system. Also, the framework is independent of the trusted third party and is a peer to peer network. The results show that the proposed framework takes less time for the number of transactions than the traditional blockchain network, which makes it feasible to use the system.

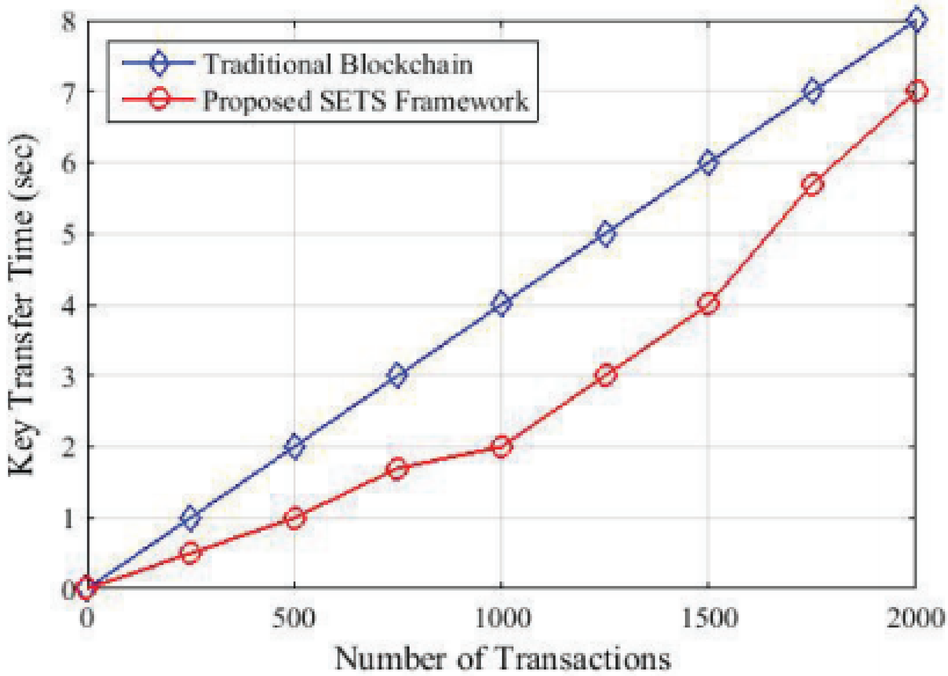

Figure 22. Key Transfer time proposed in SETS vs traditional block scheme(Kumari et al. 2020)

Accuracy of distributed systems towards Industry 4.0:

Centralized systems currently in use have a single control centre to collect the data and create global information. The system can potentially suffer from being inaccurate, especially when data is missing. The missing data results in poor decision making and leads to problems that are sometimes difficult to repair. On the other hand, decentralized systems redesign the networking system to allow each working unit to have global information without using any hubs. When the accuracy of the decentralized system over the centralized system is evaluated, the results show that the data loss has a negative effect on the accuracy of the system. Also, long periods of usage causes high inaccuracies in the centralized systems when data loss occurs, but not in decentralized systems. But, when there is no data loss, a centralized system works perfectly without any inaccuracy, while decentralized systems will give some errors at the beginning of the simulations.(P. 2018)

The error at the beginning in the decentralized system is because when the accuracy of a decentralized system is estimated, an epidemic membership protocol mechanism is used, in which sensors hold the local cache, and each sensor connects to other 20 random sensors. This results to recognize approximately 2 per cent of other sensors. In each cycle, 1/4th of the connection in the local cache will be exchanged with other sensors due to the epidemic membership protocol. As a result, the system's structure is rewired continuously in each cycle.

Therefore, these results conclude that the decentralized system is suitable under the condition when data is missing. Otherwise, a centralized system can be selected when the data will not be lost, which is an ideal condition.

### 3.3.6 Key Challenges to use the Technology and the future outlook

The projects and research in the field of blockchain show that it is a promising technology having wider applications and services. Therefore, many established energy companies and investors involved in distributed ledger technology have shown the energy industry's potential for this nascent technology. However, the technology's true long-term worth has yet to be demonstrated, especially because most projects have only tested it in small-scale projects that are still in the early stages of development. Therefore, key problems must be solved before the blockchain can be widely adopted in the energy sector.

The technology needs to prove that it can offer scalability, speed and security required in the distributed ledger. Blockchain applications like Bitcoin have limited transaction capacity, which is 3 seconds per transaction and maximum of 7 seconds per transaction currently. Various solutions have been devised to deal with challenges like the lightning network that opens direct peer to peer channels and uses the blockchain Bitcoin as underpinning for some actions that require confirmation. Also, the consensus algorithms discussed do not provide a solution that combines all the desired characteristics with the significant trade-offs. PoW algorithms, for example, are more developed and reliable, but they are also energy-intensive and slow. As a result, they're turning to energy-efficient, quicker, and more scalable algorithms like PoS schemes. Furthermore, as early adopters of blockchain technology, they must select the appropriate mechanisms, algorithms, and architecture of the system to have a long-term vision of the benefits and drawbacks that each mechanism offers. The system has clearly proved its initial concept for various applications, but it still has to be improved to meet required performance and operational goals. Current developments like Energy Web blockchain has the potential to scale up to thousands of transactions per second future scientific research and development will have a substantial effect on technology acceptance in various applications that demand quick confirmation and a high number of transactions(“Use Cases for Blockchain Technology in Energy and Commodity Trading” n.d.).

Lack of experience with large-scale applications, bad system designs and malicious attacks are likely to cause security problems and face the danger of malfunctioning at an initial stage. The technology is primarily reliant on coding, which is prone to mistakes. Before the technology matures, there is a significant likelihood of cybersecurity incidents, resulting in negative publicity and a delay in customer acceptance. In terms of cyberattacks, Bitcoin, the first blockchain technology application, has shown to be relatively resistant. However, other platforms, like Ethereum, have already been the target of major attacks. Most importantly, cyber security breaches are caused by third-party programmes like smart contracts and digital wallets. As a result, robustness to such attacks is critical for applications in essential infrastructure like energy systems. There is no centralised authority in a distributed system architecture to whom consumers can direct their complaints, like today. It is unclear who will bear legal and technical liability for the harmful consequences of various parties' actions. In the blockchain system, rather than a known authority, trust is placed in the technology itself.(Andoni et al. 2019)

The development costs of blockchain systems are currently high and cost may be reduced by reducing circumventing intermediaries, but they may not have a competitive edge over existing established marketplaces(“EURELECTRIC Launches Expert Discussion Platform on Blockchain” 2017). Energy transactions, for example, might be recorded in traditional databases such as relational databases, which are designed to recognise relationships between stored data items. Despite the system's lack of transparency and immutability, these solutions are readily available and less expensive to operate. On the other hand, the systems in the blockchain require costly infrastructures, like ICT equipment, sensors, and software. But, the cost of implementing the technology must be outweighed by the advantages achieved by increased security, data integrity and the removal of the requirement for a trusted intermediary. Furthermore, because smart meters are being deployed without significant processing capabilities, connecting the smart grid and grid infrastructure with a distributed ledger could be costly.

Currently, data in blockchain can be shared at very little costs, but data verification and validation come with hefty energy and hardware costs. But, the proof of authority or stake algorithms can dramatically improve this in future. In grid communications, the blockchain is up against well-established technologies like telemetry, which is a mature and substantially less expensive technology (“EURELECTRIC Launches Expert Discussion Platform on Blockchain” 2017). Furthermore, blockchain systems must bear the added cost of keeping data in an ever-expanding ledger. Therefore, to this problem, it is proposed to store real data in “side chains” and operate the blockchain as a control layer rather than as a storage layer.

Lack of standardisation and flexibility is another key problem that can impede blockchain adoption. As a result, standards for blockchain architecture must be defined in order for technology solutions to communicate with one another. Additionally, any changes to the ruling protocol or code must be approved by system nodes if a blockchain system is established. This can lead to mistrust and fragmentation as a result of conflicts between the developer and many system forks (“EURELECTRIC Launches Expert Discussion Platform on Blockchain” 2017). Furthermore, blockchain adoption could be hindered by Bitcoin's negative reputation coming from its early affiliation with criminal activities. However, as blockchain technology advances, this feature may become less significant.

Adoption of the technology faces significant obstacles in both the legal and regulatory domains. Regulatory bodies must support consumer participation. Several officials must also put supportive policies to encourage low-carbon technologies, lower consumer costs,  and combat fuel poverty. Blockchain technology can help the accelerated goals set by regulators to amend larger adoption of distributed ledger technology. Currently, the regulatory frameworks do not promote peer to peer energy trading projectsNew contract types and frameworks will be required to specify agreements between consumers and producers when using the public grid. Also, a framework needs to be developed for more flexible power tariffs, which are currently governed.

Finally, present regulatory prices would need to be linked into microgrid energy markets. Because peer-to-peer trading infrastructures are still in their early stages of development, their adoption is currently limited. But, it can potentially disrupt the market and the existing energy companies who regulate the monopolies and own the physical infrastructure. Regulatory boards have started promoting pilot projects trialling to understand the benefits of consumers and energy system operations. In addition, blockchain technology works on the decentralisation principle that can lead to complex energy systems management. All these challenges necessitate regulatory reforms and may cause blockchain implementation to be delayed.(Andoni et al. 2019)

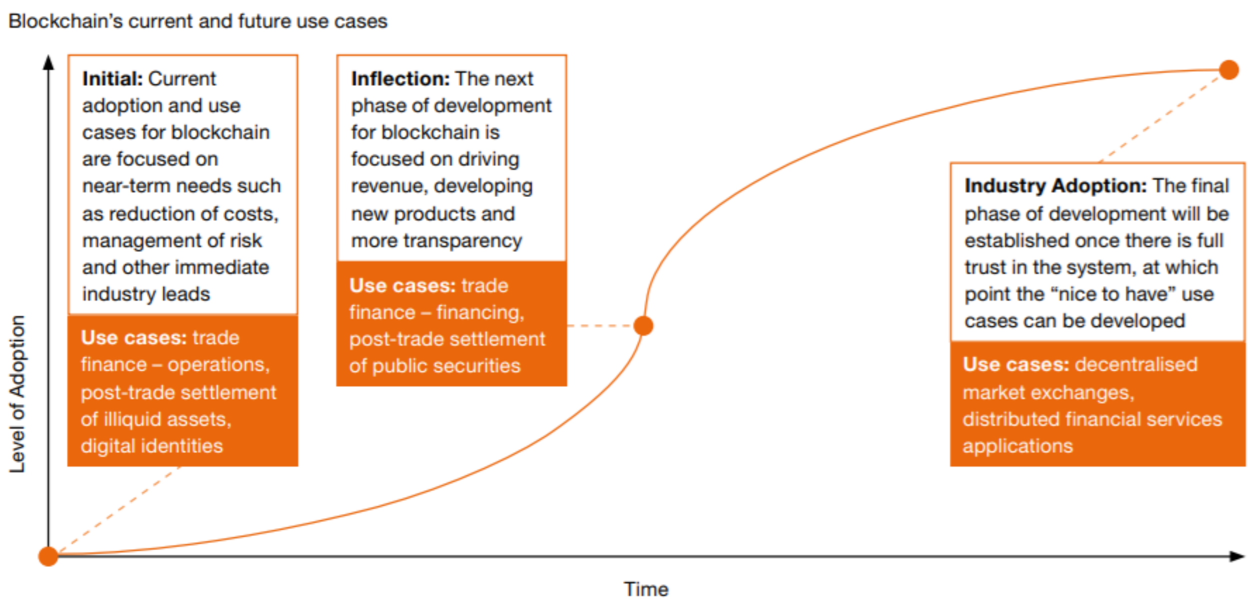


Figure 23. Future Blockchain Development(“Use Cases for Blockchain Technology in Energy and Commodity Trading” n.d.)

# Chapter 4

## 4.1 Conclusion and Results

The main objective of the research was to develop a technical model for implementing Hydrogen technology in community-based scenarios. Therefore, the main research question was:

***What could be the technical model to implement Power to Hydrogen technology in the subcommunities that could be used by the government or private parties?***

Based on models studied, Chapter 3 proposes how the future could look using hydrogen technology in the community-based scenario. Firstly, the current models in the hydrogen technology proposed by articles and research papers were studied. The loopholes were understood so that the model developed takes care of current flaws in the design. Figure 7. and Figure 8. proposes the model of how hydrogen technology and renewable energy can be integrated to make the sub-community self-reliant to consume the energy from a hundred per cent of its renewable sources. To take it further, the model discusses how hydrogen technology can be expanded and how energy trading is possible within a sub-community or between the sub-communities using smart grids and Industry 4.0 technology. Industry 4.0 technologies used in other sectors like trading were studied. After the multi-criteria decision analysis, Blockchain technology was found to be a feasible solution that can be used according to the current application of technology in other fields and already providing a proof of concept to use the technology. Then the workflow system to create a secure energy trading environment using the blockchain technology was discussed, and theoretical analysis validated the performance and accuracy of the system over the traditional centralized trading system.

The technology has already shown its proof of concept in other fields like trading in cryptocurrencies; however, it is implemented in small-scale projects and is still in the early development phase in the energy sector, as shown in Figure 19. However, as the technology evolves and matures, it is not far away that the technology will be adopted in the industry. However, still, the technology has to face some key challenges before the mainstream adoption of blockchain technology in the energy sector.

a) The technology has to prove that it can offer scalability, speed and security required in the distributed ledger. To cope with the challenge, different solutions are developed. One of them is a lightning network that opens peer to peer channels and uses blockchain bitcoin for some operations that need confirmation.
b) The technology relies heavily on coding. Suppose inadequate systems are developed, and malicious attacks cause security risks of malfunctioning. In that case, it can cause a loss of trust in consumers' minds, which can cause a delay in the adoption of the technology. Therefore, the technology should be fully proven before its implementation. Bitcoin, the first blockchain technology application, has shown to be relatively resistant and has been able to keep up with the consumers' trust.
c) The development cost of blockchain is currently high and might not have a competitive advantage over the established markets. However, the cost of implementing the technology must be outweighed by the advantages achieved by increased security, data integrity and the removal of the requirement

for a trusted intermediary. Also, the operating cost will be much less in the long run, which will recover the initial investment cost to develop the technology.

d) Another essential factor that needs to be taken care of is standardization and flexibility to use the technology. Lack of standardization and flexibility can lead to disagreements between the developer and multiple system forks, leading to mistrust and fragmentation. Furthermore, blockchain adoption could be hindered by Bitcoin's negative reputation coming from its early affiliation with illegal activities. However, as blockchains evolve, this attribute may become less important in the future.

e) Adoption of the technology has both regulatory and legal barriers, and as the technology is new, the regulatory bodies are not aware of the potential benefits of the technology. Therefore, the regulatory bodies need to be aware and play a vital role in endorsing the active participation of the consumers.

Stage 1 in Chapter 3 discusses the basics of the power to hydrogen technology and creates a foundation to develop a model in Stage 3. First, the technology processes are discussed in detail, and the current technological barriers associated with technology are understood. Then, recommendations are provided to overcome the barriers associated with it. For example, after analysing different electrolysers using the weighted sum method, PEM electrolysers are selected according to the parameters needed to implement in a community. In the same way, recommendations using the Analytical Hierarchical process on how hydrogen transportation is feasible currently and in the future is discussed. Next, Stage 2 in Chapter 3 discusses the technical barriers that hinder the deployment of hydrogen technology. Then what government policies are in place and whether the policies align well to foster hydrogen deployment in a community-based scenario is studied.

## 4.2 Recommendations

- After understanding the processes in power to hydrogen technology, it is understood that selection of electrolyzer is critical to convert surplus power into hydrogen. Then, the hydrogen stored can be used by a community when in need via fuel cells. Currently, the electrolyzers are divided into four main technologies depending on various parameters like the temperature of operation, different materials, efficiency, durability and cost of the electrolyzer. These four types are:

  a) Alkaline
  b) Polymer Electrolyte Membrane(PEM)
  c) Anion exchange membrane(AEM)
  d) Solid oxide

  Efficiency, durability and cost of an electrolyzer are dependent on each other, and improving one results in a decrease in the performance of the other. Therefore, tradeoffs have to be made according to the needs and select the electrolyser for our application.

  In our application, electrolyzers will be coupled to PV and wind energy , typically operating less than 2000 hours in a year, making capital cost an important aspect to address. Durability may be less of a problem with such limited hours("IRENA" 2019).

  PEM is moderately efficient, and the technology has matured to be used commercially. Therefore, they have a low cost of operation and a moderate investment cost as it uses expensive noble metal catalysts. On the other hand, while solid oxide and anion exchange membrane (AEM) have efficiency up to 100 per cent, they are now at lab scale and need a major step forward to use at large scale to overcome the disadvantage. In addition, the technological curve has not reached the stage where it can be used commercially. Therefore, the cost of investment is high.

  Therefore, PEM electrolysers will be the best-suited option as it is technologically matured and commercially available with moderate efficiency. In addition, it has a low cost of operation and moderate cost of operation.

- There is a mismatch between the supply and demand of hydrogen, and hydrogen distribution methods and infrastructure are crucial for increasing the overall size of the hydrogen market. The storage and transportation of hydrogen become the most challenging phase for the redistribution of hydrogen. The construction costs of installing a new hydrogen pipeline can vary significantly with the estimation that it will currently cost around 10 to 20 per cent more than the construction of a natural gas pipeline with a lifetime of 50 years. In addition, the feasibility of technology has to gain trust in the eyes of investors.

The existing natural gas pipelines are already well established. Therefore, before the infrastructure is developed for hydrogen pipelines, existing natural gas pipelines can be combined to supplement the new pipelines. This recommendation also aligns with the policies stated by the government of the Netherlands. But, the addition of hydrogen to the natural gas pipeline is an acceptable short term solution because:

a) The addition of about 10 per cent into natural gas pipelines is technically feasible with minor ignition risks, no increased leakage risks and no increase in pipeline fatigue.
b) Transportation of hydrogen will be economically acceptable, and till the early market development phase of the hydrogen transport develops, it can be treated as an alternative way to transport hydrogen.
c) The public already accepts the transportation of flammable gas, and operating such cases will be essential to understand the future utilisation of the existing natural gas pipelines.

On this basis, the transportation of hydrogen using existing gas pipelines will be an interim solution. However, pure hydrogen needs to be separated from natural gas. Two techniques are recommended to separate the hydrogen from natural gas in the section “Selection of Membrane” in section 3.

- Stage 3 in Chapter 3 recommends a technological framework to assess the implementation of hydrogen in a community-based scenario. Blockchain technology is a feasible solution to manage the supply and demand of electricity and energy trading in the community. As the technology is trialled in small scale projects in the energy field, there are few key challenges to use the technology. The key challenges and the future outlook of the technology are discussed to understand how it can foster its use.

## 4.3 Limitations of the research

- Blockchain technology and the smart grid is still rapidly evolving. Also, data and communication processing technologies are constantly developing and progressing. The model developed considers the current state of the technology, and it is hard to predict what technology will look like in the next five to ten years.

- The research does not focus on the reliability and integration of various technologies discussed. Since the technology is dependent on real-time data processing, it is important to investigate the reliability of individual components used and the reliability of integrating various technologies to provide recommendations for more reliable solutions to apply and identify fault areas to overcome. Additionally, the technologies used to develop the framework were developed for other purposes.

- The model developed is based on considering the known parameters before the actual implementation of the project. This means that the model considers the ideal situation, but while implementing it in real life, external factors can hinder the deployment of power to hydrogen technology. Therefore, the model does not consider the external factors to recommend a modified model for the same.

- The technology is at a nascent stage, and currently, it is not widely adopted. Also, while doing the literature survey, few articles talked about the integration of hydrogen in a community. Therefore, there may be factors that are not considered while developing the model.

## 4.4 Management of Technology relevance

The course guidelines emphasize the use of scientific-analytical study and should highlight technical aspects like technology, strategy, innovation, etc. Moreover, the outcome of the thesis should help the stakeholders or the organization involved to implement the technology or the process qualitatively.

Managing different technologies and their integration to implement or develop a new product or innovation is the core of the Management of Technology programme. It requires understanding the views of different stakeholders and coming to conclusions with the best possible solution. The thesis "Technological Framework to assess the implementation of power to hydrogen" aims to develop a framework by integrating different technologies to help the stakeholder's like the government, the companies related to the energy field and the people to implement power to hydrogen technology in a community-based scenario which is relevant to the MOT programme. To implement the framework, the thesis uses scientific study and methodologies, which were part of the courses in the Management of Technology programme. For example, the thesis uses multicriteria decision-making methods learned in the course Inter- and Intra- organisational decision making. The course has helped me to think qualitatively and critically to make decisions. The course was lacking in quantitative analysis which will be more helpful to make decisions by understanding and analysing the data. But, the thesis uses AHP method which uses both qualitative and quantitative analysis to make the decision. The data collected from the literature studies were used to develop the technological model with the strategies studied during the course**.** The main research question is parted into sub research questions to get the detailed answer to all the aspects and to come up with a deductive conclusion.

Therefore, the research represents a scientific study that represents a technological perspective of power to hydrogen technology which aligns with the MoT course guideline.

## 4.5 Scientific Relevance

To reach the target set by the current legislation of EU member states to reduce greenhouse emission, storing green hydrogen was found to be an innovative way to store renewable energy. The literature study formulated on how the Power to Hydrogen can be implemented in community-based scenarios. The technology being nascent, there are various options, elements, components and decisions to choose from while making the selection. Therefore, the multi-criteria decision analysis method to make scientific and informed decisions was unique to the research. Another distinctive result was the framework developed will be a good step to transition from using fossil fuels to a renewable-based system. The model implemented can set examples for the other countries to implement hydrogen technology according to their geographical dynamics and governmental policies. The technology is not widely known, this research helps the readers understand the potential benefits and create awareness to use the technology to create a hundred per cent renewable-based energy ecosystem. Also, the scientific research is represented so that the readers without any background in the field of hydrogen technology can understand. This creates an opportunity to carry the research further if someone is intrigued with the dynamics of power to hydrogen technology.

## 4.6 Areas of future study

The research presented can be used as a foundation to implement it according to various parameters of the region. The implementation of the power to hydrogen system is in the early stage. Therefore the design estimates are mainly qualitative, and the main task of the thesis is to complete the implementation.Therefore the future study can focus to make the estimates more quantitative, which in turn will help the design to improve. The technology is new and while doing the research it is possible that there may be factors that are not considered while implementing the technology. Therefore, many more models and frameworks can be developed so that the vision to become a carbon-neutral world becomes a reality.

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