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The Technology Monitor 2021

Hydrogen green energy and Smart roofs

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Foreword

This is already the third Technology Monitor to be released by STT. Once again, TU Delft, under the project leadership of Dr. Roland Ortt, has made an in-depth analysis of two technologies on which many have pinned their hopes, but for which it is as yet uncertain whether they will be labeled as a technological breakthrough at some point in the future. For the 2021 version, the choice was made for 'green hydrogen' and 'smart roofs'. Two technologies (or technological systems) that are different but, as the report will show, also have similarities and even can be complementary.

Dr. Patrick van der Duin,
managing director of
The Netherlands Study
Centre for Technology
Trends (STT)

December 2021

The systemic nature of both technologies is an important similarity. An agreement they share with almost all contemporary technologies. Virtually no technology can be developed in isolation these days. System technologies and system innovations are no longer the exception, but are now the rule. This does not make it any easier to make strategic policy for both government and companies with regard to the further development of the relevant technologies. Whether this is good or bad news I leave to the reader. But it does shed some light on how fast technological developments and the diffusion of the resulting products and services are going. I mean, the systemic nature of technology and innovation means developers can no longer do it on their own. Technology development and innovation are 'distributed processes' (as it is so beautifully called) that are becoming increasingly complex. Collaboration is good and necessary, but does not automatically lead to acceleration. Who does not know the African saying: 'If you want to go fast, go alone; but if you want to go far, go together'.

“If you want to go fast, go alone; but if you want to go far, go together.”

The speed of technological developments should therefore not be exaggerated. For example, the Technology Monitor states that in 1895 (!) the first experiments with hydrogen were carried out in Denmark. And as for smart (green) roofs, I refer the reader to the famous Hanging Gardens of Babylon. What does go faster is the diffusion of new products and services (based on technology). Here we do see exponential curves describing the diffusion (market acceptance) of innovations. An interesting question that arises is what relationship there is between technological development and innovation diffusion curves. A possible hypothesis is that technological collaboration is not only stimulated by increasingly necessary collaboration, but that the steeper diffusion curves lead to shorter payback times, i.e. more business risks and that these can be limited if the development trajectories are shared (i.e. more collaboration). Perhaps this question can be addressed in follow-up research by STT.

'All things may change' ('Het kan verkeren'), the poet Bredero once said. For example, hydrogen was not so 'hot' a few years ago, but in 2021 it is considered promising. It is therefore important to keep a cool head, not to overestimate the pace of technological development and, above all, to continue to analyse well. This Technology Monitor is exactly intended for that: an analysis of the current status of the development of hydrogen and 'smart roofs' and based on this determine what needs to be done to give these technologies a serious chance. In my humble opinion, this report provides the right background and the right tools for this.

Introduction

The Netherlands Study Centre for Technology Trends (STT) conducts broad futures studies on the crossroads of technology and society. Those crossroads can be approached from a societal perspective. Society is a large unit to study, which is why it is divided into various domains. In most cases, the foresight studies are conducted from the point of view of such societal domains, like education, healthcare, industry and security. STT's reports often include an exploration in one of those domains, as a building block of a multidisciplinary picture of society as a whole. In each domain, technological developments play a role. The interplay of the broader social influences and developments in specific domains is an important basis for an exploration at the crossroads of technology and society in the existing work at STT.

The crossroads of technology and society however, can also be approached from the perspective of new technological developments. As such, new technological developments together present a large unit of research, which is why they are divided into separate technologies, like gene therapy, robotics, blockchain and self-driving cars. Each of these technologies typically develops and diffuses over a longer time period, in which the technologies are often applied in various domains. The interplay of the broader social influences and the developments in specific domains, and their joint effect on the development and diffusion of a technology are an important basis for an exploration at the crossroads of technology and society that complements the existing work at STT.

In domains like education or healthcare, different technologies are applied that set changes in motion. In turn, new technologies like the Internet, developed and diffused by being applied in various consecutive domains. In some cases, technologies even create new social domains or combinations of domains. In short, if we want to examine the crossroads of technology and society, we need complementary perspectives, including social domains as well as new technological developments.

This report describes a 'Technology Monitor', in which two societally significant new technological developments, 'Green hydrogen' and 'Smart roofs', are examined. Earlier versions of the 'Technology Monitor' were released in 2018 and 2020 (See Ortt and Dees, 2018; Ortt, 2020).

This report focuses on two research questions:

- ➔ **What is the current status regarding the development and diffusion of two potential breakthrough technologies, notably 'Green hydrogen' and 'Smart roofs'?**
- ➔ **What conditions have to be met for these technologies to become actual breakthroughs?**

Methodology

Technology definition

Technology is a broad concept that can include many things, which is why, in this report, an approach is presented for providing an unequivocal definition of a technology. We define a technology by describing three characteristics: its working principle(s), its functionality and the first tier of components or subsystems. This approach is then applied to the two selected technologies for this report, 'Green hydrogen' and 'Smart roofs'.

Pattern of development and diffusion

To map the development and diffusion of those technologies, we use an initial model, which describes a pattern of development and diffusion of technologies over time. The model, which distinguishes three generic phases, can be used to indicate how technology was developed and applied in the past, and how it could continue to be developed and applied in the future. Depending on the length of each of these generic phases, different scenarios can be distinguished for specific technologies. The pattern can also be used to visualize the consecutive applications of the technology over time. To answer the question as to the status of the development and diffusion of the technological breakthroughs, we will use the pattern to indicate in which phase the technology currently is.

Framework with actors and factors

The pattern of development and diffusion is the outcome of the interplay of a large number of actors and factors (further referred to in short as factors) that ultimately determine technological and societal change. To explain the changes over time, this report uses a framework that represents a large number of factors that set technological change in motion. Those factors are presented as a dashboard representing conditions for large-scale diffusion. So if large-scale diffusion has not yet begun, this method can be used to determine which conditions have not yet been met. Or, to put it differently, the method can help to find the main barriers preventing large-scale diffusion. As such, the model is used to answer the second research question.

In an electricity grid it is important that the electricity characteristics (Voltage, current, Hz) are kept constant although the use varies. The usage shows fluctuations which, if the production of the electricity wasn't adapted accordingly, would lead to voltage drops and other problems, that in turn would damage appliances connected to the grid. In a traditional electricity grid the electricity production and the management of its transport are centralized. Maintaining the electricity characteristics by managing the production and transport of electricity were already very complex in a traditional electricity grid.

In a modern electricity grid, the production is even more complicated. Firstly, because electricity production includes input from wind farms and other sustainable electricity sources next to the centralized production. The electricity generation from such sustainable sources depends on the wind and sun for example, and those natural sources do not vary in line with the usage fluctuations. Secondly, many users of electricity, be it business or consumer households, have become both producers and users of electricity, because they installed solar panels and wind turbines or other sources of electricity that are connected to the grid. So households use electricity but also feed electricity back to the grid. These two developments, multiple sources of electricity and users that also became producers, have complicated the management of the production and the transport of electricity.

For a short description of problems in the electricity network requiring changes in the grid see:

<https://spectrum.ieee.org/a-plugandplay-microgrid-for-rooftop-solar>

Applying the methodology for 'Green hydrogen' and 'Smart roofs'

The three parts of the methodology are developed over the years and are combined in one instrument, the 'Technology Monitor', which is developed for STT by the first author of this report, Roland Ortt. For a more detailed description of the Technology Monitor see Appendix 1. The methodology is applied in this report for two cases, 'Green hydrogen' and 'Smart roofs'. The methodology starts with a literature research to track the origin of both technologies and to describe their development and application over time. The literature research for 'Green hydrogen' is completed by Florian Schmidt, the one for 'Smart roofs' is completed by a group of authors: Petrik Buitenhuis, Dennis Geutjes, Parikshit Nikumbh, Ashok Willis, Vaishnavi Yerram and Irene Zanutto. In addition to the literature research, some experts are consulted to complete the report. The final report is edited and completed by Patrick van der Duin, Franca Gribnau and Roland Ortt.

Two breakthrough technologies 'Green hydrogen' and 'Smart roofs'

Green hydrogen, an energy source and carrier, and Smart roofs, a combination of different innovations that can be fitted on or integrated with the roof of buildings, have a few things in common. Both represent examples of sustainable technological innovations that help in managing the stability of the electric grid (See the text in purple).

Both may turn out to become breakthrough technologies. Breakthrough technologies are technologies that can be applied in several domains in society and that have the potential to initiate a structural change in those domains. Another thing that both technologies have in common is the fact that their wide-scale use requires a change in the larger system of energy provision and use. A final commonality of both technologies is that they consist of parts or modules most of which are already available. It is the combination of the parts and the necessary changes in the larger system that still need to be implemented.

The technologies are seen as important parts of the transition towards sustainable energy provision and use. Interestingly, the two cases also have a direct link because hydrogen can be used to store energy for a rooftop micro-grid. This is why we decided to choose these technologies for the current version of the Technology Monitor for STT.

Reading guide

Chapter 1 will start with defining green hydrogen. Green hydrogen is a type of hydrogen that is created in a sustainable way. Hydrogen is a feedstock for the chemical industry, a fuel and a carrier of energy. We focus on the latter application and discuss in what stage of the pattern green hydrogen currently is and what actors and factors do either block or stimulate large-scale use of green hydrogen. Chapter 2 will show a similar line of reasoning in describing smart sustainable roofs. Smart (sustainable) roofs are systems that combine and connect different technologies in a smart way. Chapter 3 will summarize the answer to the research questions and will discuss differences and commonalities between the two technologies.

“Green hydrogen and smart roofs are important for the transition towards sustainable energy provision and use.”

Chapter 1

Green hydrogen



Introduction

195 countries have signed the Paris agreement and many are currently implementing measures to slow down the global warming (Fuel Cells and Hydrogen 2 Joint Undertaking, 2019). The de-carbonization of the energy system requires a radical change in how humanity generates, distributes and stores energy. Carbon-free energy generation is the cornerstone of the energy transition that the world must undergo. But additional technologies, such as green hydrogen, are required to leverage a carbon-free energy generation.

We will focus on green hydrogen. After defining what green hydrogen is, we will describe the pattern of development and diffusion and indicate in what stage green hydrogen currently is. The actors and factors that either stimulate or hamper further development and diffusion will be discussed next.

Defining the technology

Hydrogen

Hydrogen is a colourless, odourless, but highly flammable gas (Dawood et al., 2020). For more than 100 years hydrogen is known and explored. But the recent awareness of a carbon-free society accelerated hydrogen research.

Despite its colourless appearance hydrogen usually classifies in three colour categories distinguishing its production method (Dawood et al., 2020; Kakoulaki et al., 2021):

- **Grey hydrogen:** The primary source of grey hydrogen is fossil-based. It is produced from steam methane reforming or coal gasification, leading to high degrees of pollution during the production. CO₂ is set free to the environment.
- **Blue hydrogen:** Fossil-based hydrogen incorporating a carbon capture and storage technologies. CO₂ emitted during the production will be captured with an efficiency of 85-95%, leaving 5-15% of the CO₂ in the atmosphere (IRENA, 2019). However, the large-scale diffusion of blue hydrogen is hampered due to its reliance on finite resources.
- **Green hydrogen:** Renewable energy is used during the production of green hydrogen. Therefore this is the only production method which has near-zero carbon emissions.

Besides of the above-mentioned categories other more specific or local classifications exist, e.g. yellow for solar-powered production or purple for nuclear-powered production of hydrogen (Dawood et al., 2020).

Green hydrogen

Functionality

Green hydrogen is usually used in three different use cases (Fuel Cells and Hydrogen 2 Joint Undertaking, 2019):

1. Energy carrier to store and transport renewable energy during production peak times;
2. Mobility as a fuel¹ for the transportation industry;
3. Gas and feedstock for industries, such as steel and heating industries.

For this report we will mainly focus on the developments of green hydrogen as an energy carrier and mobility solution. In these two use cases, green hydrogen stands in a competition to other alternative fuels and energy carriers. Therefore, the diffusion of green hydrogen in these use cases is especially fascinating. Green hydrogen has different benefits but also barriers for each use case. Hence, the technical comparison, patterns and conditions will be analysed separately.

Use case: energy carrier

Hydrogen research used to focus on the transportation industry (IRENA, 2020). However, the applications have broadened and especially in the energy industry green hydrogen has distinctive benefits (Koochi-Fayegh & Rosen, 2020).

The transportability of green hydrogen through pipelines opens unique opportunities for renewable energy. Allowing to generate renewable energy at one place with efficient characteristics and use it at another geographic location. Moreover, green hydrogen has a very high energy density allowing to store large quantities of energy at a relatively low risk and near-zero carbon emissions (see Table 1-1). Nevertheless, the production of green hydrogen has a comparatively low efficiency and the technology is not mature enough for commercial and large-scale use cases. These barriers will be further discussed in the last section.

¹ If the vehicle is using a fuel cell or hydrogen combustion is exogenous to the analysis in this report (Toyota, for example, is selling cars that apply a hydrogen fuel cell to power an electric engine. It is developing cars that directly burn hydrogen in an internal combustion engine).

Table 1-1: Comparison of energy storages (adapted from Hameer & Niekerk, 2015; Koohi-Fayegh & Rosen, 2020; Olabi et al., 2021)

Criteria	Flywheel	Hydrogen	Battery	Thermal	Compressed air ²	Pumped hydro ²	Magnetic
Energy density	medium	very high	high	high	low	low	low
Power density medium	high	medium	high	N/A	low	low	
Efficiency	high	low	high	low	medium	medium	high
Capital cost	low	high	medium to high	low	low	medium	high
Maturity	high	medium	high	medium	high	high	medium
Capacity	medium	medium	low	medium	high	high	medium
Environmental impact of the storage	medium	medium	high	low	low	medium	medium
Safety	low	medium	low	high	low	high	medium
Self-discharge rate	high	medium	medium	medium	medium	low	medium

² Requires special location.

The criteria have been collected based on extensive technical analyses by other researchers. The quantitative analysis is transformed into a qualitative assessment for increased comparability. The criterion 'efficiency' is measured in cycle efficiency. While the criterion 'environmental impact of the storage' assesses long-term effects of the storage on the environment, such as recycling, the criterion 'safety' measures the immediate safety of the storage solution, such as mechanical risks or gas and chemical leakage.

Use case: mobility

For the second application, hydrogen as a mobility solution, the gas is also quite competitive compared to the other fuel types (see Table 1-2). Especially its very low environmental impact during use is remarkable. However, the price still stands in the way of large-scale diffusion, which will be further discussed in the last section.

Table 1-2: Comparison of fuels (adapted from Nicoletti et al., 2015)

Criteria	Methane	Gasoline	Coal	Hydrogen
Environmental impact during use	medium	high	medium	very low
Price	medium	medium	low	very high
Flammability	high	low	high ³	medium
Safety	medium	medium	high	medium

Operational principles

The operational principles for green hydrogen are limited. In fact, the most important and only requirement is the use of renewable energy for the production. If other energy sources are used the hydrogen is not declared as green anymore, as described above.

Components

As part of this section the components to produce, transport and store green hydrogen will be explained. Consumers of green hydrogen such as fuel cells, cars, buses, but also the steel production are excluded from this analysis. These are classified as complementary goods and analysed later on.

³ Coal is a solid fuel and 'does not create significant problems of expansiveness and flammability' (Nicoletti et al., 2015, p. 207).

Production

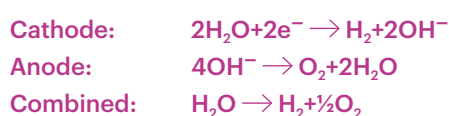
Normal hydrogen can be obtained from different sources, however the most relevant sources are water, hydrogen sulphide, biomass and fossil hydrocarbons (Dincer, 2012). While fossil fuels or fossil hydrocarbons are currently the main source for hydrogen via steam reforming (Bičáková & Straka, 2012), they cannot be used for a carbon-zero production of green hydrogen.

The number of sources decreases if an environmentally friendly solution is required (see Operational principles). The most mature technology for a large-scale production of green hydrogen is water electrolysis (IRENA, 2020). Furthermore, the water electrolysis process allows to reap synergy effects by combining sectors to level out peaks and fluctuations of renewable energy.

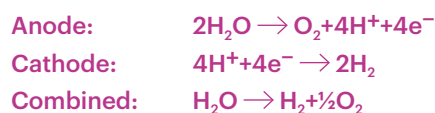
Two technologies are available to extract the hydrogen during the water electrolysis: alkaline process and the proton exchange membrane (PEM) process (Bičáková & Straka, 2012). Both technologies have a rather similar efficiency of roughly 50-65%, 50-75% respectively (Dincer, 2012). Input into the production process is H_2O with the straightforward output of H_2 and O_2 (see formulas below).

The alkaline electrolyser is the most common technology (Bičáková & Straka, 2012). A cathode and anode are hanging in a water tank separated by a microporous separator. Salt is used as a medium to increase the conductivity of the water. At each of the electrodes a different chemical reaction happens.

At the cathode water is split into hydrogen and hydroxyl ions (OH^-). Then, the hydroxyl ions are moving through the solution over to the anode where oxygen is created. Lastly, the hydrogen leaves the solution and is separated in a gas-liquid-separator.



Compared to alkaline electrolyzers, the PEM electrolyzers are usually slightly more efficient and corrosion resistant (Bičáková & Straka, 2012). As a semi-permeable separator a polymer membrane is used to divide the anode and cathode. This allows the reactants to travel through the water and block the electronic path between the electrodes. At the anode, water is dissociating into hydrogen cation (H^+) and oxygen. Moving through the membrane, the hydrogen cations react with electrons creating hydrogen gas.



Transportation

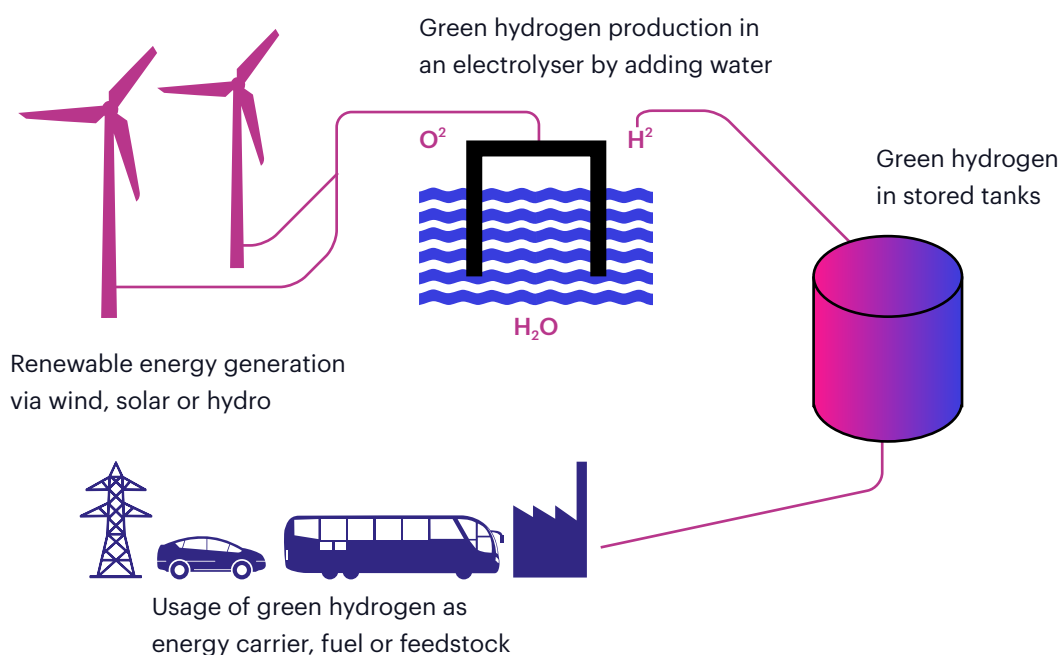
Hydrogen is mostly transported via pipelines (Mulder et al., 2019). For this purpose, dedicated pipelines need to exist which connect places of production and consumption. Alternatively, if pipelines do not exist or are not economical, hydrogen can be transported in tanks over road, rail or water in a gaseous or liquid state.

Storage

Until now, only two storage options are in use. On one hand, hydrogen can be stored in high-pressure tanks for a small-scale storage of 45 MWh (Mulder et al., 2019). On the other hand, emptied salt caverns can be used for storing larger amounts of up to 150 GWh of hydrogen.

All these components combine into the production, storage and usage process of green hydrogen as seen in Figure 1-1.

Figure 1-1: Green hydrogen production, storage and usage



Green hydrogen is a gas produced in an electrolyser from renewable energy and water. Its carbon emissions are near-zero. Green hydrogen can be used for a variety of use cases: energy carrier, mobility solution and feedstock. In this report, we will focus on green hydrogen as an energy carrier and mobility solution. Each of these use cases have different requirements. One major distinguishing characteristic is required cost-efficiency. Further conditions will be analysed later in the report.

Despite the different production processes, the electrolyzers have different requirements for each use case. If green hydrogen is used as an energy carrier, the total runtime of the electrolyzers is limited. The electrolyzers are only running during peak times to take the load off the electric grid. Hence, the operational expenditure (OPEX) only plays a subordinate role. More important is the capital expenditure (CAPEX) during the construction of the water electrolyser plant. The initial investment has a larger effect on the bottom line, compared to the running costs.

In contrast, if green hydrogen is used as a mobility solution or feedstock electrolyzers are running constantly. The price of green hydrogen is predominantly driven by the OPEX of the electrolyser and its efficiency. CAPEX is far less relevant compared to the OPEX due to the full-load hours of the electrolyzers. This essentially creates the demand for two different kinds of electrolyzers:

- ➔ Budget electrolyser with low CAPEX for the use case as an energy carrier;
- ➔ High-efficiency electrolyser with low OPEX for the use case as a fuel and feedstock.

Pattern and applications of green hydrogen

Invention

The first technical demonstration of green hydrogen as an energy carrier dates back to 1895 in Denmark (Nissen, 2019). Poul la Cour coupled one of his windmills with a DC dynamo and electrolyser process at the College of Askov. His idea was to store energy in times when wind was scarce to power the gas lamps of a school. The school was in a remote rural area of Denmark that was not yet connected to the electricity grid. The windmill he used resembled much the well-known Dutch windmills with four blades. The demonstrational project has been used for seven years until further research money was freed to continue the research at the State Experimental Wind Laboratory in Denmark.

Market introduction

In this section applications of green hydrogen as an energy carrier and mobility solution will be discussed. Pure demonstration or research projects are excluded from this analysis. Only productive projects with a long-term focus count towards a market introduction of green hydrogen (see Table 1-3).

Use case: energy carrier

Since the first technical demonstration of green hydrogen in 1895, much time has passed but the applications as an energy carrier were limited. Nevertheless, the interest in green hydrogen is growing recently and a first project started in 2003 in Europe (Thema et al., 2019; Wulf et al., 2018). Many of these (more than 85 projects, Thema et al., 2019) are small-scale applications to demonstrate a proof of concept for a limited time. One of the first real applications is the 'Energiepark Mainz' (Engl.: Energy Park Mainz) which started as a project in 2015 in a collaboration between the government, academia and companies (Energiepark Mainz, 2021). The project uses a PEM electrolyser with a capacity of 6000 kW to generate hydrogen from wind energy. Back in 2015 it was the biggest water electrolyser worldwide (Energiepark Mainz, 2018). Since 2017 the hydrogen production is operational and since 2018 economically viable. This project can be seen as the first market introduction of green hydrogen as an energy carrier in Europe. The project distributes its green hydrogen to local companies, houses and public transportation companies.

Use case: mobility

Although the 'Energiepark Mainz' also distributes its green hydrogen to public transportation companies, a few specialized projects exist which focused on green hydrogen as a fuel. One of the earliest projects is the Wasserstofftankstelle HafenCity (Engl.: Hydrogen fuel station HafenCity) with a capacity of 960 kW. The project started in 2012 and fuelled buses as well as

cars. Since then, more projects have emerged such as the Multi-Energie-Tankstelle H2BER (Engl.: Multi energy fuel station H2BER) or the Hydrogen Bus Project Aberdeen in 2014 or 2015, respectively. Especially the Hydrogen Bus Project is remarkable as it grew from a small application of 10 vehicles to 57 vehicles such as cars, double-decker buses, waste trucks and sweepers.

Table 1-3: Largest applications for green hydrogen as a fuel and energy carrier (Source: Daly, 2021; Energiepark Mainz, 2018; H2orizon, 2021; Hydrogen - Case Study: Aberdeen, 2021; Thema et al., 2019)

Year	Name	Application	Capacity
2012	Wasserstofftankstelle HafenCity, DE	Mobility	960 kW
2014	Multi-Energie-Tankstelle H2BER	Mobility	500 kW
2015	Hydrogen Bus Project Aberdeen, GB	Mobility	1.000 kW
2015	Energiepark Mainz, DE	Energy carrier, mobility, feedstock	6.000 kW
2016	Don Quichote Project, BE	Mobility	undisclosed
2017	H2orizon, DE	Mobility (rocket fuel), feedstock	880 kW
2020	PtG-BW, DE	Feedstock (mobility will be evaluated later)	1.000 kW
2021	Refhyne, DE	Feedstock (energy carrier and mobility will be evaluated later)	10.000 kW

In Table 1-3 it can be seen that the capacity of subsequent green hydrogen plants increase gradually. Besides of the here mentioned operational projects, many more projects are supposed to be completed in the coming years. For example in Delfzijl, NL, an electrolyser of a capacity of 20.000 kW (possible scale-up to 60.000 kW) is about to be finished, however yet to open (Groningen Seaports, 2020). Similarly, the Port of Rotterdam Authority is completing a 250.000 kW electrolyser (Port of Rotterdam Authority, 2021). This also includes options of two more electrolyzers with a total capacity of 300.000 kW.

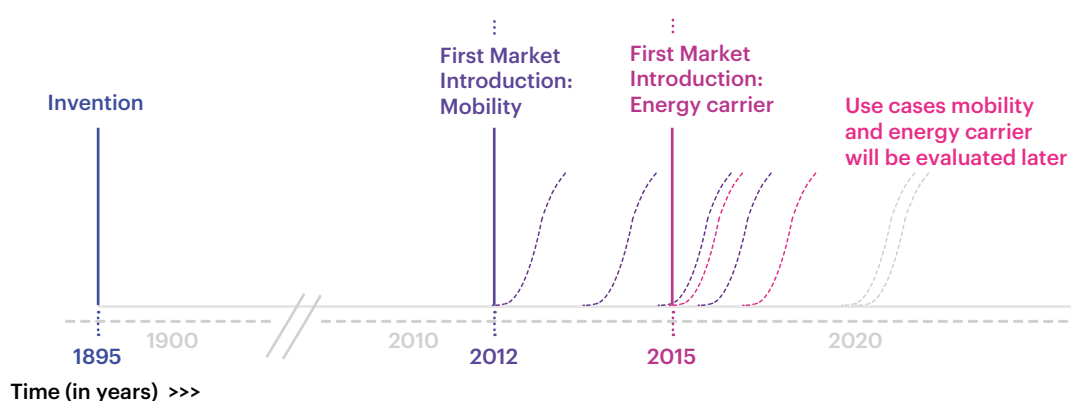
Additionally, events like the 2022 Winter Olympics Games are likely to increase the momentum and awareness of green hydrogen further. Zhangjiakou City, China, has announced to operate the event with green electricity and green transportation (Shell (China) Limited & Zhangjiakou City Transport Construction Investment Holding Group, 2020). A 20.000 kW electrolyser is planned to power up to 1.000 fuel-cell vehicles during the event.

Large-scale diffusion

Until green hydrogen will be produced comprehensively on a large scale time has to pass. Although the 'Energiepark Mainz' is still running, its application is locally confined. Large-scale diffusion is not reached until green hydrogen is available nationwide, as well as cross-country, in sufficient quantity (see Figure 1-2). Currently, no mass market application exists for green hydrogen (Hydrogen Council, 2017). Such a large-scale diffusion is projected to be reached in 2040. Barriers which are currently blocking the large-scale diffusion are explained in the next section.

Fuel applications emerged first, yet are confronted with higher barriers. This means that we think that green hydrogen as a carrier will probably enter the stabilization phase first.

Figure 1-2: Pattern of development and diffusion for green hydrogen use cases energy carrier and mobility



Conditions

In this section, the barriers blocking the large-scale diffusion of green hydrogen will be explained. To assess the barriers in detail, the two use cases (green hydrogen as an energy carrier and fuel) will be evaluated separately. An overview of the influencing and core factors split into the two use cases is given in Figure 1-3.

Figure 1-3: Comparing the conditions for green hydrogen as an energy carrier and mobility solutions

Core factors	Energy carrier	Mobility	Influencing factors	Energy carrier	Mobility
1 Product performance	Green	Red	8 Knowledge of technology	Orange	Orange
2 Product price	Orange	Red	9 Knowledge of applications	Green	Green
3 Production system	Red	Red	10 Employees and resources	Green	Green
4 Complementary products and services	Red	Red	11 Financial resources	Green	Green
5 Actors and network formation	Green	Green	12 Macroeconomic and strategic aspects	Orange	Orange
6 Customers	Green	Orange	13 Sociocultural aspects	Green	Green
7 Standards, rules and laws	Green	Green	14 Accidents and unexpected events	Orange	Red

Although green hydrogen as a mobility solution has more applications, the barriers blocking the diffusion are larger than for green hydrogen as an energy carrier. Recent accidents at hydrogen fuel stations created negative press and that is influencing potential customers' opinions. Additionally, the electrolyser performance as well as the product price are not competitive to gasoline.

For both use cases the production system and complementary products and services, such as pipelines and distribution centres, are lacking. The lack of these core factors hampers the diffusion substantially. Less severe barriers exist regarding the knowledge of technology and macroeconomic and strategic aspects. Especially regarding the last-mentioned factor political friction and indecisiveness exist which hinders the diffusion of green hydrogen.

Based on these barriers, the large-scale diffusion of green hydrogen lies still ahead. Especially, the missing momentum of two (four) core factors for the use case energy carrier (mobility) creates an issue for the large-scale diffusion. In the meantime, more niche applications will emerge which can benefit from green hydrogen's strengths on a smaller scale (Morris, 2020).

Sector coupling could be the key to reach the large-scale diffusion faster. While niche applications have by definition a low demand, combining different niche applications could be the solution for bigger green hydrogen plants that are future proof (see also (Raven, 2007) who explains the idea of niche accumulation). Combining the sectors energy, transportation and feedstock increases the overall demand for green hydrogen. A large green hydrogen plant can then fulfil the demand responsively per application depending on necessity and price.

Chapter 2

Smart sustainable roofs



Introduction

Roofs have traditionally served two purposes: to prevent rain and snow infiltration and to provide good thermal insulation (Juanico, 2010). Therefore, we consider a roof to be an object that is meant primarily to protect the top part of a building and is able to perform the above-mentioned functions. We will focus on a particular type of roofs: so-called smart sustainable roofs. After defining what a smart sustainable roof entails, we will explore the pattern of development and diffusion to indicate in what stage these roofs currently are. The actors and factors that either stimulate or hamper further development and diffusion will be discussed next.

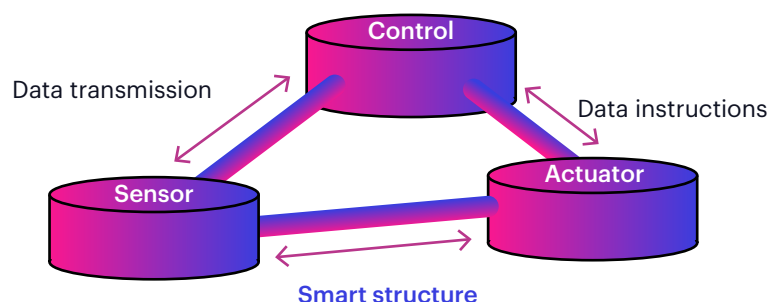
Defining the technology

Smart sustainable roofs are roofs that apart from providing thermal insulation and shelter against rain and snow (the traditional functions of a roof) also incorporate a smart system to make a roof environmentally sustainable. We will start with describing smart systems in general and indicate what smart sustainable systems are. We will then apply this to roofs by distinguishing between different types of sustainable roofs and then focus on sustainable smart roofs. In short: 'Smart sustainable roofs' represent a subset of sustainable roofs that contain a smart system.

Smart systems

A smart system is composed of different components (see Figure 2-1). The core idea of a smart system is that raw data is acquired through sensors. This data is then forwarded to the control system through 'data transmission'. The control system interprets and controls the raw data and decides on actions that are then forwarded as instructions to the actuator via 'data instructions'. The actuator can be anything that performs a task. In short: a smart system contains sensors, a control system, actuators and a network between these components to communicate data and instructions.

Figure 2-1: Basic components of a Smart System. Source (Akhras, 2000)



Adaptive cruise control in cars represents an example of a smart system. Sensors provide raw data about the speed and the distance to the next car. The raw data is sent to the control unit that combines the data and then calculates the best action after which instructions are sent to the motor and brake (the actuators in this example). The change in speed and distance to the next car is then measured again in a subsequent cycle.

Smart sustainable systems

In the context of sustainability, one of the most well-known smart systems is the smart grid. Smart grids are simply the application of various modern communication technologies to the electricity grid (Blumsack & Fernandez, 2012).

Smart grids enable system operators to control energy flows on the grid with more precision, allowing for the integration of renewable energy that requires management of distributed energy production and intermittent energy sources. Smart roofs mimic the purpose of a smart grid albeit on a much smaller and more localised scale.

Sustainable roofs

In this report the focus is on environmental sustainability rather than economic and social sustainability. Sustainable roofs, apart from thermal isolation, provide additional environmental sustainability. Table 2-1 shows the different types of sustainable roofs encountered in this research.

In the Table it is visible that different types of sustainable roofs can be distinguished. All of these roofs are (environmentally) sustainable yet only specific versions of such roofs also contain a smart system. A cool roof containing a reflective surface to reduce the heat in a building is not smart because it doesn't contain sensors, a control unit and actuators. The same is true for a green roof with vegetation to isolate the roof.

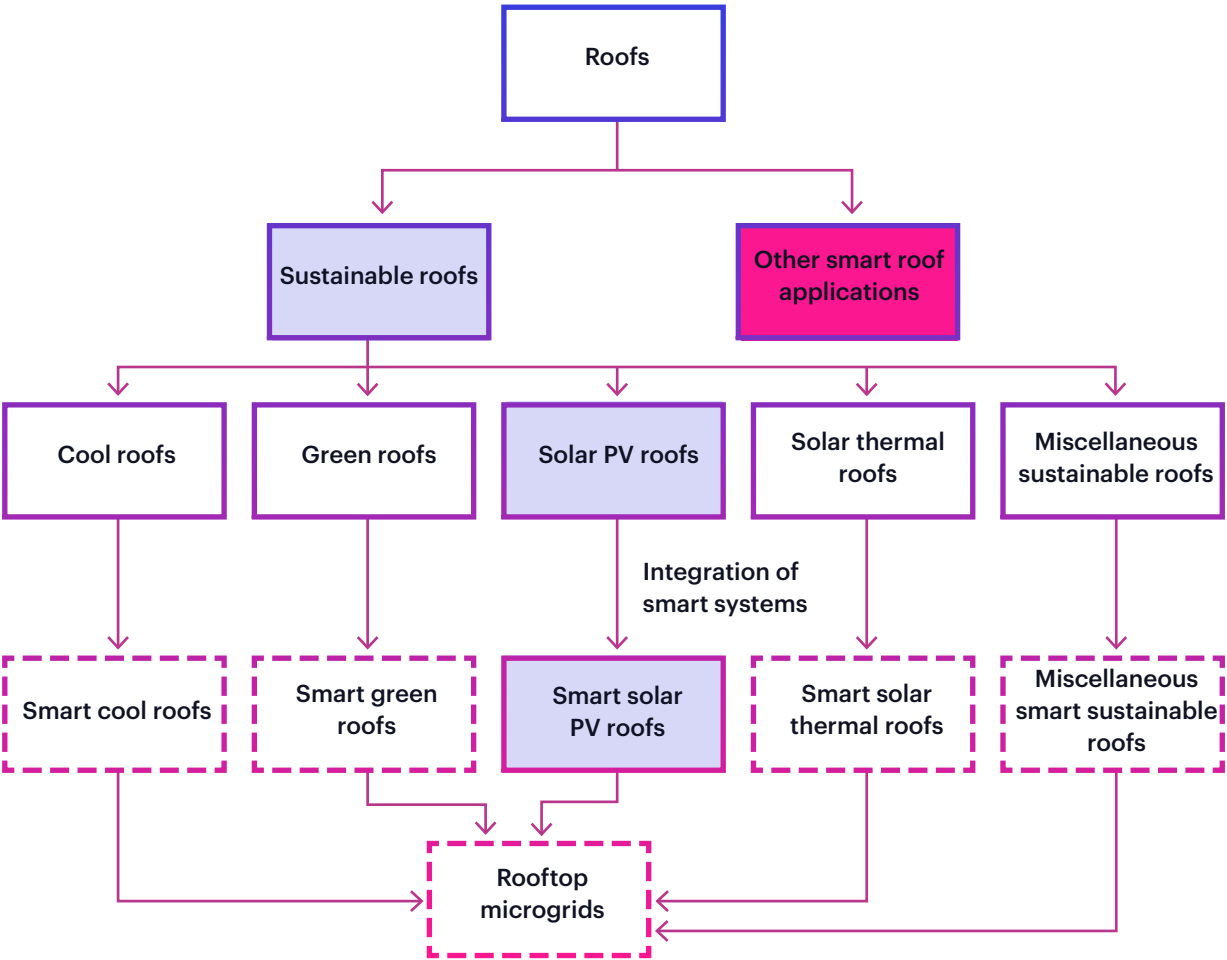
Table 2-1: Categories of sustainable roofs

Type of sustainable roof	Definition
Cool roofs	Cooling roofs use the mechanism of reflective surfaces to reduce the heat transfer to the indoor surfaces. It works on the principle of minimising solar absorption and maximising thermal emittance (Akbari, 2008).
Green roofs	Green roofs are roofs that have urban greenery installed on top of them like green canopies, green pavements and bio-retention areas.
Solar PV roofs	Roofs that convert the energy from the sun in terms of solar irradiation into electricity.
Solar thermal roofs	Roofs that harness the heat from the sun for heating activities including water and household heating.

Smart roofs

Smart roofs are roofs that contain multiple components, for example sensors, a control unit, actuators and connections between those parts to transmit data and instructions. Not all smart roofs are also sustainable. There are some companies that have developed 'smart roofs' and use their smart system to respond to weather for home comfort such as automatic opening and closing due to response to rain such as Smartroof (2021). Similar smart systems are also applied in horticulture. These sorts of smart roofs are not considered sustainable. As can be seen in Figure 2-2 below, the purple highlighted branch is not considered.

Figure 2-2: Different categories of smart roofs



Smart sustainable roofs

Figure 2-2 above shows that there are many kinds of sustainable roofs, only some of which can be considered as a smart sustainable roof. In Table 2-2 are some examples of different types of smart sustainable roofs.

Table 2-2: Examples of smart sustainable roofs focussing on a single function

Type of smart sustainable roof	Example of a smart sustainable roof	Reference
Smart cool roofs	Integration experiment of roof cooling techniques using solar powered fans and sensor equipment.	(Yew et al., 2021)
Smart green roofs	Smart irrigation strategy on roofs using expected evapotranspiration.	(Bandara et al., 2017)
	Proposal of an integrated rooftop greenhouse that is connected with the interior of the building.	(Balas et al., 2018)
Solar PV roofs	Proposal of a smart algorithm for integrating rooftop solar panels and local battery storage with the distribution network.	(Parvez et al., 2020)
	Integrating of rooftop solar panels, local battery storage and smart meter data to optimize energy spending.	(Chatterji, 2020)
	Feasibility study of a system that combines rooftop solar PV and a local electrolyser for storage of excessive energy.	(Touili et al., 2019)
	Combining solar roofs and EV charging to mitigate variability in supply.	(Longo et al., 2017)
Solar thermal roofs	Development of a solar roof design for household cooling and heating improving energy efficiency.	(Juanico, 2010)

After defining what smart sustainable roofs are and after giving some examples of such roofs it is important to distinguish different types of smart sustainable roofs. We will distinguish single-function and multiple-function systems and we will look at open versus closed systems.

Single versus multiple functions

In Table 2-2 are smart sustainable roofs focussing on one particular function, be it temperature moderation using heat absorption and reflection or cooling, water moderation using rainwater retention and transport or irrigation, or electricity moderation by managing electricity production and use. Smart

cool roofs, for example, focus on cooling roofs using solar powered fans. Smart green roofs, for example, focus on irrigation of vegetation on roofs depending on the rain and evaporation. Smart solar PV roofs focus on electricity production and depending on the household electricity usage, feed electricity into the grid. Smart solar thermal roofs focus on heat absorption for different purposes. These are all single-function smart sustainable roof systems. In rooftop micro-grids multiple functions are combined or connected. Giriantari et al., 2018, for example evaluate the performance of a rooftop smart micro-grid setup by comparing its actual performance to simulation performance.

Below is a summary of the different types of roofs:

- Roofs are part of the construction of a building and have the function to provide shelter against rain, snow, low temperature and wind.
- Sustainable roofs add an additional function such as sustainable electricity production, water moderation or temperature moderation. These roofs therefore contain additional (environmentally sustainable) components such as PV-panels, solar thermal collectors, irrigation systems and so on.
- Smart sustainable roofs embed the environmentally sustainable components in a smart system composed of sensors, a control unit and actuators that actively manage the environmentally sustainable components.
- Single-function smart sustainable roofs focus on single environmentally sustainable components, such as PV-panels or solar thermal collectors and embed it in a smart system.
- Multi-function smart sustainable roofs connect different types of environmentally sustainable components and embed it in a smart system. These roofs are also referred to as rooftop micro-grids.
- Rooftop micro-grids can be standalone (closed system) or can be connected with the (public) electricity grid (open system).

Why does it make sense to combine multiple functions in a smart sustainable roof? Firstly, external (the weather) and internal conditions (water, electricity and temperature requirements differ during the day and night) can change and that may require more emphasis on one or another function depending on the time of the day. Secondly, different functions can be complementary such as solar panels providing electricity and heat-pumps using electricity.

Open versus closed systems

Smart roofs can exhibit two types of 'smartness'. They can be connected smartly to external systems like the connection of rooftop solar panels to the distribution network, or the different elements of the local rooftop system can be interconnected within the household only. The former smart roofs are open, and the latter ones are closed systems. An example of an open smart roof system is a system that, depending on the situation, feeds back electricity into the grid or uses electricity from the grid. An example of a closed smart roof is the use of rooftop solar panels to power green roof irrigation.

Why does it make sense to have an open system? The advantages of open smart sustainable roofs are obvious, if the electricity use for example exceeds the electricity production, then the difference can be obtained from the grid. Conversely, if the production exceeds the use, then the difference can be fed back into the grid.

If multiple components of these roofs may be connected to each other, a rooftop micro-grid is developed. These rooftop micro-grids are 'smart' because of the integration of sensors, and control systems which moderate the function of the interconnected environmentally sustainable components using communications technology.

Most of the smart sustainable roofs are demonstrated in pilot projects (and hence are in the so-called innovation phase, between invention and first introduction) or are sold in very small numbers in specific market niches (and hence are in the so-called adaptation phase, between first introduction and the start of large-scale diffusion). Rooftop micro-grids incorporating all aspects represent a modern technology that is not yet mature.

Pattern and applications of smart roofs

Smart sustainable roofs are in an early stage of the pattern of development and diffusion, with little literature present on multi-function smart sustainable roofs or rooftop micro-grids. Almost all relevant literature on the topic describes the implementation of standalone smart rooftop applications, with little to no literature on rooftop micro-grids.

Cool roofs

Historical recap for cool roofs

Conventional cool roofs are roofs that are designed to reflect more sunlight and absorb less heat (Department of energy, 2021). They are far from a new concept. For centuries, mainly in areas with hot climates, people have been applying cool roof concepts in order to increase the thermal properties of their houses (Cool California, 2020). When thinking of Greece, who doesn't think of the white roofs of Santorini as seen in Figure 2-3? However, they have never been widely adopted in the West.

In the 1980s the Californian Department of Education started investigating the benefits of cool roofs regarding temperature reduction and energy savings (Cool California, 2020). Through the years cool roofs have been more widely adopted throughout the US and since the end of the 1990s have also been widely adopted as part of energy-efficiency standards in both residential and non-residential buildings (Akbari & Levinson, 2008). The regulatory embedding of cool roofs quickly led to wide-scale adoption in industry standards. More recently, smart applications have found their way into the cool roof sector.

Recent developments in cool roofs

Smart roof applications can be added that can control the thermal properties of roofs with the main benefits of increasing building user comfort and reducing electricity consumption. Yew et al. (2021) experimented with combining several roof applications into one in order to create a synergetic effect. In the smart roof system, they combined three main components: (1) a moving-air-cavity (MAC) ventilation, (2) a solar powered fan and (3) a rainwater harvesting system. The solar powered fan increases the air velocity inside the MAC, increasing the cooling potential of the system. The rainwater harvesting system was added to reduce heat transfer through the roof, further reducing roof temperature. The combination of these systems allow for a better control of roof temperature, increasing control on building temperature and subsequently improving occupant comfort levels.



Figure 2-3: White roofs of Santorini, Greece

In a similar experiment, Lee et al. (2020) proposed a ‘smart skin’ roof that, using fibrous insulation materials and a control unit, can heat a house during winter and dehumidify it during summer. The heating and dehumidifying aspects of the system are passive and are therefore not fit for interconnection with other rooftop systems. We do not consider this an example of a smart sustainable cool roof.

The pattern of development and diffusion of cool roofs

Cool roofs have been around and are widely used for centuries in specific regions, especially in regions with high temperatures. So specific technologies that are part of cool roofs, such as roofs that reflect the sun because of their colour and structure, or roofs that use water to cool the roof, are obviously already for centuries in the last stage of the pattern of development and diffusion, the so-called stabilization phase. Some other specific technologies that can be part of cool roofs, such as solar powered fans integrated in the roof to cool it, are more recent and only applied in pilots or are sold in very specific market niches. The same is true for cool roofs combining different technologies and integrating one or more of these technologies into smart systems.

Green roofs

Historical recap for green roofs

Green roofs are roofs that have urban greenery installed on top of them like green canopies, green pavements and bio-retention areas. There are many social, environmental and economic benefits related to urban greenery like providing space for relaxation and social interaction, improving the air quality by purifying greenhouse gas emissions and urban greenery has even proved to reduce crime and increase productivity (Mutani & Todeschi, 2021). When installed on buildings green roofs can increase the thermal comfort and reduce energy spendings by controlling solar absorption and increasing thermal insulation (Mutani & Todeschi, 2021). Green roofs also positively influence zoological biodiversity and water retention (Korol et al., 2018).

Similar to cool roofs, green roofs have been around for centuries. The first green roofs known in history were the Hanging Gardens of Babylon, one of the Seven Wonders of the Ancient World, constructed around 500 B.C. (Stormwater Institute, 2006). These ancient green roofs were simple gardens on top of houses that kept houses cool in summer and warm in winter. Through the centuries, many people around the world have used greenery to isolate their dwellings. Examples are turf walls, turf roofs and grass roofs (Abass et al., 2020).



Figure 2-4: The hanging gardens of Babylon

In 1867, the first model of a modern green roof on top of a concrete house was presented at the World Expo in Paris. It had a waterproofed layer and drainage system and can be seen as the first 'modern' green roof. In the early 1900s architects started integrating green roofs into their building designs (Abass et al., 2020). In modern times green roofs are subject to many technological advances making them far more efficient. In the 1960s a multi-layer soil application was developed to create more efficient green roofs. This application has since spread to many countries (Stormwater Institute, 2006).

Recent developments in green roofs

Korol and Shushunova (2016) propose a modular green roof strategy that uses standard sized trays that are easily installed and make the design of green roofs easier. Green roofs can only hold limited amounts of water in their soil. Artificial irrigation is therefore necessary to provide green roofs with sufficient amounts of water. Bandara et al. (2017) proposed a smart irrigation system that irrigates based on the amount of expected evapotranspiration. This system has the potential to be integrated with other systems and can be considered an example of a smart sustainable green roof. Another smart system is described by Balas et al. (2018) who proposed an integrated rooftop greenhouse strategy in which the greenhouse is connected with the interior of the building with controlled flows of oxygen, carbon dioxide, energy and water. Depending on the local climate, smart systems can be installed in the integrated rooftop greenhouses like heat pumps, solar panels and sensors. This application will truly move towards smart green roof systems, or once integrated into rooftop micro-grids.

The pattern of development and diffusion of green roofs

Green roofs like cool roofs have been around and are widely used for centuries. So specific types of green roofs are obviously already for centuries in the last stage of the pattern of development and diffusion, the so-called stabilization phase. Some other specific technologies that can be part of green roofs, such as irrigation systems, are more recent and only applied in pilots and are hence in the innovation phase or adaptation phase. The same is true for green roofs linking the green roof with the building's interior. The combination of different green technologies into smart systems are experimental yet, and are in most cases just in the innovation phase.

Solar PV roofs

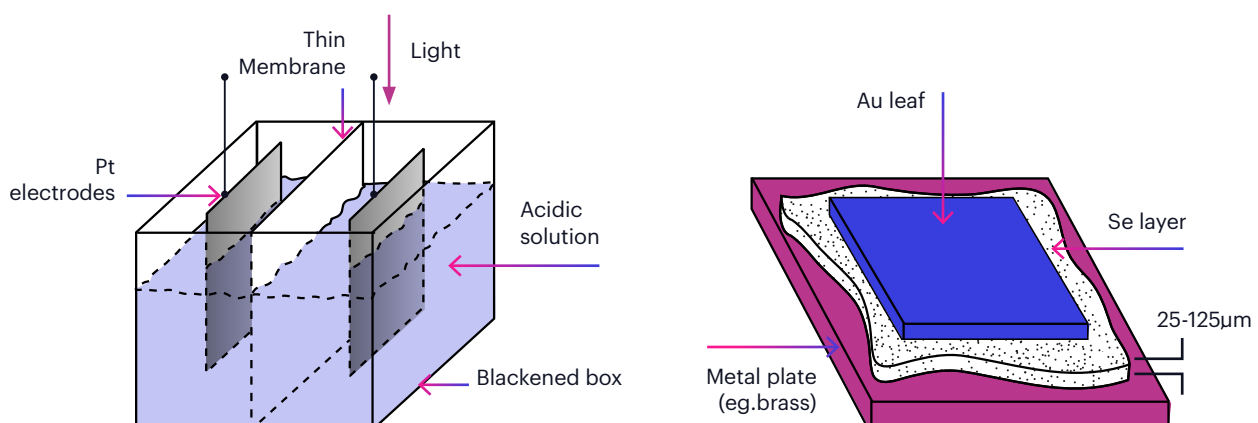
Solar roofs refer to two distinctly different types of roofs. The first type refers to roofs with solar modules that capture solar irradiation and transform it into electrical energy (these are referred to as solar PV roofs). The second type refers to roofs that capture solar energy and use it for heating and cooling purposes by using mechanical circulation and heat transfer of fluids. These systems have been referred to as building integrated solar thermal (BIST) technologies (Archibald, 1999). We start with describing solar PV roofs.

Historical recap for solar PV roofs

The principle of Photo-Voltaic cells (PV) was invented in 1839 by Becquerel (Green, 2005), who showed that two metal plates immersed in a solution in separate compartments but connected by a wire, would yield a small current once one of the plates was struck by light. This was a so-called wet PV-cell. Later on, during the 19th century, when solid state semi-conductors were found, early versions of the solid Photo-Voltaic cells as we know them today, were created. A solid-state selenium cell was for example created in 1883 by Fritts.

In 1932 the first solid-state Photo-Voltaic cells were used as light intensity measurement instruments for photography. Later on, PV was applied in satellite systems and in specific niche applications such as buoys on sea. Large-scale diffusion of Photo-voltaic cells started in the late 1970s. The market adaptation phase lasted about 40 years for Photo-Voltaic cells (PV), from 1932 to the 1970s, again quite long when compared to an average length of 10 years that was found after studying market formation for 50 cases of radically new technologies (Ortt, 2010).

Figure 2-5: Becquerel's wet PV cell from 1838 (left) and Fritts' first solid state PV cell (right) from 1883



(Source: <http://www.pveducation.org/pvcdrom/manufacturing/first-photovoltaic-devices>)

Recent developments in solar PV roofs

Solar PV roofs are the application of solar PV panels on rooftops to provide a decentralised means of electricity generation on buildings. When focusing on smart roof applications, a lot of literature was found on the mitigation of variability of supply using several smart roof applications. Parvez et al. (2020) proposed a multi-layer perceptron-based PV forecasting method to locally control rooftop solar PV energy storage and selling electricity to the grid. The method makes use of historical irradiance data, wind speed, zenith angle, relative humidity and temperature to decide when to store and when to sell to the grid.

Chatterji (2020) in research into the integration of rooftop solar panels, rooftop battery storage and smart meter data has found that smart integration of these different rooftop applications prove useful in minimizing total energy costs. An alternative way of storing the excess energy would be to use an electrolyser to produce green hydrogen with the excess energy, and use that green hydrogen to power the house in times of shortage (see section 2.1.2). Touili et al. (2019) found that it is feasible to combine rooftop solar PV production with a local electrolyser to store the excess of energy produced during sunny days. The stored hydrogen can later be used when the PV production is lower. The system can fully satisfy the demands of an average Moroccan household.

Instead of using battery storage solutions to mitigate variability in rooftop solar energy supply, consumption patterns can also be influenced. With the increase of smart appliances in households, the potential for consumption optimization is rising. Oprea et al. (2019) propose an algorithm for consumption optimization that uses data from smart home appliances. Jain et al. (2018) proposed a similar energy management system combining solar roofs with data from smart home appliances. Liu et al. (2019) add to these proposals and include a system for integration of consumer preferences in which the building occupant can, for instance, prioritize certain appliances.

Chandra and Chanana (2018) investigated the integration of rooftop solar installations with Electric Vehicles (EVs), battery storage and demand response with smart appliances. They found significant energy costs savings and also proposed an interconnection between several households in a neighbourhood to increase system performance. A similar study was performed by Longo et al. (2017) and they reported similar findings.

The pattern of development and diffusion of solar PV roofs

PV panels are already several decades in the last stage of the pattern of development and diffusion, the so-called stabilization phase. Increased production by decentralised solar PV panels, including rooftop installations, are driving innovations in local smart inverter solutions that mitigate voltage fluctuations and secure grid stability and security (Jha & Dubey, 2019; Montenegro & Bello, 2018).

Smart sustainable roofs using solar PV systems are probably most advanced in the pattern of development and diffusion. Solar panel systems connected to the grid are commonplace. Data about electricity generation and use as well as the net electricity use from the grid is easily available using apps. Smart sustainable solar PV roofs are late in the adaptation phase. For smart sustainable roofs containing solar panels, three companies are found: Tesla, SolarEdge and Vivint Solar (Elliot, 2020).

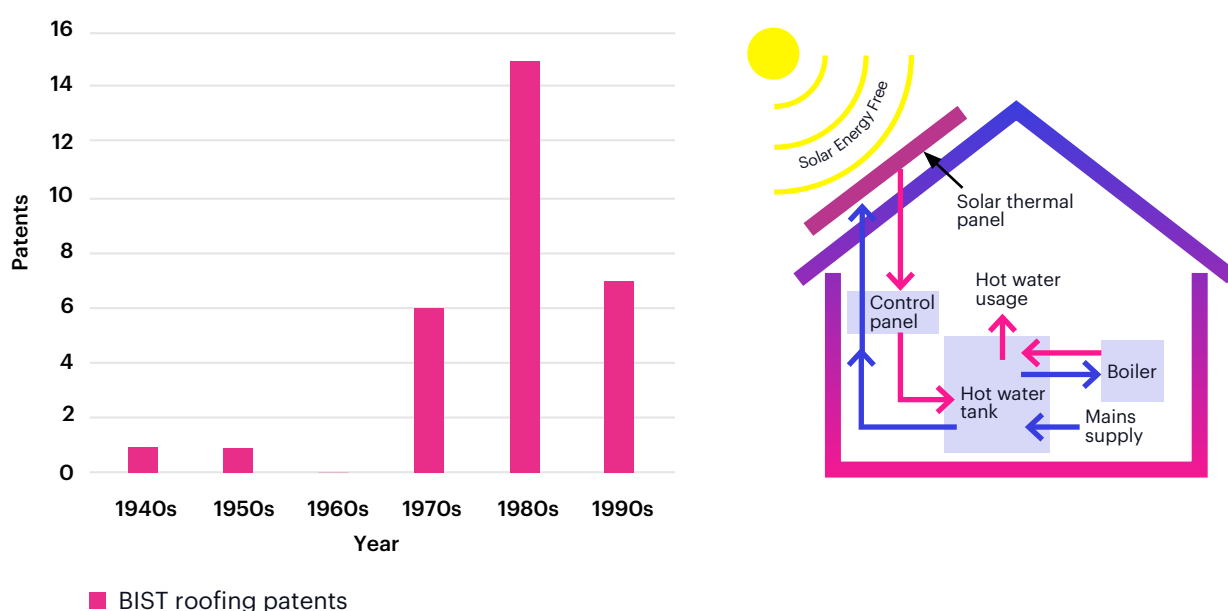
Tesla solar panels can be considered smart sustainable roofs and are certainly one of the most developed solar roofing technologies. Tesla roof solar panels are not just a singular solar module, but rather a whole system (TESLA, 2021) including the solar modules, a battery for storage, an inverter and a 24/7 monitoring system. The monitoring system through its use of sensors and communication technology can always tell the user how much power there is available and allows users to decide how they want to use the power based on their needs. For example, with the click of a button the user can either use the power at home or redistribute it to the grid. Tesla has also developed their own solar roof tiles. These solar roof tiles work similarly to the solar panels but instead of panels that are placed on existing roofs, the solar modules are integrated into the tiles themselves. Like Tesla, SolarEdge is a company that integrates power optimising technology into the system. Users can control each module separately from an app and get all of their performance reports. Vivint Solar also allows for controlling and monitoring of the solar roofing system from an app.

Solar Thermal roofs

Historical recap for solar thermal roofs

Archibald (1999) explains the history of solar thermal roofs, also referred to as building integrated solar thermal (BIST) technologies. The first BIST patent was filed in 1944 for a system that controls air and water temperature through solar radiation. The technology accelerated in terms of patents in the 1970s with the oil embargo in 1973 as is shown below in Figure 2-6.

Figure 2-6: BIST Roofing patents until 1999 (Source: Archibald, 1999) and the system outline



(Source: <https://www.chilternsolar.co.uk/solar-thermal-bedfordshire/>)

As explained above, solar roofs can either serve the purpose of heating or cooling based on mechanical heat transfer. Juanico (2010) developed a solar roof design for household cooling and heating improving energy efficiency. While this is an energy efficient roof it cannot be considered 'smart' as it does not incorporate communications technologies.

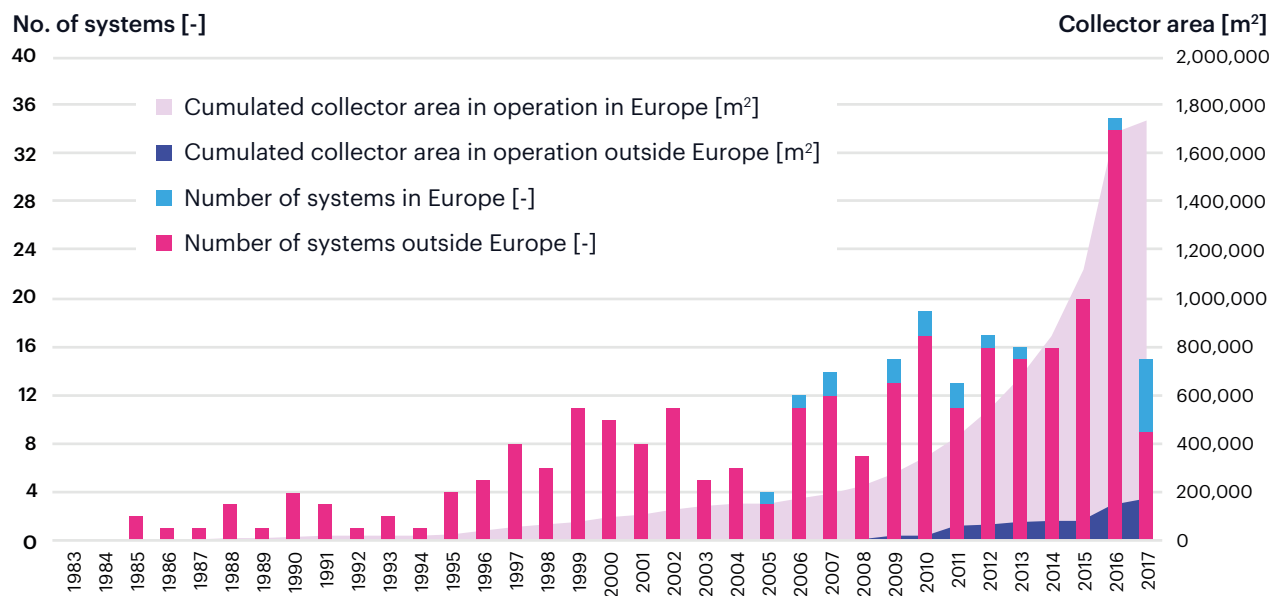
Recent developments

Evangelisti et al. (2019) provide a review of the technological developments in solar thermal systems.

Status in the pattern of development and diffusion

Figure 2-7 shows how the cumulative solar thermal collector area is steadily increasing in Europe. Yet, the diffusion of new systems per year is still fluctuating considerably and the use is also highly region-specific.

Figure 2-7: Solar thermal market development



(Source: <https://www.sunwindenergy.com/solar-thermal/global-market-data-trends-increased-use-solar-heat-large-buildings-industry>)

If we compare the global capacity of solar water heating collectors in 2016 (456 Gigawatts) with the global capacity of solar PV (303 Gigawatts) then the conclusion is that solar thermal systems are undoubtedly in the stabilization phase.

(source: https://energypedia.info/wiki/Solar_Water_Heater)



A rooftop thermal solar system (Photo © iStockphoto.com | AlSimonov)

Rooftop micro-grid

Historical recap for micro-grids

Micro-grids have emerged relatively recently, at least when compared to cool roofs or green roofs. Asmus (2010) shows how the wide-scale electricity network emerged from small micro-grids in the 19th century which were interconnected afterwards. The micro-grids as we know them today are local electricity networks that are connected to the public network but, when needed, can be isolated from that same network, especially when that network is out or becomes unstable. 'Perhaps the most compelling feature of a micro-grid is the ability to separate and isolate itself from the utility's distribution system during brownouts or blackouts.'⁴ (Asmus, 2010, p. 73).

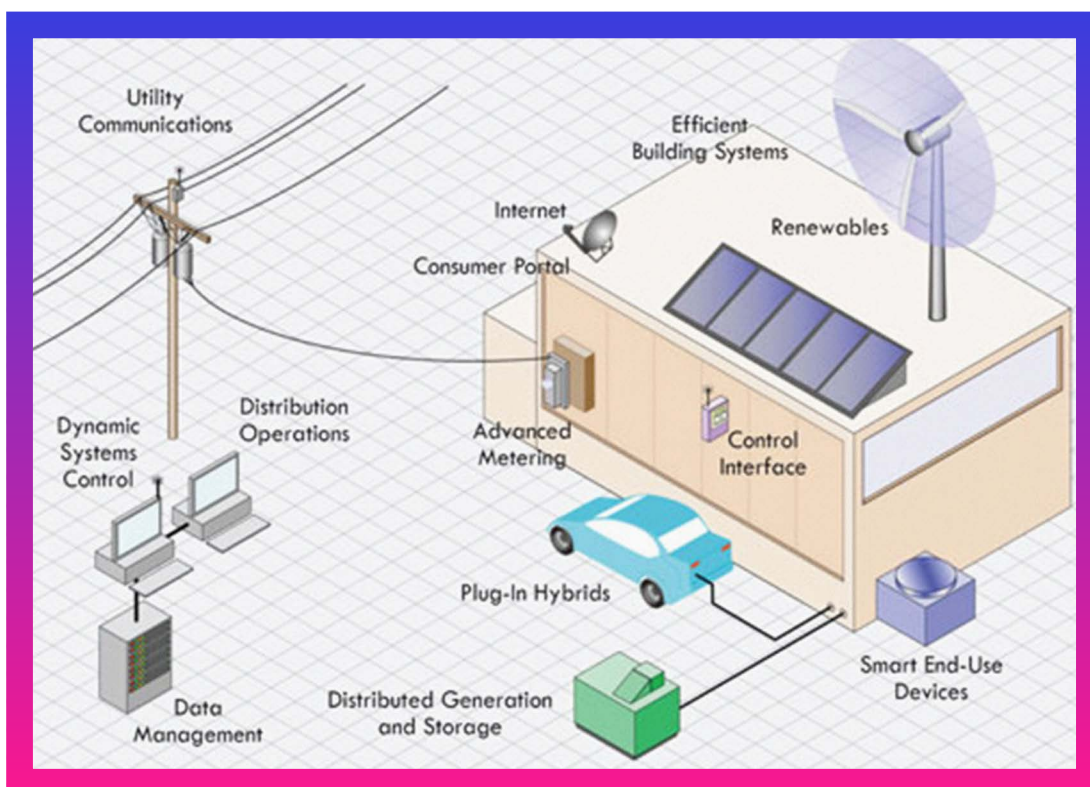


Figure 2-8: Micro-grid at home

(Source: <https://www.facebook.com/microgridsstpetersburg/>)

⁴ A brownout is a drop in voltage in an electrical power supply system. A blackout is a complete electrical power stop.

A rooftop micro-grid connects local electricity production systems such as PV-panels on a roof with appliances in the household using the generated electricity. Micro-grids often require electricity storage using batteries, capacitors, or hydrogen because electricity usage and generation are not synchronized.

Recent developments

Rooftop micro-grids are mostly experimental, some of which are built as part of a consumer household while others are built on public buildings. For example, at Udanya University, Indonesia, a rooftop micro-grid was installed that consists of ten 500W wind turbines, eighty 330Wp solar PV panels, 192kVAh batteries and a 20kVA diesel generator. The feasibility study found that system performance was lacking behind simulation performance and that further research has to be conducted to increase rooftop micro-grid performance (Giriantari et al., 2018).

The pattern of development and diffusion of rooftop micro-grids

'Although micro-grids have been researched for over a decade and recognized for their multitude of benefits to improve power reliability, security, sustainability, and decrease power costs for the consumer, they have still not reached rapid commercial growth.' (Soshinskaya et al., 2014, p. 659).

'While the concept and first trials of the micro-grid date back to the 1980s, they have only recently started crossing over from the experimentation to commercialization phases, with pilot projects popping up all over the world. However, scaling up of micro-grids is proving difficult because renewable energy and storage technologies are still very expensive, and pilots are demonstrating that challenges exist in micro-grid operation and control.' (Soshinskaya et al., 2014, p. 660).

Feng et al. (2018) indicate that in the last decade, not only in the US, but also in Europe and Asia, development and demonstration of micro-grids have increased considerably.

Following these texts implies that micro-grids are commercialized albeit on a small scale. That means that these micro-grids are in the adaptation phase that started before 2014.

Conditions

All of the components for a rooftop micro-grid are available. Different types of sustainable roofs, i.e. several types of cool roofs, green roofs, solar PV roofs and solar thermal roofs, are produced and implemented on a large scale⁵. However, the combination of connected components in a micro-grid, including local energy storage and/or a connection to the public grid with a control unit to monitor and moderate the electricity production and usage, is still rare.

The first type of micro-grids that have become mainstream are micro-grids around PV-panels. If the PV-panels do not only generate electricity for local usage but are also connected to the grid and if there is a control unit that manages the input of electricity from either the public grid or the PV-panels and that manages the (timing of the) usage of electricity, then we may consider this a micro-grid around PV-panels. It is interesting to see how micro-grids may evolve further.

The technology is available, the knowledge of the application is available. In fact most of the influencing factors are no longer blocking further micro-grid development and diffusion. However, in the core factors together making up the 'Technology Innovation System' (TIS) several factors are still not ready for large-scale diffusion. The required investments to install a rooftop micro-grid are still high, actors in the network still need to align to make all the components compatible, and the public network may have to be adapted to cope with the new sustainable electricity sources and combined local production and usage.

Figure 2-9: Conditions for micro-grids

Core factors		Influencing factors	
1 Product performance		8 Knowledge of technology	
2 Product price		9 Knowledge of applications	
3 Production system		10 Employees and resources	
4 Complementary products and services		11 Financial resources	
5 Actors and network formation		12 Macroeconomic and strategic aspects	
6 Customers		13 Sociocultural aspects	
7 Standards, rules and laws		14 Accidents and unexpected events	

⁵ The diffusion depends on the specific types of sustainable roofs and some of the diffusion patterns are highly region-specific. Cool roofs using reflective light surfaces on roofs are applied on a large scale in Mediterranean countries for example. Cool roofs using solar-powered fans are more experimental.

Chapter 3

Conclusions



Introduction

In this report we explore the status of two environmentally sustainable technologies: green hydrogen and smart roofs. We explain both technologies and introduce the research questions before we present our conclusions.

The research questions:

1. What is the current status regarding the development and diffusion of two potential breakthrough technologies, notably 'Green hydrogen' and 'Smart roofs'?
2. What conditions have to be met for these technologies to become actual breakthroughs?

Green hydrogen

Hydrogen is green when it is produced using sustainable electricity sources such as wind turbines or PV-panels. We focus on hydrogen as a mobility solution or as an energy storage and discard hydrogen as feedstock for processes in the chemical industry.

Smart roofs

Roofs are smart and sustainable when they interconnect sustainable energy sources fitted on the roof (such as wind turbines, solar PV panels or solar thermal panels) with the appliances using electricity. Smart roofs usually also contain a subsystem for storing energy and a connection with the public grid. Such smart roofs are also referred to as rooftop micro-grids.

Micro-grids that are disconnected from the public electricity grid need to be able to store electricity because energy supply and use are usually not synchronized in the case of local rooftop sustainable energy sources. If the usage of energy in the household can be managed (shifted over time), then a smart control unit can be useful to decide when to store energy and when to use it and how to schedule the use of electric appliances. Micro-grids that have a local storage unit and are connected to the grid definitely require a control system to see when it is most economic to store locally generated electricity or to feed it back into the public grid.

The research questions

This report explored the status of development and diffusion of both technologies. Are they just experimental technologies applied in pilots and demonstration projects, are they applied on a small scale in specific niche market applications only, or are they already applied on a large scale in a mainstream market? To address these issues, we formulated the following research question:

→ **What is the current status regarding the development and diffusion of two potential breakthrough technologies, notably ‘Green hydrogen’ and ‘Smart roofs’?**

Assessing the status of development and diffusion is a first step for which we used a model: the pattern of development and diffusion of radically new technologies (see Appendix 1). The pattern helps to describe the current status of a technology. In order to explain that status, we decided to look at conditions that stimulate or block development and diffusion of radically new technologies. These conditions are summarized in a framework and can be used to explore actors and factors that either hamper or stimulate development and diffusion (see Appendix 1). To address these conditions, we formulated the following research question:

→ **What conditions have to be met for these technologies to become actual breakthroughs?**

Answers to the research questions

Green hydrogen

Green hydrogen refers to a system composed of interconnected subsystems which require coordination. If we look at the subsystems for production, transportation, storage and usage of green hydrogen, we see that some of the subsystems are already in place, yet other subsystems and their combination in one interconnected system are still lagging behind.

Hydrogen is already produced on a large scale, and there is more and more sustainable (wind or solar) electric energy available, yet the portion of hydrogen production that is green is still marginally small. Regarding transportation we see that pipelines for gas are available, some of which are idle and can possibly be re-used for hydrogen. Yet, a full public wide-scale hydrogen transportation and distribution system is not in place. Storage of hydrogen is possible but large-scale storage required to balance out the peaks in sustainable energy production and thereby align the available energy with the fluctuations in demand, is not yet available. Local storage systems, for example in consumer households, are available. In fact, experimental systems are used already for more than a century. Yet, mainstream energy storage systems using hydrogen are not yet in place on a large scale in the market. A final bottleneck seems to be adapting all the systems required to use green hydrogen as a mobility solution or energy carrier. Hydrogen cars, for example, are commercially available, but these cars represent a very specific and small niche only.

As an answer to the first research question, we conclude that green hydrogen (as mobility solution and energy carrier) is in the adaptation phase, it is applied on a small scale in specific niche applications. The reason that green hydrogen is not yet applied on a large scale as an energy carrier or fuel is visible in the status of the conditions. These conditions provide an answer to research question 2.

Figure 3-1: Comparing the conditions for green hydrogen as an energy carrier and fuel

Core factors	Energy carrier	Mobility	Influencing factors	Energy carrier	Mobility
1 Product performance	Green	Red	8 Knowledge of technology	Orange	Orange
2 Product price	Orange	Red	9 Knowledge of applications	Green	Green
3 Production system	Red	Red	10 Employees and resources	Green	Green
4 Complementary products and services	Red	Red	11 Financial resources	Green	Green
5 Actors and network formation	Green	Green	12 Macroeconomic and strategic aspects	Orange	Orange
6 Customers	Green	Orange	13 Sociocultural aspects	Green	Green
7 Standards, rules and laws	Green	Green	14 Accidents and unexpected events	Orange	Red

The main barriers to large-scale diffusion can be found in the green production of hydrogen as fuel or energy carrier and in the availability of complementary products and services. The complementary products and services lack in terms of a wide-scale transportation network and local connections to that network but also appliances to use the green hydrogen as fuel or energy carrier are not yet widely available. The performance and price (especially for the use of green hydrogen as a mobility solution) are not yet competitive.

Rooftop micro-grids

Rooftop micro-grids also represent systems of interconnected subsystems, like the green hydrogen technology. In contrast to the wide-scale system for green hydrogen, the rooftop micro-grid is a local system situated in one building. The rooftop micro-grid consists of subsystems, most of which are also produced and used on a large-scale on buildings, meaning these subsystems are in the stabilization phase. That is true for solar PV panels, solar thermal systems and wind turbines. All of these systems started to diffuse on a large scale before the turn of the century. Most locally fitted Solar PV panels are connected to the public grid. Yet, local systems to store electric energy are experimental and in the adaptation phase and so are the control units connecting all of the subsystems and optimizing the production and usage of electricity over time. We conclude that rooftop micro-grids are in the adaptation phase, similar to green hydrogen.

Figure 3-2: The conditions for rooftop micro-grids

Core factors		Influencing factors	
1 Product performance		8 Knowledge of technology	
2 Product price		9 Knowledge of applications	
3 Production system		10 Employees and resources	
4 Complementary products and services		11 Financial resources	
5 Actors and network formation		12 Macroeconomic and strategic aspects	
6 Customers		13 Sociocultural aspects	
7 Standards, rules and laws		14 Accidents and unexpected events	

In contrast to green hydrogen, the main subsystems for rooftop micro-grids are available, they should become more economic in operation and standard control units are required when interconnecting the subsystems. Finally, subsystems should be made compatible. In short, the main barriers to large-scale diffusion refer to the product price of some of the subsystems and the availability of complementary compatible subsystems. To interconnect subsystems close collaboration or coordination between a range of market actors is required.

Although both technologies are in the so-called adaptation phase, the status of the conditions do reveal that the barriers for large-scale diffusion for smart roofs are lower than for green hydrogen. We thus expect that large-scale diffusion for smart roofs is more likely in the near future than for green hydrogen.

Recommendations

A straightforward recommendation is to remove barriers blocking large-scale diffusion. For green hydrogen as a fuel, removal of such barriers requires actions from both governmental institutes as well as companies.

Green hydrogen as a fuel caused and may cause serious accidents, for example. The prevention of such accidents requires experiments and tests to create safety norms. The creation and implementation of such norms requires collaborative efforts from many actors. If networks of companies and governments are able to create standards that may limit the competition between different formats of the same technology, the so-called intra-technology competition will reduce. Setting such standards is difficult because there is a complex optimum between delaying standard-setting to stimulate innovation and speeding up standard-setting to create clarity for actors that helps them to align with the standard and thus make subsystems (complementary products and services) compatible. The delay of standardization may stimulate different types of innovative efforts regarding the central parts of the technology, speeding up standardization may help to build ecosystems of actors around one format of such new technology. Both are important, but not at the same time.

To help green hydrogen's development and diffusion, governmental institutions can also subsidize local and niche market applications and bring actors together in an ecosystem required for such ecosystems. This has the effect that standards and collaborations between actors can emerge more freely giving room for innovation.

The price/performance of green hydrogen as a fuel is not competitive in the face of alternative technologies. This may require investments in research to improve the production processes and thereby the price/performance ratio and it may require subsidies to attain economies of scale that lower the costs and the price.

For rooftop micro-grids, removal of barriers is also important. There are less barriers and they are not that large, compared to green hydrogen. It is important to stimulate addition of subsystems to current specialized systems. PV-systems are the most widely diffused subsystem of rooftop micro-grids. Governments can play a role in advising and subsidizing customers how to make a rooftop micro-grid by extending their PV-systems. Governments can also stimulate standard setting to safeguard compatibility of the subsystems. In order to dampen fluctuations in the public electricity grid due to asynchronous production and use of electricity, micro-grids should be able to store electrical energy. Governments may subsidize local storage units and standard-setting of such units.

Discussion

Commonalities and differences between the cases

The two technologies, rooftop micro-grids and green hydrogen, are similar in several ways. Both technologies are complex systems composed of several subsystems.

They have in common that most of their basic subsystems are available, tested and diffusing on a large scale in the market. Hence, most subsystems are in the stabilization phase. However, the combination of those subsystems is rarer and hence we conclude that both technologies are in adaptation phase of the pattern of development and diffusion.

A difference between the two technologies is that the rooftop micro-grids are local systems fitted in (or on) one building whereas green hydrogen requires changes in large-scale transport and distribution systems in a wider area. For large-scale use of green hydrogen, we see more and larger barriers than for rooftop micro-grids. That means that, although both systems are in the adaptation phase and thus are applied in specific market niches, we expect that rooftop micro-grids will start to diffuse on a large scale and thus enter the stabilization phase sooner than green hydrogen given an equal research and development speed.

Interesting is the direct connection that both technologies have. Green hydrogen can serve as a fuel for heating systems in buildings and hydrogen fuel cells combined with tanks can serve as a battery to store electric energy. In fact, green hydrogen represents an important technology that can play an important role in the rooftop micro-grids. There is a double connection: Hydrogen as energy-storage can be used as a battery for rooftop micro-grids. Both rooftop micro-grids and hydrogen systems can be connected to the public electricity grid and may have a considerable effect on that grid.

Competition and expectations

The answers to the research questions seem to imply that direct action is required to promote both systems and push them into large-scale diffusion. Why then does it take the actors, organizations, companies, customers so long?

One explanation is the size of investments required to implement both systems. Green hydrogen fuel and energy carrier require a fine-grained infrastructure that requires considerable investments, either by governments or companies involved. Furthermore, it takes investments in the products or systems, be it cars or production processes in companies that have to be adapted to use hydrogen as a fuel or as an energy carrier. Those investments would seem logic if green hydrogen were economically viable compared to the current mainstream alternatives and if green hydrogen were the only competitive sustainable alternative to substitute those alternatives, the fossil-fuel based current systems. Neither is true. Electric cars, for example, can drive on batteries, which are also developing rapidly. Many companies formed ecosystems around alternative new and sustainable technologies. It seems a bit of a gamble to decide to join one such ecosystem.

Finally, for each of the new alternatives, green hydrogen or rooftop micro-grids, alternative formats (or standards) are being developed. The outcome is uncertain. The combination of these uncertainties is a serious barrier.

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Appendices

**The Technology
Monitor 2021**

Hydrogen green
energy and
Smart roofs

Appendix 1

The Technology Monitor as a method

The Technology Monitor maps the development and diffusion of a technology. The method consists of three interrelated components:

1. The definition of the technology, to make it clear what it is exactly that is being mapped.
2. The pattern of development and diffusion of a technology, to make it clear how the technology has developed and what its current state is.
3. The system of actors and factors that play an important part in the development and diffusion of the technology, to be able to indicate which factors impede or stimulate the further development and diffusion. This system is also referred to as 'conditions'.

Each of the three components provides a model or simplification of reality and is therefore based on assumptions. The assumptions themselves are not discussed in this brief description.

Definition of a technology

A technology can be defined on the basis of three aspects:

1. The technological principle
2. The functionality
3. The components

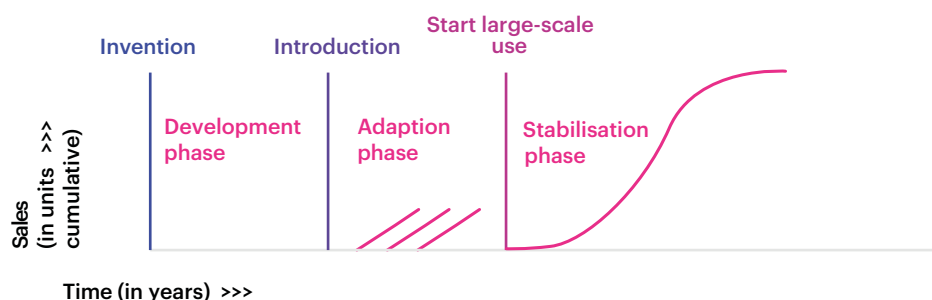
A solar cell is based on the photovoltaic principle (technical principle). It consists of two types of semiconductors close to each other (main components) that, when struck by light or other radiant energy, produce an electrical voltage or current when connected by a conducting wire (extra component). The cell can continue to provide voltage and current autonomously i.e., without external power source, as long as light continues to fall on the two materials. This current can be used to measure the brightness of the incident light or as a source of power in an electrical circuit, as in a solar power system (functionality).

The technological principle indicates the principle of the operation, the functionality indicates what you can do with the technology and the components make up the basic elements of the technology. See the purple text for an example of a definition of a technology, the solar cell.

Pattern of development and diffusion of a technology

The Technology Monitor by STT contains a model that is a realistic representation of the development and diffusion of a technological breakthrough over time (see Figure A1-1).

Figure A1-1: the more realistic pattern of development and diffusion of technological breakthroughs



In the pattern of development and diffusions, three important moments in time are distinguished:

1. The invention: the first demonstration of the operation of the technological breakthrough.
2. The first market introduction: the first time the technological breakthrough is sold and applied.
3. The start of the industrial production and large-scale diffusion and application of the technological breakthrough.

With these important moments, the three consecutive phases can be distinguished:

1. **The development phase:**
This phase runs from the invention to an initial introduction of products on the basis of the technological invention. The invention is the demonstration of a working principle that often is not yet ready to be manufactured and marketed. In the development phase, research takes place to improve the principle and there are often one or more development trajectories designed to make a product on the basis of the principle that can be sold and applied.
2. **The adaptation phase:**
This phase runs from the first introduction to the start of production and large-scale diffusion of products on the basis of the technology. This phase often involves a trial-and-error process in which different product versions are introduced in various market niches. Adaptation takes place between the product, different customer groups and different applications. That adaptation can ultimately lead to a standard product. Innovation of products, (production) processes and research into improvement of the technology keep going on as before during this phase.

3. The stabilisation phase:

This phase begins with industrial production and large-scale diffusion. It starts with a standard product that can be manufactured on a large scale and that is applied and sold on a large scale. The product versions and applications have at this point stabilised. Often, the innovation of products, processes and research to improve the underlying technology will keep going as before.

The *pattern* is a generic model within which, in practice, the length of the phases can vary considerably. The average length of the development phase is about 10 years, and a similar length has been established for the adaptation phase (see Ortt, 2010). Each phase can be skipped or be longer than average. There are technologies where both the development and adaptation phase took only a year (for instance in the case of dynamite) and there are technologies where those phases take a century (for instance in the case of the fax). The pattern can stop or be interrupted at every stage. The pattern provides the basis for a large number of scenarios that can occur in practice.

Conditions that hamper/stimulate development and diffusion

The pattern of development and diffusion of technological breakthroughs provides a *description* of the process of development and diffusion. It does not provide an *explanation* why that pattern occurs in a specific shape. We are looking in particular for explanations that indicate why the first two phases in the pattern, the development phase and the adaptation phase, sometimes cost very little time and sometimes a lot of time.

We have compiled a list of general factors that are needed for the large-scale diffusion of technological breakthroughs. When those factors are in place, they can stimulate the development and diffusion, when they are absent or incomplete, they can be a barrier. The factors are divided into fourteen categories. Seven categories make up the social, economic and technological system: the core factors. The other seven factors can

affect the core factors, these are influencing factors that can provide an explanation for the impediment on those core factors. This collection of factors represent a considerable expansion of the factors that Rogers (2010) uses to explain diffusion in the standard innovation-diffusion model. Table A1-1 describes the seven core factors that need to be in order to enable large-scale diffusion. Table A1-2 describes the influencing factors.

Table A1-1: Core factors for large-scale diffusion of technological breakthroughs

Core factors	Description
1 Product performance	A product (with all components and software) with a sufficiently good performance and quality (in absolute terms or relative to competing products) is needed for large-scale diffusion. A poor performance, quality or unintended side-effects of, or accidents with products can impede large-scale diffusion.
2 Product price	The price of a product includes financial and non-financial investments (for instance time and effort) to obtain and use a product. A product (with all its components and software) with a reasonable price (in absolute terms or relative to competing products) is needed for large-scale diffusion. A high price can impede large-scale diffusion.
3 Production system	A production system that can deliver large quantities of products of sufficient quality and performance (in absolute terms or relative to competing products) is needed for large scale diffusion. A lack of such a production system, unintended side-effects of, or accidents during production can impede large-scale diffusion.
4 Complementary products and services	Complementary products and services for the development, production, distribution, adoption, use, repair, maintenance and disposal of products are needed for large-scale diffusion. A lack of or incompatible system components, unintended side-effects of, and accidents with complementary products and services can impede large-scale diffusion.
5 Actors and network formation	Availability of necessary actors and sufficient coordination of the their activities for the development, production, distribution, adoption, use, repair, maintenance and disposal of products is necessary for large-scale diffusion. Coordination can be emergent or implicit (for instance the market mechanism) or it can be formal and explicit (for instance an industry association). If certain actors or coordination mechanisms are necessary but lacking, that can impede large-scale diffusion.
6 Customers	Customers are needed for large-scale diffusion. Customers must have knowledge of the product and its use, and they need to want to have, be able to afford and want to use the product. If there are no customers, that will impede large-scale diffusion.
7 Standards, rules and laws	Standards, rules and laws in relation to the product, production, complementary products and services, or how actors (on the supply and demand ends of the market) must handle the product and the surrounding socio-technological system are needed for large-scale distribution. The absence of standards, rules and legislation can impede large-scale diffusion.

The **core factors** make up a complete system surrounding a new technology. If one or more of those factors are absent or incomplete, or if there is insufficient coordination between the factors, that will impede large-scale diffusion.

The **influencing factors** can explain why one or more of the core factors are incomplete, absent or do not fit. As such, these influencing factors explain problems in the system of core factors and give an indication of (future) changes in the core factors. In other words, the influencing factors can explain impediments in the core factors and show changes in those core factors (see Table A1-2).

Table A1-2: Influencing factors for large-scale diffusion of technological breakthroughs

Influencing factors	Description
8 Knowledge of technology	This includes fundamental and applied knowledge of the technology. Fundamental knowledge has to do with technological principles involving the product, production, complementary products and services and knowledge for the development (design), production and management of technological principles. If relevant actors are lacking technical knowledge that is vital to their role, that can impede large-scale diffusion.
9 Knowledge of applications	This includes knowledge of potential applications, knowledge of the market (structure) and the actors involved. This knowledge is needed by all actors, including customers, in order to formulate strategies and product requirements, and to find other actors. If relevant actors are lacking knowledge of applications that is relevant to their role, that can impede large-scale diffusion.
10 Employees and resources	The availability of employees with the necessary knowledge and skills and the availability of resources and input like components and materials are needed for the production and usage of a product, for production, complementary products and services. Organisations that play a role in managing these aspects, like trade unions, are also included. A lack of such resources can affect the core factors and thus impede large-scale diffusion.
11 Financial resources	Financial resources and the organisations (for instance banks) or platforms (for instance crowdfunding) to deliver these resources are needed for the development and diffusion of new products, production systems, complementary products and services, and for the adoption, implementation and maintenance of the products. A lack of financial resources among actors on the demand or supply end of the market (two important core factors) can impede large-scale diffusion.
12 Macroeconomic and strategic aspects	Macroeconomic and strategic aspects refer to the general economic situation in a country or industry, like a recession or industry-wide stagnation. Strategic aspects refer to the interests of countries and industries. Macroeconomic and strategic aspects of countries and industries can affect the core factors and thus impede large-scale diffusion.
13 Sociocultural aspects	Sociocultural aspects refer to the norms and values in a certain culture or industry. They include methods and habits in a country or industry and can also refer to interest groups outside of the supply chain. These aspects tend to be less formalised than formal standards, laws and rules. Sociocultural aspects can influence the core factors and thus impede large-scale diffusion.
14 Accidents and unexpected events	This includes accidents and events outside of the socio-technological system with a major impact, like wars, nuclear accidents, natural disasters and political revolutions. These accidents and events, or the risk of them occurring, can influence the core factors and thus impede large-scale diffusion.

An example indicates why that combination of core factors and influencing factors is so important. If a core factor is missing, for instance because there are no consumers, large-scale diffusion is impossible. Consumers are an important core factor, one that can be influenced by various factors. For instance, consumers can lack knowledge regarding the technology and its applications (influencing factors 8 and 9) or the technology can be too expensive for the consumers (influencing factor 11). Each of the influencing factors has a different effect on the core factor ‘consumers’ and therefore requires a different policy from regulatory organisations or governments, or a different strategy from organisations wanting to market the technology.

Appendix 2

Conditions in detail

Green hydrogen

Energy carrier

Fuel

Influencing factors

Knowledge of technology

The first small-scale application of green hydrogen is more than 125 years old and knowledge since then has accumulated. The first larger projects to explore hydrogen as a future energy carrier for renewable energies have started (see Section Pattern and applications). Generally, the generation of hydrogen from renewable energy sources is nowadays feasible (IRENA, 2019). Alkaline electrolyzers have the highest possible technology readiness level, and PEM electrolyzers only rank slightly lower (Wulf et al., 2018). The core technology, electrolysis, is proven to work, but the technology is not ready for a large-scale and long-term application (van der Burg, 2021). Nevertheless, experts expect that the technology will mature rapidly in the next years. The core factors will deep-dive to further explain the challenges needed to overcome.

Knowledge of applications

As discussed earlier, green hydrogen has three main applications. Besides of this, ideas to reap synergies in the hydrogen economy are diverse. Many institutes, such as the Hydrogen Council, worked on various plans to apply the gas in an economical manner (Hydrogen Council, 2017).

Natural and human resources

Renewable energy seen as a natural resource is widely available in Europe. Especially, frontrunners in the renewable energy sector like Germany have an urgent need for hydrogen as a energy carrier to use its large share of renewable energy economically. Nevertheless, on a global scale the availability of renewable energies and hydrogen electrolyzers have to grow simultaneously due to its reliance on each other. The need for human resources to run green hydrogen plants is limited. Like many plants in the process industry, green hydrogen electrolyzers only require a small number of employees. Besides this, researchers and engineers are required to refine technologies and plan green hydrogen projects. However, no major barriers are known hampering the access to human resources.

Financial resources

Due to its lack of technology knowledge, financial resources are needed to improve the product performance, efficiency, and infrastructure. However, many governments are funding green hydrogen research, as well as demonstration projects (Clark, 2008). Moreover, funding from the corporate side also exists. For example, the Hydrogen Council has more than 100 members from various sectors, including the energy and infrastructure, automotive, chemical, logistics and finance industry (Hydrogen Council Press Office, 2021). According to the council, all members from more than 20 countries are committed to a growth of hydrogen.

Energy carrier

Fuel

Influencing factors

Macroeconomic and strategic aspects

Green hydrogen is crucial for the energy transition and decarbonization (IRENA, 2020). The EU supports green hydrogen initiatives since the early 2000s (Clark, 2008). However, the Covid-19 pandemic might hamper these efforts. Although implications are currently not entirely clear, the goals to reduce the decarbonization might be postponed in order to guard the health and economies in countries around the world (Leal Filho et al., 2020).

Sociocultural aspects

As the strategic aspects have already suggested, green hydrogen is needed for the energy transition. Not reaching the climate goals has far-reaching consequences for humans and the earth as we live on it. Green hydrogen might be one solution, and if not the best solution, to make renewable energies practically feasible in large-scale applications.

Accidents and unexpected events

Unexpected events influence the negative press and appearance of green hydrogen in the society. These events can be clustered into two categories: indirect and direct events.

For example, the Covid-19 pandemic is indirectly influencing the diffusion of green hydrogen. Other goals are in a short term more important than the decarbonization leading to a postponement of funding.

On the other hand, events in which hydrogen played a major role or it seems like hydrogen played a major role create negative press. One such event might be the famously known Hindenburg drama. This press especially influences the opinion of the society. Therefore, such direct events rather affect the diffusion of green hydrogen as a fuel.

For example, a recent accident at a hydrogen fuel station in Norway led to a sudden stop of sales of Toyota's hydrogen cars and closing of similar hydrogen fuel stations in Norway and other countries (Randall, 2019). Close to Oslo a hydrogen fuel station exploded which resulted in a 500 m safety zone after the incident (Reid, 2019). Roughly a month after the incident it was found that an assembly error at a valve led to the explosion and sales stop (Løkke, 2019).

Energy carrier

Fuel

Core factors

Product performance (energy carrier)

For the use case of green hydrogen as an energy carrier product performance only plays a subordinated role. Electrolysers instead require a low CAPEX to justify the investment if the electrolyser is only running during peak times.

Product performance (fuel)

In the case of fuel, one of the major issues of green hydrogen is the lack of product performance. Although the technology is viable, losses during the production are high, decreasing the efficiency and increasing the OPEX (IRENA, 2020).

Additionally, hydrogen energy storages are also not ready for the large-scale application. Storage solutions are characterized by low efficiency, as well as safety and cost issues (Koohi-Fayegh & Rosen, 2020).

Product price (energy carrier)

As mentioned before, the CAPEX of an electrolyser is highly relevant for the use case energy carrier. Experts say that the current prices are too high for the use of green hydrogen as an energy carrier. However, prices will decrease if mass production of electrolysers starts.

Product price (fuel)

Due to the high inefficiency in production green hydrogen prices are high. In 2020 a kilogram of green hydrogen costs 5,09€ (Hydrogen Council, 2020). However, prices are projected to decrease to competitive 2,12€ per kilogram in 2030 as production scales up. The product price not only depends on the efficiency but also on the electricity price. The product price of green hydrogen must be seen in comparison to other fuels in the mobility sector and the range of the vehicle.

Production system

The practical demand for green hydrogen is low because of the product performance and price. This should not be confused with the theoretically existing demand to store renewable energy in peak times. However, due to high prices and inefficiency the production of green hydrogen is essentially non-existent (IRENA, 2019).

Complementary products and services

There is a lack of infrastructure to support production. Hydrogen requires a new physical infrastructure. Moreover, costs for the equipment are high. Nevertheless, it is prognosticated that costs for equipment and supply chains reduce once green hydrogen is deployed in larger applications (IRENA, 2019).

The last four conditions (product performance, product price, production system, and complementary product and services) create a major problem for the diffusion of green hydrogen. A self-reinforcing cycle has been created. Although the need exists, a high product price for the machinery, as well as the hydrogen itself, discourages companies and governments to invest into production facilities. However, large-scale production facilities are needed to deploy learning-by-doing effects (IRENA, 2019).

Energy carrier

Fuel

Core factors

Besides a physical infrastructure, cars, buses, and other modes of transport are seen as complementary goods from the perspective of green hydrogen. Hydrogen-compatible consumers are required to create a demand for green hydrogen as a fuel.

Actors and network formation

A variety of actors influence the development and diffusion of green hydrogen. Two major players have emerged with IRENA as an intergovernmental organization (more than 180 countries) and the Hydrogen Council as a company led initiative (more than 100 companies) (Hydrogen Council Press Office, 2021; IRENA, 2021). These two major actors are bundling and shaping opinions of the most important actors.

Customers (energy carrier)

Customers for green hydrogen have to be seen two-folded. The application of green hydrogen as an energy carrier is mostly applicable to companies such as energy companies. Companies usually adopt a new technology once its mature and the return of investment is ensured. But also, the commercial application of hydrogen must be seen apart depending on its application. While most energy corporations see the need for green hydrogen as an energy carrier, green hydrogen as a feedstock is facing a lack of demand (IRENA, 2020).

Customers (fuel)

Green hydrogen as a fuel will be adopted by two kinds of customers: companies and consumers. Niche applications currently exist for local transportation companies such as the Hydrogen Bus Project Aberdeen. Return on Investment as well as safety are important values for these companies. In the case of personal transportation, consumers are a crucial factor. The ease of use, as well as the opinion towards a technology plays a major role during the buying process. Direct events, such as the accident in Norway, have an influence on a customer's opinion.

Standards, regulation, and legislation

In 1990, the committee for hydrogen technologies has been created in the International Organization for Standardization (ISO). Their scope is the development of standards 'in the field of systems and devices for the production, storage, transport, measurement and use of hydrogen' (ISO, 2021). No information has been found of standards or regulations hampering the diffusion of green hydrogen.



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