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Introducing Power-to-H3: Combining renewable electricity with heat, water and hydrogen production and storage in a neighbourhood

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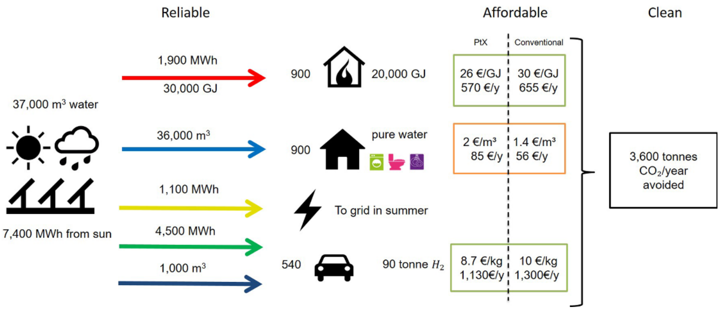
HIGHLIGHTS

- Integration of renewable electricity, water, heat and hydrogen in a neighbourhood.
- Illustration of a high temperature seasonal heat storage system.
- A reliable, affordable and clean energy and water system is presented.
- Five year simulations with hourly calculations including avoided costs.
- Investigation of a Dutch case and first steps to realisation of the system.

GRAPHICAL ABSTRACT

A reliable, affordable and clean energy system for a neighbourhood. The arrows show how the energy is distributed over the different products, while the symbols show the demands for the different products. Under affordable, the production cost (above) is compared with the current selling price (below), under clean, the CO_2 savings of the system are shown. Values shown are rounded and valid for a system without additional electricity import from the grid (case: Nieuwegein, the Netherlands).



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ABSTRACT

In the transition from fossil to renewable energy, the energy system should become clean, while remaining reliable and affordable. Because of the intermittent nature of both renewable energy production and energy demand, an integrated system approach is required that includes energy conversion and storage. We propose a concept for a neighbourhood where locally produced renewable energy is partly converted and stored in the form of heat and hydrogen, accompanied by rainwater collection, storage, purification and use (Power-to-H3). A model is developed to create an energy balance and perform a techno-economic analysis, including an analysis of the avoided costs within the concept. The results show that a solar park of 8.7 MWp combined with rainwater collection and solar panels on roofs, can supply 900 houses over the year with heat (20 TJ) via an underground heat storage system as well as with almost half of their water demand (36,000 m^3) and 540 hydrogen electric vehicles can be supplied with hydrogen (90 tonnes). The production costs for both hydrogen (8.7 €/kg) and heat (26 €/GJ) are below the current end user selling price in the Netherlands (10 €/kg and 34 €/GJ), making the system affordable. When taking avoided costs into account, the prices could decrease with 20–26%, while at the same time avoiding 3600 tonnes of CO_2 a year. These results make clear that it is possible to provide a neighbourhood with all these different utilities, completely based on solar power and rainwater in a reliable, affordable and clean way.

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Nomenclature

Abbreviations

AC	alternating current
AEC	alkaline electrolysis cell
APX	Amsterdam power exchange
ATES	aquifer thermal energy storage
CAPEX	capital expenditure
CEDI	continuous electro de-ionization
DC	direct current
FCEV	fuel cell electric vehicle
OM	operation and maintenance
OPEX	operational expenditure
PEM	proton exchange membrane
PV	photovoltaics
RO	reversed osmosis
SOEC	solid oxide electrolysis cell

Subscripts

α	capital recovery factor
cond	condenser
evap	evaporator
hd	heat demand
i	system component
j	product type
r	discount rate

1. Introduction

Over the past century, the energy system has been focussed on centralised fossil-based energy production and distribution. In the coming decades, this energy system will transform into a renewable-based system, in order to limit the effects of climate change and due to the fact that fossil resources are exhaustive [1,2]. In this renewable-based energy system, energy will be abundant [3] as prices for solar and wind-based electricity are rapidly decreasing over the last few years [4]. The prices for solar and wind energy are the lowest at places with high solar irradiation or high wind speeds, such as in the middle of the Atlantic ocean, or in deserts, which are not necessarily places where most people live. Thus, we will need to find ways to convert and store this renewable energy in some form that we can transport it to the place where the energy is actually needed. A suitable energy carrier could be hydrogen [3,5], either compressed, liquefied, or converted to ammonia.

In addition to large scale centralised renewable energy production at mostly remote locations, there will be local, decentralised production of renewable energy, such as photovoltaic (PV) on roofs, PV parks or small wind parks. These decentralised forms of energy production will mainly be situated in or closeby urban areas, where space is scarce. Yet, there is a need to fulfil different utilities next to electricity, such as heat, water and mobility. In these urban decentralised energy systems, there is an opportunity to utilise as much local energy as possible by applying different conversion and storage mechanisms to overcome the temporal mismatch in supply and demand. At the same time, these conversion and storage mechanisms should make optimal use of the limited space available.

How could decentralised renewable energy production combined with conversion and storage fulfil most of the neighbourhood-utility functions? Solar or wind energy can fulfil the electricity utility in a neighbourhood and (partly) the mobility utility when electric cars are used. Currently, the energy used for mobility is mainly based on gasoline or diesel, but electric driving is rapidly increasing [6]. The electric motor of an electric car can either be provided with electricity via a battery (BEV, battery electric vehicles) or via a fuel cell, which converts hydrogen to electricity within the car (FCEV, fuel cell electric vehicle). The batteries of electric cars could certainly be involved in day-night storage, but are less suitable for seasonal storage [7]. Additionally, when mobility is electrified, this could lead to increased pressure on the electricity grid and again demand will not always match supply.

The third utility in neighbourhoods, next to electricity and mobility, is heat. In general, most neighbourhoods will have a surplus of (mainly solar) energy in the summer, while the largest part of their energy demand consists in the form of heat during winter. This heat demand will increasingly be electrified [8,9], which results in a large unbalance between the surplus energy from roofs that is fed to the electricity grid in summer, and the high electricity demand of the heat pumps in electrified houses in winter. Moreover, a solar or wind park near an urban area needs a strong grid connection to feed its excess electricity to the grid in summer. Within a neighbourhood, both effects could lead to inefficient systems and could cause problems at the connection with the high voltage grid, which results in a less reliable energy system [10].

In addition to these three energy-related utilities, water is very important in the urban environment. Coastal area's worldwide will face challenges regarding salinisation, because of increasing water demand, climate change and relative sea-level rise [1,11]. Even in a country with as much water as the Netherlands, the availability of fresh water can be limited, mostly in the western part of the Netherlands. Freshwater shortages should be prevented, which points out the need for a more robust freshwater provision. On a yearly basis, there is no freshwater shortage, but mainly a lack of storage capacity. Underground freshwater storage could contribute to large scale freshwater storage [12,13]. In addition, water storage systems could help to reduce inundation by storage of excess water. This stresses the importance of not only focussing on electricity but to integrate the different utilities (electricity, heat, mobility and water) into one system within a neighbourhood.

The concept we propose is an integrated system for a neighbourhood combining different utilities. The system utilises solar or wind energy to produce heat in summer or to produce hydrogen as an energy carrier and is thus an example of a Power-to-X system. The produced heat is stored in the subsurface, and during winter this stored heat is used to heat houses directly. The hydrogen is produced from peaks in renewable electricity production and utilised as a transport fuel for mobility. Furthermore, rainwater is collected from solar panels, stored in the subsurface and used for hydrogen production and for a part of the water supply in houses. The system hereby fulfils the utility demands for heat (Heat), mobility (Hydrogen), electricity and (partly) water (H_2O) in a neighbourhood. The concept is summarised by the term Power-to-H3, were the H stands either for heat, hydrogen or water (H_2O).

Besides being reliable, the purpose of this system is to be affordable and clean. For the system to be affordable, the production costs for each product should not exceed the regular market prices. As the market prices are influenced by the investment costs of the applied technologies, it is important to note that most of the technologies applied in the concept are still influenced by economies of scale and learning. This means that in the near future, the system costs will decrease. Nevertheless, in this study, the current costs of these technologies will be used to calculate the affordability. In order to be clean, the system should minimize environmental impacts, such as CO_2-emissions. This means for example that the hydrogen production should avoid CO_2 emissions, which means that only green hydrogen is part of the concept, which can be produced by using renewable energy to split ultrapure water into hydrogen and oxygen with an electrolyser.

The combination of utilities as described in the Power-to-H3 concept, especially of energy and water, is not often found in literature. It is highlighted that energy storage is necessary and therefore we should not only look to electricity storage, but integrate different sectors and energy storage technologies to create a *smart energy system* [14]. Different types of *smart energy systems* that focus on neighbourhoods exist [15–22], but only a few include hydrogen [20–22] and even less include hydrogen as a transport fuel [21]. Furthermore, water is never included in these studies. Heat production and storage for buildings or neighbourhoods in aquifers are well-known techniques [23–25], and the heat system from Power-to-H3 is comparable to a low or ultra-low temperature district heating [26,27]. However, in this concept the storage temperatures (40–60 °C) are high compared to the state of the art heat storage temperatures for seasonal storage (max. 25 °C) that are mentioned in literature. Thus, the combination of fulfilling all neighbourhood utilities in addition to the high temperature seasonal heat storage make the Power-to-H3 concept a unique and innovative system.

The objective of this paper is to introduce a reliable, clean and affordable integrated energy and water system for a neighbourhood. In the next sections we will further explain the general Power-to-H3 concept (Section 2). The concept will be evaluated with a techno-economic analysis based on a simulation model (Section 3), to determine whether the concept can fulfil its goals to be reliable, affordable and clean. In the economic analysis, we include avoided (social) costs, as the concept illustrates the importance to think about urban energy supply and demand at a system level. The concept will be applied to an existing case of a neighbourhood in the Netherlands (Section 4). Here, the first steps towards the realisation of a first Power-to-H3 system are taken, based on an 8.7 MWp solar park and a neighbourhood of 900 houses. The concept will thus be applied to an existing neighbourhood with the final aim to realise as many Power-to-H3 elements as possible. Results will be shown in Section 5. Finally, we will discuss the findings and draw conclusions (Sections 6 and 7).

2. System description

To be able to match demand and supply during every moment of the year in a reliable, affordable and clean way, Power-to-H3 focusses on a novel energy and water system for a neighbourhood. This proposed system can be divided into the energy source, conversion, storage and consumption of utilities. Within consumption, there are demands for demi water, heat, electricity and transport (see the left side of Fig. 1). The sources consist of wind turbines, PV panels that include rainwater collection and a source for heat production, represented here as surface water, but air could be an option too. In order to connect the sources with the consumption, different conversion and storage techniques are proposed (see Fig. 1).

The heat demand is met by storing heat (water) with a heat pump in a warm aquifer (40–60 °C), while the return flow of the heat grid is stored in a medium temperature aquifer (15–30 °C). The electricity supplied by the wind turbines and PV panels is converted from DC to AC in order to be used within households. In addition, this electricity is converted to hydrogen in order to fulfil the transport utility and cover short term fluctuations within supply and demand of electricity. The production of hydrogen requires water which is supplied by the rain water collection after purification in a reverse osmosis system. As the rain water is in excess compared to the hydrogen demand, the remainder of water fulfils part of the demi water demand in the neighbourhood. The subsystems are described in more detail in the following paragraphs.

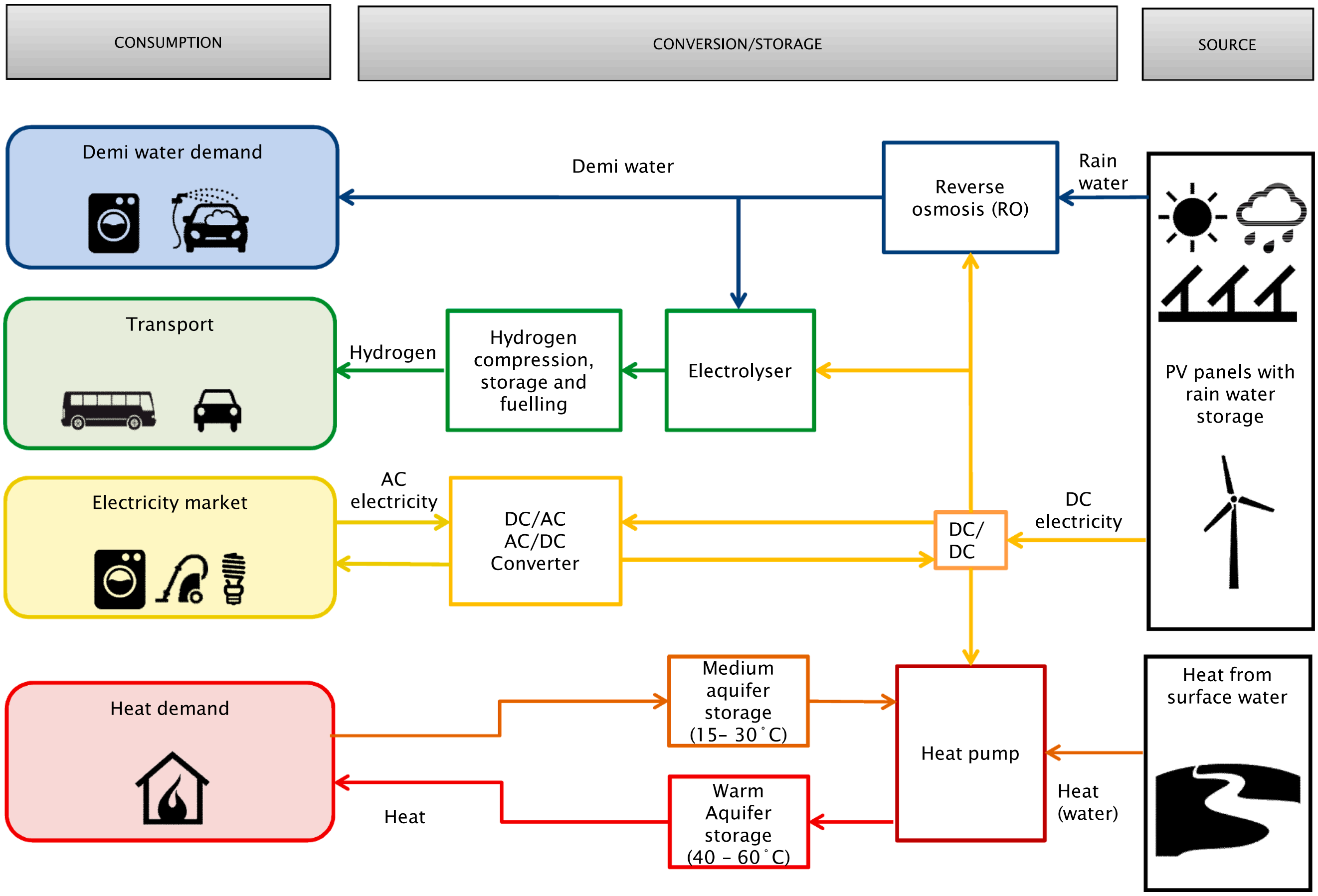

Fig. 1. Overview of the Power-to-H3 concept with household utility functions as consumption the left, conversion and storage technology in the middle and renewable energy and water sources on the right side of the figure.

When proposing this integrated concept, we do not advocate that neighbourhoods should be autark systems. When supply and demand do not match within the neighbourhood, the local system will communicate with the large scale energy system via the electricity grid, or via the energy carriers produced from large scale wind and solar parks at other places in the world to resolve the unbalance. This communication increases the reliability of the system. Thus, in the current system design, we assume that the electricity demand from houses is fulfilled with solar PV on roofs and a grid connection and any excess electricity from houses is sold to the electricity grid. This means that the electricity demand of households is not included in the concept at this moment, but the heat, water and mobility demand are.

2.1. Electricity to heat

During summer, when there is an abundance of solar power that cannot be used directly, electricity is converted to heat by a large scale heat pump. The heat pump produces heat with an output (condenser) temperature of 40–60 °C. The heat source for the heat pump is surface water. As the heat pump mainly runs during summer when the surface water temperature is relatively high, the operation results in a high coefficient of performance (COP) of the heat pump. When surface water is not available, an air-source heat pump could be used as well.

The produced heat is stored in an Aquifer Thermal Storage (ATES)-system with two or three wells, also called a (high temperature) geothermal doublet/triplet [28]. One warm well is used for the storage of the 40–60 °C heat. The medium well is used to store the return flow from the district heating network that connects the houses to the ATES-system as shown in Fig. 2. Additionally, the system could be extended with a third cold well for cooling purposes, but this aspect is not covered in this study.

Storage of heat at this temperature is a relatively new concept, as the standard storage temperature in the Netherlands is around 25 °C [29]. Yet, storage of heat at higher temperatures can increase both energy storage capacity and overall energy efficiency [30,31]. Firstly, by eliminating heat pumps in households and saving space. Secondly, by enabling the use of energy in a more balanced way as this approach eliminates the use of electricity in the winter for heating, when the power output of the solar panels is low.

2.2. Electricity to hydrogen

Electricity can also be stored as hydrogen which acts as an energy carrier. This carrier can fulfil different functionalities in the future energy system, as means of energy storage, high temperature heat, mobility, feedstock for industry or even use in households [5]. In the Power-to-H3 concept, hydrogen will be used for mobility as well as storage of energy. In this study, we mainly consider the utilisation of hydrogen in mobility as a transport fuel for cars as they are mainly used by the inhabitants of the neighbourhood. Earlier research has shown the role that hydrogen could play within a neighbourhood, with the car as power plant concept [21]. Fuel cell electric vehicles (FCEV) are seen as an important trend in the automotive industry and are expected to have similar shares to electric, hybrid and internal combustion cars by 2040 [32]. Furthermore, prices will decrease rapidly when mass production starts, similar to the current trend of electric vehicles [5].

Fig. 3 gives an overview of the hydrogen production in the Power-to-H3 system. Hydrogen is produced at 30 bar in the PEM electrolyser and subsequently compressed to 200 bar, to allow more efficient transportation to a fuelling station by a tube trailer, as shown in Fig. 3. In this paper, the PEM electrolyser is chosen for the concept, because its characteristics seem to fit best when converting intermittent solar power, in a system that should fit within a neighbourhood and with hydrogen that needs to be pressurised for transport [33].

After arrival at the fuelling station, the hydrogen is compressed further to 900 bar. Cars can tank around 5–6 kg of hydrogen at 700 bar via hydrogen dispensers, which gives them a driving range of 500–600 km.

2.3. From rain and electricity to demi water production

The production of hydrogen requires very pure water (or demi water), that will be produced from rainwater captured from solar panels. In general, the amount of water captured from solar panels is abundant in comparison with the water necessary to produce hydrogen. One solar panel of 270 Wp in the Netherlands could produce around 230–240 kWh/year [34], enough for the production of around 4 kg of hydrogen. For 4 kg of hydrogen, about 36 L of demi water is needed, which requires with conversion and losses no more than 80 L of rainwater. However, this same solar panel could capture about 1300 L of

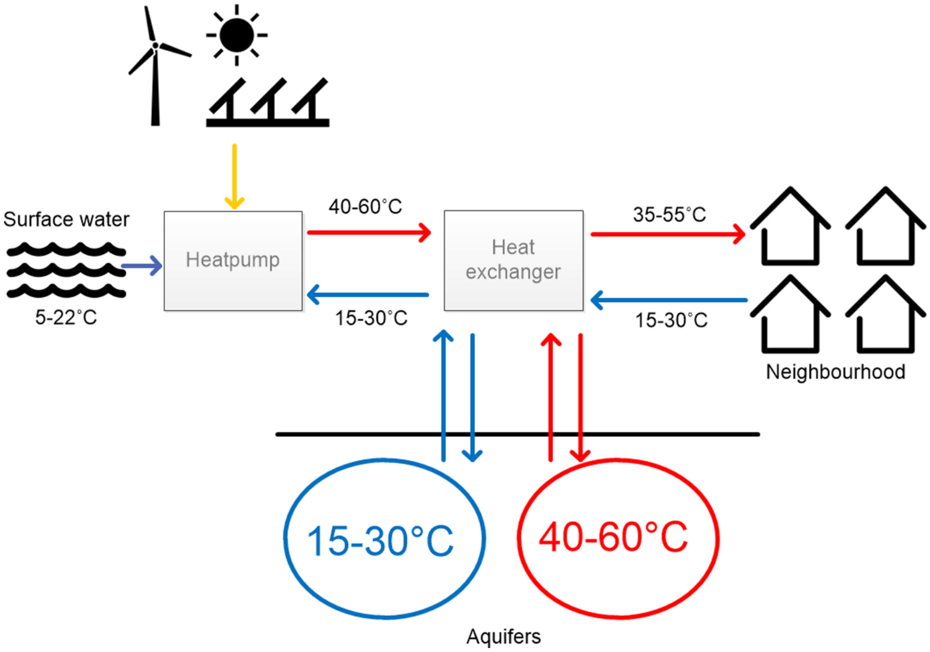

Fig. 2. Overview of the heat system in the Power-to-H3-concept, with a large-scale heat pump, aquifer thermal storage and a district heating network.

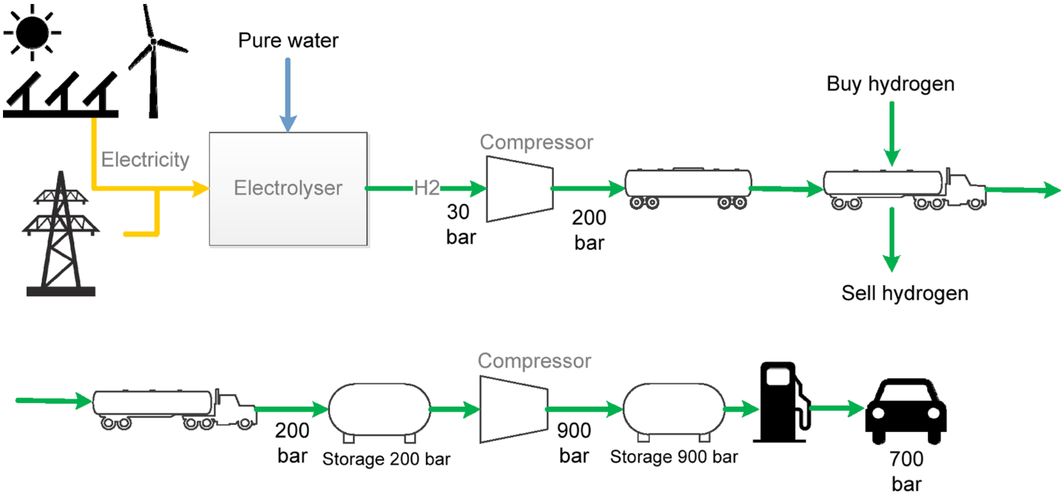

Fig. 3. Overview of the hydrogen system in the Power-to-H3 concept, including hydrogen production by electrolysis, compression, transport and fuelling infrastructure.

rainwater a year, based on average precipitation of 880 mm per year in the Netherlands [35], leaving a substantial amount of demi- or rainwater available for other purposes. This demi water could be stored and used in the neighbourhood, for specific applications such as the dishwasher and washing machine, to save on detergent use and to prolong the lifetime of the appliances. Other possible uses are watering of green areas within the neighbourhood in the dry summer season with stored rainwater.

The design of the (demi)-water system in the Power-to-H3 concept is shown in Fig. 4. Rainwater is caught from roofs (via the gutter) or solar panels with a draining-off system. The rainwater is filtered and then stored in an aquifer as a freshwater buffer [12,13]. When there is a demi water demand, water is taken from the buffer and purified to demi water quality by a reversed osmosis installation. A ground-level tank serves as a demi water buffer for the neighbourhood and as a basis for Continuous Electro De-Ionisation (CEDI). During this process, ions in the water are removed under influence of an electric field in combination with cation and anion membranes [36]. Furthermore, ionic resins are used to accelerate the process. After this step, the water has a conductivity of less than 0.1 µS/cm, which is suitable as input for the electrolyser.

The demiwater demand of households is fulfilled via a separate water network and used in, for example, washing machines and dishwashers. The water from aquifer storage could also be utilised directly for watering of green areas in the neighbourhood.

3. Methodology

In order to analyse whether the Power-to-H3 concept could result in a reliable, affordable and clean energy and water system for a neighbourhood, we developed a simulation model. This model is able to perform hourly calculations for at least one year or a multitude of years. It provides the energy- and water balance (reliable), economic (affordable) and environmental calculations (clean).

Fig. 5 shows the model structure, with the model input on the left side, which is specified per case and is further described in Section 4. The calculations section of the model (in the middle of Fig. 5) include the calculations for conversion and storage of electricity, heat, water and hydrogen. Between those systems, there is interaction on an hourly basis. This interaction is partly determined by a scheduling strategy that distributes the available renewable energy over the different utilities, which is further explained in Section 3.1.3. All calculations and inputs from the different parts of the model are integrated within hourly timesteps, which results in the model output shown at the right-hand side of Fig. 5. The energy and water balance are monitored and adjusted every hour, while the economic and environmental calculations are carried out at the end of a run.

The most important input for the energy and water balance is explained in the next paragraph, followed by the environmental analysis and finally the economic calculations. Lastly, we zoom in on the avoided costs that are an integral part of the Power-to-H3 concept, and how those could partly be included in the business case.

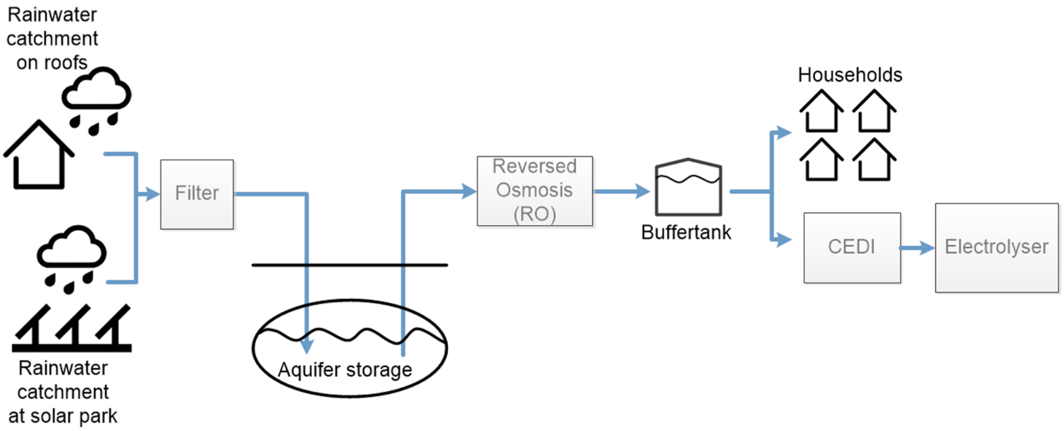

Fig. 4. Overview of the water system within the Power-to-H3 concept, which consists of rainwater catchment, aquifer storage, purifying by reversed osmosis and continuous electro de-ionisation for an extra purification step in case the water is used as a source for hydrogen production.

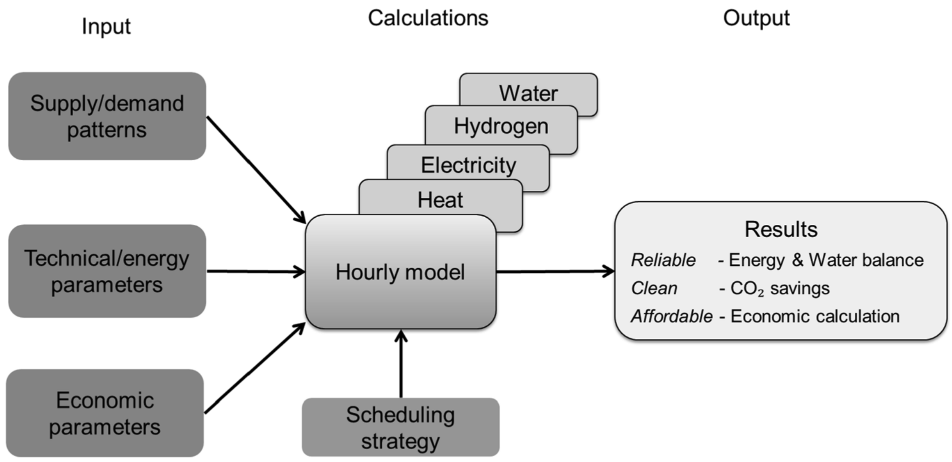

Fig. 5. Overview of Power-to-H3 model structure with the model input, calculations with for the different utilities (water, hydrogen, electricity and heat) as well as the model outputs.

3.1. Reliable, the system components

3.1.1. Input

Within the Power-to-H3 concept, the balance between supply and demand of both water and energy is checked every hour during the simulation. Therefore, the model has input in the form of external supply and demand patterns. The supply patterns include weather data about solar irradiation, temperature and rain, as well as the surface water temperature. The energy demand includes parameters such as the heat demand per house, amount of houses, yearly hydrogen demand or size of equipment. Those patterns and parameters depend on a specific case and are therefore specified in Section 4. The economic parameters are further explained in Section 3.2.

3.1.2. Conversion and storage calculations

For energy supply and conversion, the most important energy parameters are summarised in Table 1.

To balance supply and demand, there are options for (1) heat storage in the subsurface, (2) water storage in the subsurface and buffer tanks, and (3) hydrogen storage in high- pressure tanks. The buffers should always be able to fulfil a minimum demand for hydrogen, heat or water. In addition, all storage media have a specified maximum storage capacity. The main objective of the storage systems is to distribute the available energy in such a way that the storage levels are kept on a predetermined acceptable level.

3.1.2.1. Heat. A maximum heat storage capacity is defined that varies over the year. The purpose of the heat storage is to balance the seasonal difference in supply and demand of energy. Therefore, most heat will be produced in summer, while the largest heat demand occurs in winter. In addition, there should be a sufficient amount of heat stored to fulfil the demand, without creating an oversupply of heat. An oversupply of stored heat will degrade over time resulting in efficiency losses for the heat system. If at any moment in time the heat storage system has not enough heat stored to fulfil the heat demand, heat is produced directly with the heat pump based on grid electricity while utilising surface water as a heat source. This ensures a reliable system operation.

In order to comply with these requirements, a heat storage pattern is developed whereby the total heat demand is divided over the year. Each week a certain percentage of the total heat demand is added to the maximum amount of heat that is allowed to be present in the aquifer at that moment. Every hourly step a check is performed of how much heat can be stored at that hour based on the available produced energy and if this agrees with the amount of heat that can be stored in that week. If the weekly value is already reached, the storage of heat is paused until the next week.

The amount of heat stored needs to exceed the heat demand to take the losses during heat storage into account. Therefore, the weekly heat storage values are multiplied with a certain factor. In Eq. (1), the relationship between the weekly maximum storage values and total heat demand is shown.

$$HD_{week,maxi} = \frac{HD_{week,\%i}}{100}\cdot HD_{sum}\cdot f_{hd} \qquad (1)$$

where $HD_{week,maxi}$ (kWh) is the maximum amount of heat stored in a certain week, $HD_{week,\%i}$ (%) the percentage of the total heat demand that can be stored in that week. With surface water and electricity from PV as a heat source, the heat storage can only be filled in the summer period. Therefore, the weekly storage value is set to 0 from November up until the end of February. From March to October, the surface water temperature is expected to be high enough to extract heat, with a peak in late summer. Solar irradiation is expected to peak in June and July. Based on this knowledge, a storage pattern was created that starts ascending from around 1% in March to 4.6% in July and August and starts decreasing again to 1% in October. HD_{sum} (kWh) is the total annual heat demand and $f_{hd}$is a factor that takes the heat losses during storage into account. In this study, the factor is 1.2, as a heat loss in the subsurface of approximately 20% is assumed. This factor is determined by an iterative process and will change depending on the size and temperature range of the system and can therefore not be generalised.

Table 1
Important technical and energy parameters within the Power-to-H3 model.

System element	Energy consumption/efficiency
PV system	17%[a]
Heat pump	COP = 7.5 – 0.07 ($T_{cond\ (out)}$ – $T_{evap\ (in)}$)[b]
Infiltration temperature warm aquifer ($T_{cond\ (out)}$)	65 °C [c]
Electrolyser (PEM)	50 kWh/kg[d]
RO system	90%[e]
Electricity conversion (AC/DC and DC/AC)	95%[f]

[a] Report from IRENA [4].

[b] Based on Dorin software [37].

[c] Bases on different configurations for the heat system [38].

[d] Combined number for electrolysis, gas cleaning and compression to 200 bar, based on literature [5] and commercially available information from Thyssenkrup [39] and Hydrogenics [40].

[e] On water basis, based on expert knowledge (Hans Huiting & Emile Cornelissen, KWR, 21-02-2017).

[f] Assumption, based on [15].

3.1.2.2. Hydrogen. Hydrogen is stored at a pressure of 200 bar in tanks on tube trailers. At the hydrogen fuelling station, there is a 200 bar buffer tank installed as well. If the volume in this storage tank comes below a certain minimum, while there is not enough hydrogen produced yet to refill the tank, hydrogen can either be produced with electricity from the grid or be bought from an external source, again ensuring a reliable system. When the maximum hydrogen storage capacity is reached, a full hydrogen tank is transported to the hydrogen fuelling station or a third party. Meanwhile, the system starts filling a new tank or tube trailer with hydrogen.

3.1.2.3. Water. Water is stored in the subsurface and partly in buffer tanks. If the buffer tanks reach a certain minimum level, they are filled with water from the aquifer. If there is not enough rainwater stored at that time, groundwater can be used as a source for (pure) demi water production, as long as the system is in balance over a period of a number of years.

Another option to fulfil a shortage of pure water would be to buy pure water from an external source. For water storage in the subsurface, there is no real maximum, but the difference between the infiltrated volume and restrained volume is provided. If over a number of years, the infiltrated volume is significantly larger than the restrained volume, it is possible to withdraw some extra water for irrigation in summer months, while at the same time creating a balanced water storage system.

3.1.3. Scheduling strategy

The available energy in the form of solar or wind electricity can be distributed over at least three different alternatives producing hydrogen, producing heat or feeding electricity into the grid. The model thus needs an energy distribution strategy and we decided to design two distribution scenarios. The first one is to ensure reliable heat production where the use of locally produced energy is maximised, while hydrogen can be imported from external sources. With this scenario, priority is given to heat production, whereby the generated electricity is in principle allocated to the heat pump. If the amount of available renewable electricity is larger than the capacity of the heat pump, or when the warm aquifer if full enough for that moment in time, the electricity is available for the electrolyser. When there is still renewable electricity left after usage by the electrolyser, this is fed into the electricity grid. However, if the demand for hydrogen is higher than the production by the electrolyser with the available energy, this means that hydrogen has to be imported from elsewhere.

The other option is to produce all heat and hydrogen on-site in a reliable way. In this scenario, there is a priority for hydrogen production, which means the electricity from the solar panels and wind turbines is first available for the electrolyser. When the electrolyser runs at full capacity, the remainder of the generated electricity is allocated to the heat pump. Whether this electricity is used to produce heat by the heat pump depends (as before) on the capacity of the heat pump and on the amount of heat already stored in the aquifer. If there is still renewable electricity available, it is fed into the electricity grid.

When hydrogen is set as a priority, there should always be enough hydrogen to fulfil the hydrogen demand at the fuelling station. Therefore, electricity is bought from the grid if the level of the hydrogen buffer tank comes below a certain level ensuring the production of hydrogen on-site. Furthermore, there is an obligation to fulfil the heat demand of the neighbourhood at any time, because heat cannot be easily imported. Hence, it is possible to buy electricity from the grid to fill the heat storage, whereby the user sets the maximum price for electricity. Moreover, if the warm aquifer should become empty at any moment, the system switches over to direct heat production with electricity from the grid, with surface water as a heat source.

Table 2
Product market prices used to calculate the affordability of the Power-to-H3 system.

Product	Price (VAT excluded)	
Hydrogen	10 €/kg[a]	
Heat – price per unit	22.5 €/GJ[b]	34 €/GJ[c]
Heat – fixed charges	252 €/year[b]	
Heat – connection costs (one occurrence)	821 €[b]	
Demi water	1.4€/m^3[d]	

[a] This value is not market driven, but currently used as hydrogen price because the costs per km driven are on the same level as gasoline.

[b] Based on the regulations for heat delivery by the Dutch authority for consumers and market (ACM) [41].

[c] Based on an average heat demand of 22 GJ/year for a well isolated Dutch house [42,43]

[d] Approximate price for drinking water in the Netherlands [44].

3.2. Affordable, the system economics

The Power-to-H3 system aims to be affordable, which means that the costs should not be higher than regular market prices. Table 2 shows the current market prices used for the different products, based on the Dutch prices for heat, hydrogen and drinking water. The heat price consists of a fixed charge per year and price per GJ, to have a fair comparison with the price for heat from a Power-to-H3 system, we have chosen to combine this two cost factors in one price per GJ based on an average heat demand of a well isolated Dutch house. To check whether the Power-to-H3 system is affordable, we then calculated the production costs for the different products and check whether the production cost exceeds the current market price for this product. If needed, these market prices can easily be adjusted to match prices in other areas.

The production cost per product is calculated according to Eq. (2).

$$Production\ \ cost_j = \frac{\sum (\alpha \cdot CAPEX_i + OM_i + Ecost_i)}{\sum N_{product,year}} \tag{2}$$

where $Production\ \ cost_j$ (€ per GJ, kg or m^3) represents the production costs for a certain product j, being either hydrogen, heat or water. The right-hand side of the equation represents the sum of the yearly costs of the components i that are part of a certain system, divided by the total yearly production in kilos of hydrogen, gigajoules (GJ) of heat or cubic meters (m^3) of pure water. Here the $CAPEX_i$ (€) covers the capital expenditures for a particular system component i (i.e. the electrolyser, compressor or storage tank) and OM_i (€/year) represent the operational expenditures for a particular system component. $Ecost_i$ (€/year) are the electricity costs for a system component i and lastly $\sum N_{product,year}$ (in GJ, kg or m^3) is the amount of heat, hydrogen or water sold during a year. The capital recovery factor (α, no unit) in Eq. (2) is calculated according to Eq. (3).

$$\alpha = \frac{r}{1-(1+r)^{-L_i}} \tag{3}$$

With α the capital recovery factor (no unit), r the discount rate (in %) and L_i (year) the lifetime of a particular system component i.

The most relevant *economic parameters* for the calculations from Eqs. (1) and (2) are shown in Table 3, based on current technology costs. All those parameters could be adjusted to adapt the model to different locations, scales or new developments.

3.3. Clean

Besides being a balanced and affordable system, the Power-to-H3 system has the objective to provide a clean and safe living environment. It fulfils this objective in many different ways (1) it is only based on renewable energy, which reduces CO_2 emissions, (2) the risk of CO related deaths [52,53] by the central heating boiler is avoided when

Table 3
Relevant economic parameters in the Power-to-H3 model, based on current costs of technology.

	Cost(function) for CAPEX	Operation and maintenance (OM)	Lifetime in years
System elements			
Solar Park	900 €/kWp[a]	1%	20
Heat pump	1400€/kW$_{el}$[b]	1% [45]	20 [46]
District heating network	(214 + 1725 * d$_{pipe}$) * L$_{network}$[c] in € with d$_{pipe}$ de pipe diameter in m and L$_{network}$ the length of the network in m	1% [46]	50 [47]
Electrolyser	1100€/kW[d]	2%[e]	20 [21]
Hydrogen fuelling station	1.3 M€[e]	70,000€/y[e]	15[f]
RO system	15,000 + 8000 * V$_{RO\ in}$ € with V$_{RO}$ in m^3/hr[f]	2.5%[f]	15[f]
CEDI system	30,000 * V$_{CEDI}$/18 + 1000 * V$_{CEDI}$[f]	2.5%[f]	7.5[f]
Aquifer thermal storage	1.5 M€[g]	1.5%[g]	40 [g]
Water storage	0.55 M€[h]	0.5%[h]	40 [h]
Other economic parameters			
Purchase grid electricity	On average 6.5 €₵/kWh [i]		
Discount rate	3%[j]		

[a] Based on the investment price for solar PV larger than 1 MW in the Netherlands [48].

[b] Based on different quotations from heat pump suppliers, and validated with expert knowledge.

[c] The pipe diameter is a model parameter, and the formula is valid for outer city areas based on an IEA document on District Heating [46].

[d] Costs based on literature [5] combined with expert knowledge from (Ekinetix, November 2017).

[e] Based on literature [21,49] and quotation from a Dutch based green fuel company (PitPoint).

[f] Based on calculations with a membrane that produces 20 L/m^2/hour for RO, and based on data from Pure Water Group for CEDI (Hans Huiting, KWR, 09-10-2017).

[g] Costs are a sum of investments in boreholes, casting, pipes, pumps, injection valves, heat exchanger, technical room and preliminary design, exact formulas can be found in the project report [38].

[h] Costs for water storage in the subsurface [50], including rainwater collection, self-cleaning filters and pumps [38].

[i] For electricity purchase from the grid, APX prices from 2016 were used. On top of the APX, a network price of 1.7€₵/kWh plus taxes (VAT excluded, 1.6€₵/kWh) are added, together 3.3 €₵/kWh in 2016, based on CBS data voor wholesale users in the 200–200,000 MWh/year category. Fixed charges are not taken into account, these are paid by the company that builds the solar park.

[j] The average recommended discount rate by the study group discount rate [51].

Table 4
CO_2 emission factors for heat, mobility and electricity applied in the Power-to-H3 model.

	Amount	Unit	Reference
CO_2 emission heat	59.7[a]	kg CO_2/GJ	Boiler on natural gas (December 2017)
CO_2 emission car	0.22[a]	kg CO_2/km	Average car and fuel use (2014)
CO_2 emission electricity	0.413[a]	kg CO_2/kWh	Representative Dutch electricity mix (December 2017)

[a] Data are taken from the CO_2-emission factors database [54].

applying a district heating network instead of natural gas, (3) there is less air (and noise) pollution by cars when driving fuel-cell/electric instead of on gasoline or diesel. In this publication, we do not go further into detail on all those effects, but instead, we have taken the avoided CO_2 emissions in the system as a measuring unit for a clean system. In order to calculate the avoided emissions, the current conventional situation with heat delivery via a gas boiler, a gasoline car and the emissions of the electricity mix in the Dutch electricity grid are used for comparison with the Power-to-H3 system. These emissions are summarised in Table 4. As with the economic parameters, these parameters can easily be adjusted to reflect different situations.

To monetise avoided CO_2 emissions, a price of 60€/tonne CO_2 is taken as a reasonable value. This CO_2 price corresponds to the price projected necessary to achieve the goals as set in the 2015 Paris Agreement [55]. The $CO_{2_{costsavings}}$ in € are calculated according to Eq. (4).

$$CO_{2_{costsavings}} = CO_{2_{emissionfactor}} \cdot Product_{delivered} \cdot CO_{2_{price}} \tag{4}$$

where $CO_{2_{emissionfactor}}$ (in kg CO_2 per GJ, km or kWh) are the factors as shown in Table 4, $Product_{delivered}$ is the amount of electricity (in kWh), heat (in GJ) or hydrogen (in kg) that are sold to the grid, house owner or car driver and $CO_{2_{price}}$ (€/tonne) the price of a tonne CO_2.

3.4. Avoided costs

In an integrated concept such as Power-to-H3, there is a need for alignment between technology and institutional arrangements. When a Power-to-H3 system is realised, there is an impact on different aspects of society. Examples of possible impacts are already mentioned in Section 3.3, however, there are more possible impacts. A large impact can be realised if an extension of the electricity grid is avoided when part of the energy is converted and stored locally. Moreover, a decreased risk of water inundation and less water scarcity during droughts will occur when rainwater is stored in the neighbourhood. All those effects are expected to have a contribution to a cleaner, quieter, safer and greener living environment from a societal perspective, yet are hard to quantify and do not directly improve the business case.

In this research, two possible effects of a Power-to-H3 system in a neighbourhood are quantified. The first one concerns CO_2 savings, which are monetised by a CO_2 price as explained in Section 3.3. The second element of the avoided cost calculations are the savings on electricity grid extension. In a standard situation, the installation of a solar or wind park will require reinforcement or extension of the electricity grid in order to dispatch the electricity peaks in the summer. By converting the electricity peaks in summer to other forms of energy, the required grid connection capacity can be reduced. The cost savings related to this grid connection reduction will vary depending on the situation and can be very hard to quantify as is pointed out by Agora Energiewende [56] as well as KU Leuven [57].

Network costs can be calculated in kWh (transported energy) and kW (peak power). The required investment is generally based on peak power capacity, but both units are used when avoided cost are calculated. For example, the transmission and distribution costs for added wind/solar (land-based) in Germany as reviewed by Agora Energiewende are estimated at approximately 7.5 €/MWh [56]. For Belgium, these costs vary between 2.4 and 3.1 €/MWh for additional renewable energy capacity [57]. If conversion and storage systems are installed, savings on these grid connections could occur. A recent study about the impacts of a form of high-temperature seasonal heat storage in the Netherlands calculated a saving on the grid extension of 3.3–8.5 €/GJ of heat delivered [58]. From a study focussing on different power-to-hydrogen possibilities, the savings on grid extension costs for an agricultural area are around 1000 €/kW, while for large scale PV (100 MW) the savings are approximately 280 €/kW [59]. However, these cases are not applicable to the urban environment where the Power-to-H3 system will be situated and therefore the savings on grid extension will most likely be lower.

Next to savings on the grid connection of the solar or wind park, there is an additional advantage for the neighbourhood. Because of the relatively high temperature at which heat is delivered, no heat pumps need to be installed in the houses which have an approximate capacity of 6 $kW_{electric}$ each. In the Power-to-H3 concept, either no heat pumps at all or only small booster heat pumps of 0.5 $kW_{electric}$ for tap water are installed in each house, saving at least 5.5 $kW_{electric}$ per household [60]. This saving in electrical connection is quantified by van Melle et al. [60] at a value of 204–700 €/kW. However, as mentioned before this saving is highly depended on the location and the capacity of the already existing grid.

In this study, we assume the lower value of 200 €/kW for avoided grid connection costs for both the solar and wind park as well as the neighbourhood, since the Power-to-H3 system is located in an urban area. This means that there is already a grid connection available and the costs for reinforcement are not as high as in a remote or agricultural area. The costs for grid reinforcement are calculated according to Eq. (5).

$$C_{grid} = P_{additional} \cdot C_{reinf} \tag{5}$$

With C_{grid} are the costs for grid reinforcement in €, $P_{additional}$ the additional grid capacity needed in kW and C_{reinf} the cost for grid reinforcement in €/kW, in this study this value is set to 200 €/kW.

4. Case study of Power-to-H3 in Nieuwegein, the Netherlands

The Power-to-H3 system is applied to an existing neighbourhood in Nieuwegein, the Netherlands to investigate the reliability, affordability and cleanness of the system. The final aim will be to realise as many elements from the Power-to-H3 concept as possible.

In Nieuwegein, a solar park of 8.7 MWp is installed for the production of heat and hydrogen in order to fulfil the demands for heat and mobility of a neighbourhood of 900 houses, which are situated about 2 km from the solar park (Fig. 6). There is no direct physical electrical connection between the houses and the solar park, so both the neighbourhood and the solar park have their own grid connection.

The main parameters that describe the Nieuwegein case are depicted in Fig. 7. The solar electricity production will be 8.7 MWp and the current electricity connection is 4 MW (MVA). To prevent grid extension, the heat pump and electrolyser are scaled at 2.5 MW. Probably, this capacity is more than necessary to just fulfil heat and hydrogen demand, but here we have chosen to relate the size of the conversion technology to the supply side instead of the demand side, which is a consequence of taking a system approach. In the neighbourhood of 900 houses, we expect that in the near future approximately half of the households will have a fuel cell electric vehicle, while the other households have an electric car [32]. More background information about the system size, years simulated, weather conditions and supply and demand in the case study can be found in the supplementary information (SI-A).

For the economic analysis, it is important to note that Waternet, the water company for the Amsterdam region, will install the solar park

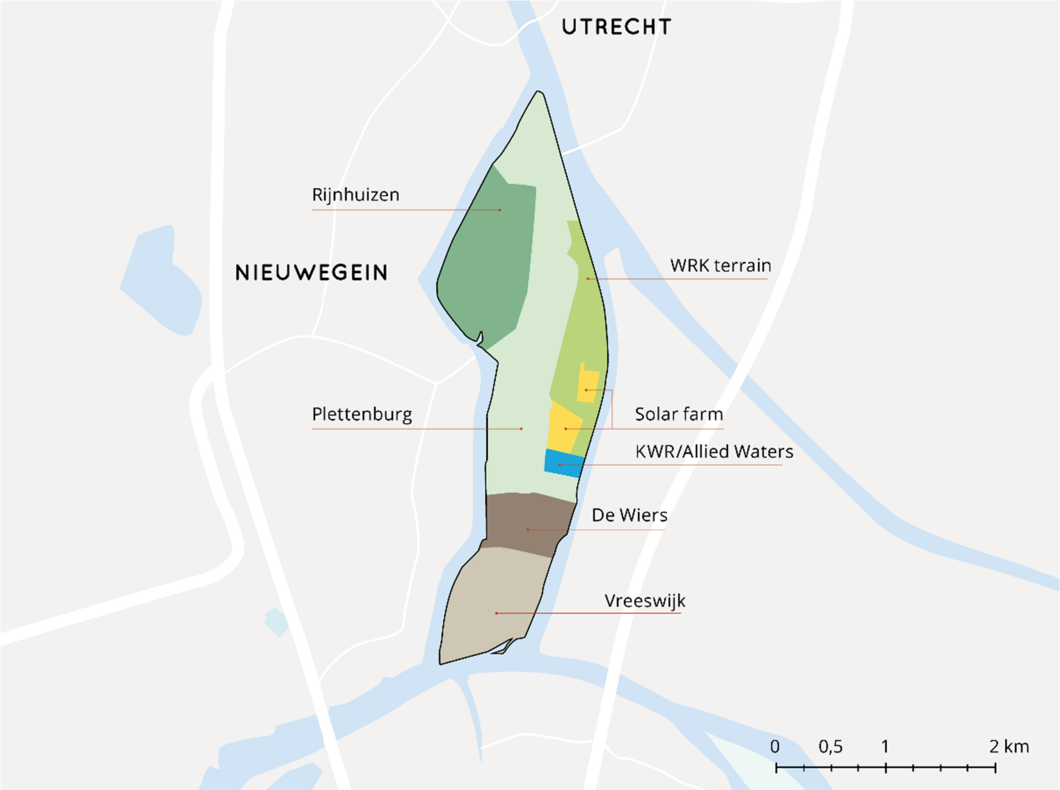

Fig. 6. Overview of the first Power-to-H3 project location, the colours show different locations in the project area, including the solar farm (yellow) and the Neighbourhood Rijnhuizen (dark green) [3].

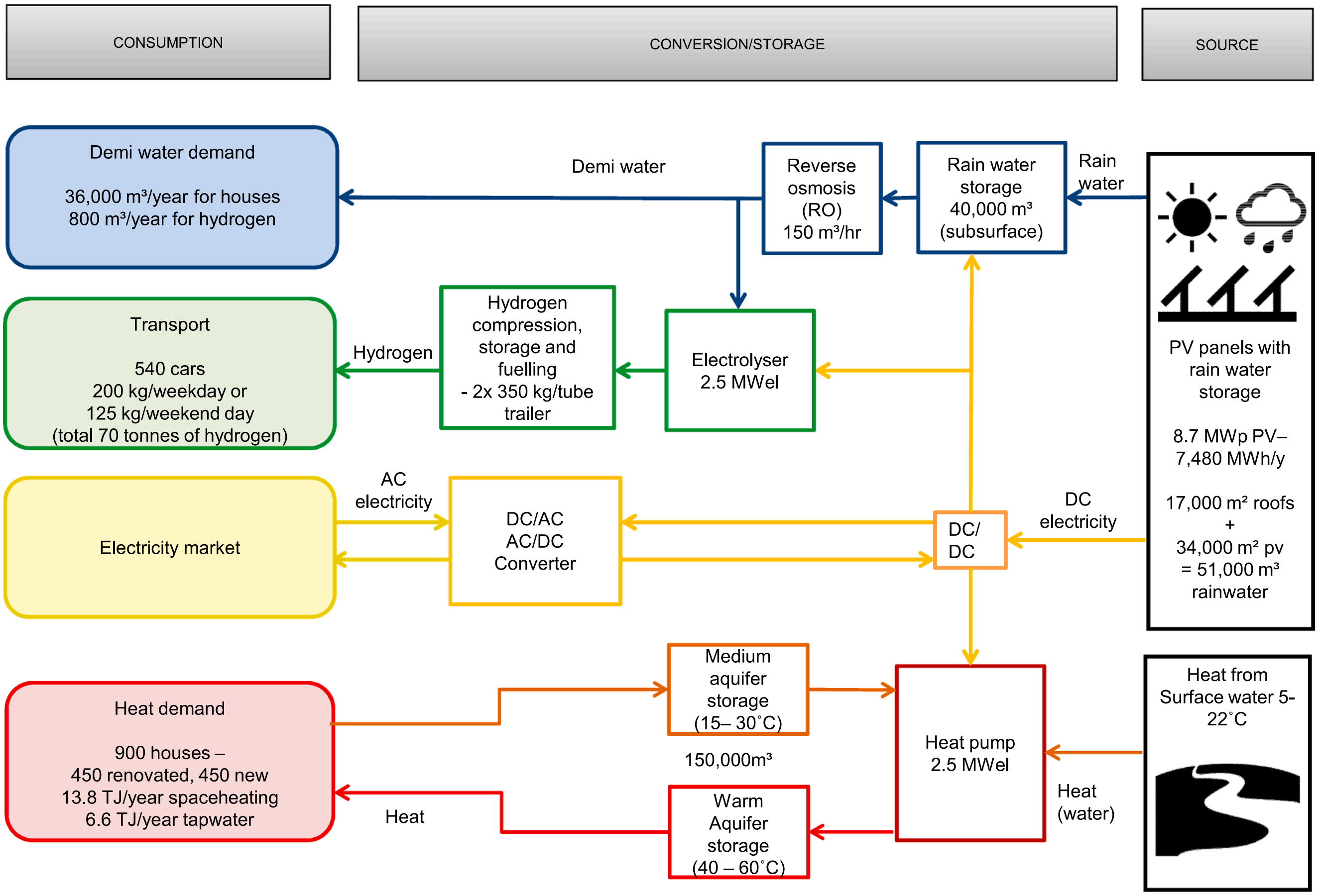

Fig. 7. Schematic overview of the Power-to-X system with supply, demand and system component sizes for the case of Nieuwegein, the Netherlands.

and sell the produced electricity to the Power-to-H3 system at a price of 3.9 €₵/kWh, which is comparable to the fossil-based electricity price. Waternet can afford this selling price as the solar park is subsidised. Therefore, the investments for the solar park are thus outside of the system boundary and instead an electricity purchase price is included in the energy costs of the system. This electricity price is part of the sensitivity analysis that is carried out for a total of ten parameters in the Nieuwegein case. The values and ranges chosen are further explained in Table A.4.

5. Results

This section is based on the results of the case study as described in Section 4, whereby heat production is set as a first priority. Results of the hydrogen scenario are shown in the SI-B.

5.1. Renewable energy distribution

When the Power-to-H3 system is applied to a neighbourhood in Nieuwegein with a nearby solar park, the yearly electricity production is 7480 MWh. The monthly distribution pattern of solar electricity for the complete 5 year period is shown in Fig. 8. There is a clear production peak in June and July, as electricity production in July is almost 10 times higher than in December. The average energy distribution per year is summarised in Table 5.

In this scenario, 60% of the yearly electricity output is utilised for hydrogen production, 25% for heat and the surplus (15%) is fed back into the grid. The electricity consumption for pure water production is so little (0.1% of the total energy production) that it is seen as negligible. In the period from November–February, almost all electricity is used for hydrogen production, while the rest of the year there is a combination of heat and hydrogen production and some surplus electricity which is fed into the grid.

5.2. Reliability of the system

5.2.1. Heat

Fig. 9 shows the heat production with electricity from the solar park, the heat demand from the neighbourhood and the surface water temperature, which is heat source for the heat pump. With heat as a priority (see Fig. 9), heat is produced in the warmer months when the temperature of the surface water is at least 7 °C. The figure clearly shows the idea of the seasonal storage heat is produced and stored in summer while being supplied during the winter. All heat is produced with electricity from the solar park, with an average COP of 4.2. With

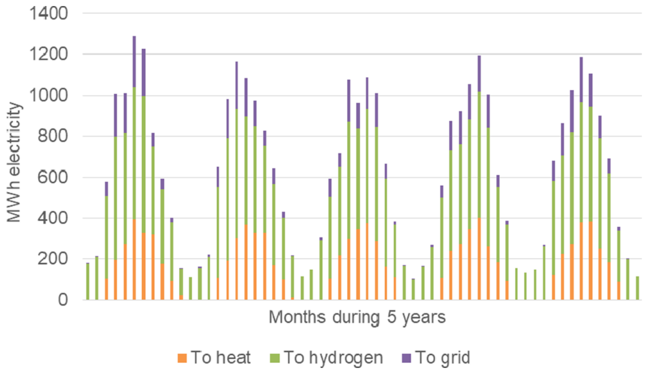

Fig. 8. Monthly energy distribution for the heat as priority system, the period shown here is 2010–2014, with monthly values.

Table 5
Distribution of energy over the different Power-to-H3 products on a yearly basis (5-year average).

In MWh/year	Heat priority
Renewable electricity to heat	1910
Renewable electricity to hydrogen	4500
Renewable electricity to grid	1070
Total renewable electricity production	*7480*

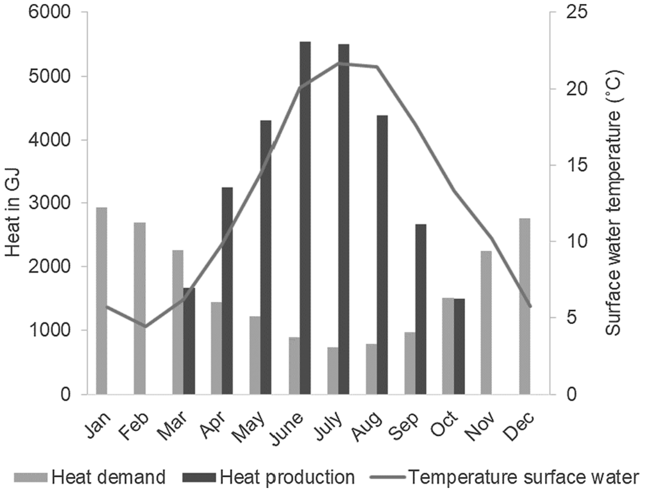

Fig. 9. Heat demand and supply in a Power-to-H3 system for a neighbourhood of 900 houses, monthly average over five years.

this average COP, the total heat production is 28.8 TJ, while the total heat demand is 20.4 TJ, resulting in an overall efficiency of 70% for the heat system. The efficiency does include heat losses during storage in the aquifers, during transport in the district heating network up until the delivery of heat in the houses. The heat demand of the neighbourhood is fulfilled at any time, resulting in a reliable heat system.

5.2.2. Hydrogen

How hydrogen demand and production are matched over the year is shown with monthly averages in Fig. 10. The electrolyser uses 4500 MWh of solar power and produces 90 tonnes of hydrogen per year compressed to 200 bar. The yearly hydrogen demand based on 540 hydrogen cars is around 70 tonnes, which means there is a surplus of 20 tonnes of hydrogen each year, mainly produced during the summer months. However, while the (monthly) demand is more or less constant, the production peaks in summer during winter there is a shortage of 9.1 tonne of hydrogen, which corresponds to 13% of the total yearly hydrogen demand. One solution would be to store the surplus hydrogen in summer, to be able to use it in winter, in a similar way as the heat storage system. However, hydrogen storage in pressurised tanks is expensive, and therefore the best option at this point in time would be to sell the surplus hydrogen in the summer and import hydrogen in the winter when production falls short. In the mid-term future, the gas grid and/or salt caverns could serve as a hydrogen buffer.

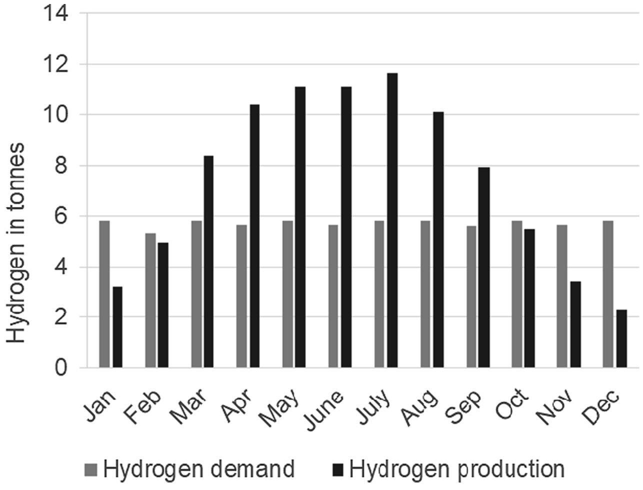

Fig. 10. Hydrogen demand and supply over a year for a Power-to-H3 system with a supply of 540 cars, monthly average over five years.

5.2.3. Pure water

For the hydrogen production as discussed in 5.2.2, 900 m^3 pure water is needed. The pure water demand for hydrogen is only a fraction of the total yearly (rain)water supply of 51,000 m^3/year, of which 17,000 m^3 is captured from the solar park, and 34,000 m^3/year from roofs. The pure water demand in the neighbourhood is 40,000 m^3, including loss factors during purification steps. This leads to a surplus of 10,000 m^3/year that could be used for irrigation purposes in the summer months. Over the year, the water storage ensures a reliable water supply, even in months where the water supply is lower than the demand. This situation merely happens during spring, as can be seen in Fig. 11.

5.3. Sustainability, a clean system

The total CO_2 savings would be 3090 tonnes per year if the

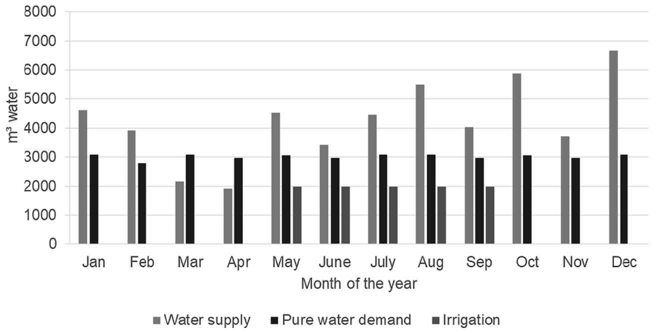

Fig. 11. Rainwater supply and (pure)water demand, monthly average over five years.

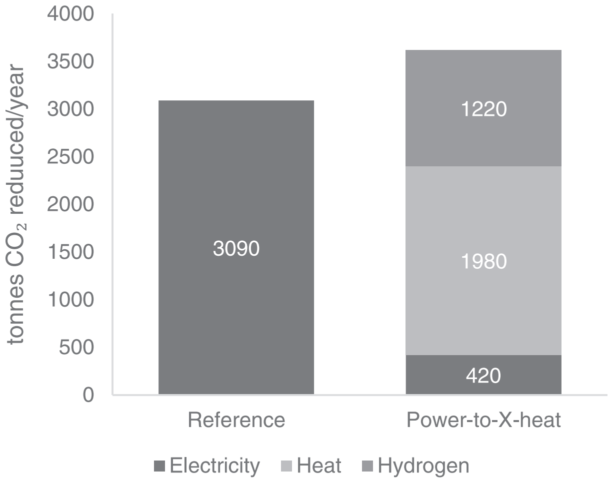

Fig. 12. Reduction of CO_2 emissions in a reference scenario where all electricity would be sold to the grid versus the reduced CO_2 emissions in a Power-to-H3 system, split in electricity, heat and hydrogen.

renewable electricity from the solar park would be completely sold to the grid and replace electricity needs elsewhere. When operating the Power-to-H3 system, the CO_2-reduction is 3620 tonnes per year (see Fig. 12), based on CO_2 reduction factors as given Section 3.3. The Power-to-H3 system is thus saving more CO_2 because of the conversion of electricity to other products.

5.4. Affordability of the system

5.4.1. System costs

The Power-to-H3 system produces four different products; heat, hydrogen, water and electricity. The costs for the system are shown in Table 6. These costs include the investments (CAPEX or Capital Expenditure) and the operation and maintenance (OM or OPEX, Operational Expenditure) costs, which also cover the transport of hydrogen and costs for buying electricity from the solar park. The investments in the solar park are excluded from the CAPEX of the Power-to-H3 system because the solar park will be installed independently of the realisation of the Power-to-H3 system (as mentioned in Section 4).

The total CAPEX is 13.7 million euro (M€), of which the heat system represents 53%. Another 33% of the total CAPEX consists of investments in the hydrogen system, and 10% of the CAPEX corresponds to the water system. The OM costs are on average 2% of the total CAPEX, at 280 k€/year. In the breakdown of the OM and transport costs, almost 50% is related to the hydrogen system, mainly because of hydrogen transport. The fuel costs are the cost made for buying electricity from the solar park which adds up to 260 k€/year.

5.4.2. Product production costs

In Table 7 the total costs as shown in Table 6 are broken down per utility function. For heat and water, the costs per household are shown based on a neighbourhood with 900 households. The current maximum end-user price for heat in the Netherlands is 22.5 €/GJ [61], plus a fixed charge of 252 €/year [41], leading to a selling price of 34 €/GJ based on the yearly heat demand of an average household. The calculated heat price for Power-to-H3 heat is 26 €/GJ, which indicates that heat can be delivered at an affordable price.

For pure water production, the end-user price is set at the average price of around 1.4 € per m^3 drinking water [44]. The actual production cost for pure water 50% higher than the end-user price, as can be seen in Table 7. This specific part of the Power-to-H3 system is thus not affordable as an independent system, but within the total system costs, these costs are almost negligible.

For hydrogen, costs per household are not calculated, because the household will not invest in the production of hydrogen and the hydrogen fuelling station directly, but via the hydrogen price. Producing green hydrogen with electrolysis on a 2.5 MW scale leads to production costs of 5.4 €/kg, and transport and fuelling infrastructure add another 3.3 €/kg to the hydrogen costs. The end-user price is currently 10 €/kg, leaving a margin of 1.3 €/kg, which shows that hydrogen can be produced for an affordable price.

A household that has a district heating connection, only drinking water instead of partly demi water and drives a hydrogen car would spend approximately a total of 2100 €/year on heat (€ 750), water (€ 56) and hydrogen (€ 1300). A household that is part of a Power-to-H3 system would pay 315 €/year less on utilities, as the total costs in Power-to-H3 are 1785 €/year. Thus, overall the Power-to-H3 system is more affordable than a house with similar facilities without an integrated system approach.

5.5. Avoided costs, the economics

As stated before, avoided costs are an essential part of the Power-to-H3 system. In this analysis, we have considered two types of avoided costs; one related to network reinforcement and the other to avoided CO_2 emissions.

The current connection of the site in Nieuwegein where the solar park will be installed is 4 MVA, and with the addition of 8.7 MWp of solar PV, the connection has to be reinforced with an additional 4.7 MVA to assure that all produced solar power can be transported to the grid. By installing the Power-to-H3 system, both the heat pump and the electrolyser can facilitate peak-shaving at times when the solar output is high. Together, they are able to convert 5 MW of solar power, which results in a lower maximum output power of the solar park (+Power-to-H3) of 3.7 MVA, see Table 8. Thus, the existing connection does not need to be reinforced if a Power-to-H3 system is installed. With average reinforcement costs of 200€/kW (see

Table 6
CAPEX and OM of the Power-to-H3 system for a neighbourhood.

	Total CAPEX (M€)	OM and Transport (k€/year)	Fuel Cost (k€/year)
Heat production, storage, transport, distribution and delivery	7.4	80	75
Hydrogen production, storage and fuelling	3.2	70	175
Hydrogen fuelling	1.3	110	10[a]
Rainwater capture, storage, pure water production, transport and distribution.	1.3	10	1
Electricity infrastructure within the system	0.5	5	–
Total investments Power-to-H3-system	13.7		
Operation and maintenance per year		280	260

[a] The electricity for the hydrogen fuelling station is bought from the grid at a price of 8 €₵/kWh.

Table 7
Cost break-down per production unit for heat, pure water and hydrogen, as well as the total costs per household per year.

Costs are shown per house, except for the production cost	Heat	Pure water	Hydrogen production + Hydrogen transport & fuelling station[a]
Investment costs	8290 €	1500 €	–[b]
Operation & Maintenance per year	90 €	1€	–[b]
Costs for electricity from solar park per year	1 €	1 €	–[b]
Production cost	26 €/GJ	2.1 €/m^3	5.4 €/kg + 3.3 €/ kg = 8.7 €/kg
Cost per household per year[c]	570 €/y	85 €/y	1130 €/y

[a] The '+' sign between the values in the columns shows the values for hydrogen production (above the '+') and transport & fuelling (under the '+').

[b] Costs are not shown per house, as the households pay for the hydrogen, and not for the infrastructure itself. Total investment costs for hydrogen are shown in Table 6.

[c] Based on the demand of an average household for heat (22 GJ/year), demiwater (40 m^3/year) hydrogen (130 kg/year), see also 4.2.1.

Table 8
Overview of required additional grid connection capacity and costs with Solar PV and with Power-to-H3.

Solar park	Standard situation	With Solar PV	With Power-to-H3
Grid connection – demand (MVA)	4	4	4
Solar PV – supply (MVA)	–	8.7	8.7
Heat pump – demand (MVA)	–	–	−2.5
Electrolyser – demand (MVA)	–	–	−2.5
Extra connection capacity (MVA)	0	4.7	0
Grid connection costs (k€)	–	940	–
Avoided grid connection costs (k€)	–	–	940

Table 9
Overview of required grid connection capacity and costs in a neighbourhood with heat pumps and PV or with a district heating network (DHN) and PV.

Neighbourhood	Standard situation	With heat pump & PV	With DHN & PV (PtX)
Grid connection – demand (MVA)	0.9	0.9	0.9
Solar PV – supply (MVA)		3.1	3.1
Heat pump – demand (MVA)		5.4	0.45
Extra connection capacity (MVA)	0	5.4	3.1
Grid connection costs (k€)		1080	612
Avoided grid connection costs (k€)			468

Section 3.4) the avoided cost of the Power-to-H3 system at the solar park sum up to € 940,000. This amount is equally divided over hydrogen and heat production and subtracted from the investment cost of the electrolyser and heat pump respectively.

For the neighbourhood, a similar grid capacity analysis is shown in Table 9. We should either investigate a situation with heat pumps and PV panels on roofs and compare to a district heating network and PV panels on roofs (which represents PtX). Currently, the average electricity demand of a Dutch household is around 1 kW [60]. When all houses would have enough solar panels to fulfil their electricity demand of 3000 kWh [62] a household would need approximately 3.4 kWp of solar PV. If all solar PV systems would produce at peak capacity at a time when there is no electricity use, 3.1 MVA of additional grid capacity is required.

If heat pumps with a COP of 1 on a cold winter day [60] would be installed in the neighbourhood, this results in an additional 5.4 MVA grid capacity (see Table 9). The electricity demand for heat pumps in winter thus leads to a higher grid load than solar PV would do during summer. Therefore, in a neighbourhood without a district heating network (DHN), the additional grid capacity would be around 5.4 MVA. When a Power-to-H3 system is in place, only small booster heat pumps are installed in homes with a maximum capacity of 0.45 MVA. In this situation, the solar PV is the determining factor for grid reinforcement (see 3.4 for an analysis of the grid connection costs). So, in both cases, there is additional capacity required from the grid, but with a Power-to-H3 system including a DHN, about €468,000 is avoided compared to a system with heat pumps installed in homes. This avoided grid reinforcement costs are completely allocated to the heat system of Power-to-H3, because the hydrogen system is of no importance for the grid within the neighbourhood.

The avoided costs due to reduced CO_2-emissions consist of replacing natural gas with (renewable) heat and gasoline with hydrogen (see Section 3.3). For both types of avoided costs, the effect on the production cost for heat and hydrogen was investigated, and the results are presented in Table 10. If avoided costs could be part of the business case of the Power-to-H3 system, the heat production cost would decrease by 26%, while hydrogen production costs decrease by 20%.

In addition to the more elaborated sensitivity analysis below, we carried out a sensitivity analysis on the CO_2-price to investigate the effect of a changing CO_2-price on the avoided costs calculations. The sensitivity of both the heat and hydrogen price is about 2.5% for a change in CO_2-price of 10€/kg. This means that in case the CO_2-price would be 20€/tonne instead of 60€/tonne, the reduction in production costs of heat would be 16% instead of 10%, and for hydrogen 10% instead of 20%.

5.6. Sensitivity analysis

For some important parameters, a local sensitivity analysis was carried out. The sensitivity of a certain parameter is shown for three outputs; the production cost of heat, hydrogen or water. In the graphs, the range of effect on the output is cut off at −40% and +40%, which has the implication that the full variation for the discount rate (see SA Table A.4) is not always shown. For every product, the three parameters for which the product price is most sensitive are discussed.

Fig. 13 shows the sensitivity analysis of the heat production costs. The heat production cost is most sensitive to the number of houses in the neighbourhood, as can be seen by the high slope at smaller numbers of houses. The figure also demonstrates that the influence decreases as the number of houses increases. However, even at a higher number of households, this parameter has the highest impact on the heat production costs of all evaluated parameters. The space heat demand of a household has the second-largest impact on the heat production price, which indicates that a more exact knowledge of household heat demand is necessary. Thirdly, the heat pump costs influence the heat production cost significantly and therefore it is important to learn more about the costs developments for heat pumps.

For the hydrogen production cost, the sensitivity analysis is shown in Fig. 14. Based on the slope of the lines in this figure, the energy use of the electrolyser, which in essence reflects the efficiency, is an important factor that influences the hydrogen production cost. The electrolyser investment costs are the second most important factor with respect to sensitivity on the hydrogen production price. It is therefore valuable to have more information about learning curves, which will be further discussed in Section 6. The electricity price has a significant influence on the hydrogen production costs as well and is clearly more important for hydrogen than for heat. Probably this difference exists because the investment costs for the heat production system are more than 50% higher. This implies that the electricity costs, which are part of the OPEX, have a smaller influence on the heat price than the investment costs.

The most substantial changes in the pure water production price occur due to changes in the number of people per household (pphh), which is shown in Fig. 15. The numberof houses have a considerable effect on the price as well. The discount rate has a moderate influence on the pure water production cost. However, not the complete curve is shown which means the uncertainty is high. To decrease the uncertainty in the pure water production cost, it will be necessary to get

Table 10
Results of avoided cost analysis of a Power-to-H3 system in a neighbourhood.

	Production cost without avoided costs	Avoided grid reinforcement costs	Monetised CO_2 emission reduction	Production cost with all avoided costs	Total reduction of production cost by avoided costs (%)
Heat (€/GJ)	26.0	3.1	3.6	19.3	26
Hydrogen (€/kg)	8.7	0.4	1.3	7.0	20

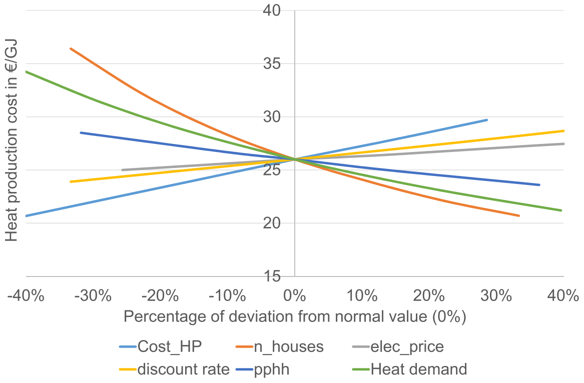

Fig. 13. Sensitivity analysis on the heat production costs. Cost_HP are the heat pump investment costs, n_houses the number of houses in the neighbourhood, elec_price the electricity purchase price from PV and pphh the number of people per household.

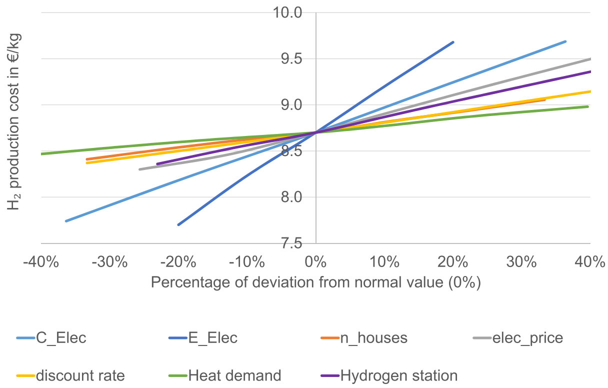

Fig. 14. Sensitivity analysis on the hydrogen production costs, C_Elec are the investment costs of the electrolyser, E_Elec the energy use of the electrolyser, n_houses the number of houses in the neighbourhood and elec_price the electricity purchase price from PV.

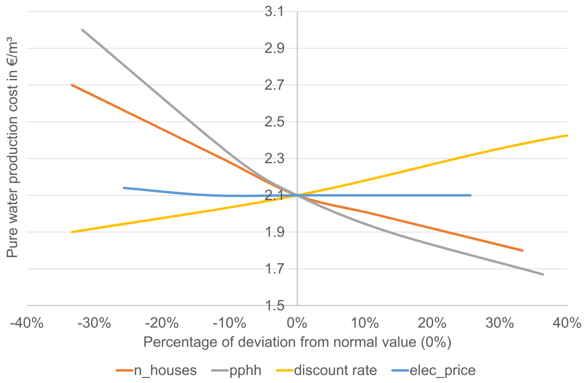

Fig. 15. Sensitivity analysis on pure water production costs, with n_houses the number of houses in the neighbourhood and pphh the number of people per household.

more insight into the number of people per household, the number of houses and the discount rate.

Overall, most of the chosen parameters seem to have a moderate to large effect on the production cost of heat, hydrogen or water. This means it is important to obtain more information about the exact values of these parameters in further research. Based on the results, below we suggest the priority list in order of importance:

1. Number of houses
2. Energy use electrolyser
3. Electrolyser costs
4. Heat pump costs
5. Space heating demand per household
6. People per household
7. Electricity price
8. Hydrogen fuelling station cost
9. Discount rate

6. Discussion

6.1. The subsurface as a storage medium

Conversion and storage mechanisms are key elements of the proposed Power-to-H3 system. For both heat and (rain)water, the subsurface is chosen as a storage medium. This means that when Power-to-H3 concepts are to be applied in urban areas, multi-purpose use of the subsurface will become increasingly important. On ground level, there is a lot of pressure on the available space and storage applications need a lot of space in general. By utilizing the subsurface, there is almost no impact of the storage system on street level, while still making energy conversion and storage in urban energy areas possible. However, the subsurface is not an empty space. Therefore, there is a need for collaboration with other stakeholders that have an interest in the subsurface, such as drinking water companies that rely on groundwater in the subsurface as a source for drinking water production. Using the subsurface as a way of energy storage thus requires more collaboration between different stakeholders with an interest in the subsurface.

6.2. Scenario comparison

Switching priority from heat to hydrogen has a significant effect on the energy balance of the system, as can be seen in Fig. 16 (full results of the system with hydrogen as a priority can be seen in SI-B). Because the hydrogen demand in the hydrogen priority scenario should always be fulfilled with local hydrogen production, there is a small amount of import from the grid at times when PV generation is low to ensure continuous hydrogen production. This does not occur in the heat as priority scenario, because here hydrogen is bought from third parties when demand cannot be fulfilled with own production. An alternative solution would be long-term hydrogen storage, for which salt caverns are the most feasible option [5]. Currently, a Power-to-H3 neighbourhood would rely on small scale high-pressure hydrogen storage, which is too expensive for seasonal storage. However, when in the coming decades a hydrogen infrastructure is developed, long term hydrogen storage would become an option.

The production cost for heat will increase from 26 to 27 €/GJ in the hydrogen priority scenario, while the cost for hydrogen production decrease (from 8.7 to 7.9 €/kg) and electricity from the grid is required to fulfil both heat demand and hydrogen demand. The heat production price increases, because the heat system has a lower overall efficiency as not enough heat is stored during summer and electricity from the grid is imported at a higher price. The hydrogen production price decreases mainly because of increased hydrogen production, both with electricity from the solar park and (more expensive) electricity from the grid. An increase in the capacity factor of the electrolyser thus leads to lower costs, even when the electricity price for buying electricity from the grid is higher than from the solar park.

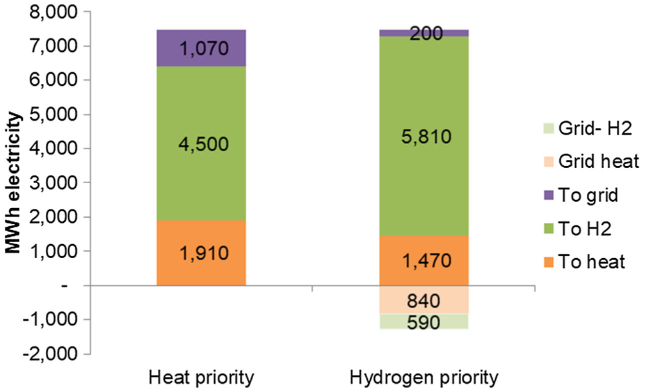

Fig. 16. Aggregated yearly energy distribution of the Power-to-H3 system with heat and hydrogen as priority, whereby the negative values represent purchase of electricity from the grid.

To lower the hydrogen production price and the system costs, it could be an option to install a smaller electrolyser, so the capacity factor increases while still producing enough hydrogen. Here some optimisation could still be done in further research. In addition, there will be different stakeholders involved in both heat and hydrogen production and sales, who will aim at the lowest production cost for their product. This analysis has shown there can be a significant price difference when switching priority from heat to hydrogen. Therefore, a sophisticated control system needs to be developed that is able to control both the heat and hydrogen production in order to optimise the production costs.

6.3. System size

A sensitivity analysis on the production costs of heat, hydrogen and pure water was carried out, which shows that the number of houses and therefore the heat and water demand have a large impact on the heat price and pure water price. Economies of scale are important for a system like Power-to-H3. A district-heating network requires a large investment, which implies that a certain minimum amount of houses is necessary to obtain a feasible business case.

Next to an economic perspective, from a technical point of view a small heat storage system will be difficult to manage in an optimal way. The relative heat loss will increase with decreasing storage volume, as the surface area of a spherical volume of warm water increases in relation to the volume of the sphere. With small storage volumes, these conduction effects become more apparent [29]. Both from an economic and technical point of view, 900 houses are close to the minimum amount necessary to create a reliable and affordable heat system.

6.4. Learning curves and their effects

From the results of the sensitivity analysis, we have seen that the production costs for heat and hydrogen are sensitive to changes in the heat pump and electrolyser costs, as well as the energy use of the electrolyser. In the analysis, both higher and lower values were chosen. However, it is expected that investment costs of heat pumps and electrolysers will mainly decrease because of further development in technology, manufacturing and economies of scale, which will have a positive effect on the business case of both hydrogen and heat. Schmidt et al. stated in an overview paper that the learning rate of alkaline electrolysis for different forms of electrical energy storage is 18% ± 6% [63]. The technology for PEM electrolysis has a higher development rate than alkaline and an expert elicitation study that included different electrolyser types estimated 8 – 24% decrease in production costs for PEM electrolysis based on R&D funding [64]. Another paper by Saba et al. investigates costs projections over the last thirty years and concludes that the projections for PEM electrolyser cost are within a range of 397–955 €/kWel (HHV) in 2030 [65]. Those projections and calculations clearly show a high level of confidence towards significant price reductions. Besides, developments in hydrogen infrastructure and storage in salt caverns [5] will likely lead to a higher reduction in hydrogen production prices because the costs of storage will decrease.

Data about learning effects of industrial heat pumps are scarce, despite the expected large role of heat pumps in the energy system. There is a twenty-year-old study that focussed on household appliances including heat pumps that found a learning curve of 25–42% based on Swiss data [66], but this does not seem to apply for the large scale industrial heat pumps in the Power-to-H3 concept. Recently, another Dutch report estimated a 10% learning rate for heat pumps [67], although they also report a lack of data for a good discussion. A report from the European Heat Pump Association from 2014 pointed out a cost reduction of around 20% in 10 years based on a doubling of the heat pump market, which means a learning rate of 20% [68]. From these studies, it can be concluded that more data is needed to get insight into heat pump learning curves. However, the estimated learning rates lie between 10% and 20%, which indicates a significant potential for a reduction of the heat pump cost.

Learning effects are valid for solar PV as well, with prices decreasing by 80% over the period 2010–2016 and an average learning rate of 35% [4]. The solar electricity price adopted in this paper is still subsidised, but this will probably change because solar PV will become inexpensive without subsidy. In conclusion, all learning effects are expected to have a positive effect on the affordability of a Power-to-H3 system.

6.5. Avoided costs

The analysis of the avoided costs (see Section 5.5) has shown that avoided costs can have an important role in a Power-to-H3 system with savings on the production cost of heat and hydrogen between 20% and 26%. Currently, only network reinforcement and CO_2 savings were included in the analysis, but other factors such as reduction of air-pollution and reduced risk of CO-poisoning would be interesting to include in future research. However, even when these effects would be quantified, these avoided costs can not be allocated to the business case.

Even the saved costs on electricity grid extension, which are relatively simple to quantify, can be difficult to include in the business case. In the current Dutch institutional model, the internal costs associated with gas and electricity transport, hence the networks, are fully regulated and allocated to the grid operators (transmission and distribution) but funded by the end-users as these services are socialised into the energy tariffs. A Power-to-H3 system will contribute in solving the unbalance between supply and demand on a more local scale and therefore avoids grid extension or redispatch, which means costs are reduced for the grid operators. However, these costs were not planned to be spent yet, and therefore are not easily incorporated in a business case.

The other part of the analysis was on CO_2-emission reduction. There is a market for CO_2-emission allowances, but only for power & heat companies and energy-intensive industry and not (yet) for small scale systems or neighbourhoods. Furthermore, the current CO_2 price is not at the level necessary to achieve the goals from the 2015 Paris agreement, which are calculated to be 60€/tonne, which is the value used in this paper [55]. Therefore, a sensitivity analysis was done which shows that if the CO_2 price would stay at 20 €/tonne, the production costs decrease of heat and hydrogen will still be 10–16%.

To be able to solve the suboptimal allocation of costs and benefits within a Power-to-H3 system, institutional interventions are needed in the form of legal measures like fiscal arrangements, changes in policy and legislation and financial compensation schemes.

6.6. Future research and steps to realisation

The concept presented in this paper was verified by a simulation model. As the purpose of this paper is merely to introduce the concept, the model presently has some simplifications. For example, the high temperature heat storage in this paper does not include a groundwater flow model. However, the model has a flexible structure and can easily be extended with a more sophisticated groundwater flow model that includes the hydrological dynamics within the subsurface to gain more insight in the subsurface dynamics and heat losses. At the moment, cooling demands have not been included in HT-ATES modelling, but with rising cooling demand due to climate change [69], in future research this could be a relevant addition. Regarding the HT-ATES, field test are carried out to get more insight into the chemical and microbiological changes as well as storage efficiency when heat is stored in aquifers at 40-60 °C. The results can lead to a better design of the HT-ATES system as proposed in this paper. Lastly, this paper has focused on the conversion and storage system and its costs, but in future research, the concept could be extended by taking into account the PV production by households, as well as investment costs in households for (booster) heat pumps and cars.

Besides model improvements and experiments, the first steps to realisation of a Power-to-H3 system are carried out in Nieuwegein, the Netherlands. The first phase of the solar park (3.8 MWp) has been built, a small hydrogen refuelling point is installed, there are ongoing discussions with the local government about the heat storage system and we work towards a more detailed system design. Many of the challenges of the Power-to-H3 system will not be technical but more related to governance and social aspects, such as investigating an organisational form for producing and selling the different products, informing project developers in the neighbourhood and try to incorporate the avoided costs in the business case. From our perspective, we argue that actual practice is the proof of the socio-economic importance of this research project.

7. Conclusions

In this paper, we present an energy and water system for a neighbourhood based on the conversion and storage of heat, hydrogen and water, called ‘Power-to-H3’. The results of our modelling have shown that Power-to-H3 is capable of fulfilling the demand for heat, hydrogen and (pure) water in a neighbourhood of 900 houses at every hour of the year. The heat storage makes it possible to produce heat (at 65 °C) in summer with solar power and surface water, and deliver it directly to houses (at 50–55 °C) in winter with an overall efficiency of 70%. By capturing rainwater on the solar park and on the roofs, it is possible to fulfil the pure water demand of the households during the year (almost 40,000 m^3), with the aquifer serving as a buffer. On a yearly basis, there is enough hydrogen production to fulfil the demand of 540 fuel cell electric vehicles. Costs for heat production will be 26 €/GJ and 8.7€/kg for hydrogen under the heat priority scenario and 27€/GJ for heat and 7.9 €/kg for hydrogen with the hydrogen priority scenario. In both cases, demi water production costs are 2.1 €/m^3. Based on this concept, the modelling results and the discussion, we conclude the following:

- For a case of a neighbourhood in Nieuwegein, it is shown that the Power-to-H3 concept is
  - Reliable – demands for heat, mobility and (pure) water are fulfilled at every hour of the year.
  - Affordable – Households connected to a Power-to-H3 system spend on average € 1300/year on heat, mobility and water, in comparison to 1785 €/year for a household in a neighbourhood without an integrated system approach.
  - Clean – completely based on renewable energy, thereby saving 3600 tonnes of CO2 per year compared to a conventional system and 500 tonnes compared to a system where all renewable electricity would be used as electricity directly.
- In a renewable-based energy system, the subsurface will become increasingly important, as a means for energy and water storage to balance demand and supply of intermittent renewable energy sources.
- Future renewable energy systems should focus increasingly on system costs, instead of system efficiency. The economic analysis of the Power-to-H3 system has illustrated that despite the energy losses that belong to the conversion and storage methods described, the system is still affordable.
- The analysis shows the importance of a sophisticated control mechanism for integrated systems as Power-to-H3, because a priority within the distribution of renewable energy for either heat or hydrogen has a significant impact on the business case of these products.
- Further investigation of how avoided costs can be allocated is important. A Power-to-H3 system has impacts on different parts of society and when those effects would be an integral part of the business case, the concept becomes even stronger and more convincing. In this case, it could lead to a 26% in heat production costs and a 20% decrease in hydrogen production costs.

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Supplementary material

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