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Fuel cell electric vehicle as a power plant: fully renewable integrated transport and energy system design and analysis for smart city areas

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Abstract

Reliable and affordable future zero emission power, heat and transport systems require efficient and versatile energy storage and distribution systems. This paper answers the question whether for city areas, solar and wind electricity together with fuel cell electric vehicles as energy generators and distributors and hydrogen as energy carrier, can provide a 100% renewable, reliable and cost effective energy system, for power, heat, and transport. A smart city area is designed and dimensioned based on European statistics. Technological and cost data is collected of all system components, using existing technologies and well-documented projections, for a Near Future and Mid Century scenario. An energy balance and cost analysis is performed. The smart city area can be balanced requiring 20% of the car fleet to be fuel cell vehicles in a Mid Century scenario. The system levelized cost in the Mid Century scenario is 0.09 €/kWh for electricity, 2.4 €/kg for hydrogen and specific energy cost for passenger cars is 0.02 €/km. These results compare favorably with other studies describing fully renewable power, heat and transport systems.

Highlights

- Smart city area design for fully renewable and reliable energy and transport.
- Detailed statistical analysis of European characteristics for an average city area.
- Fuel cell electric vehicles provide transport, energy distribution and balancing.
- Wind, solar, electricity and hydrogen are the only energy sources and carriers.
- Scenario analysis shows the design results in affordable energy and transport.

Keywords

Smart City, Fuel Cell Electric Vehicle, Vehicle-to-Grid, Hydrogen Production, Energy analysis, Cost Analysis

Nomenclature

Abbreviation	
AF	annuity factor
BEV	battery electric vehicle
CoE	cost of energy
CC	annual capital cost
C&C	compression and cooling

DOE	department of energy
€	euro
EC	energy consumption
EP	energy production
EU	european union
EUR	euro
FC-DLC	fuel cells dynamic load cycle
FCEV	fuel cell electric vehicle
H_2	hydrogen
h	hours
HFS	hydrogen fueling station
HHV	higher heating value
IC	installed investment cost
LED	light emitting diode
LT	economic lifetime
NEDC	new european driving cycle
OM	annual percentage of operation and maintenance costs
O&M	operation and maintenance
OMC	Annual operation and maintenance costs
PEM	proton exchange membrane
PEMFC	proton exchange membrane fuel cell
Q	installed component capacity
SCoE	specific cost of energy
SEC	specific energy consumption
SLCoE	system levelized cost of energy
TC	total annual capital and operation and maintenance costs
$TSCoE_{SCA}$	smart city area total system cost of energy
USD	united states dollar
US	united states of america
V2G	vehicle-to-grid
W	wind
WACC	weighted average cost of capital

Subscript	
dir	direct
e	electricity
FCEV	fuel cell electric vehicle
H	hydrogen
HFS	hydrogen fueling station
i	component number
n	total number of components
S	from solar
surp	surplus
TTW	tank-to-wheel
veh	vehicle
W	from wind

Greek symbol	
η	efficiency

1 Introduction

The urgency to significantly reduce the impacts of climate change is felt around the globe. December 12, 2015, 195 governments agreed on a long-term goal of keeping the increase in global average temperature to well below 2°C above pre-industrial levels and aim to limit the increase to 1.5°C [1].

In view of these goals both the energy and transport systems need to change into zero emission systems. Both systems need to become clean while remaining reliable and affordable. This will require major technological, organizational and social changes in both the energy and the transport system. We envisage major transitions in and integration of both systems.

The transition in the electricity system will be from fossil fueled power plants to renewables. However, the intermittent nature of many renewables such as wind and solar require a more flexible electricity system, which may be provided by flexibility in demand, electricity storage, electricity conversion into fuels, chemicals or heat and (distributed) smart grids [2].

The major technological transition in the transport system will be from combustion engines to electric engines. The electricity will be provided by batteries or fuel cells that can produce electricity with high efficiencies from a fuel such as hydrogen. In addition, an electricity charging infrastructure and/or hydrogen fueling infrastructure is needed to accommodate the introduction of electric vehicles.

Until today both the electricity and transport system have developed independently from each other. However, the integration of these two systems may solve major problems related to the separate transitions described above, and create synergies benefiting both systems [3–9]. To our knowledge, no such comprehensive study has been performed up to now. Many studies and pilot projects investigate (stand-alone) renewable energy systems using hydrogen as energy storage and stationary fuel cells for re-conversion of the stored hydrogen [10–30]. Some studies use the produced hydrogen for transport [3,12,31–39] or solely use the fuel cell in the vehicle as an electric generator [40–42] without considering hydrogen production. None of the aforementioned studies integrates grid connected hydrogen fuel cell powered transport, renewable electricity and hydrogen production and hydrogen reconversion on the scale of a smart city area, analyzing energy demand and cost of energy in different time frames.

Balancing excess and shortage of electricity can be handled in three ways:

Power to Power. At moments of excess electricity generated by renewables, the electricity can be *stored* in batteries of electric vehicles which are connected to the grid. When there is a shortage of power production by renewables, the stored electricity in car batteries could be used to feed into the grid. At present the electricity stored in batteries of a car is between 10 and 90 kWh.

Power to Gas and Power to Chemicals [30]. At moments of excess electricity by renewables the electricity can be *converted* into hydrogen. The hydrogen can be stored under pressure and transported by boat and/or truck to car fueling stations as a clean fuel. Hydrogen has a high energy density, 39 kWh/kg (HHV). Pressurized hydrogen tanks in present fuel cell cars contain 5 to 6 kg hydrogen [43]. Hydrogen can also be used as a feedstock to produce chemicals and other fuels such as ammonia, methanol, methane, and formic acid.

Gas to Power. At moments of electricity shortage, the fuel cells in vehicles could *supply* electricity to the grid [40,42,44–51], using the hydrogen stored in their tank. Fuel cells can produce electricity from hydrogen with a high efficiency. Peak energy efficiencies of the present PEM fuel cells in the cars are about 51.5% (HHV) in part load, with United States (US) Department of Energy (DOE) targets of 60.0% (HHV) [52,53]. One kilogram of hydrogen can therefore supply between 20 and 25 kWh to the electricity system.

Cars have sufficient power to influence the energy system world-wide. Summarizing an analysis done by [54]: Worldwide power plant capacity is about 5.000 GW. At present the typical fuel cell of a car has a capacity of about 100 kW, sufficient to power on average 100 European homes. Every year worldwide more than 80 million new cars are sold. The number of new cars multiplied by 100 kW capacity per fuel cell per car, would amount to 8.000 GW new power production capacity on the road every year. In a renewable electricity production system, fuel cell cars can therefore provide all necessary flexible electricity production capacity.

Hydrogen can be produced from all kind of renewable energy sources, such as biogas, biomass, direct sunlight or renewable electricity [55–59]. Also hydrogen can be produced far from load centers [60]. It can be stored and transported by boat and truck to these load centers, mainly associated with urbanized areas [61]. For example floating wind turbines far in the ocean at very high wind speed locations, can produce electricity which is converted into hydrogen by electrolysis and shipped to the load centers [62,63]. This creates flexibility in supply and demand for renewable energy production both geographically and in time and avoids huge investments in electricity transmission lines between renewable energy generation sites and demand centers [64].

Market introduction of Fuel Cell Electric Vehicles (FCEVs) is gaining momentum [65–68]. Many scenarios show substantial penetration of fuel cell vehicles in the coming decades [52,69–76]. The Japanese government wants to create a market for hydrogen and fuel cell cars, with projected annual market size increasing to 800,000 fuel cell electric vehicles sold in 2030 [77]. Similar in Germany, a program is initiated to build 400 hydrogen fueling stations in the coming years in Germany, combined with car fleet development [78,79].

Studies [80] show strong evidence of achievable cost reductions for hydrogen technologies, to approx. 30 USD/kW for automotive PEM fuel cell systems in production volumes of 500,000/year; with comparable cost reduction for hydrogen generation cost [80]. But also hydrogen storage tank costs, electrolyzer costs and compressor costs will decrease considerably in the coming decades, based on technology improvements but primarily on increasing production volumes [52].

Inspired by the concept of a "Hydrogen Economy" [31,65,81–87], the question arises: *Can solar and wind electricity together with fuel cell electric vehicles and hydrogen as energy carrier, provide a 100% renewable, reliable and cost effective energy system, for power, heat, and transport for smart city areas?* To get insights and answers to this question, this study performs the design, energy balance, and cost analysis of an integrated electricity and transport system, based on renewable electricity production, hydrogen as an intermediate energy carrier and fuel cell electric vehicles for transport and providing all the necessary flexibility for the electricity system, in two time frames: Near Future and Mid Century.

2 Methodology

2.1 Approach

The research is performed in five steps:

1) Design and dimensioning of a fully autonomous renewable and reliable integrated transport and energy system for a smart city area based on European statistics. Requirements are listed in section 2.2.
2) Analyzing annual energy demand for the designed smart city area in two time frames: a Near Future (around 2020) and Mid Century scenario (around 2050), see section 2.3.
3) Calculating the annual energy balance by matching energy demand with solar and wind electricity production, energy storage in the two scenarios, see section 2.4. Selection of technologies for the components of the energy system in the smart city area and analyzing their technological and economical characteristics in two time frames.
4) Calculating cost of energy for the two time frames, by calculating in section 2.5
   a) Smart city area total system cost of energy
   b) System levelized cost of energy
   c) Specific cost of energy
5) Sensitivity analysis for the cost of energy in the Mid Century scenario for a wide range of key assumptions and parameters used, see section 2.6.

2.2 System design requirements and dimensioning

A fully autonomous renewable and reliable energy and transport system is designed for a smart city area. The smart city area energy and transport system is designed in such a way that it fulfills the following design requirements:

- uses only electricity and hydrogen as energy carriers and is all electric in end use
- uses only hydrogen to power all road transport vehicles
- is an average European city area.
- is integrated into existing infrastructure and buildings
- does not require a new-build underground infrastructure, for example an underground hydrogen pipeline network
- uses abundant renewable energy sources in Europe: solar and wind only
- is independent of High and Medium Voltage electricity grids, natural gas and district heating grids or expansion of these.

Section 3 describes the design and dimensioning of such an energy system starting by a statistical analysis of the European characteristics for an average city area. The dimensioning includes a wide range of aspects defining a city area, for example the number of inhabitants and households, floor and roof area of buildings, road transport vehicles and refueling stations.

2.3 Analyzing energy demand

The annual energy demand of such an integrated transport and energy system for a smart city area started by a statistical analysis of the European Union (EU) energy consumption in buildings and for road transport, see section 4. Building energy consumption consists of heating, cooling and electrical appliances in the residential sector and the services sector. Road transport energy consumption analysis looks into average transport kilometers per vehicle type and its energy consumption. For such an average city area, the Near Future and Mid Century energy demand in buildings and for transport, are based on statistical historical data and studies about future energy efficiency improvement in end use, use of different technologies such as heat pumps for heating and by replacing conventional internal combustion powered road vehicles by hydrogen powered fuel cell electric vehicles.

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The two scenarios can be characterized as follows:

- The Near Future scenario uses *current state of the art* renewable and hydrogen technology and current energy demand for buildings and transport. It is already an all-electric energy system in the end use, which means space heating is done via heat pumps fulfilling present heat demand for houses and buildings. Only commercially available hydrogen technologies are used. For all systems, including hydrogen technologies, present technology characteristics and cost figures are used. The near future scenario presents a system that could be implemented around 2020.
- In the Mid Century scenario a *significant reduction of end-use energy* consumption is assumed. Hydrogen and fuel cell technology *has become mature with mass production* and performing on the cost and efficiency targets projected for 2050. Also for all the other technologies, such as solar, wind, electrolyzers the learning curves are taken into account.

In both scenarios it is assumed that the number of vehicles and the annual kilometers driven per vehicle are the same as nowadays.

2.4 Calculating the energy balance

The maximum amount of generated solar electricity in the smart city is calculated with the available roof area on buildings, based on the statistical analysis of the average European city area in section 3. Due to the possible insufficient solar electricity production and mismatch with building and transport energy consumption (see section 4.4), additional wind electricity and energy storage is required.

A technology choice is performed and an assessment is conducted for, efficiencies, sizes, cost and development in time for all involved components of the smart city area energy system, see section 5. Component sizes are determined using calculation methods from other studies or are based on average day patterns.

Once the technology choice and assessment is performed, the energy balance is calculated. In both scenarios wind electricity closes the annual energy balance of energy demand and local solar electricity generation, taking into account all efficiencies of the different conversion and storage technologies.

2.5 Calculating cost of energy

Three components for the cost of energy (CoE) will be calculated.

- Smart City Area Total System Cost of Energy, $TSCoE_{SCA}$ in Euro per year.
- System Levelized Cost of Energy for electricity $SLCoE_e$ in Euro per kWh and for hydrogen $SLCoE_H$ in Euro per kg Hydrogen.
- Specific Cost of Energy for Buildings $SCoE_B$ in Euro per m^2 per year and for Transport $SCoE_T$ in Euro per km.

2.5.1 Smart city area total system cost of energy

The $TSCoE_{SCA}$ in Euro per year is the sum of the Total annual capital and operation and maintenance Costs TC_i (€/year) of the total number of components (n) in the Smart City Area:

$$TSCoE_{SCA}\left(€/year\right)=\sum_{1}^{n}TC_i \tag{1}$$

The TCi of an individual component are calculated with the annual Capital Cost CC_i (€/year) and Operation and Maintenance Cost OMC_i (€/year):

$$TC_i\left(€/year\right)=CC_i+OMC_i \tag{2}$$

The CC_i (€/year) of a component is calculated with the annuity factor AF_i (%), installed component capacity Q_i (component specific capacity) and Investment Cost IC_i (€ per component specific capacity):

$$CC_i\left(€/year\right)=AF_i\times Q_i\times IC_i \tag{3}$$

Where the annuity factor AF_i [88,89] is based on the weighted average cost of capital WACC (%) and the economic lifetime of a component LT_i (years):

$$AF_i=\frac{WACC\times\left(1+WACC\right)^{LT_i}}{\left[\left(1+WACC\right)^{LT_i}\right]-1} \tag{4}$$

The annual operation and maintenance costs OMC_i (€/year) are expressed as an annual percentage OM_I (%) of the Q_i and IC_i:

$$OMC_i\left(€/year\right)=OM_i\times Q_i\times IC_i \tag{5}$$

The cost analyses are in constant 2015 euros. An exchange rate of 0.88 USD to EUR is used. The website [90] is used to convert all USD values to USD_{2015} values. A WACC of 3% is used.

2.5.2 System levelized cost of energy

The system levelized cost of energy, for either electricity $SLCoE_e$ (€/kWh) or hydrogen $SLCoE_H$ (€/kg H_2) are calculated by allocating a share of the $TSCoE_{SCA}$ related to either electricity $TSCoE_{SCA,e}$ or hydrogen consumption $TSCoE_{SCA,H}$. These shares are then divided by either the annual electricity EC_e (kWh/year) or hydrogen consumption EC_H (kg H_2/year) and resulting in respectively the $SLCoE_e$ or $SLCoE_H$:

$$SLCoE_e\left(€/kWh\right)=\frac{TSCoE_{SCA,e}}{EC_e} \tag{6}$$

$$SLCoE_H\left(€/kg\,H_2\right)=\frac{TSCoE_{SCA,H}}{EC_H} \tag{7}$$

2.5.3 Specific cost of energy

The specific cost of energy is defined as the energy cost per physical unit [91]. For transportation services, the Specific Cost of Energy for transport $SCoE_T$ is defined as the energy cost for driving a vehicle over a distance of 1 km. For FCEVs the $SCoE_{T,veh}$ is the Specific Energy Consumption of hydrogen per hundred kilometer for each type of vehicle, $SEC_{T,veh}$ (kg H_2/100 km), times the $SLCoE_H$ and divided by 100 kilometer:

$$SCoE_{T,veh}\left(€/km\right)=\frac{SLCoE_H\times SEC_{T,veh}}{100\,km} \tag{8}$$

For building energy consumption, the Specific Cost of Energy for Buildings $SCoE_B$ (€/m^2/year) is defined as the cost of the annual Specific Energy Consumption SEC_B (kWh/m^2/year) by all energy-consuming equipment within that building per square meter:

$$SCoE_B\left(€/m^2/year\right)=SLCoE_e\times SEC_B \tag{9}$$

2.6 Sensitivity analysis

A sensitivity analysis for the Mid Century scenario is performed for the parameters that have a large impact on the $TSCoE_{SCA}$. Amongst others the specific energy consumption of FCEVs, cost of hydrogen technologies, specific energy consumption of buildings and annual solar irradiation.

3 Design of a fully autonomous renewable and reliable energy system for a smart city area

3.1 Smart integrated energy and transport city functional design

Main energy consumers in cities are buildings and transportation vehicles and account for 67% of the final energy consumption in the EU [92]. Buildings in cities belong to either the residential or services sector, as industrial buildings are often located outside city areas. Energy consumption of road transportation vehicles energy accounts for 80% of the EU final energy consumption for transportation [92]. The road transportation vehicles are owned by either the residential or services sector and energy is consumed in or between smart city areas. By applying the design requirements from section 2.2, the integrated system design of the smart city area has the following 6 major elements (*Fig. 1*):

- Buildings: The residential and services sector buildings. All buildings have rooftop solar electricity systems and water collection systems. The buildings are all electric, without any natural gas connection. Industrial and agricultural buildings are excluded from the analysis.
- Hydrogen production & purification, and storage system.
- Smart electric grid, managed by a controller, which connects all buildings and cars.
- A hydrogen tube trailer transporter and a Hydrogen Fueling Station (HFS).
- A fleet of hydrogen fuel cell cars and other road transportation vehicles.
- An off-site wind turbine park, not located near or in the smart city area, with water collection, purification and hydrogen production and storage system, with no electrical grid connection

The functional energy performance of the smart city area comprises of the following conversion steps:

- Electricity is generated by solar modules on all roofs.
- Rainwater is collected from the roofs of buildings and is demineralized and purified and used in the electrolysis process. Purification is needed for good operation of the electrolyzer.
- Surplus solar electricity is converted via water-electrolysis into pure hydrogen. The hydrogen is compressed and stored into tube trailer modules. Full tube trailer modules are transported by a trailer tractor to the nearby Hydrogen Fueling Station (HFS).
- At the HFS, the hydrogen is further compressed depending on vehicle demand. Electric energy required for hydrogen compression at the HFS comes from the city area.
- The hydrogen is used as a transport fuel for all types of fuel cell powered electric vehicles; passenger cars, vans, motorcycles, buses and trucks.
- In case of a temporary shortage in production of solar electricity, the fuel cells in grid-connected passenger cars provide the necessary electricity by converting hydrogen from the on-board hydrogen storage tanks. At parking places at home or at the local shopping area, vehicle-to-grid points connect the cars to the smart city electrical grid.
- All wind-electricity produced is converted at the wind turbine park into hydrogen via water-electrolysis. These wind turbines are located either on-shore or off-shore. The produced hydrogen from wind is transported via tube trailers to a hydrogen fueling station.
- Surface or seawater in the vicinity of the wind turbines is purified and used in the water-electrolysis process.

The system design configuration is flexible to use other renewable energy sources if present, for example as biomass or hydropower to hydrogen, but is not analyzed in this study.

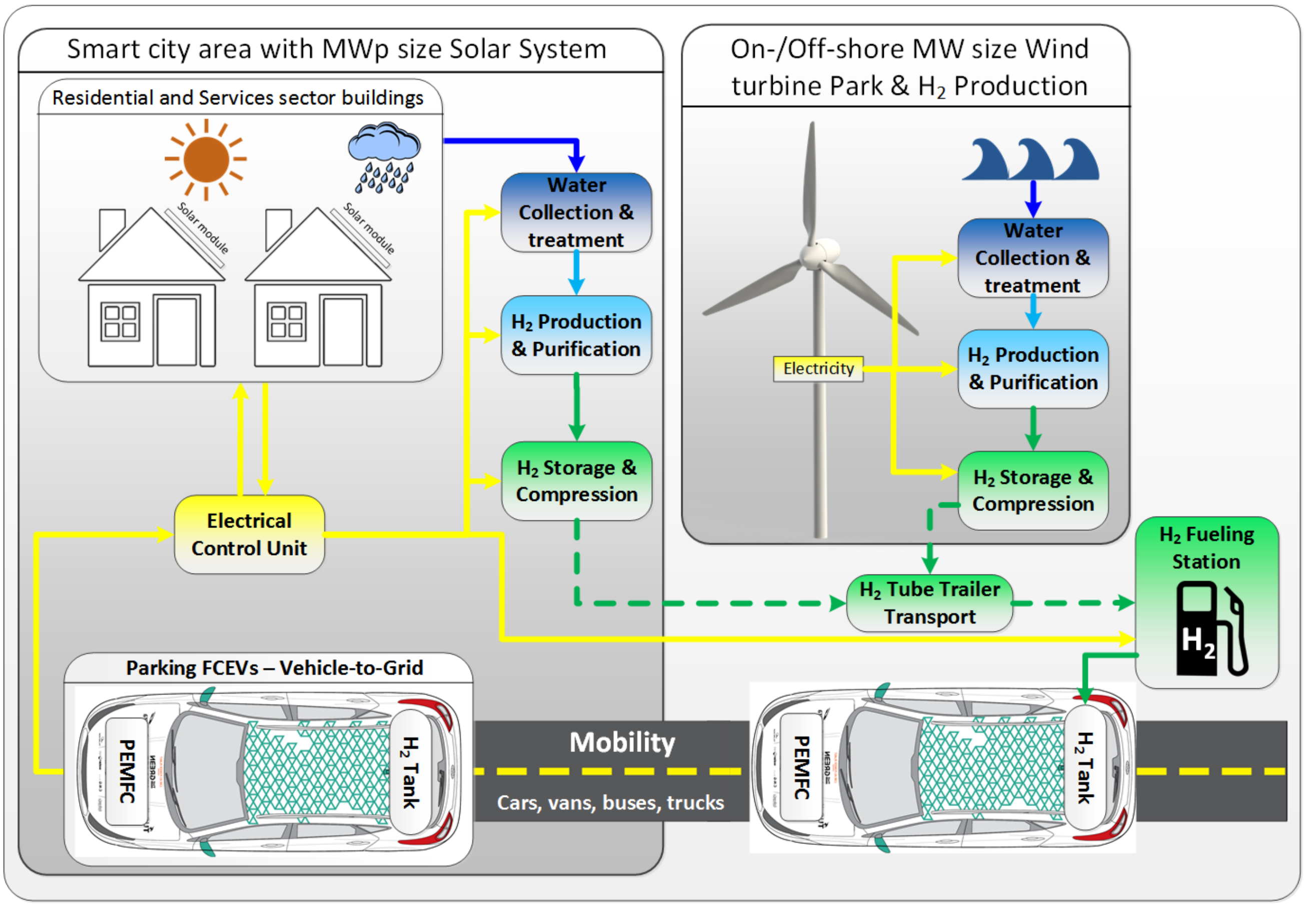

Fig. 1 — Smart City Area key elements and functional energy performance.

3.2 Dimensioning of smart integrated city area

The size of a European city area for this study is determined using the dispersion of supermarkets and petrol stations. In the EU 28, for every 1,900 households there is one petrol station [93,94] and for every 2,100 households there is an medium-sized supermarket so 2,000 households is a good indicator for dimensioning the smart integrated city area. This hydrogen fueling station will serve a similar vehicle population as current gasoline stations [95]. Total capital cost per capacity for large HFS (≥ 1,500 kg/day) is lower than for smaller HFS [96]. Also in the future with lower specific energy consumption for transport the hydrogen fueling station will still dispense sufficient amount of hydrogen [96] with the benefits of lower total capital cost per capacity.

On average 2,000 households correspond to 4,700 persons, with in total 2,300 cars, 190 motorcycles and some 320 other vehicles and each household using 89.75 m^2 of built area, according to European statistical data [93,94,97–104], see Table 1. Of the lorries and vans, approximately 10% are lorries [105–111].

Table 1 — Characteristics of a smart European city area.

Parameter	Quantity
Petrol stations	1
Food retail shop	1
Households and dwellings[1] in smart integrated city	2,000
Persons	4,680
Floor area buildings residential (m^2)	179,500
Floor area buildings services (m^2)	57,200
Passenger cars	2,300
Motorcycles	190
Lorries and Vans	300
Large Trucks with trailers (road tractors)[2]	18
Buses	8

[1] *Assumed that only 1 household lives in a dwelling.*
[2] *The number of large trucks with trailers includes the number of tractors used for transporting hydrogen tube trailers*

4 Energy demand and production in two scenarios

4.1 Residential Sector

The building-related energy demand of the residential sector accounts for 27% of the total EU final energy consumption [92]. The present European residential building floor space of 18.95 million m^2 and present-day energy consumption was, 3,493 TWh/year [92,101]. For the Near Future scenario, all electric buildings are assumed, where heat pumps with an estimated annual average COP of 3.5 replace conventional heating & cooling [112–115]. In the Mid Century scenario, buildings are also all-electric, and significant energy savings will be achieved: 95% savings on space heating and cooling and 50% on water heating [116]. It is assumed cooking energy consumption [101] in the Mid Century scenario will be the same as in the Near Future scenario. Although lighting energy savings will be significant by LED technologies, electrical consumption will increase due to an increased number and use of electrical appliances and home-automation. Therefore it is assumed that the combined electricity consumption for electrical appliances, lighting and cooking is the same as in the Near Future scenario.

Road transport energy accounts for 26% of the total EU final energy consumption [92], of which 1,959 TWh/year (59%) is due to passenger cars [99]. For the Near Future and Mid Century scenario, 100% hydrogen powered FCEVs are foreseen, with a $SEC_{T,car}$ of 1.0 and 0.6 kg H_2/100 km, respectively [52]. The final energy consumption for motorcycles is not included as it represents only 1.3% [56] of the total road transport final energy consumption.

In both scenario's, the present European passenger cars average annual driven distance of 11,940 km [99] is used. With the specific energy consumption and energy content of 39.41 kWh/kg of hydrogen (on a HHV basis), the annual final energy consumption of a FCEV passenger car, equivalent to 62 respectively 37 kWh per square meter residential floor area per year.

Summarizing: the total specific energy consumption in the residential sector for transport and buildings is calculated using data from Table 1, [52,92,94,98,99,101,103], and results in 288, 142, and 89 kWh/m^2/year at present, Near Future, and Mid Century, respectively, see Table 2. The specific energy consumption in buildings is comparable with the values in [117].

Table 2 — Specific energy consumption (kWh/m^2/year) per consumption category for the residential sector.

	SEC [kWh/m^2/year]		
Energy consumption category	**Present**	**Near Future**	**Mid Century**
Space heating & cooling	126.3	27.4	6.3
Water heating	23.3	19.6	11.7
Electrical appliances, lighting, cooking	34.7	33.4	33.4
Total in buildings ($SEC_{B,residential}$)	184.3	80.4	51.4
Passenger cars relative to floor surface	103.4	62.0[1]	37.2[1]
Total transport and buildings	287.7	142.4	88.6

[1] Specific energy consumption on a HHV basis.

4.2 Services Sector

The building-related energy consumption of European services sector accounts for 1,850 TWh per year (with climatic corrections) [100], equal to 14% of the total EU final energy consumption [92]. For the Near Future scenario a combined energy saving of 50% is assumed compared to the present situation, by virtue of application of heat pumps [118–123] for all thermal energy demands [124]. For the Mid Century scenario energy saving of 50% is assumed for hot water and 85% for other thermal demands compared to the present situation, based on [116].

Road transport of the services sector, excluding passenger cars, accounts for 10 % of the total EU final energy consumption, 1,302 TWh/year [92,99]. In both scenarios, all vehicles are powered by hydrogen fuel cells. Table 3 shows the average annual distance driven [105–111,125–129] and the $SEC_{T,veh}$ (kg H_2/100km) for vans, lorries, road tractor and buses for both scenarios. The specific energy consumption in the Near Future of vans is based on the average of [130] and [131] with an assumed average fuel cell system Tank-To-Wheel (TTW) efficiency of 51.5% (HHV) [52]. For lorries and road tractors it is based on the specific energy use of Battery Electric Vehicle (BEV) type lorries and road tractors [130] and the fuel cell system Tank-To-Wheel (TTW) efficiency [52]. FCEV bus specific energy use for the Near Future is taken from [132]. An efficiency improvement of 30% for vans (somewhat lower than the 40% expected for cars [52] and 20% for FCEV buses, lorries and road tractors [132], is assumed in Mid Century scenario.

Table 3 — Average annual distance driven and Near Future and Mid Century specific energy consumption for van, lorry, road tractor and bus type FCEVs.

Vehicle type	**EU average annual distance driven [km/year]**	**Near Future $SEC_{T,veh}$ [kg H_2/100km]**	**Mid Century $SEC_{T,veh}$ [kg H_2/100km]**
Van	20,725	1.3	0.9
Lorry	46,176	4.6	3.7
Road tractor	87,152	6.9	5.5
Bus	47,611	8.6	6.9

With the specific energy consumptions given in Table 3 and the energy content of 39.41 kWh/kg of hydrogen (HHV basis), the annual final energy consumption of FCEVs is calculated. In Near Future as well in Mid Century the average annual distance driven remains constant. The number of tube trailer trucks for hydrogen transport and their driven kilometers are assumed to be included in the number of road tractors and their annual driven kilometers. Using the data from [52,92,99,100,103,124], Table 1 and Table 3, total specific energy consumption for the service sector area is calculated, see Table 4. The total specific energy consumption is 522, 411, and 307 kWh/m^2/year at present, Near Future, and Mid Century, respectively. The specific energy consumption in buildings is comparable with the values in [117].

Table 4 – Specific energy consumption (kWh/m^2/year) per energy consumption category for the services sector.

	SEC [kWh/m^2/year]		
Energy consumption category	**Present**	**Near Future**	**Mid Century**
Space heating & cooling, process heating & cooling (with climatic corrections)	166.1	83.1	25.0
Water Heating	27.0	13.5	13.5
Electrical appliances, lighting	113.4	113.4	113.4
Total in buildings ($SEC_{B,services}$)	306.6	210.0	152.7
Road vehicles (vans, lorries, buses, road tractors) relative to floor surface	215.7	198.8[1]	154.1[1]
Total transport and buildings	522.3	411.7	306.7

[1] Specific energy consumption on a HHV basis.

4.3 Local energy production by solar electricity systems

Residential and service sector roofs will be used for solar electricity systems and for rainwater collection [133–135]. Solar electricity systems are installed on all technically suitable roof areas: 9 m^2 per person on residential buildings and 4 m^2 per person on service sector buildings area [136,137]. Façades are not considered. In the Near Future scenario the performance ratio and solar module efficiency are 0.75 and 0.20 kWp/m^2, and in the Mid Century scenario these are 0.90 and 0.35 kWp/m^2 [138–143]. Thus 12.4 and 21.3 MWp are installed in Near Future and Mid Century scenario, respectively. The electricity generated is calculated using a typical global irradiation on optimally inclined modules in European urbanized areas of 1,300 kWh/m^2/year [144–146].

4.4 Overview energy consumption and production

The final energy consumption for each category and solar electricity production for the two scenarios is shown in Fig. 2. The total final energy consumption for the smart city is 48 and 33 GWh/year in the Near Future and Mid Century scenario, respectively. The solar electricity production is 12 respectively 25 GWh/year.
In the Near Future scenario, demand exceeds supply, and solar electricity systems are insufficient to cover the residential and service sector demand nor the transport energy demand in the Near Future scenario. To balance demand and supply, additional energy has to be generated or imported. Exchange between residential and service sector does not solve this imbalance. In the Mid Century scenario, demand still exceeds supply, but for the residential sector there is a small net surplus of energy, and additional energy is still required. No attention has been given yet to temporal mismatch between solar electricity production and electricity consumption, and storage losses. The next section will address this.

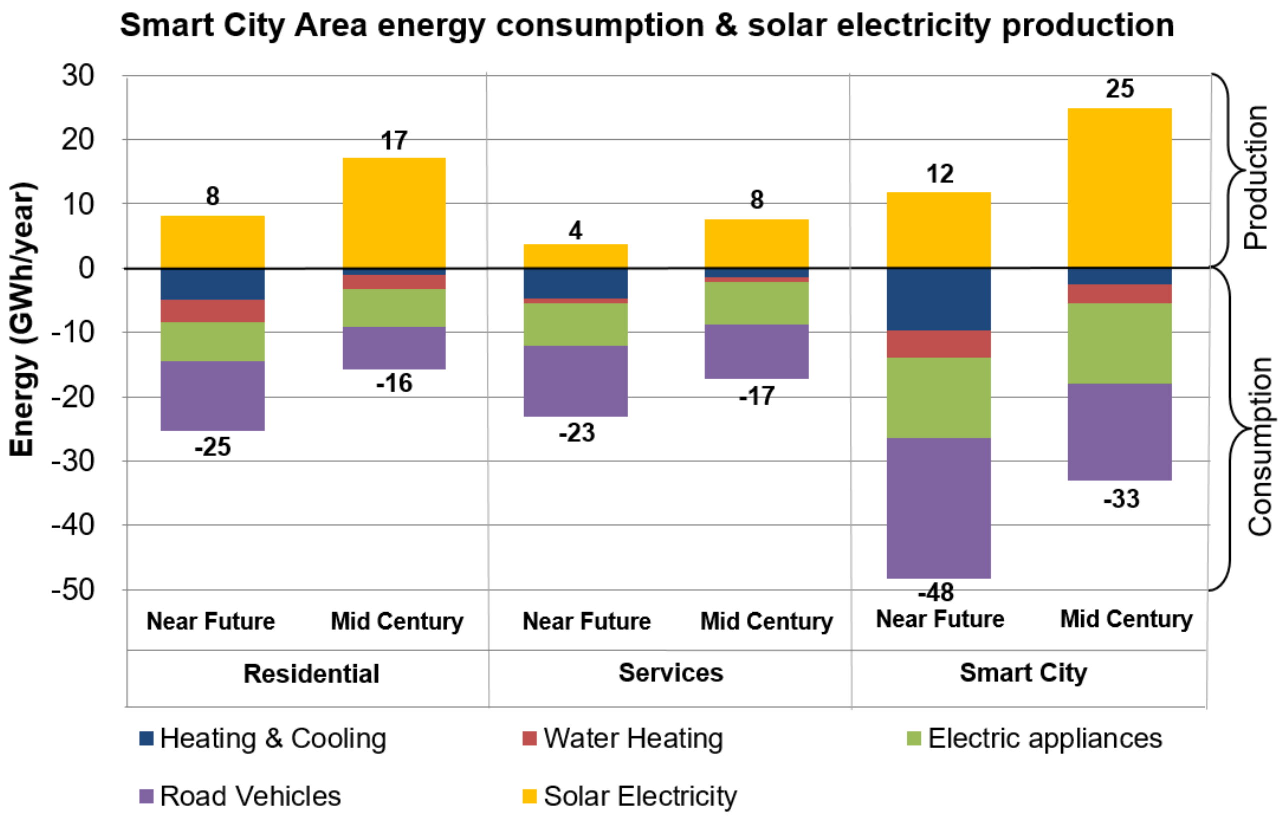

Fig. 2 — Generated solar electricity in each scenario compared to the building and transport final energy consumption categories.

5 Technology choices, sizing, characteristics and development

5.1 Data structuring

The relevant conversion processes in the smart city, as shown schematically in Fig. 3, are:

- hydrogen production and purification,
- hydrogen compression, storage and transport,
- hydrogen fueling station (compression, storage, dispensing and cooling)
- fuel cell electric vehicle power production,
- water collection and storage,
- water treatment,
- solar electricity production,
- wind electricity production

In both scenarios, the most appropriate, commercially available technologies are selected. The size of the components can be deducted from the energy balance. That requires meticulous evaluation of system component characteristics and calculation of the intermediate conversion efficiencies (and losses) especially from electricity to hydrogen production and the partial re-conversion to electricity. Cost characteristics of all these components are determined for both scenarios, using present-day technologies, discarding technologies with Technology Readiness Levels less than 7.
For the system cost calculations, the energy producing equipment, solar modules and wind-turbines including their installation, connection, maintenance and auxiliary component costs are included in this study. Energy saving measures and appliances and equipment, such as heat pumps, LED lights, washing machines, building automation and improved insulation are *not* taken into account.

All hydrogen related equipment including their installation, connection, maintenance and auxiliary component costs are included. Amongst hydrogen related equipment we consider the electrolyzers, hydrogen purification, compressors, tube trailers and tractors, high pressure compressors, high pressure stationary storage, hydrogen chillers and dispensers.

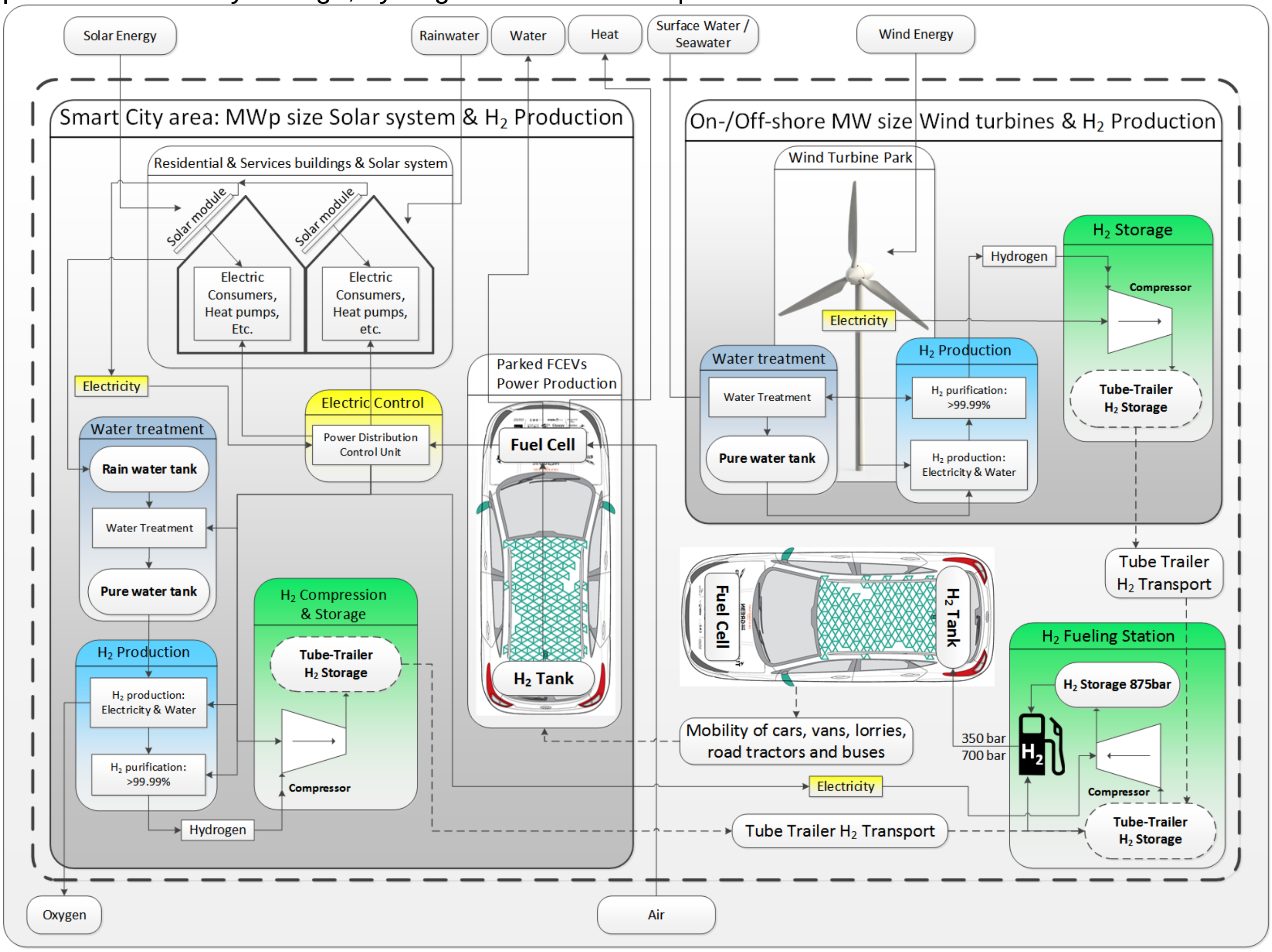

Fig. 3 — The relevant conversion processes in the smart city area.

5.2 Hydrogen production and purification: PEM water electrolysis

Technology

The most mature and commercial available technologies in MW-scale systems are alkaline and PEM type electrolyzers [147]. Hydrogen from electrolyzers is not sufficiently pure [148] for FCEV use and needs to be purified [149,150]. PEM electrolyzers are used, because are more suitable to couple with intermittent renewable electricity sources as wind and solar electricity [147,151,152]. Also PEM electrolysis has a higher cost reduction potential and efficiency improvement potential compared to alkaline electrolysis [52,153]. The electrolyzer and purifier energy requirements [52,154–156] are assumed constant over the entire operating range and are listed in Table 6. The purifier hydrogen output pressure is 30 bar in both scenarios [147,148,150,155,156].

To calculate the required peak capacity of the electrolyzer connected to the solar system, it is assumed that all hydrogen is produced from the surplus solar electricity within 5 full-load hours per day. Here we assume that if the electrolyzer produces hydrogen, the purification module and compressor run simultaneously and also consume a part of the surplus electricity. The actual operational hours, which determine the stack degradation, are assumed to be 10 hours per day.

The capacity of the electrolyzer connected to the wind turbine park is the wind-turbine capacity minus the electric power requirement of the hydrogen purification module and compressor. The actual operational hours are assumed to be 24 hours per day. It is assumed that the calculated electrolyzer size is available in the market, or larger size electrolyzers are cost-shared with other smart cities.

Cost
Installed capacity capital cost for the PEM electrolyzer is based on an extensive, detailed analysis in power to gas applications [153,157], which concludes 300-350 Euro/kW for a single produced 100MW system in 2030. For the smart city electrolyzer, cost reductions are possible because of higher volume production, economies of scales for membrane production [158] and component reduction, thus coming to 250 Euro/kW for the Mid Century scenario. Other sources have less detail in system size, production volume and components used in 2050 [52] or only have estimations for 2025 [154]. System lifetime is 20 to 30 years, but lifetime of the PEM stack and major components are 80,000 hours in the Near Future scenario and 90,000 in the Mid Century scenario [147,148].

The OM can be found in Table 7 for both scenarios for both electrolyzer locations. The OMC consist of a fixed part dependent on electrolyzer size [147] and a variable part due to stack and major component replacement. Replacement costs occur in case operational hours during system lifetime exceed the stack lifetime. The variable part is 15% of the installed electrolysis system cost in the Near Future and 12% in Mid Century [155,156].

5.3 Hydrogen storage and transport

Technology
Several types of hydrogen storage exist [159–161], but compressed hydrogen storage is selected, because it is the most mature and commercially available technology in mobile and stationary applications [162,163]. Using tube trailers [164–166] for exchange between wind site and urban area. In the Near Future scenario tube trailers can store 720 kg an effective mass of hydrogen at a pressure is 250 bar. In Mid Century scenario this will be 1350 kg of hydrogen at 500 bar [164,166]. At the hydrogen fueling station hydrogen is stored at 875 bar in variable storage sizes [162,164,167–169].

Storage capacity of the hydrogen tube trailers is two times the average daily hydrogen production at each electrolyzer location. The high-pressure stationary storage is sized to contain the average daily dispensed hydrogen. Both types of storage (tube trailer and stationary storage) are not rounded off to the closest available storage tank or tube trailer capacity. The calculated storage capacity is used directly to calculate the (installed) costs. Either a larger or smaller fueling station will be built and shared with a smaller or larger vehicle fleet, as this smart city is based on an illustrative number of vehicles.

The number of tractors for trucking in the tube trailers to the fueling station are calculated using the amount average daily dispensed hydrogen, the capacity of a tube trailer, average driving speed (50km/h), roundtrip distance (100km), loading and unloading time (2 hours) and working hours per day (8 hours) [170], coming to approx. 1 respectively 3.5 tractors in Mid Century versus Near Future scenario. The tractor driver also executes the charging operations so that no further personnel is required [170].

Cost
Economic parameters of the tube trailers, tractors and stationary storage [165–171] are listed in Table 7. Especially tube trailer have long lifetimes of 30 year and an OM of 2% [170]. The OMC consist of the tractor maintenance costs (12% of IC), fuel costs and labor costs (35€/hour) [170]. Fuel efficiency of the tractor is listed Table 3. Sea transport costs of hydrogen produced off-shore are not included.

5.4 Hydrogen Compression

Technology
Compressors used in hydrogen production and fueling stations selected are of reciprocating multi-stage piston and diaphragm [164]. The electrolyzer and storage pressures define the operating pressures ranges of the compressors. The maximum flow per compressor is assumed to be 250kg/h. If a larger flow is required, multiple compressors will be installed.

The compressor at the solar system and at the wind-turbines are medium-pressure compressors. Maximum flow rate of the medium-pressure compressors are equal to the maximum hydrogen production flow rate from the electrolyzers. Energy consumption of the low pressure compressors is calculated according [95,172].

The compressor at the hydrogen fueling station is a high-pressure compressor. The maximum flow rate of the high-pressure compressor is the average daily dispensed hydrogen compressed in 12 hours [95,172,173]. Energy consumption for the high pressure compressor(s) at the fueling station are calculated using [174], taking into account a variable inlet pressure from the emptying tube trailer.

Specific compression electric energy is assumed constant over the entire operating range of the compressors and can be found in Table 6. It is assumed that equal work is done by all three compression stages with intercooling between stages back to original feed temperature. Isentropic compressor efficiency is 60% in the Near Future and assumed 80% in Mid Century [164]. Using the specific compression electric energy with the flow rate of the compressor, the compressor electric power is calculated. The motor rating of the compressor is defined according [95,172,174].

Cost
For the Near Future scenario compressor costs are taken from [175], using the calculated motor power of the compressor for medium- and high-pressure compressors at low production volumes. For the Mid Century scenario compressor costs are calculated with the formulas for high production volumes. Economic parameters of the compressors for both scenarios can be found in Table 7, reflecting OM of 4% and 2% in Near Future and Mid Century [176].

5.5 Hydrogen dispensing and cooling

Technology
Hydrogen fueling at 700 bar requires cooling [164] to reduce the temperature increase caused by the gas expansion, done by a chiller. Specific cooling electric energy [177,178] is assumed constant over the entire operating range of the chiller and can be found in Table 6.

Sizing
Most vehicles are fueled between 6a.m. and 12p.m. [172]. About 1/12th of the average daily dispensed fuel is refueled during peak hour [95,172,174]. The filling rate for dispensers in the Near Future is 0.65 kg/min [179] and 2.0 kg/min [162] assumed in the Mid Century scenario. Therefore, hydrogen chiller capacity need to be matched with the peak fueling capacity. An average lingering time of 0.5 min per kg fueled is assumed. The average filling hose occupancy during peak hour is estimated to be 50% [155,156]. The chiller capacity is sized with the number of dispensers, dispenser filling rate and average filling hose occupancy during peak hour.

Cost
Economic parameters of the dispensers and chillers [164,175] for both scenarios can be found in Table 7.

5.6 Fuel Cell Electric Vehicles

Technology

The FCEVs have a fuel cell and a battery for regenerative braking. The combination of fuel cell and battery makes it possible to deliver almost every kind of energy service [180,181], from balancing to emergency power back-up or primary reserve. Batteries in present FCEVs for regenerative braking have capacities of approximately 1 kWh with 24kW power [66]. Tank-To-Wheel efficiency (η_{TTW}) of 51.5% (HHV) for the Near Future scenario and 61.0% HHV for the Mid Century scenario [52,53]. In Vehicle-To-Grid (V2G) mode, the efficiency of converting hydrogen from the FCEV tank to electricity is assumed equal to the Tank-To-Wheel efficiency (η_{TTW}).

Cost

For the Near Future scenario a durability of 4,100 hours in automotive drive cycle is assumed [182], 53 USD/kW (47.6€/kW) [80] at a production rate of 500,000 units per year. For the Mid Century scenario, US DOE targets for a passenger car fuel cell system are assumed: durability of 8,000 hours in automotive drive cycle, fuel cell system cost of 30 USD/kW (26.9 €/kW) [53] at a production rate of 500,000 units per year.

A Fuel Cells Dynamic Load Cycle (FC-DLC) [183] based on the New European Driving Cycle (NEDC) [184] is defined. With an average speed of 44.8 km/h excluding idling time [185]. Maximum fuel cell power in the FC-DLC is approx. 34 kW [186] for constant speed driving at 120 km/h. The average load level calculated over the FC-DLC cycle is 29.02% [183], corresponding to 9.9 kW. A study [187] recommends to use cumulative produced energy as degradation indication/parameter for dynamic operated fuel cells instead of power or voltage loss over time. Annual driven distance for a passenger car is 11,940 km, see section 4.1, resulting in 267 operational hours and producing 2630 kWh. At 9.9 kW, a fuel cell system of a passenger car could produce 78,950 kWh during its lifetime in automotive driving cycle in the Mid Century scenario and 40,460 kWh in the Near Future. These values would correspond to respectively 30.0 and 15.4 years of operational lifetime in automotive drive cycle only for the Mid Century and the Near Future scenario.

It can be deducted from [130,188] that approximately 14-16 hours of balancing power is required on an average day basis, during the no/low solar electricity hours. The largest share of this balancing energy is condensed in 6-8 hours, therefore we assume an average of 6 full-load hours of balancing per day at 10 kW per passenger car. This corresponds to 21,900 kWh of annual balancing energy per car in both scenarios. The required number of passenger cars for balancing is calculated in section 6.2. It is assumed every produced kWh for electricity balancing is causing 50% of the degradation as a produced kWh in driving mode. So the production of 21,900 kWh of balancing equals 10,950 kWh degradation by driving. 10,950 kWh out of 13,580 kWh per year driving and balancing represents 81%. If fuel cell durability is larger or degradation by balancing is lower, degradation due to balancing is smaller.

Durability depends on the type of load; constant load, load changing or start-stop [189–194]. Different US DOE durability targets are set for fuel cells; 25,000 for fuel cell transit buses, 10,000 hours for fuel cell back-up power systems and 60,000-80,000 hours for fuel cell CHP units [53]. The assumption for lower degradation rate per produced kWh in balancing mode is made because we expect the load ramps, one of the main degradation factors, are smaller in balancing mode than in driving mode. This is due to the limitation of 10 kW for balancing, whereas in driving mode load ramps can be up too 100kW. Also the load ramps can be divided amongst the connected cars resulting in even smaller load ramps.

An OM of 5% [52] is included, proportional to the degradation share of electricity balancing to the total degradation for driving and electricity balancing. It is assumed the battery and other components present in the FCEV are not degraded due to electricity balancing or included in the OMC. Furthermore, it is also assumed that the actual replacement is included in the capital cost of the replacement fuel cell. The V2G output plug on the FCEVs is assumed to be a standard feature at no further cost. The cost of other fuel cell powered transport vehicles (vans, buses, trucks) are not included either, as in principle the transport vehicles are bought for the transporting services.

5.7 Electric Infrastructure, control and Vehicle-to-Grid (V2G) connection

Technology
An electric grid and an IT infrastructure are present in the smart city. A central electrical control unit is in charge of managing all the power flows, measuring and predicting power consumption and production from the solar modules and power to the hydrogen production and storage and required power from the FCEVs. For FCEVs, only a V2G connection is required. Here the technology selected is based on a solar power converter technology [139]. Discharging poles will have 4 connections points of each 10kW and 1 power converter with 40kW rating. The amount of V2G connections is approximately half the amount of passenger cars in the smart city.

Cost
The costs of V2G connections is calculated using mass production and installation of 4-point 40 kW poles, consisting of 30 Euro/kW [139,139] in the Mid Century and 110 Euro/kW [139], for both scenarios an installed cost of 2,000 Euro/pole is assumed. The installed poles include all intelligence and interconnections between buildings and vehicles. The electrical connection cost for the solar modules and hydrogen production and compression equipment is already included in those component specific installed cost. The electrical connection cost of the buildings is assumed included in the building.

5.8 Water Collection and Storage

Technology
Urban rainwater is collected in a rainwater tank and then demineralized and stored in a pure water tank. Interconnecting tubing, filters and transfer pumps complete the system. Energy consumption by the rainwater collection system [195] is presented in Table 6. It is assumed that the ground floor area taken from [136] is equal to the roof area suitable for rainwater collection. The roof area potential for rainwater collection for residential buildings is 105,200 m^2 and for buildings of the services sector 44,500 m^2.
Maximum collected rainwater from roofs is calculated by assuming a roof run-off coefficient of 0.95 [196]. No first flush volume is accounted [196]. Average European precipitation is 785 L/m^2/year [197,198]. Maximum rainwater collection potential on a year basis by using the roofs of the residential buildings is 78,490 m^3 and 33,140 m^3 when using the roofs of the services buildings. Only the water required for electrolysis is collected and the size of the system is determined from the energy balance.
At the wind turbine site surface water or sea water is used, assuming sufficient supply at all times. The holding tank capacity for demineralized water is equal to 7 days of average daily demineralized water consumption from the electrolyzer.

Cost
For rainwater collection the piping to and related equipment of the reverse osmosis system are included. The CC and OMC for all components are deducted from [133,199] and presented in Table 7.

5.9 Water treatment: Reverse Osmosis

Technology

Reverse Osmosis systems can demineralize rain- or seawater for use in electrolyzer systems [200] using electric energy [201]. Energy use is listed in Table 6, for rainwater, surface water or seawater [195,201,202]. Capacities of reverse osmosis systems in the smart city are small compared to large drinking water treatment plants [148,201,203], and relatively low recovery rates of only 50% [201,204] are assumed. The capacity of the reverse osmosis equipment is equal to the maximum water requirement by the electrolyzer.

Cost

The installed cost includes piping and connections, pre-treatment of the water such as basic filtration and infrastructure-related costs. Cost parameters [201] are listed in Table 7.

5.10 Solar modules

Technology

Technical parameters of the solar electricity system are given in section 4.3. The share of direct self-consumed electricity of new-built solar electricity systems in both scenarios is assumed 38%, as given for 40kW to MW systems in [130].

Cost

Utility scale solar system cost parameters [139] are assumed and listed in Table 7. The installed system cost includes the module cost, balance of system and inverter cost. Balance of system includes all other cost components: Mounting system, installation, DC cables, infrastructure, transformer, grid connection, and planning and documentation.

5.11 Wind Power

Technology

Wind power on- or offshore is used to balance demand and supply. For the Near Future all wind power is assumed to be located on-shore. For the Mid Century scenario, half of the wind turbine power will be installed off-shore and half on-shore. The averaged capacity factor for the wind turbines installed is 35% and 46% in the Near Future scenario and the Mid Century scenario, respectively [205]. The installed wind power is calculated by completing the energy balance.

Cost

The wind turbines are connected directly to the electrolyzers. Therefore, grid connection costs are not applicable. For on-shore wind turbines grid connection costs are on average 11.5% and for off-shore wind turbines 22.5% [206,207]. Other cost parameters [208–211] can be found in Table 7. It is assumed that wind parks are cost-shared with other smart cities, thus not requiring rounding of wind capacities to turbine sizes.

Table 5 shows the specific electricity and water production parameters. Solar and wind specific electricity production are higher in the Mid Century scenario due to the increase in solar system efficiency (section 4.3) and wind power capacity factor (section 5.11). The pure water production from collected rainwater per square meter of roof area includes the reverse osmosis recovery factor of 50% (section 5.9). The conversion of hydrogen to electricity by the FCEV is respectively 20.3 and 23.6 kWh/kg H_2 in the Near Future and Mid Century scenario, corresponding to the Tank-To-Wheel efficiency (η_{TTW}) given in section 5.6.

Table 5 ─ Electricity and water production parameters.

Component	Specific production parameters	
	Near Future	**Mid Century**
Solar electricity system [kWh/(kWp × year)] [138–146]	975	1,170
Wind Power [kWh/(kW × year)] [205]	3,065	4,030
Pure water production [m^3/(m^2 roof × year)] [136,196–198,201,204]	0.37	0.37
FCEV hydrogen to electricity [kWh/kg H_2] [52,53]	20.3	23.6

Table 6 list the specific electricity consumption in the Near Future and Mid Century scenario for the different conversion processes, from rainwater collection to hydrogen fueling at 700 bar. The specific electricity consumption for PEM electrolysis, hydrogen purification and specific cooling electric energy decrease in the Mid Century scenario compared to the Near Future, due to an increase in efficiency. The specific electricity consumption for the compressors in the smart city area and at the wind turbines increase in the Mid Century due to the higher pressure of the tube trailers in the Mid Century. Total specific electricity consumption of the compressors decreases from 3.3 kWh/kg H_2 in the Near-Future to 3.0 kWh/kg H_2 in the Mid Century. In this study no reduction of specific electricity consumption is foreseen in the Mid Century for reverse osmosis and the transfer of rainwater from the buildings to the reverse osmosis unit. From electricity to fueled hydrogen at 70 bar, is respectively 68% and 79% efficient in the Near Future and Mid Century scenario. The roundtrip efficiency from electricity via fueled hydrogen at 700 bar to electricity is respectively 35% and 47% efficient in the Near Future and Mid Century scenario.

Table 6 ─ Specific electricity consumption (kWh/kg H_2) of the conversion processes in the smart city for both scenarios.

Conversion processes	Specific electricity consumption	
	Near Future [kWh/kg H_2]	**Mid Century [kWh/kg H_2]**
PEM Electrolysis [52,154]	53.4	45.8
Hydrogen Purification [155,156]	1.3	1.1
Compressor in smart city area [95,164,172–174]	1.5	1.9
Compressor at wind turbines [95,164,172–174]	1.5	1.9
Compressor at hydrogen fueling station [95,164,172–174]	1.8	1.1
Specific cooling electric energy [177,178]	0.20	0.15
Reverse Osmosis – seawater [195,201,202]	0.0405	0.0405
Reverse Osmosis – rainwater [195,201,202]	0.0056	0.0056
Rainwater transfer [195]	0.0028	0.0028

Table 7 gives an overview of all economical parameters of the Smart City Area components for the Near Future and Mid Century scenario. Annual operational and maintenance cost (OM_i) of the electrolyzers can vary due to difference in system size and different operational hours per year, the latter which influence stack lifetime. Installed capital costs (IC_i) of the various compressors used varies due to difference in final discharge pressure and mass flow, both influencing compressor motor size and cost.

Table 7 — Economical parameters of the Smart City Area components for the Near Future and Mid Century scenario. IC_i = installed capital cost, OM_i = annual operational and maintenance cost expressed as an annual percentage of the installed investment cost, LT = Lifetime.

	Near Future			Mid Century		
Subsystems and components	**IC_i**	**OM_i [%/year]**	**LT_i [years][1]**	**IC_i**	**OM_i [%/year]**	**LT_i [years][1]**
Hydrogen Production, Storage and Transport						
PEM electrolyzer at solar system [147,148,153,155–157]	1,790 €/kW	2.8%	20	250 €/kW	2.3%	30
PEM electrolyzer at wind turbines [147,148,153,155–157]	1,790 €/kW	2.7%	20	250 €/kW	3.2%	30
Tube trailers at solar system [165–171]	730 €/ kg H_2	2.0%	30	510 €/ kg H_2	2.0%	30
Tube trailers at wind turbines [165–171]	730 €/ kg H_2	2.0%	30	510 €/ kg H_2	2.0%	30
Trailer tractors [165–171]	160,000 €/tractor	109%	8	160,000 €/tractor	91%	8
Compressor at solar system [175,176]	8,170 €/ kg H_2/h	4.0%	10	3,650 €/ kg H_2/h	2.0%	10
Compressor at wind turbines [175,176]	5,890 €/ kg H_2/h	4.0%	10	4,200 €/ kg H_2/h	2.0%	10
Hydrogen Fueling Station (HFS)						
Compressor at HFS [175,176]	11,090 €/kg H_2/h	4.0%	10	4,940 €/ kg H_2/h	2.0%	10
Stationary storage at HFS 875 bar [165–171]	1,100 €/ kg H_2	1.0%	30	575 €/ kg H_2	1.0%	30
Dispensers units [164,175]	91,810 €/unit	0.9%	10	72,890 €/unit	1.1%	10
Chiller units [164,175]	143,880 €/kg H_2/min	2.0%	15	118,520 €/kg H_2/min	2.0%	15
Fuel Cell system in FCEV for balancing only [52,53,80,182–194]	3,830 €/100 kW	5.0%	4,100h	2,170 €/100 kW	5.0%	8,000 h
Smart grid, Control and V2G infrastructure [139]	6,400€/ 4-point dischargers	5%	15	3,200€/ 4-point dischargers	5.0%	15
Water collection, storage and purification						
Rainwater collection and storage [133,199]	21,030 €/m^3/day	0.33%	50	21,030 €/m^3/day	0.33%	50
Pure water tank at wind turbines [133,199]	120 €/m^3	0.33%	50	120 €/m^3	0.33%	50
Reverse Osmosis at solar system [201]	1.20 €/L/day	4.8%	25	1.20 €/L/day	4.8%	25
Reverse Osmosis at wind turbines [201]	1.20 €/L/day	4.8%	25	1.20 €/L/day	4.8%	25
Energy Production						
Solar electricity system [139]	995 €/kWp	2.0%	25	440 €/kWp	2.3%	30
Wind Turbines onshore [206–211]	1,110 €/kW	2.8%	20	800 €/kW	3.2%	25
Wind Turbines off-shore [206–211]	1,880 €/kW	4.5%	20	1040 €/kW	4.7%	25

[1]Lifetime = Economic lifetime of components in years, except for the fuel cell system in the FCEV for which the lifetime is expressed in operating hours.

6 Energy balance results

6.1 Energy balance results

Fig. 4 shows the calculated energy balance in the smart city system in the Near Future and Mid Century scenario. The consumption of 48 GWh/year in the Near Future can be covered fully by 106 GWh renewable electricity production. Consisting of 12 GWh/year rooftop solar electricity and 95 GWh/year distant wind electricity. The difference between production and consumption is due to hydrogen conversion efficiencies. In the Mid Century scenario, consumption of 33 GWh/year is covered by 48 GWh/year production, more than two-third (69%) of the production reaches final energy consumption or 57% final energy. In the Mid Century scenario renewable electricity supply consists of 24 GWh/year rooftop solar electricity and 23 GWh/year distant wind electricity.

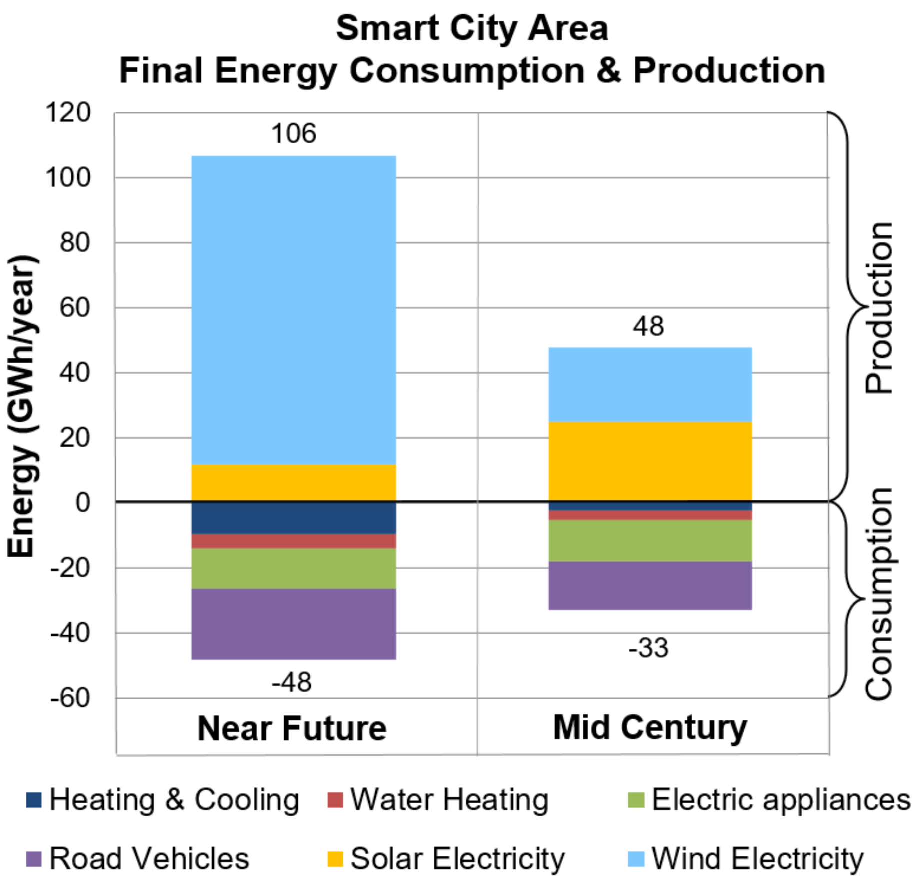

Fig. 4 — Smart City Final Energy Consumption and Production.

Fig. 5 shows all energy flows in the smart city, for both scenarios. In the Near Future scenario, the amount of wind energy is 89% of all energy needed, solar electricity provides the remaining 11%. In the Mid Century scenario, solar and wind electricity provide approximately 50% of the required energy each. In the Mid Century scenario, direct use of solar electricity is 9.5 GWh/year, 53% of all building energy used. Respectively 72 GWh/year and 31 GWh/year hydrogen is produced from surplus solar and wind electricity in the Near Future and Mid Century scenario. The hydrogen used for energy balancing is of similar magnitude as for driving in the Mid Century scenario, whereas the majority of hydrogen is for balancing the electricity demand, in the Near Future scenario. In this balancing, 48% of the energy is lost due to conversion in the Near Future scenario, whereas in the Mid Century scenario this is 40%, due to the higher fuel cell efficiency, see section 5.6.

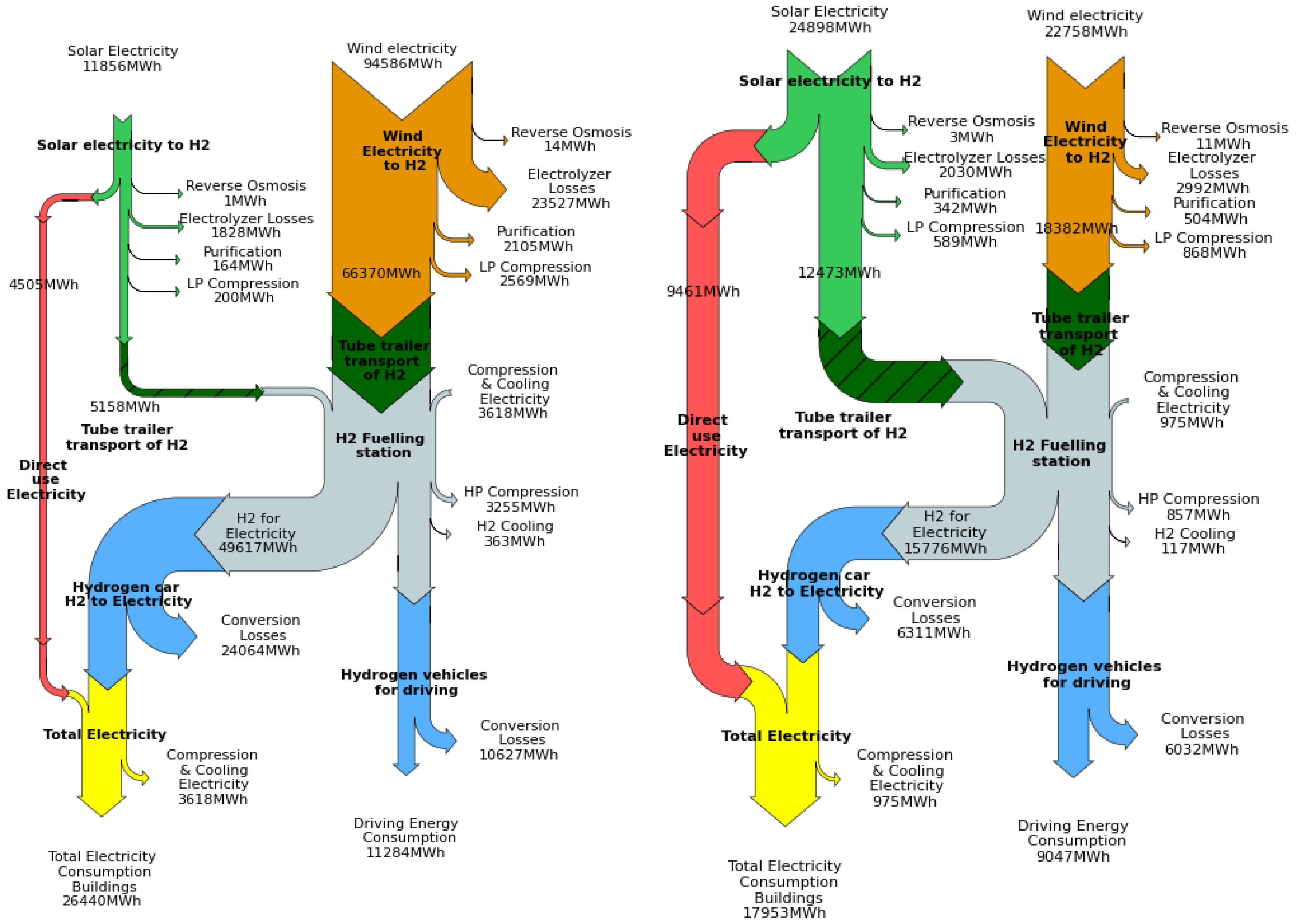

Fig. 5 — Energy Balance Near Future (left) and Mid Century scenario (right).

6.2 Energy balance discussion & evaluation

Balancing by FCEVs and H_2 transport

Electricity generated from V2G connected FCEVs is 25,553 MWh/year in the Near Future scenario and in the Mid Century scenario, 9,465 MWh/year are needed. These amounts of electricity can be produced by respectively 1,167 and 423 FCEVs, 51% and 19% of the car fleet, assuming each car generating 60 kWh per day, at max power 10 kW. It can be deducted from [130,188] that approximately 14-16 hours of balancing power is required per day, during the no/low solar electricity hours. The largest share of back-up power is condensed in 6-8 hours peak hours, assuming 6 hours in this study. With 430-1170 cars, it can be managed to provide the required power at all times. If the cars can generate 20 kW (20% of the installed power) [212,213], halve the required amount of passenger cars would suffice. If more hours of balancing per car per day are assumed, proportionally less cars are needed.

When using all cars in the fleet, the average daily amount of hydrogen used for re-electrification per car is 1.5 kg for the Near Future scenario and 0.5 kg for the Mid Century scenario. With hydrogen tank storage of 5 kg [44,67,214] for the Near Future and 6.5 kg [52] for the Mid Century scenario, the average daily amount of hydrogen for re-electrification would be respectively 30% and 7% of the usable hydrogen tank content, requiring one extra tank stop per 2.7 days and 9.7 days, respectively. The normal use of the cars (home-work commuting) arranges presence of cars at demand centers: during the day at office / service sector buildings, and in the evening and at night at home [215].

Share of direct solar electricity consumption

In the Mid Century scenario solar electricity generation is larger than in the Near Future scenario due to higher solar module efficiency. In Near Future, 17% of consumption is directly generated by the solar electricity system, whereas in Mid Century this is 53%. Because of the larger installed power and a significant demand reduction, in the Mid Century the share of direct solar electricity consumption has risen so much. It is also based on the assumption that demand response technology is well developed [216].

Water balance

In the Mid Century and Near Future scenario rainwater use for hydrogen production in the urban area is 6,000 respectively 2,500 m^3/year. Rain water collection from roofs far exceeds this water consumption, and only 2-5 % of the roofs are really required for collection.

7 Cost of energy results and allocation methodology

7.1 Smart city area total system cost of energy overview

Installed capacities, annual capital and O&M costs of all components, are presented in Table 8. Total annual costs, $TSCoE_{SCA}$, are 15.2 million Euro in the Near Future and 2.5 million Euro in the Mid Century scenario. In the Mid Century scenario costs are due to significant energy demand reduction, increased conversion efficiencies and cost reduction in the hydrogen cycle and renewable energy production.

Distribution of these costs are shown in Fig. 6. In the Near Future scenario, PEM electrolyzer and wind energy account for more than half of both annual capital and O&M costs of the Smart City Area. In the Mid Century scenario, PEM electrolyzer costs are reduced considerably, and wind energy and solar energy account for approximately half of both annual capital and O&M costs.

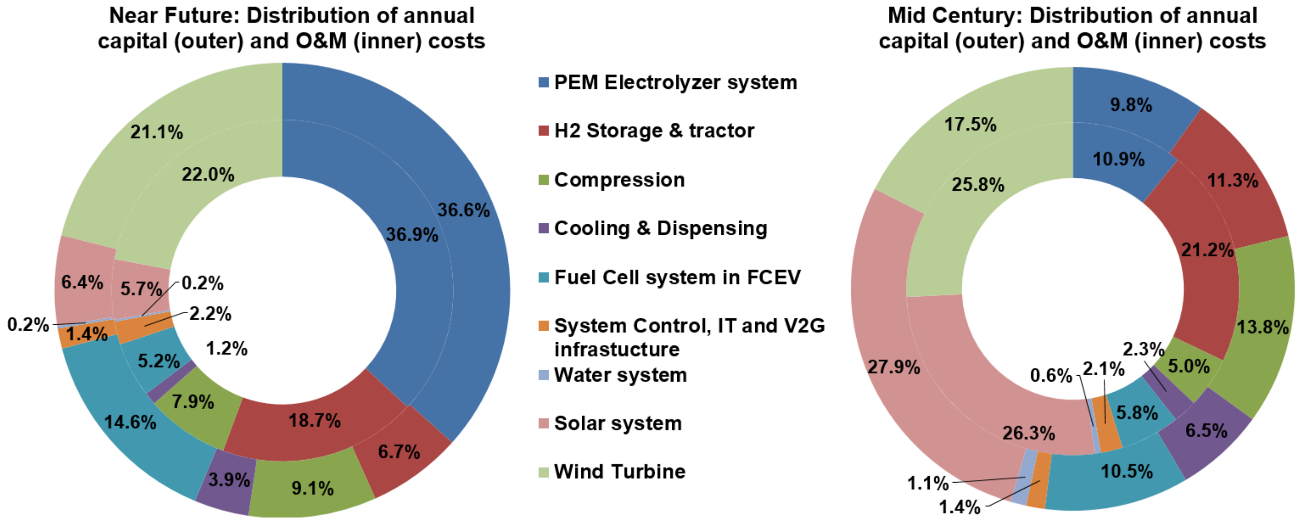

Fig. 6 — Near Future (left) and Mid Century (right) Smart City Area annual capital cost and O&M cost distribution.

Table 8 – Calculated installed capacities, capital, O&M and total costs for the components in the Smart City Area.

		Near Future				Mid Century			
Subsystems and components	**i**	**Q_i**	**CC_i [k€/year]** Eq. (3)	**OMC_i [k€/year]** Eq. (5)	**TC_i [k€/year]** Eq. (2)	**Q_i**	**CC_i [k€/year]** Eq. (3)	**OMC_i [k€/year]** Eq. (5)	**TC_i [k€/year]** Eq. (2)
Hydrogen Production, Storage and Transport									
PEM electrolyzer at solar system	S4	3,740 kW	450	190	640	7,760 kW	100	45	140
PEM electrolyzer at wind turbines	W5	29,330 kW	3,530	1,390	4,930	5,310 kW	68	43	110
Tube trailers at solar system	S6	720 kg H_2	27	10	37	1735 kg H_2	45	18	63
Tube trailers at wind turbines	W7	9,230 kg H_2	340	130	480	2555 kg H_2	66	26	92
Trailer tractors	HFS1	3.45 tractors	79	600	680	0.80 tractors	18	120	130
Compressor at solar system	S5	72 kg H_2/h	69	23	92	173 kg H_2/h	74	13	87
Compressor at wind turbines	W6	550 kg H_2/h	380	130	510	116 kg H_2/h	57	10	67
Hydrogen Fueling Station (HFS)									
Compressor at HFS	HFS2	415 kg H_2/h	540	180	720	179 kg H_2/h	104	18	120
Stationary storage at HFS 875 bar	HFS3	4,980 kg H_2	280	55	330	2145 kg H_2	63	12	75
Dispensers units	HFS4	29 # units	310	23	340	6 # units	51	4.8	56
Chiller units	HFS5	9.2 kg H_2/min	110	26	140	6.0 kg H_2/min	59	14	73
Replacement cost of Fuel Cell systems (100kW) in FCEVs for balancing	FCEV2	1167# systems of 100kW	1,590	220	1,810	432# systems of 100kW	180	47	230
Smart grid, Control and V2G infrastructure	FCEV1	292 4-point dischargers	160	93	250	108 4-point dischargers	23	17	41
Water collection, storage and purification									
Rainwater collection and storage	S2	6.5 m^3/day	5.3	0.5	5.7	15.6 m^3/day	13	1.1	14
Pure water tank at wind turbines	W3	290 m^3	1.3	0.1	1.4	80 m^3	0.4	0.03	0.4
Reverse Osmosis at solar system	S3	15.5 m^3/day	1.6	0.9	2.5	37.5 m^3/day	3.8	2.2	6.0
Reverse Osmosis at wind turbines	W4	118.7 m^3/day	12.0	6.9	18.9	25.0 m^3/day	2.5	1.4	4.0
Energy Production									
Solar electricity system	S1	12,160 kWp	690	240	940	21,280 kWp	470	210	690
Wind Turbines onshore	W1	30,850 kW	2,290	940	3,240	2,825 kW	130	72	200
Wind Turbines off-shore	W2	0 kW	0.0	0.0	0.0	2,825 kW	170	140	300
Total			10,880	4,280	15,150		1,700	810	2,500

7.2 Cost of energy allocation methodology

In a fully renewable and autonomous city area, electricity is produced by solar systems on the roofs of the houses and buildings. Electricity is also produced by fuel cell cars when there is a shortage of electricity from solar, which is during the night and in winter. So the system levelized cost of electricity is determined by both the levelized cost of electricity from solar and the levelized cost of electricity by fuel cell cars.

Hydrogen is produced by a wind farm which is located outside the city area and from surplus solar electricity. So the levelized cost of hydrogen is determined by both the wind farm cost and the surplus solar electricity cost.
The question is how to allocate these cost to both the system levelized cost of energy for electricity and the system levelized cost of energy for hydrogen.

7.2.1 Levelized cost of energy

First the levelized cost of energy for solar electricity and wind electricity is calculated.

The Levelized Cost of Energy for Solar electricity $LCoE_{e,S}$ (€/kWh) is calculated by dividing the TC_{S1} (see Table 8 for component numbering), with the annual Energy Production of solar electricity $EP_{e,S}$ (kWh/year) from Fig. 5:

$$LCoE_{e,S}\left(€/kWh\right)=\frac{TC_{S1}}{EP_{e,S}} \qquad (10)$$

The levelized cost of energy for electricity from onshore wind $LCoE_{e,W\text{-}onshore}$ (€/kWh) or off-shore wind $LCoE_{e,W\text{-}onshore}$ (€/kWh) is calculated by dividing the TC_{W1} or TC_{W2} (€/year) of the on- or offshore wind turbines, with the annual Energy Production of on- or off-shore wind electricity, $EP_{e,W\text{-}onshore}$ or $EP_{e,W\text{-}offshore}$ (kWh/year):

$$LCoE_{e,W\text{-}onshore}\left(€/kWh\right)=\frac{TC_{W1}}{EP_{e,W\text{-}onshore}} \qquad (11)$$

$$LCoE_{e,W\text{-}offshore}\left(€/kWh\right)=\frac{TC_{W2}}{EP_{e,W\text{-}offshore}} \qquad (12)$$

The wind electricity is partly from onshore and offshore wind farms. The levelized cost of energy for wind electricity $LCoE_{e,W}$ (€/kWh) is calculated by dividing both the TC_{W1} and TC_{W2} of the on- and offshore wind turbines (€/year) with the total annual Energy Production of wind electricity $EP_{e,W}$ (kWh/year) from Fig. 5):

$$LCoE_{e,W}\left(€/kWh\right)=\frac{TC_{W1}+TC_{W2}}{EP_{e,W}} \qquad (13)$$

Now the levelized cost of energy for hydrogen from wind and solar surplus electricity is calculated, $LCoE_{H,W}$ (€/kg H_2) and $LCoE_{H,S\text{-}surp}$ (€/kg H_2). In both on- and off-shore wind cases it means that besides the cost for electricity production by on- or off-shore wind, the TC for pure water production by reversed osmosis TC_{W3} and storage TC_{W4}, hydrogen production and purification by electrolysis TC_{W5}, low pressure compression TC_{W6} and tube trailer storage TC_{W7} needs to be included. The sum of aforementioned costs is divided by the Energy Production of hydrogen $EP_{H,W}$ (kg H_2/year). For wind onshore hydrogen production this results in the following levelized cost of energy $LCoE_{H,W\text{-}onshore}$ (€/kg H_2):

$$LCoE_{H,W\text{-}onshore}\left(€/kg\ H_2\right)=\frac{TC_{W1}+\left(\sum_{W3}^{W7}TC_i\right)\times\left(\frac{EP_{e,W\text{-}onshore}}{EP_{e,W}}\right)}{EP_{H,W\text{-}onshore}} \qquad (14)$$

For wind offshore hydrogen production the levelized cost of energy $LCoE_{H,W\text{-offshore}}$ (€/kg H_2) is calculated in a similar way:

$$LCoE_{H,W\text{-offshore}}\left(€/kg\ H_2\right)=\frac{TC_{W1}+\left(\sum_{W3}^{W7}TC_i\right)\times\left(\frac{EP_{e,W\text{-offshore}}}{EP_{e,W}}\right)}{EP_{H,W\text{-offshore}}} \quad (15)$$

The Levelized Cost of Energy of hydrogen from wind $LCoE_{H,W}$ is calculated as follows:

$$LCoE_{H,W}\left(€/kg\ H_2\right)=\frac{\sum_{W1}^{W7}TC_i}{EP_{H,W}} \quad (16)$$

The levelized cost of energy for hydrogen produced by the solar surplus electricity is calculated $LCoE_{H,S}$ (€/kg H_2). The solar surplus electricity is that part of the solar electricity that cannot directly used as electricity in the smart city area $EP_{e,S\text{-surp}}$ (kWh/year), see Fig. 5. The fraction of the solar modules costs TC_{S1} that is responsible for generating the surplus electricity and the total cost of the hydrogen production components, divided by the hydrogen production $EP_{H,S}$ (kg H_2/year), result in the $LCoE_{H,S}$. The TC of the hydrogen production components consists of the costs for the rainwater collection and storage TC_{S2}, reverse osmosis TC_{S3}, hydrogen production and purification TC_{S4}, low pressure compressor TC_{S5} and tube trailer storage TC_{S6}.

$$LCoE_{H,S}\left(€/kg\ H_2\right)=\frac{\left(\frac{EP_{e,S\text{-surp}}}{EP_{e,S}}\right)\times TC_i+\sum_{S2}^{S6}TC_i}{EP_{H,S}} \quad (17)$$

Because only solar surplus electricity is converted into hydrogen, the capacity factor of the hydrogen production and storage equipment is relatively low and implies a relatively high price per kg hydrogen produced from surplus solar.

7.2.2 System levelized cost of energy

For transportation energy only hydrogen from wind is used. Electricity for buildings is supplied, directly from the solar system and from conversion of hydrogen from surplus solar and wind by FCEVs. Therefore first the system levelized cost of energy for electricity from wind hydrogen $SLCoE_{e,W}$ (€/kWh) needs to be calculated.
Hydrogen produced from wind and surplus solar electricity needs to be transported, compressed to 875 bar, stored at the hydrogen fueling station, cooled and dispensed, before it can be reconverted into electricity by FCEVs. The components involved by these additional steps are used for both hydrogen produced from wind and surplus solar electricity. Therefore, the term system is added to the levelized cost of energy term. The energy consumption of the tube trailer tractor is included in the OMC of the tube trailer tractor. The energy consumption of the compressor and chiller at the HFS $EC_{H,HFS}$ (kg H_2/year), is supplied by FCEVs converting hydrogen from wind into electricity. A fraction of; the energy consumption of the compressor and chiller at the HFS $EC_{H,HFS,H\text{-}W}$ (kg H_2/year), the HFS cost of energy $CoE_{HFS,H\text{-}W}$ (€/year) and HFS cost $TC_{HFS,H\text{-}W}$ (€/year) are allocated to the system levelized cost of dispensed hydrogen from wind $SLCoE_{H,W}$ (€/kg H_2):

$$SLCoE_{H,W}\left(€/kg\ H_2\right)=\frac{\left(LCoE_{H,W}\times EP_{H,W}\right)+CoE_{HFS,H\text{-}W}+TC_{HFS,H\text{-}W}}{EP_{H,W}} \quad (18)$$

Where the cost of energy for compressing and cooling the hydrogen from wind $CoE_{HFS,H\text{-}W}$ (€/year) consist of; the hydrogen cost used for electricity consumption at the HFS $EC_{e,HFS,H\text{-}W}$ (kWh/year), a fraction of the costs for the smart grid, control, V2G infrastructure TC_{FCEV1} and the replacement of fuel cell systems in FCEVs TC_{FCEV2}, relative to the electricity production by FCEVS $EP_{e,FCEV}$ (kWh/year):

$$CoE_{HFS,H\text{-}W}\left(€/year\right)=\left(EC_{H,HFS,H-W}\times LCoE_{H,W}\right)+\left[\left(\frac{EC_{e,HFS,H\text{-}W}}{EP_{e,FCEV}}\right)\times\left(TC_{FCEV1}+TC_{FCEV2}\right)\right] \tag{19}$$

The fraction of the HFS cost for hydrogen from wind is calculated with costs of the tube trailer tractors TC_{HFS1}, compressor TC_{HFS2}, stationary storage TC_{HFS3}, dispenser TC_{HFS4} and chiller TC_{HFS5} units.

$$TC_{HFS,H\text{-}W}\left(€/year\right)=\left(\frac{EP_{H,W}}{EP_{H,W}+EP_{H,S}}\right)\times\sum_{HFS1}^{HFS5}TC_i \tag{20}$$

In a similar way, a fraction of; the energy consumption of the compressor and chiller at the HFS $EC_{H,HFS,H\text{-}S}$ (kg H_2/year), the HFS cost of energy $CoE_{HFS,H\text{-}S}$ (€/year) and HFS cost $TC_{HFS,H\text{-}S}$ (€/year), are allocated to the system levelized cost of dispensed hydrogen from surplus solar $SLCoE_{H,S}$ (€/kg H_2):

$$SLCoE_{H,S}\left(€/kg\,H_2\right)=\frac{\left(LCoE_{H,S}\times EP_{H,S}\right)+CoE_{HFS,H\text{-}S}+TC_{HFS,H\text{-}S}}{EP_{H,S}} \tag{21}$$

$$CoE_{HFS,H\text{-}S}\left(€/year\right)=\left(EC_{H,HFS,H-S}\times LCoE_{H,S}\right)+\left[\left(\frac{EC_{e,HFS,H\text{-}S}}{EP_{e,FCEV}}\right)\times\left(TC_{FCEV1}+TC_{FCEV2}\right)\right] \tag{22}$$

$$TC_{HFS,H\text{-}W}\left(€/year\right)=\left(\frac{EP_{H,W}}{EP_{H,W}+EP_{H,S}}\right)\times\sum_{HFS1}^{HFS5}TC_i \tag{23}$$

The dispensed hydrogen from wind and surplus solar is then distributed by the FCEVs and converted into electricity. The system levelized cost of electricity from wind hydrogen $SLCoE_{e,W}$ or surplus solar hydrogen $SLCoE_{e,S}$ depends on five factors; system levelized cost of dispensed hydrogen from surplus solar $SLCoE_{H,W}$ or wind $SLCoE_{H,W}$, the Tank-To-Wheel efficiency of the FCEV η_{TTW} (%) from section 4.1, Higher Heating Value of hydrogen HHV_H (kWh/kg H_2), the relative costs of the smart grid, control, V2G infrastructure TC_{FCEV1} and replacement cost of fuel cell systems in FCEVs TC_{FCEV2}:

$$SLCoE_{e,W}\left(€/kWh\right)=\left(\frac{SLCoE_{H,W}}{HHV_H\times\eta_{TTW}}\right)+\left(\frac{TC_{FCEV1}+TC_{FCEV2}}{EP_{e,FCEV}}\right) \tag{24}$$

$$SLCoE_{e,S}\left(€/kWh\right)=\left(\frac{SLCoE_{H,S}}{HHV_H\times\eta_{TTW}}\right)+\left(\frac{TC_{FCEV1}+TC_{FCEV2}}{EP_{e,FCEV}}\right) \tag{25}$$

Electricity for buildings is supplied via three routes, directly from the solar system $EP_{e,S\text{-}dir}$ (kWh/year), see Fig. 5, electricity from the conversion of hydrogen from surplus solar $EC_{e,B,H\text{-}S}$ (kWh/year) and wind $EC_{e,B,H\text{-}W}$ (kWh/year). Therefore the system levelized cost of energy for electricity $SLCoE_e$ (€/kWh), see section 2.5.2, is a weighted average of the aforementioned electricity supply routes:

$$SLCoE_e\left(€/kWh\right)=\frac{LCoE_{e,S}\times EP_{e,S-dir}+SLCoE_{e,S}\times EC_{e,B,H\text{-}S}+SLCoE_{e,S}\times EC_{e,B,H\text{-}W}}{EP_{e,S-dir}+EC_{e,B,H\text{-}S}+EC_{e,B,H\text{-}W}} \tag{26}$$

This system levelized cost of energy for electricity includes all the cost to supply electricity to the area at all moments, so all storage and balancing cost are taken into account.

7.2.3 Specific cost of energy

Equation (8), $SCoE_T$, can be re-written into the following as only hydrogen from wind is used for transportation:

$$SCoE_{T,veh}\left(€/km\right) = \frac{SLCoE_{H,W} \times SEC_{T,veh}}{100\,km} \qquad (27)$$

For building energy consumption, the Specific Cost of Energy for Buildings $SCoE_B$ (€/m^2/year), Equation (9) can be made specific for each sector, either residential or services:

$$SCoE_{B,sector}\left(€/m^2/year\right) = SLCoE_e \times SEC_{B,sector} \qquad (28)$$

7.3 Cost of energy results

7.3.1 System levelized cost of energy

The (system) levelized cost parameters are presented in Table 9 for the Near Future and Mid Century scenarios.
A levelized cost of energy of wind and solar electricity of respectively 0.034 ($LCoE_{e,S}$) and 0.079 ($LCoE_{e,W}$) €/kWh in the Near Future scenario results in a system levelized cost of energy for electricity ($SCLoE_e$, equation (26)) of 0.41 €/kWh. Converting solar electricity into hydrogen and back into electricity again, electricity price increases from 0.079 €/kWh ($LCOE_{e,S}$) to 0.70 €/kWh ($SLCoE_{e,S}$) for the Near Future. For re-electrified hydrogen from wind electricity in the Near Future, price increases from 0.034 €/kWh ($LCoE_{e,W}$) to 0.45 €/kWh ($SLCoE_{e,W}$).
For the Mid Century $LCoE_{e,S}$ and $LCoE_{e,W}$ of respectively 0.028 and 0.022 €/kWh result in an $SCLoE_e$ of 0.088 €/kWh. Converting solar electricity into hydrogen and back into electricity again, electricity price increases from 0.028 €/kWh ($LCOE_{e,S}$) to 0.70 €/kWh ($SLCoE_{e,S}$) for the Mid Century. For re-electrified hydrogen from wind electricity in the Near Future, price increases from 0.034 €/kWh ($LCoE_{e,W}$) to 0.45 €/kWh ($SLCoE_{e,W}$).

Table 9 – Calculated (System) levelized cost parameters for the Near Future and Mid Century scenarios.

(System) Levelized Cost parameter	Near Future	Mid Century
$LCoE_{e,S}$ [€/kWh] - Eq. (10)	0.079	0.028
$LCoE_{e,W}$ [€/kWh] - Eq. (13)	0.034	0.022
$LCoE_{H,S}$ [€/kg H_2] - Eq. (17)	10.4	2.3
$LCoE_{H,W}$ [€/kg H_2] - Eq. (16)	5.4	1.7
$SLCoE_{H,S}$ [€/kg H_2] - Eq. (21)	12.5	3.1
$SLCoE_{H,W}$ [€/kg H_2] - Eq. (18)	7.6	2.4
$SLCoE_{e,S}$ [€/kWh] - Eq. (25)	0.70	0.16
$SLCoE_{e,W}$ [€/kWh] - Eq. (24)	0.45	0.13
$SLCoE_e$ [€/kWh] - Eq. (26)	0.41	0.088

It has to be kept in mind that other allocation principles will result in different System levelized cost of electricity and system levelized cost of hydrogen for transport. If for example all the hydrogen cost from the surplus electricity from solar is allocated to transport, the system levelized cost of electricity will be lower and the system levelized cost of hydrogen for transport will be higher (Table 9). Therefore in all renewable integrated energy systems, it is important to compare total energy cost for buildings and transport with these total cost for other fully renewable and reliable integrated energy systems.

Fig. 7 shows the Near Future (left) and Mid Century (right), cost distribution (outer) of 1 kWh final electricity consumption ($SLCoE_e$) & energy distribution (inner) of 1 kWh primary electricity input. The outer ring shows the cost distribution of the System levelized cost of energy for electricity $SLCoE_e$, which in the Near Future is 0.41 €/kWh and in the Mid Century 0.088 €/kWh (Table 9). In the Near Future the two largest cost contributors for the $SLCoE_e$ are the Electrolysis and water production equipment (Purple, 34.5%) and the Low and High Pressure Compression, Storage and Transport equipment (Cyan, 20.2%). For the Mid Century the two largest cost contributors are the share of the cost of solar electricity which is not used directly but converted into hydrogen (Red, 27.0%) and the Low and High Pressure Compression, Storage and Transport equipment (Cyan, 24.9%).

The inner ring, represents the primary input energy distribution for the consumed electricity in Buildings. The final electricity consumption consists of Electricity Solar direct use (Blue, 6.1% and 33.7%), Electricity Solar H_2 re-electrification (Red, 3.6% and 26.7%) and Electricity Wind H_2 re-electrification (Green, 26.2% and 4.3%), together respectively 35.9% and 64.0% in the Near Future and Mid Century scenario of the primary input energy. The remainder part of respectively 64.1% and 36% in the Near Future and Mid Century represent the energy losses. The energy losses are primarily dominated by the hydrogen to electricity conversion in the grid connected FCEVs (Orange, 31.2% and 21.3%), into a lesser extent the hydrogen production via electrolysis (Purple, 27.1% and 10.6%) and the Low and High Pressure Compression, Storage and Transport equipment (Cyan, 5.7% and 4.2%).

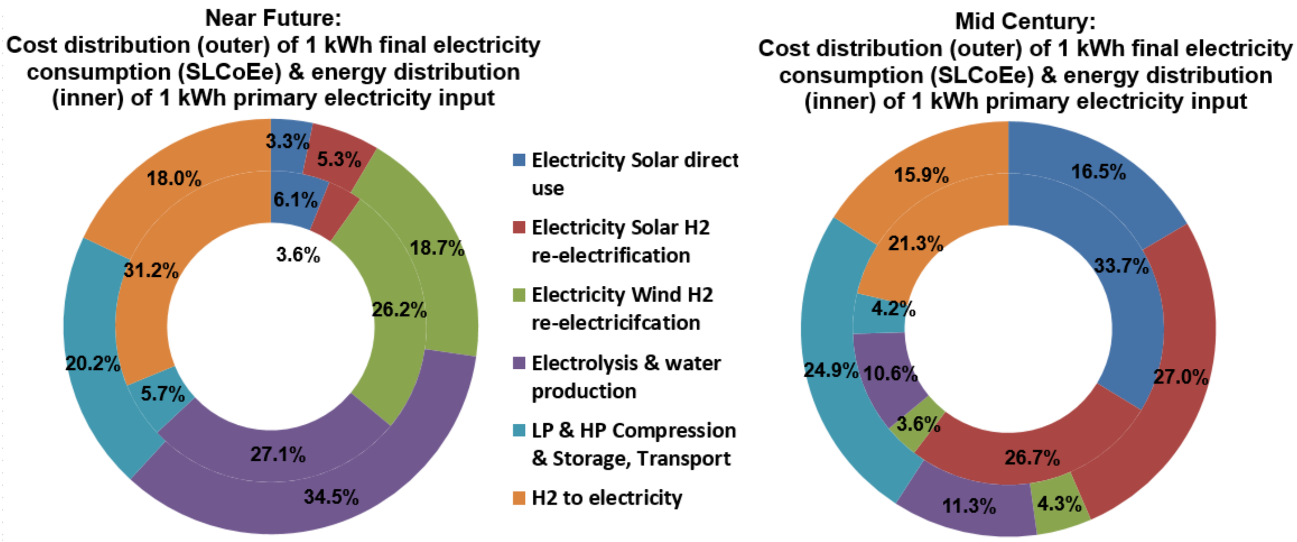

Fig. 7 – Near Future (left) and Mid Century (right), cost distribution (outer) of 1 kWh final electricity consumption ($SLCoE_e$) & energy distribution (inner) of 1 kWh primary electricity input.

7.3.2 Specific cost of energy

Fig. 8 shows the $SCoE_B$ and $SCoE_T$ for the residential and the services sector. For the residential sector, the $SCoE_B$ is 33.3 €/m^2/year and 4.5 €/m^2/year in the Near Future and Mid Century scenario. The $SCoE_T$ is 0.076 €/km and 0.015 €/km in the Near Future and Mid Century scenario (Table 7). For the services sector, the $SCoE_B$ is 87.0 €/m^2/year and 13.4 €/m^2/year in the Near Future and Mid Century scenario. The $SCoE_T$ is ranging between 0.10-0.65 €/km and 0.022-0.17 €/km in the Near Future and Mid Century scenario (Table 7). The large reduction in specific costs of energy for either transport or buildings occur due to the combined decrease of system levelized cost of energy for electricity and hydrogen as well as the specific energy consumption for transport and buildings.

7.3.3 Smart city area total system cost of energy

Fig. 8 shows the $TSCoE_{SCA}$ (M€/year) in the Near Future and Mid Century scenario. The $TSCoE_{SCA}$ decreases from 15.2 M€/year in the Near Future scenario to 2.5 M€/year in the Mid Century scenario.
The large reduction in smart city area total system cost of energy and costs of energy per sector are due to the reduction of total capital and O&M costs of all components as well as the specific energy consumption for transport and buildings.

Fig. 8 – Specific Cost of Energy for Buildings ($SCoE_B$ in €/m^2/year) and Transport ($SCoE_T$ €/km) per sector (Services sector upper diagram, Residential sector lower left diagram) and Smart City Area Total System Cost of Energy ($TSCoE_{SCA}$ in M€/year) (lower right diagram).

Fig. 9 shows the annual cost of buildings and transport energy distribution for residential and services sectors. The largest cost share is due to energy consumption in residential and services sector buildings: in the Near Future scenario 72%, in the Mid Century scenario 63%. Using the number of households 2,000 (Table 1), it can be calculated that the household annual energy costs for transport and household energy decreased from 4,030 €/year in the Near Future to 605 €/year in the Mid Century.

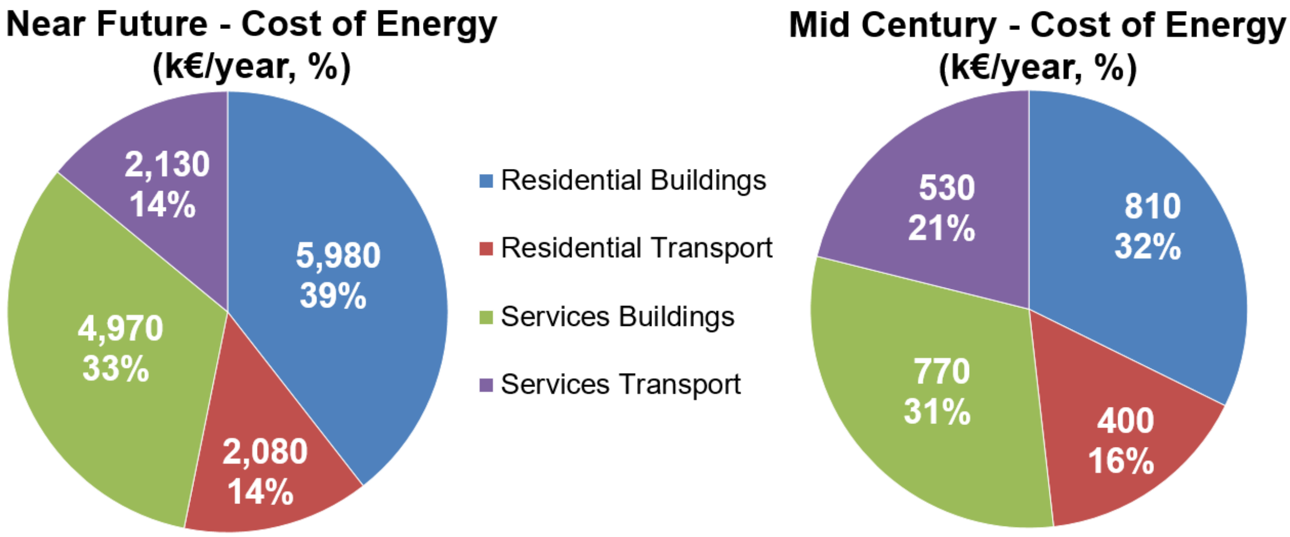

Fig. 9 — Cost of Energy distributiuon for the Residential and Services sector for buildings and transportation in the Near Future and Mid Century scenario.

8 Cost sensitivity results

A cost sensitivity analysis is performed for the Smart City Area Total System Cost of Energy ($TSCoE_{SCA}$ in M€/year) by changing key input parameters and assumptions for the Mid Century scenario for 'pessimistic' and 'optimistic' deviations from the baseline, see Table 10. The pessimistic values result in a higher costs ($TSCoE_{SCA}$), the optimistic values in lower costs ($TSCoE_{SCA}$).

A higher or lower WACC has a direct impact on the $TSCoE_{SCA}$. The assumed range of the WACC in the sensitivity study is based on [211,217]. External factors such as (national) economic and market conditions or interest rate can have influence on the WACC [217,218]. As hydrogen technologies are still in development, future costs can deviate from predictions made today. If the learning rate or the rate of installed capacities deviates from what is expected, Mid Century costs could deviate by 30% [52,219,220]. Fuel cell cost still decreases [220,221]. In a Mid Century scenario, apart from cost, also future fuel cell efficiency and degradation rate can vary from predictions made and so influence the $TSCoE_{SCA}$. Application of new materials or fuel cell types, improved balance of plant or smart power management strategies could increase fuel cell system efficiency and durability. Therefore a relative increase of 7.5% in fuel cell system efficiency (η_{TTW}) and specific energy consumption for transport ($SEC_{T,veh}$) is assumed in the optimistic scenario. 7.5% relative increase would result in an efficiency of 64.5% HHV, less than the maximum theoretical fuel cell efficiency of 83% [222,223]. Direct solar electricity consumption [130,216], fuel cell efficiency or energy consumption reduction in buildings [224], all have a direct impact on the energy balance. Any deviation of these parameters results in more or less imported hydrogen from wind, or smaller or larger hydrogen equipment size and so influences the $TSCoE_{SCA}$. A wide range of building energy consumption as well as the global irradiation on optimal inclined modules in urban areas is included. These wide ranges represent the entire European continent.

Table 10 ─ Sensitivity parameters for a pessimistic and optimistic scenario of the Mid Century case.

Sensitivity parameter	**Mid Century Baseline**	**Optimistic Scenario relative change**	**Pessimistic Scenario relative change**
Weighted Average Cost of Capital (WACC)	3%	-30%	+30%
Hydrogen equipment cost	1.1M€	-30%	+30%
Share of direct solar electricity consumption	38%	+30%	-30%
FCEV η_{TTW} and vehicle specific energy consumption for transport ($SEC_{T,veh}$)	60.0% HHV and $SEC_{T,veh}$	+7.5%	-7.5%
Fuel cell degradation factor V2G Mode	50%	-30%	+30%
Energy consumption in buildings	18.0 GWh/year	-30%	+30%
Global irradiation on optimal inclined modules in urban areas	1,300 kWh/m^2/year	+30%	-30%

Fig. 10 shows the results of the sensitivity analysis. The four sensitivity parameters with the largest impact on the $TSCoE_{SCA}$ are the estimated energy savings in buildings, global irradiation on optimal inclined modules in urban areas, hydrogen equipment costs and share of direct solar electricity consumption. The sensitivity parameters impact is in the range of -2% to -27% and +2% to +27% on the Smart City Area relative change in the $TSCoE_{SCA}$. The optimistic cases for the share of direct solar electricity consumption, energy consumption in buildings and global irradiation on optimal inclined modules in urban areas result in situation where the buildings energy balance is positive and do not require hydrogen from wind for electricity production. Therefore a part of the hydrogen from sun can be used for driving. A relatively higher surplus solar hydrogen price therefore results in higher transportation costs, despite the decrease of the $TSCoE_{SCA}$ and the smart city area system levelized cost of electricity $SLCoE_e$.

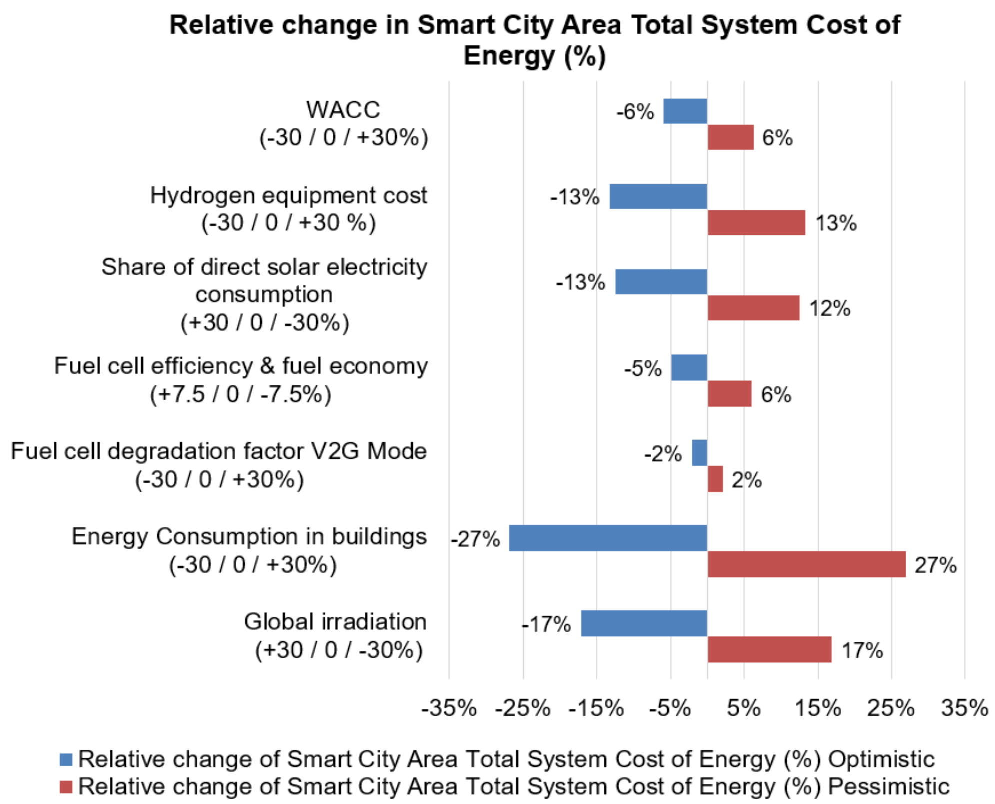

Fig. 10 ─ Relative change in Smart City Area Total System Cost of Energy compared to the Mid Century base scenario.

9 Discussion

It was concluded that the smart city design can provide the required energy at all times without any grid connection to a medium or high voltage grid. However, the potential of the smart city area with fuel cell electric cars depends on several aspects, the most important of which are discussed here.

9.1 Car availability and developments

The V2G electricity can be supplied by 1,170 cars for the Near Future and 430 cars in the Mid Century scenario, during 6 hours on an average day basis. For a day without any solar power, for the Near Future and Mid Century scenario, the cars can still supply all power, requiring respectively 1,375 and 865 cars, representing 60% and 38% of the car fleet.

The normal car use profiles arranges that cars are present at demand centers: during the day at office / service sector buildings and in the evening and at night at home [215] or at a car park in the smart city area [47,225]. A high degree of monitoring and automation, e.g. self-connecting and driving cars, and incentives for car owners to participate will help assuring car availability and energy security at all times at the desired locations.

New developments, such as free-floating car sharing-fleets [226] combined with autonomous driving [227,228] could provide mobility and power on demand. Due to car sharing initiatives, the number of cars per person will decrease. Most balancing electricity from FCEVs is required during night [130]. So even if car sharing spreads widely, most likely with heavy use during day time, during night time FCEVs will still be available to provide power.

The system uses only hydrogen fuel cell powered vehicles. In future it is likely to have a mix of electric powered vehicles: battery, fuel cell and hybrids of these [68], all zero emission technologies. These technologies could complement each other and could share facilities, for example the possibly future wireless V2G infrastructure [229].

9.2 Local climate and population density

In the sensitivity analysis a wide range of building energy consumption as well as the global irradiation on optimal inclined modules in urban areas is included. These wide ranges represent the entire European continent and its widely available solar and wind energy sources. Not included in the sensitivity analysis, is the available solar rooftop area per capita in cities, which varies as a function of population density [137].

The system size based on 2,000 households and one hydrogen fueling station results in a cost effective system. Smaller system sizes could result in slightly higher costs, as certain components are relatively more expensive at lower capacities.

9.3 Technology synergy effects and development

A fully autonomous smart city area is considered. However in reality these smart city areas will be interconnected with other city areas and industry sites, rural areas, etc. Therefore, system integration will result in more complex systems, with synergies leading to lower costs and higher reliability. For example if surplus electricity from solar in the summer time could be directly used for cooling at cold stores, less electricity conversion into hydrogen is needed in the smart city area, which will reduce cost. Or producing hydrogen from hydropower or biogas from agricultural residues, manure and waste water treatment plants could lead to lower prices for hydrogen. Smart integration with local heat grids and heat storage [6,230] can reduce system cost and affect economies of scale of hydrogen technologies.

The levelized cost of energy of wind or solar electricity is less than 0.03€/kWh in the Mid Century scenario, but balancing fluctuating renewable energy with energy storage and additional generators comes at a price. The hydrogen related components account for half of the total annual cost of the Smart City Area. Solar annual irradiation, energy savings measures in buildings and the share of direct solar electricity consumption have a large impact on the hydrogen equipment size and thus system cost.

For most of the hydrogen technologies used in the calculations, other technologies are being developed which are likely to be more energy efficient and/or cost effective. Examples are high temperature solid oxide or proton conducting electrolyzers [152,231], alkaline membrane [232–234] electrolyzers and direct solar to hydrogen technologies replacing solar panels and electrolyzers [235–240]. Ionic liquid piston compressors [241] and electrochemical hydrogen compression and purification [242,243] could replace compressors and purification systems. Several types of hydrogen storage methods are being investigated [159–161], but in particular liquid organic hydrogen carriers could be a cost effective alternative [244–247] and (partly) avoid the need for compressors. Also some research is performed in the field of reversible unitized (PEM) fuel cells, combining an electrolyzer and fuel cell in one device [248–251].

9.4 Comparing system costs with other power and transport systems

A comparison with other integrated power and transport systems is not straightforward due to combination of an integrated design, scale of the system, technologies used and projections in two technology and cost development scenarios. Balancing is commonly done using fossil resources, unlike the presented system.

The levelized cost results of the Near Future scenario can be compared with present day levelized costs of electricity. The levelized costs of electricity from wind and solar for the two scenarios are comparable with other studies, 0.02-0.08 €/kWh [139,188,211,252]. The levelized cost of dispensed hydrogen from wind or solar electricity in the Mid Century scenario is in a similar range as other studies, 2-4 €/kg H_2 [52,153,157]. Specific Costs of Energy for Transportation for the Near Future scenario for passenger cars is lower than the hydrogen cost per kilometer of 0.10-0.31€/km calculated by NREL [3] for a smaller integrated power and transport system with electricity grid connection. The levelized cost of electricity including storage and reconversion of 0.40€/kWh as calculated by NREL [3] is comparable with the Near Future $SLCoE_e$ of 0.41€/kWh. The Mid Century $SLCoE_e$ of 0.09€/kWh is of similar magnitude as the 100% renewable system electricity cost 0.10€/kWh in 2050-2055 in [253]. In conclusion, the designed system has equivalent costs for the parameters where comparison with other studies could be performed.

System levelized electricity costs are very hard to compare to other studies, and in this discussion we focus on some methodological observations. The $SLCoE_e$ cannot be compared directly with any future conventional or fossil based electricity cost [253]. For example conventional electricity cost projections do not integrate transportation, power and heating/cooling. Conventional calculations do not account for a multitude of avoided costs, such as health and climate related savings [254,255], possible avoidance of electric grid congestion problems [256–259] or using different energy carriers than electricity and hydrogen. Avoided costs are more complex to estimate than levelized costs because it requires information about how a similar system would have operated without the described system changes [260]. Therefore attempts are made to include these in cost calculations, such as the methodology of the Levelized Avoided Cost of Electricity [261]. The designed system is independent of any future fuel costs or High and Medium Voltage electricity grids, natural gas and district heating grids or expansion of these, and including these as avoided costs seems reasonable, hard to quantify, and for various stakeholders arguable.

10 Conclusion

It is concluded that for smart city areas, solar and wind electricity together with fuel cell electric vehicles as energy generators and distributors and hydrogen as energy carrier, can provide a 100% renewable, reliable and cost effective energy system, for power, heat, and transport.

A smart city area is designed and dimensioned based on European statistics. The smart city area consists of 180,000 m^2 floor area of residential and 57,000 m^2 floor area services sector buildings and 2,800 fuel cell powered road transport vehicles. 2,000 households with 4,700 inhabitants is an appropriate size for dimensioning the smart city area as statistically there is one petrol station and one food-retail shop.

All electricity and hydrogen can be supplied by solar and wind to fulfill the energy demand for power, heat and transport. Electricity is generated by solar modules on all roofs. Surplus solar electricity is converted via water-electrolysis with rainwater into pure hydrogen. The hydrogen is compressed and transported by tube trailer modules to the nearby Hydrogen Fueling Station. At the Hydrogen Fueling Station, the hydrogen is further compressed to fuel all types of fuel cell powered electric vehicles; passenger cars, vans, motorcycles, buses and trucks. In case of a temporary shortage in production of solar electricity, the fuel cells in grid-connected passenger cars provide the necessary electricity by converting hydrogen from the on-board hydrogen storage tanks. At parking places at home, office or at the local shopping area, vehicle-to-grid points connect the cars to the smart city electrical grid. To provide year round energy supply, distant on-shore or off-shore wind-electricity is converted at the wind turbine park into hydrogen via water-electrolysis with surface or seawater. The produced hydrogen from wind is transported via tube trailers to a hydrogen fueling station.

An energy balance and cost analysis is performed for a Near Future and Mid Century scenario. Technological and cost data is collected of all system components, using existing technologies and well-documented technology and cost development projections. In the Near Future, renewable electricity supply consists of 12 GWh/year rooftop solar electricity and 95 GWh/year distant wind electricity producing hydrogen. 4.5 GWh/year of solar electricity is used directly and 72 GWh/year hydrogen is produced from surplus solar and wind electricity. In the Mid Century scenario renewable electricity supply consists of 24 GWh/year rooftop solar electricity and 23 GWh/year distant wind electricity producing hydrogen. 9.5 GWh/year of solar electricity is used directly and 31 GWh/year hydrogen is produced from surplus solar and wind electricity. This lower renewable electricity production is possible due to savings in final energy consumption in buildings and transport, higher use of direct solar energy due to demand side management and efficiency increase in hydrogen production and fuel cell technologies.

The smart city area energy supply is reliable at all times and independent of other energy systems and grid connections. Reliability of energy supply is guaranteed by converting temporary surplus solar and distant wind electricity into hydrogen and through electricity supply with grid-connected fuel cell electric passenger cars providing 10 kW each (10% of installed power). The balancing electricity can be supplied by 1,170 cars for the Near Future and 430 cars in the Mid Century scenario, during 6 hours on an average day basis. For a day without any solar power, for the Near Future and Mid Century scenario, the cars can still supply all power, requiring respectively 1,375 and 865 cars, representing 60% and 38% of the car fleet. If the cars can generate 20 kW (20% of the installed power) halve the required of amount passenger cars would suffice. If more hours of balancing per car per day are assumed, proportionally less cars are needed.

In conclusion, the fuel cell electric vehicle and renewable energy based smart city area can provide a future cost effective energy supply, as the annual total system cost of energy demand for power, heat and transport is 15 M€/year in the Near Future and 2.5 M€/year in the Mid Century scenario for the entire smart city area. This corresponds to an average annual cost for power, heat and mobility of 600 €/year per household for the Mid Century scenario. In the Near Future scenario system levelized cost of hydrogen for transportation is 7.6 €/kg, system levelized cost of electricity is 0.41 €/kWh and the specific cost of energy for passenger cars is 0.08 €/km. In the Mid Century scenario however, this is only 2.4 €/kg, 0.09 €/kWh and 0.02 €/km. System levelized cost of energy and specific energy costs compare favorably with other scenario studies describing fully renewable energy and transport systems.

Future dynamic simulations and tailoring to geographical demand and climate conditions is needed to calculate system cost, and FCEV fleet deployment for specific city areas in Europe. Also other configurations using different renewable energy sources and different storage and conversion technologies is of interest for future research.

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