



Environmental sustainability of renewable hydrogen in comparison with conventional cooking fuels

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ABSTRACT

Hydrogen could be used as a 'cleaner' cooking fuel, particularly in communities that rely on biomass and fossil fuels, to reduce local pollution and related health effects. However, hydrogen must be produced using sustainable feedstocks and energy sources to ensure that local impacts are not reduced at the expense of other impacts generated elsewhere in the life cycle. To this end, this paper evaluates life cycle environmental impacts of renewable hydrogen produced in a proton-exchange membrane electrolyser using solar energy. The aim of the study is to find out if hydrogen produced in this system and used as a cooking fuel is environmentally sustainable in comparison with conventional cooking fuels typically used in developing countries, such as liquefied petroleum gas (LPG), charcoal and firewood. The results suggest that hydrogen would reduce the climate change impact by 2.5–14 times to 0.04 kg CO₂ eq./MJ compared to firewood (0.10 kg CO₂ eq./MJ) and LPG (0.57 kg CO₂ eq./MJ). Some other impacts would also be lower by 6%–35 times, including depletion of fossil fuels, summer smog and health effects from emissions of particulates, both locally and across the rest of the life cycle. However, some other impacts would increase by 6%–6.7 times, such as depletion of metals and freshwater and marine ecotoxicity. These are mainly due to the solar photovoltaic panels used to generate power for the electrolyser. In terms of the local impacts, the study suggests that hydrogen would reduce local pollution and related health impacts by 8%–35 times. However, LPG is still environmentally a better option than hydrogen for most of the impacts, both at the point of use and on a life cycle basis.

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1. Introduction

Hydrogen is used extensively in industry but it is its use in energy systems that has been the main focus of research and development over the past couple of decades. Most efforts have concentrated on use of hydrogen in fuel cells, either for transport (Ball and Wietschel, 2009; Cipriani et al., 2014; Miotti et al., 2016) or provision of electricity (Pehnt, 2003; Pehnt and Ramesohl, 2003; Prakash, 2011; Valente et al., 2015). The main driver for these developments is the need to decarbonise the economy and mitigate climate change. Unlike fossil fuels, hydrogen contains no carbon and hence does not generate CO₂ emissions at the point of use. However, despite being the most abundant element, hydrogen is

not readily available but has to be produced using various resources and processes. Currently, the dominant production route for hydrogen is steam reforming of natural gas (IEA, 2006; Energy.gov, 2017). This is unsustainable for at least two reasons: using natural gas depletes fossil fuel resources and the process generates significant greenhouse gas (GHG) emissions. The latter amounts to 12 kg CO₂ eq./kg H₂ (Bhandari et al., 2014; Spath and Mann, 2001). An alternative source of hydrogen includes electrolysis of water which has a potential to produce hydrogen at lower environmental impacts (IEA, 2006). The impacts of producing hydrogen via electrolysis has been studied extensively (e.g. Acar and Dincer, 2014; Bhandari et al., 2014; Dufour et al., 2012; Ozbilen et al., 2013; Smitkova et al., 2011). Similarly, studies on the environmental benefits of its use for transport are abundant (e.g. Ahmadi and Kjeang, 2015; Ally and Pryor, 2016; Patterson et al., 2014; Walker et al., 2015; Wulf and Kaltschmitt, 2016), as are those related to electricity from hydrogen (e.g. Mori et al., 2014; Rooijen, 2006).

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Nomenclature

BAU	Business as usual
CC	Climate change
DB	Dichlorobenzene
FE	Freshwater eutrophication
FET	Freshwater ecotoxicity
FFD	Fossil fuel depletion
HT	Human toxicity
LPG	Liquid petroleum gas
MD	Metal depletion
ME	Marine eutrophication
MET	Marine ecotoxicity
NMVO	Non-methane volatile organic compounds
OD	Ozone depletion
PED	Primary energy demand
PM	Particulate matter
POF	Photochemical oxidants formation (summer smog)
TA	Terrestrial acidification
TET	Terrestrial ecotoxicity

In addition to these applications, hydrogen can also be used as a cooking fuel. In many developing economies, a high percentage of domestic energy demand is related to cooking, which primarily relies on fossil and biomass fuels. The use of these fuels has serious health consequences affecting almost 3 billion people every year, largely due to the particulate matter, carbon monoxide and hydrocarbons emitted during their combustion (OECD/IEA, 2006). Cleaner cooking systems, such as solar cookers and smokeless stoves, have been promoted in many developing countries with varying degrees of success (Gujba et al., 2015; United Nations in India, 2015; UN Programme, 2015). In parallel, electrolytic systems for production of hydrogen using solar power have also been developed and are increasingly utilised for electricity and heat generation (AlZahrani and Dincer, 2016; Oruc et al., 2016; Mura et al., 2015; Özgirgin et al., 2015). One such system, using a solar-powered electrolyser with proton-exchange membrane (PEM) has recently been developed for use in small communities in developing economies (Topriska et al., 2015). The system is capable of generating enough hydrogen for a typical annual cooking demand, demonstrating that it could contribute to energy security enhancement of small communities (Topriska et al., 2015, 2016). However, it is not clear if hydrogen produced in such a system is environmentally more sustainable on a life cycle basis than conventional cooking fuels. Moreover, its potential to reduce negative health impacts from the use of conventional cooking fuels, such as charcoal and firewood, remains unknown.

Therefore, this paper evaluates for the first time the life cycle environmental sustainability of hydrogen produced in a solar-powered PEM electrolyser and used as a fuel for domestic cooking. The results are compared with conventional cooking fuels typically used in developing countries, including liquefied petroleum gas (LPG), charcoal and firewood. A scenario analysis has been carried out to examine the effect of differing levels of hydrogen penetration into the fuel mix. Life cycle assessment (LCA) has been used as a tool for these purposes as discussed in the next section.

2. Methods

The study follows the ISO 14040/44 guidelines for the LCA methodology (ISO, 2010a, 2010b). The goal and scope of the study

are outlined below, followed by the data and assumptions in the subsequent section.

2.1. Goal and scope of the study

The main goals of the study are:

- i) to estimate life cycle environmental impacts of hydrogen produced in a solar-powered PEM electrolyser plant and used as a fuel for domestic cooking in small communities in developing countries;
- ii) to evaluate the environmental sustainability of hydrogen relative to conventional cooking fuels typically used in developing countries, such as LPG, charcoal and firewood; and
- iii) to assess the environmental implications of potential replacement of current cooking fuels with hydrogen considering different scenarios for hydrogen penetration into the fuel mix.

As indicated in Fig. 1, the hydrogen-production system comprises solar photovoltaics (PV), PEM electrolyser and water deioniser. The produced hydrogen is then stored in cylinders and transported to the user to be used as cooking fuel. The scope of the study is from 'cradle to grave', encompassing the extraction and processing of raw materials, manufacture of the components of the hydrogen-production system, its operation over the lifetime, storage and use of hydrogen, end-of-life waste management and transportation along the whole life cycle. The manufacture of the electrolyser, storage cylinders and cooking appliances is excluded from the system boundaries due to a lack of data. However, key components, such as the stack cells, electrolyser membrane and materials used for the production of storage cylinders are considered.

Two functional units are considered, corresponding to the goals of the study defined above, as follows:

- i) To evaluate the environmental sustainability of hydrogen and compare it with other fuels (goals i and ii), the functional unit is defined as "provision of 1 MJ of effective energy for cooking".
- ii) To consider different penetration of hydrogen into the fuel mix (goal iii), the functional unit is defined as "provision of effective energy for cooking, equivalent to a 20-year demand of a small community comprising 20 households". The time horizon of 20 years is considered to cover the lifetimes of different system components (specified in the next section).

The 'effective' energy provided by hydrogen and other fuels to the user takes into account the calorific value of the fuel and the efficiency of the cooking appliance. It is defined as follows:

$$E = C_p \times m \times \eta \quad (1)$$

where:

- E effective energy provided by the fuel to the user (MJ)
- C_p net calorific value of fuel (MJ/kg)
- m total consumption of fuel (kg)
- η efficiency of the cooking appliance (%).

2.2. Inventory data

This section gives an overview of the data and assumptions used in the study. The hydrogen-production system is described first,

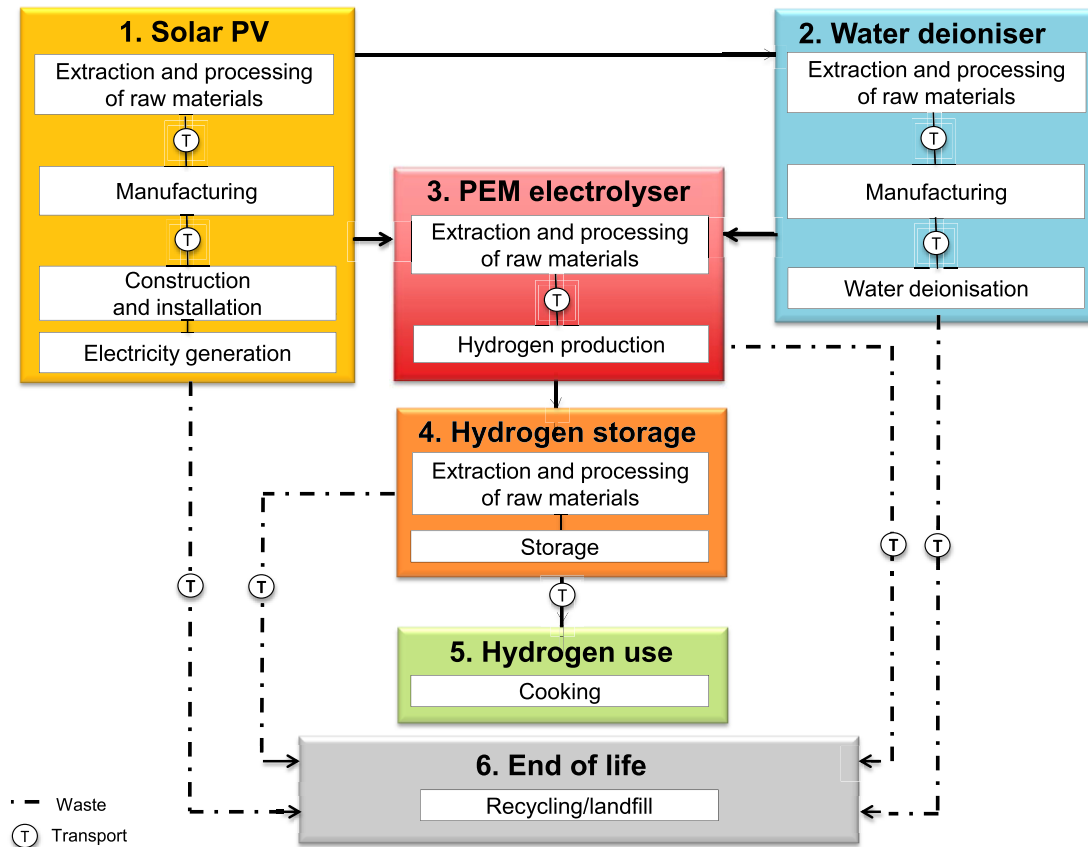


Fig. 1. The life cycle of the solar-powered PEM electrolyser system.

followed by an overview of end-of-life waste management and transportation across the supply chain. This is followed by a summary of assumptions for the current conditions related to the conventional fuels and definition of the future scenarios considered in the study.

2.2.1. System description

The core of the hydrogen-production system is the PEM electrolyser manufactured by Proton OnSite (2016). The system generates hydrogen gas with a purity of 99.999% (Proton OnSite, 2016) and at a maximum pressure of 13.8 bar. A cascading system is used for storage purposes, whereby hydrogen is first stored in high-pressure cylinders at 13.8 bar and then decompressed to be stored in low-pressure cylinders at ~3 bar, after which it is distributed to households for use as a domestic cooking fuel (Topriska et al., 2015). Solar PV panels provide electricity for the electrolyser and the water deionisation plant. The latter is used to purify tap water to a required quality standard. The assumed life-span of the plant is 20 years.

The integrated hydrogen-production system was developed by Topriska et al. (2015). It was first tested at a laboratory scale and then scaled up to provide enough hydrogen to satisfy typical annual demand for cooking energy of a small community in developing countries. The following sections provide more detail on each component of the system and their inventory data. For end-of-life management and transport, see Sections 2.2.1.6 and 2.2.1.7.

2.2.1.1. Solar PV. The solar PV system has a total installed capacity of 100.8 kWp. Ground-mounted multi-crystalline silicon panels with the efficiency of 14.2% are considered, assuming the insolation level of 5.5 kWh/m².day. The latter corresponds to the average solar

irradiation in major developing countries around the world (see Table S1 in the Supporting Information (SI)). The life cycle inventory data have been sourced from Ecoinvent V3.1 (Wernet et al., 2016), assuming the average global manufacture of solar PV. For the operation of the system, the data have been modified to account for the insolation and the efficiency considered here. Furthermore, as the capacity of the PV system in Ecoinvent is larger (570 kWp) than the one here, its impacts have been scaled down applying the “economies of scale” approach (Sinnott, 2005) but adapted for use in LCA (Greening and Azapagic, 2013):

$$I_2 = I_1 \times \left(\frac{C_2}{C_1} \right)^{0.6} \quad (2)$$

where:

- I_1 and I_2 environmental impacts of the larger and smaller system, respectively
- C_1 and C_2 installed capacities of the larger and smaller system, respectively
- 0.6 the “economy of scale” factor.

The system is assumed to be produced in China, the leading producer of PV systems (Colville, 2018; Energy Sage, 2018), and is shipped to the point of use where it remains in operation for 20 years, after which it is landfilled. The life cycle inventory data for the PV system can be found in Table S2 in the SI.

2.2.1.2. Water deioniser. The PEM electrolyser requires deionised water to operate. Life cycle inventory data for the ion-exchange resin deioniser have been sourced from Ecoinvent V3.1 (Wernet

et al., 2016). The system boundary encompasses the extraction of raw materials, construction and operation of the system as well as end-of-life waste management (for the latter, see Section 2.2.1.6). The deioniser is produced in Europe and shipped to the point of use. Its lifetime is assumed at 15 years, with the exception of the ion-exchange resins, which are replaced every five years and landfilled.

2.2.1.3. PEM electrolyser. The electrolyser comprises a stack of individual cells with the main components shown in Fig. 2. Each cell consists of an anode, cathode and a Nafion PEM membrane. The cathode consists of a porous graphite gas layer diffusor coated with platinum. The electrocatalyte used for the anode is iridium oxide on a titanium current collector (Carmo et al., 2013; Dale et al., 2008).

The inventory data for the electrolyser are provided in Tables 1 and 2. The background data have been sourced from Ecoinvent V3.1 (Wernet et al., 2016). The data for the Nafion membrane are not available due to confidentiality so that the data for per-fluorosulfonyl fluoride, the precursor for the production of the membrane, have been used instead (Carlson et al., 2005). Also due to a lack of data, the materials for the external casing of the electrolyser and its electronic components are not considered. The electrolyser is manufactured in Europe and shipped to the point of use. Its lifespan is assumed at 20 years (Proton OnSite, 2016; Topriska et al., 2016).

2.2.1.4. Hydrogen storage. As mentioned earlier, the produced hydrogen is stored and distributed in a cascade-storage system. The high-pressure (13.8 bar) cylinders are made of steel while the low-pressure (3 bar) containers are made of fiberglass. The lifespan of the cylinders is assumed at 15 years, after which they are repaired and reused (BOC, 2015).

The life cycle stages considered for the cylinders include the extraction and production of materials for the manufacture of steel and fiberglass (Table 3). The primary data for these have been

Table 1
Inventory data for the PEM electrolyser.

Materials and energy	Value	Unit
Electrolyser		
Number of stacks ^a	4	–
Number of cells per stack ^a	20	–
Cells		
Active area ^b	9.2×10^{-3}	m ²
Total area	1.08×10^{-2}	m ²
Operation		
Average hydrogen production rate ^a	1.14	Nm ³ /h
Hydrogen production pressure ^a	13.8	bar
Stack efficiency ^a	63.6	%
Water flow ^c	9.3×10^{-4}	m ³ /h

^a Topriska et al. (2015). Nm³: normal cubic meter at standard pressure and temperature conditions.

^b Active area equal to 85% of the total area (Carlson et al., 2005).

^c Proton Energy Systems (2011); Proton OnSite (2016).

sourced from manufacturers (BOC, 2015; Viking Composite Cylinders, 2014) and the background data from Ecoinvent V.3.1 (Wernet et al., 2016). It is assumed that the cylinders are produced domestically and then transported to the point of use. Only the impacts from the raw materials have been considered as data for the cylinder manufacturing process were not available.

2.2.1.5. Use of hydrogen. The use stage accounts for the cooking energy demand of the household and the community. As mentioned earlier, the system has been designed for a small community of 20 houses with the energy demand given in Table 4. The average cooking energy demand of a household consisting of four family members is assumed at 9 MJ per day, based on the data for developing countries (see Table S3 in the SI). Over the 20 year period considered here, this amounts to 1314 GJ for 20 households.

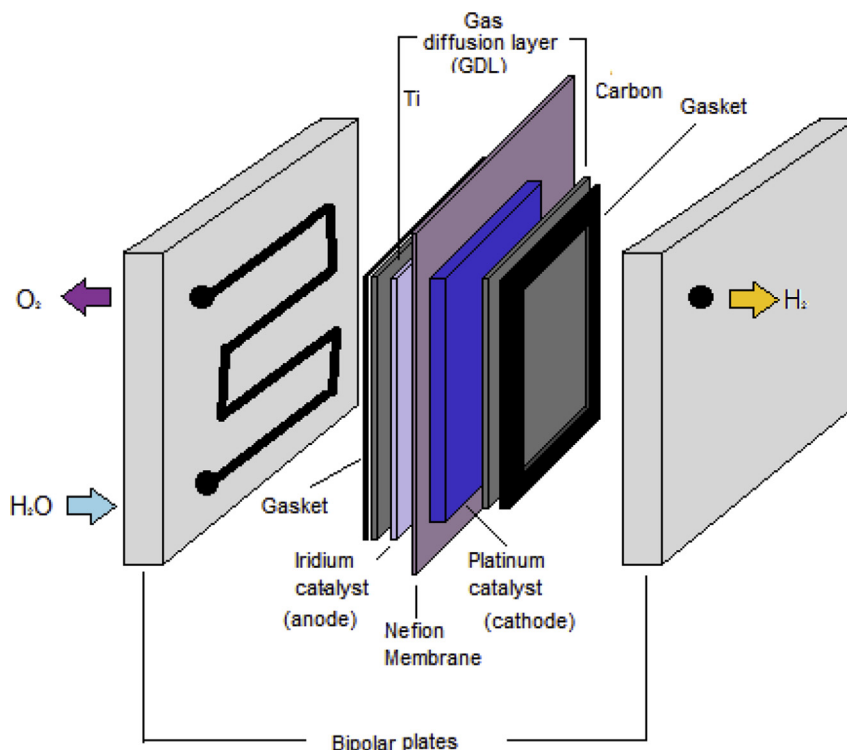


Fig. 2. The main components of a single cell in a PEM electrolyser.

Table 2
Inventory data for the cell components used in the PEM electrolyser.

Cell components	Material	Weight [g]
Membrane ^a	Perfluorosulfonyl fluoride	1.082
Anode	IrO ₂ ^b	0.184
Cathode	Pt	0.069
Bipolar plate [pair] ^a	Graphite (81%), Vinyl ester (19%)	43.034
Anode gas layer diffuser ^a	Titanium ^c	2.565
Cathode gas layer diffuser ^a	Woven carbon fibre (70%)	2.565
Frame seal ^a	Rubber	0.920
Gasket ^a	Rubber	0.195

^a Data adapted from Carlson et al. (2005) and modelled using background data from Ecoinvent V3.1 (Wernet et al., 2016).

^b Due to a lack of data, modelled as iridium, which corresponds to 0.147 g based on the stoichiometry. The inventory data for iridium were adapted from Nuss and Eckelman (2014a;b) and modelled using data from Ecoinvent V3.1 (Wernet et al., 2016).

^c Due to a lack of data, modelled as titanium dioxide, which corresponds to 4.28 g based on the stoichiometry.

Table 3
Inventory data for hydrogen storage cylinders.^a

	High-pressure cylinder	Low-pressure cylinder
Material	Steel	Fiberglass composite
Empty weight (kg)	16	8
Capacity (l)	10	10
Lifespan (years)	15	15
Reuse	95% ^b	95% ^b

^a Assumptions based on manufacturer information (BOC, 2015; Viking Composite Cylinders, 2014).

^b Assuming that not all the cylinders are fully repaired and reused but over time some are lost.

2.2.1.6. End-of-life management. This study assumes that the system components are landfilled at the end of their useful lifetime. This assumption is deemed reasonable as the deployment of the system is assumed to be in developing economies where recycling facilities are lacking. However, the effect of this assumption on the results is explored as part of a sensitivity analysis in Section 3.3. These data are provided in Table 5. The recycling rates for the metals are as follows: aluminium 90% (IAI, 2009), steel 85% (World Steel Association, 2012) and copper 45% (International Copper Association, 2014). Platinum and iridium used in the electrolyser are assumed to be 100% recycled. All other materials are landfilled. The system has been credited for the recycled materials by subtracting the impacts associated with the production of virgin materials.

2.2.1.7. Transport. As the study does not consider a particular location for the use of hydrogen, it is assumed that the system components are shipped long distance to the point of use in a developing country, e.g. in Africa or Asia; see Table 6 for the assumed distances. The PV system is assumed to be shipped from China and the rest of the hydrogen system (deioniser and electrolyser) from Europe. LPG is also imported while the solid fuels are

bought and transported locally. The hydrogen and LPG cylinders are made domestically and transported to the user.

2.2.2. Conventional cooking fuels

For comparison with hydrogen, the following fuels, typically used for cooking in developing countries, are considered: LPG, firewood and charcoal. Their respective life cycles are depicted in Fig. 3. Like the hydrogen system, the full life cycle of the conventional fuels has been considered, including their acquisition, production, use and end-of-life waste management. LPG is imported and shipped to the point of use (Table 6) where it is stored in steel cylinders (Table 3). Firewood and charcoal are sourced domestically with the assumed transport distances detailed in Table 6. The LCI data for the production of all three types of fuel have been sourced from Ecoinvent V3.1 (Wernet et al., 2016).

The main characteristics of the fuels, including hydrogen, are summarised in Table 7, together with the stove efficiencies. Total fuel consumption by the 20 households over 20 years has been calculated from eqn. (1), based on the assumed effective energy demand of 1314 GJ (Table 4). The emissions to air from burning LPG, firewood and charcoal during cooking can be found in Table 8; burning hydrogen produces only water with no other emissions. For consistency with the hydrogen system, the manufacture of the cooking stoves is excluded from the study.

2.2.3. Scenario analysis

A range of scenarios have been considered, assuming different levels of hydrogen penetration into the current fuel mix. These have been compared with the current situation, here termed as 'business as usual' (BAU). At present, most developing countries have a greater share of solid fuels than LPG (OECD/IEA, 2006). However, some more advanced developing economies, such as Brazil, Jamaica and South Africa, have already made a transition towards a majority LPG share in the fuel mix (Heltberg, 2003; The Planning Institute and the Statistical Institute of Jamaica, 2007). Therefore, two BAU scenarios are considered (Table 9):

- BAU 1 (high penetration of LPG): 70% LPG and 30% solid fuels (firewood and charcoal); and
- BAU 2 (low penetration of LPG): 30% LPG and 70% solid fuels (firewood and charcoal).

To evaluate the environmental implications of substituting conventional cooking fuels with hydrogen, each of the BAU scenarios is compared with the following five scenarios which assume different levels of hydrogen contribution:

- SC1: 50% replacement of solid fuels with hydrogen;
- SC2: 100% replacement of solid fuels with hydrogen;
- SC3: 50% replacement of LPG with hydrogen and 100% replacement of solid fuels;
- SC4: 50% replacement of LPG with hydrogen, keeping the current use of solid fuels; and
- SC5: 100% replacement of LPG and solid fuels with hydrogen.

Table 4
Assumed cooking energy demand per household and for the whole community.

Parameters	Value	Unit
Daily cooking demand per household	9	MJ/day
Number of households	20	–
Time horizon ^a	20	years
Total effective energy demand by the community over 20 years ^b	1314	GJ

^a Equivalent to the lifespan of the hydrogen-production plant.

^b Total energy demand was calculated assuming 365 days per year.

Table 5
End-of-life management options for the waste generated in the life cycle of the hydrogen system.

System component	Recycling	Landfill	Unit (per MJ hydrogen produced)
<i>Solar PV</i>			
Aluminium	0.44	0.54	g
Steel	6.98	6.70	mg
Copper wire	0.99	0.95	mg
Cardboard	–	0.19	g
Plastics	–	0.15	g
Slag from metallurgical grade silicon production	–	0.65	g
Inert waste	–	3.45	g
<i>Water deioniser</i>			
Anion exchange resin (50% water)	22.2	–	mg
Cation exchange resin (50% water)	49.2	–	g
Polypropylene (pipes, seals, and other accessories)	0.017	–	mg
<i>PEM electrolyser</i>			
Platinum and iridium	3.4	–	µg
Rubber, carbon fibre components and membrane	–	35.5	µg
<i>Storage cylinders</i>			
Steel	0.35	0.34	g
Glass fibre	–	0.17	g

Table 6
Transport modes and distances in the life cycle of the hydrogen system.

Fuel type	Transport mode	Distance (km)
<i>Hydrogen</i>		
Solar PV system	Transoceanic ship	12,000
Water deioniser	Transoceanic ship	6500
PEM electrolyser	Transoceanic ship	6500
Cylinders	Lorry (7.5–16 t)	200
<i>LPG</i>		
LPG	Transoceanic tanker	6500
Cylinders	Lorry (7.5–16 t)	200
<i>Charcoal</i>		
Wood	Van <3.5 t	200
Charcoal	Lorry (16–32 t)	100
Firewood	Van <3.5 t	25

Table 7
Characteristics of cooking fuels and stoves.

Parameter	Hydrogen	LPG	Firewood	Charcoal
Net calorific value (MJ/kg)	120	46.1	18.3	34.1
Density (kg/l or kg/m ³) ^a	–	0.55	513	–
Stove efficiency (%)	60 ^b	60 ^c	18 ^c	22 ^c
Total fuel consumption (t) ^d	18.3	48.6	398.7 ^e	175.2

^a kg/l for LPG and kg/m³ for firewood.

^b Topriska et al. (2015).

^c Jungbluth (1997).

^d For the functional unit “provision of effective energy for cooking, equivalent to the demand over 20 years of a community comprising 20 households”. Estimated from eqn. (1) using the data in this table.

^e Calculated based on the dry matter.

Thus, the scenarios assume possible fuel transitions, first from solid fuels (SC1 and SC2) which affect human health, to the replacement of LPG (SC3 and SC4) which contributes to climate change, to a complete replacement of all conventional fuels (SC5) with hydrogen. While replacing solid fuels may be more important

from the health point of view, it may be easier to replace LPG for practical reasons due to two reasons: similarities in the appliances and storage systems with hydrogen; and some traditional dishes in developing countries require preparation using solid fuels so that the use of at least some proportion of these fuels may not be avoided. In all the scenarios, an equal share of firewood and charcoal has been assumed.

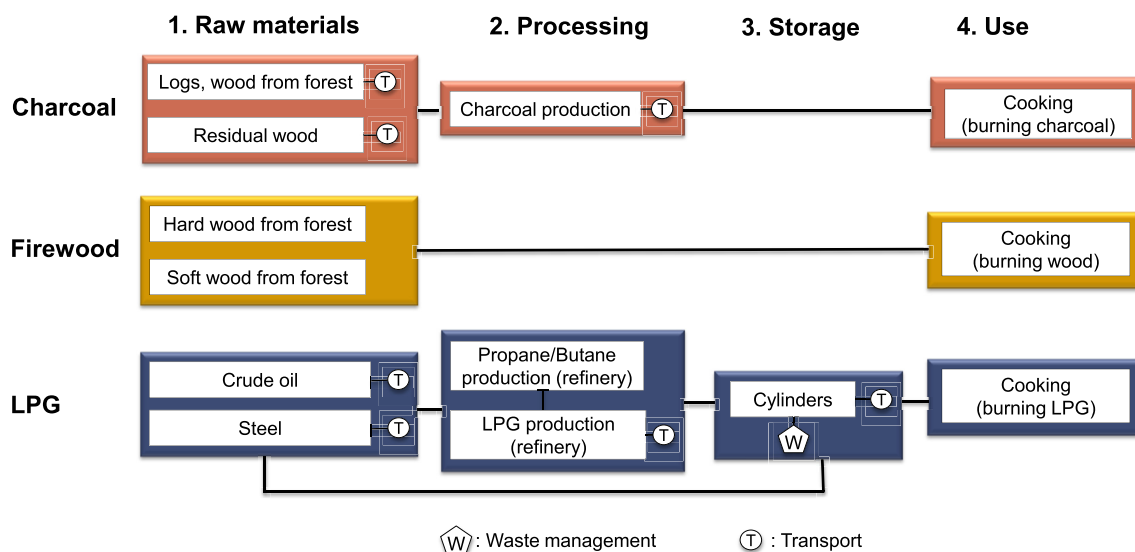


Fig. 3. System boundaries and life cycle stages for LPG, firewood and charcoal.

Table 8
Emissions from combustion of conventional cooking fuels.

Emissions	LPG ^a (g/kg)	Firewood ^b (g/kg)	Charcoal ^b (g/kg)
Carbon dioxide	2721	1548	2385
Carbon monoxide		77	189
Methane	134.1	4.86	5.29
Acetylene		0.97	0.42
Ethylene		1.53	0.44
Ethane		1.5	0.41
Propylene		0.57	–
Methanol		2.26	1.01
Phenol		3.32	–
Furan		0.4	–
Formaldehyde		2.08	0.6
Acetic acid		4.97	2.62
Formic acid		0.22	0.063
Ammonia		0.87	0.79
Nitrogen oxides		1.42	1.41
Nitrous oxide	28.74	35.6 ^a	0.24
PM 2.5		6.64	–
Black carbon		0.83	1
Organic carbon		2.89	1.3

^a EPA (2015). Only the data for CO₂, CH₄ and N₂O have been available.

^b Akagi et al. (2011).

2.3. Impact assessment

GaBi software V6.110 (Thinkstep, 2015) has been used to model the system and environmental impacts have been estimated following the ReCiPe method (Goedkoop et al., 2009). The following environmental impacts are considered: primary energy demand; depletion of fossil fuels and metals; climate change; terrestrial acidification; freshwater and marine eutrophication; human toxicity; freshwater, marine and terrestrial ecotoxicity; ozone layer depletion; and photochemical oxidants formation.

3. Results and discussion

3.1. Environmental impacts of hydrogen

The life cycle environmental impacts of hydrogen for the functional unit “provision of 1 MJ of effective energy for cooking” are summarised in Fig. 4. As can be seen, the main contributors to all the impacts is the solar PV system. The share of the PEM electrolyser and transport is notable for terrestrial acidification; transport also contributes to ozone depletion and the formation of photochemical oxidants (summer smog). These results are discussed in more detail below for each impact in turn.

Primary energy demand: The solar PV system is almost the only

contributor (97%) to the total primary energy demand estimated at 3.6 MJ/MJ H₂. However, only ~14% of the primary energy demand comes from non-renewables sources, mainly used for the extraction and processing of materials used to produce the components of the whole system.

Resource depletion: Fossil fuels depletion is estimated at 10.6 g oil eq./MJ H₂ of which 88.8% is due to the use of natural gas, hard coal and oil to produce PV panels and other electrical components in the whole system. The transport and cylinders add the remaining 6.3% and 3.3%, respectively.

The total depletion of metals is equal to 13.4 g Fe eq./MJ H₂. The electrolyser and storage cylinders have a similar contribution to this impact, with around 14% each. However, the main contributor is again the PV system (71%) due to copper, iron and manganese used for the panels and the electrical components.

Climate change: The production and use of hydrogen generates 40.2 g CO₂ eq./MJ. This is largely (90%) due to CO₂ emissions from the production of PV panels and the associated components. The rest of the impact is related to CO₂ emissions from transport (5.1%), steel and glass fibre production (3.4%) and iridium and platinum extraction (1.5%).

Terrestrial acidification: This impact is estimated at 350.5 mg SO₂ eq./MJ H₂. The majority is again due to the PV system (238.4 mg SO₂ eq./MJ H₂), with the rest being from the electrolyser (64.8 mg SO₂ eq./MJ H₂) and transport (38.3 mg SO₂ eq./MJ H₂). The main environmental burdens causing terrestrial acidification are the emissions of sulphur and nitrogen oxides from the manufacture of PV panels and the electrical components, followed by SO₂ from the extraction of iridium and platinum used in the electrolyser, and SO₂ and NO₂ emissions from long-distance shipping.

Eutrophication: Freshwater eutrophication is estimated at 22.3 mg P eq./MJ H₂, to which the PV system contributes 90%. The electrolyser and storage cylinders add a further ~4.5% each. Phosphate emissions across all the stages are the main contributor to this impact.

Marine eutrophication amounts to 16.5 mg N eq./MJ H₂. This is largely (90%) due to the nitrate emissions to the water and nitrogen oxide emissions to the air related to the PV system.

Human toxicity: Human toxicity is equivalent to 52 g 1,4-dichlorobenzene (DB) eq./MJ H₂. Manganese and zinc, and to a lesser extent, lead and silver, mainly emitted in the life cycle of the PV system, are the main contributors (~76%) to this impact. The next highest contributors are the cylinders (3.8%) and the electrolyser (3.2%) due to the emissions of arsenic, zinc and other toxic elements emitted during the production of their components.

Ecotoxicity: The solar PV system is the cause of the vast majority (94%) of freshwater ecotoxicity, estimated at 3.8 g 1,4-DB eq./MJ H₂. This is largely due to the emissions of zinc in the life cycle of the PV

Table 9
Summary of the scenarios.

Scenario	Description	LPG	Charcoal and firewood ^a	Hydrogen
BAU1	Current conditions with high penetration of LPG	70%	30%	–
SC1	Replacement of 50% of solid fuels	70%	15%	15%
SC2	Full replacement of solid fuels	70%	0%	30%
SC3	As SC2, plus 50% replacement of LPG	35%	0%	65%
SC4	As BAU1, plus 50% replacement of LPG	35%	30%	35%
SC5	Replacement of all conventional fuels	0%	0%	100%
BAU2	Current conditions with low penetration of LPG	30%	70%	–
SC1	Replacement of 50% of solid fuels	30%	35%	35%
SC2	Full replacement of solid fuels	30%	0%	70%
SC3	As SC2, plus 50% replacement of LPG	15%	0%	85%
SC4	As BAU2, plus 50% replacement of LPG	15%	70%	15%
SC5	Replacement of all conventional fuels	0%	0%	100%

^a Equal share of charcoal and firewood.

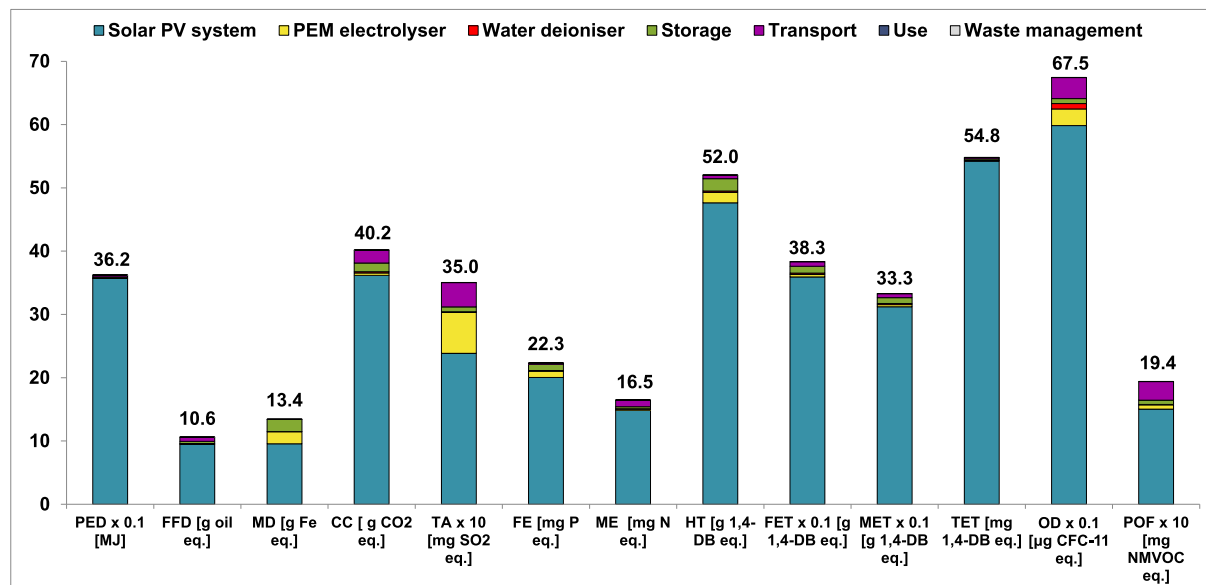


Fig. 4. Life cycle environmental impacts of hydrogen used for cooking. [All impacts are expressed per 1 MJ of effective energy delivered by hydrogen, taking into account stove efficiency. Some impacts have been scaled to fit; to obtain the original values, multiply the value shown on top of the bars with the factor shown against relevant impacts. Acronyms: PED: primary energy demand; FFD: fossil fuel depletion; MD: metal depletion; CC: climate change; TA: terrestrial acidification; FE: freshwater eutrophication; ME: marine eutrophication; HT: human toxicity; FET: freshwater ecotoxicity; MET: marine ecotoxicity; TET: terrestrial ecotoxicity; OD: ozone depletion; POF: photochemical oxidants formation (summer smog). DB: dichlorobenzene. NMVOC: non-methane volatile organic compounds].

system. The rest of the impact is from life cycles of cylinders (2.8%), transport (2%) and the electrolyser (1%).

Marine ecotoxicity is equivalent to 3.3 g 1,4-DB eq./MJ H₂. Zinc, nickel and silver emissions from the PV system contribute 3.1 g 1,4-DB eq./MJ H₂, while the transport, electrolyser and storage cylinders account for the remaining 6% of the impact, again due to zinc and nickel emissions.

Terrestrial ecotoxicity is estimated at 54.8 mg 1,4-DB eq./MJ H₂. This impact is almost entirely due to the PV system (99%), related to silver emitted in the manufacturing of PV cells.

Ozone depletion: As for the others, the majority (88.7%) of this impact, estimated at 6.8 µ CFC-11 eq./MJ H₂, is also due to the PV system. The electrolyser and transport add a further 4% and 5%, respectively, with the rest being from storage and the water deioniser. The main environmental burdens causing this impact are chlorodifluoromethane (R22), dichlorofluoromethane (R12), halon and carbon tetrachloride emitted in these life cycle stages.

Photochemical oxidants formation: This impact, also known as summer smog, amounts to 194.1 mg of non-methane volatile organic compounds (NMVOC) per MJ of hydrogen. Emissions of nitrogen oxides and NMVOC from the extraction, manufacturing and installation of the PV system are the main contributors (66%). Long-distance shipping contributes 15%, mainly due to nitrogen oxides emissions. The PEM electrolyser and storage cylinders add another 3.5% each, due to SO₂ and NO emissions from the extraction of iridium and platinum, and nitrogen oxides and NMVOC from the production of steel and glass fibre, respectively.

3.2. Comparison of results with literature

Although no other studies analysed the environmental impacts of solar-powered PEM electrolyzers or the whole life cycle of the provision of hydrogen for cooking, several studies considered climate change and acidification of other types of solar-powered electrolyzers, as reviewed by Bhandari et al. (2014). These results are compared in Fig. 5 with the findings in this study. Note that the literature data in the figure do not include PEM electrolyzers as no

previous LCA studies of these electrolyzers exist. The system boundary for the comparison is from 'cradle to gate', excluding the use stage (cooking) as the latter was not included in the other studies.

As can be seen from Fig. 5, the findings in this study are within the range of values reported in the literature. The values estimated for climate change vary widely in the literature, ranging from 19.5 to 62.5 g CO₂ eq./MJ H₂. However, the average estimate of 20.8 g CO₂ eq./MJ compares well with 25.6 g estimated in this study. The agreement is even closer for terrestrial acidification: 0.26 vs 0.23 g

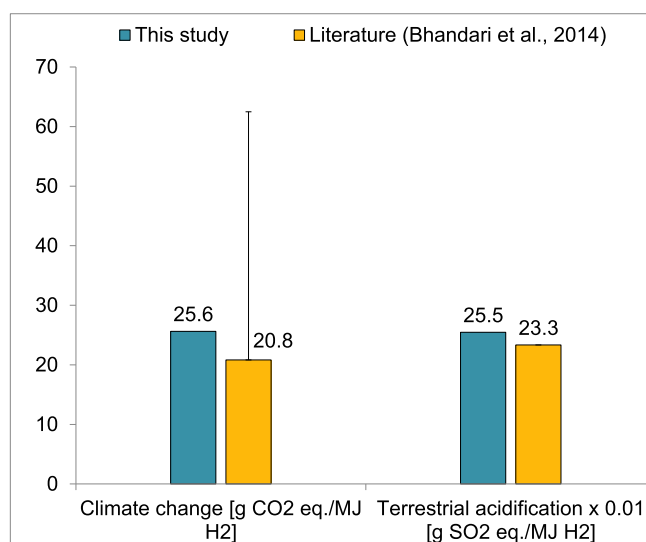


Fig. 5. Comparison with literature of climate change and terrestrial acidification of hydrogen production by solar-powered electrolyser systems. [Impacts are expressed per MJ of hydrogen produced. The literature data are based on the review by Bhandari et al. (2014) of ten different solar-powered electrolyzers used to produce hydrogen, excluding PEM electrolyzers as they were not available in the literature. To obtain the original value for terrestrial acidification, multiply by 0.01].

SO₂ eq./MJ H₂. Most studies report the high contribution of electricity to the environmental impacts, especially climate change, also seen in this study.

3.3. Sensitivity analysis

As discussed in Section 3.1, solar PV is the main contributor to the environmental impacts from the hydrogen system. Since the performance of the solar PV system is influenced by its efficiency and insolation levels, these parameters are varied as part of the sensitivity analysis to investigate their effect on the impacts. Furthermore, the influence of the lifespan of the PV system has been also tested. A further sensitivity analysis considers if recycling instead of landfilling the components of the whole hydrogen system at the end of life affects the overall environmental performance.

3.3.1. Influence of solar PV efficiency

The efficiency of the PV system is varied from 11% to 17% (Energy Sage, 2017) and the results are compared to the base case efficiency of 14.2% in Fig. 6 and Table S4 in the SI. As can be seen, all the impacts are affected by the efficiency, increasing by between 16% (terrestrial acidification) and 22% (terrestrial ecotoxicity) for the lowest efficiency. Increasing the PV efficiency to 17% improves the impacts by 12%–17%. The only exception to these trends is primary energy demand which changes by only 2%–5% within the range of efficiencies considered.

3.3.2. Influence of insolation levels

To explore the influence of this parameter on the impacts, two insolation levels are considered in comparison with the base case: 5 and 6 vs 5.5 kWh/m²/day. The results in Fig. 7 Table S5 indicate that all the impacts are affected but not significantly. For the higher insolation level, the improvements range from 6% to 8% across the impact categories. For the lower solar irradiation, the impacts increase by 6%–9%. Primary energy demand is again an exception, varying only by 1%–2% for both insolation levels.

3.3.3. Influence of the lifespan of the PV modules

The lifespan of 20 years considered in the base case has been

varied from 15 to 25 and 30 years to determine the effect of this parameter on the impacts. Fig. 8 shows that reducing the lifespan to 15 years increases the impacts by 18% (terrestrial acidification) to 25% (terrestrial ecotoxicity). The longest lifespan improves the impacts by 23%–33%. The only exception is primary energy demand, which varies by 6%–7%. For further details on the results, see Table S6 in the SI.

3.3.4. Influence of end-of-life recycling

It was assumed in the base case that all the system components are landfilled at the end of their useful lifetime. Here, we explore how the impacts may change with recycling of steel, aluminium and copper (for assumptions, see Table 5). As shown in Fig. 9 and Table S7 in the SI, all the impacts are reduced with recycling. Depletion of metals, followed by terrestrial acidification and freshwater eutrophication, are influenced most strongly, decreasing respectively by 56%, 28% and 25% on the base case values. The other impacts improve by between 3% (primary energy demand) and 19% (climate change). Hence, recycling of the equipment used in the hydrogen system would improve its environmental sustainability significantly for some impact categories.

3.4. Comparison of hydrogen with conventional fuels

The life cycle environmental impacts of different cooking fuels are compared against hydrogen in Fig. 10. Hydrogen is the best option for four impacts: fossil fuel depletion, climate change, ozone depletion and summer smog (the last, jointly with LPG). The greatest difference is noticed for climate change, which is between 2.5 and 14 times lower than for the other fuels. However, hydrogen is also the worst option for four other environmental impacts – depletion of metals, freshwater eutrophication, freshwater and marine ecotoxicity – which are between 6% and 6.7 times higher than for the conventional fuels.

The remaining impacts show different trends, depending on the fuel type. For instance, hydrogen performs better than charcoal and firewood for nine and eight impacts, respectively. The biggest differences are seen for summer smog formation, which is around 21.5 times lower for hydrogen, terrestrial ecotoxicity which is 13.6-fold better than charcoal and 35 times smaller than that of firewood. It

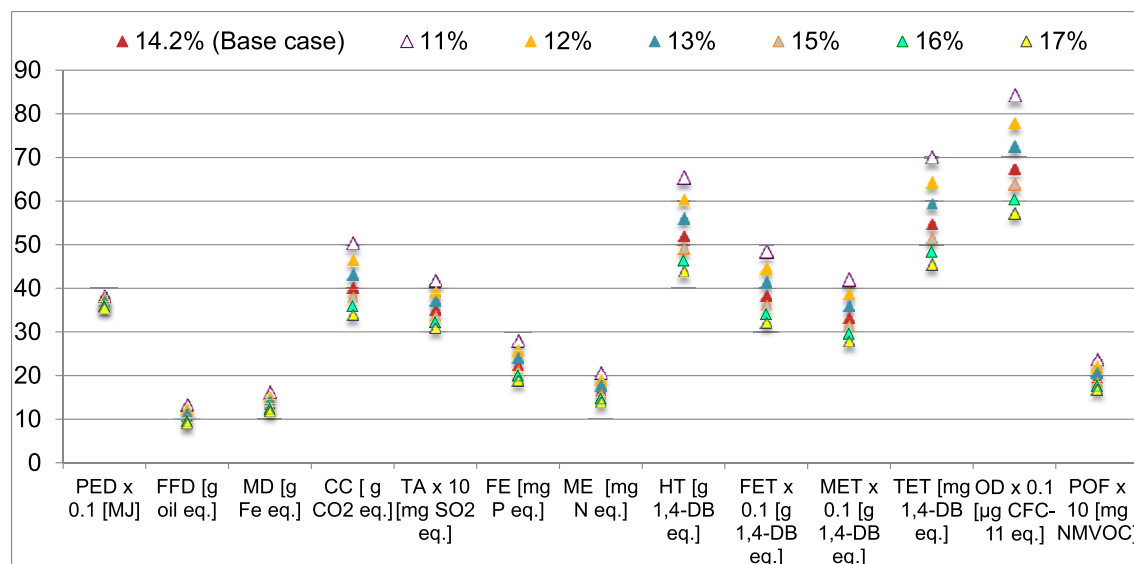


Fig. 6. Sensitivity analysis for different efficiencies of the solar PV system. [All impacts are expressed per 1 MJ of effective energy delivered by hydrogen, taking into account stove efficiency. Some impacts have been scaled to fit; to obtain the original values, multiply with the factor shown against relevant impacts. For the acronyms, see Fig. 4.]

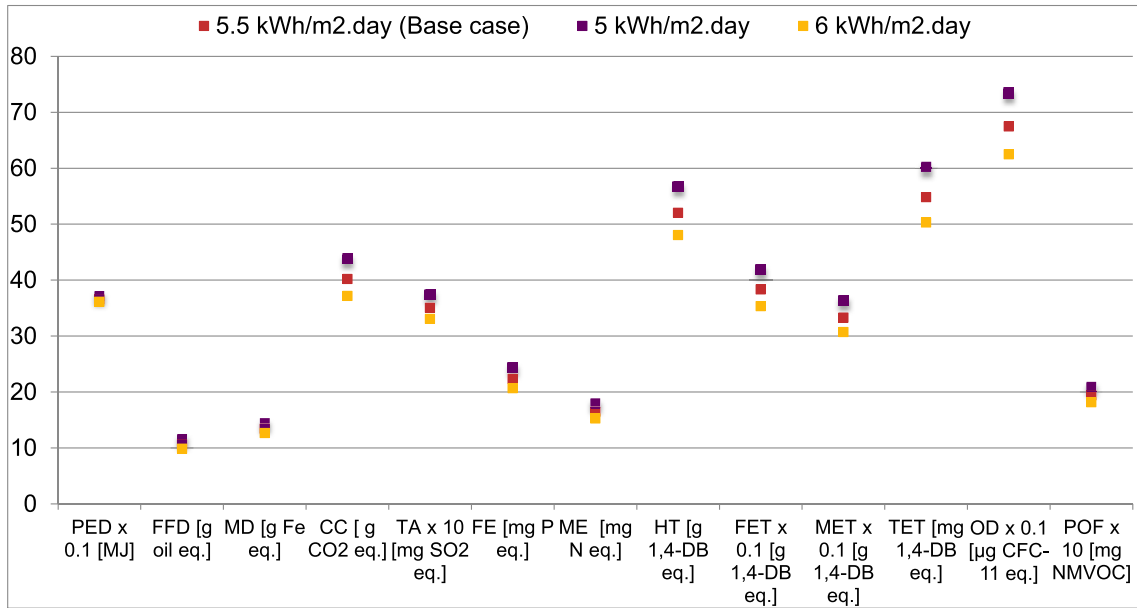


Fig. 7. Sensitivity analysis for different insolation levels. [All impacts are expressed per 1 MJ] of effective energy delivered by hydrogen, taking into account stove efficiency. Some impacts have been scaled to fit; to obtain the original values, multiply with the factor shown against relevant impacts. For the acronyms, see Fig. 4].

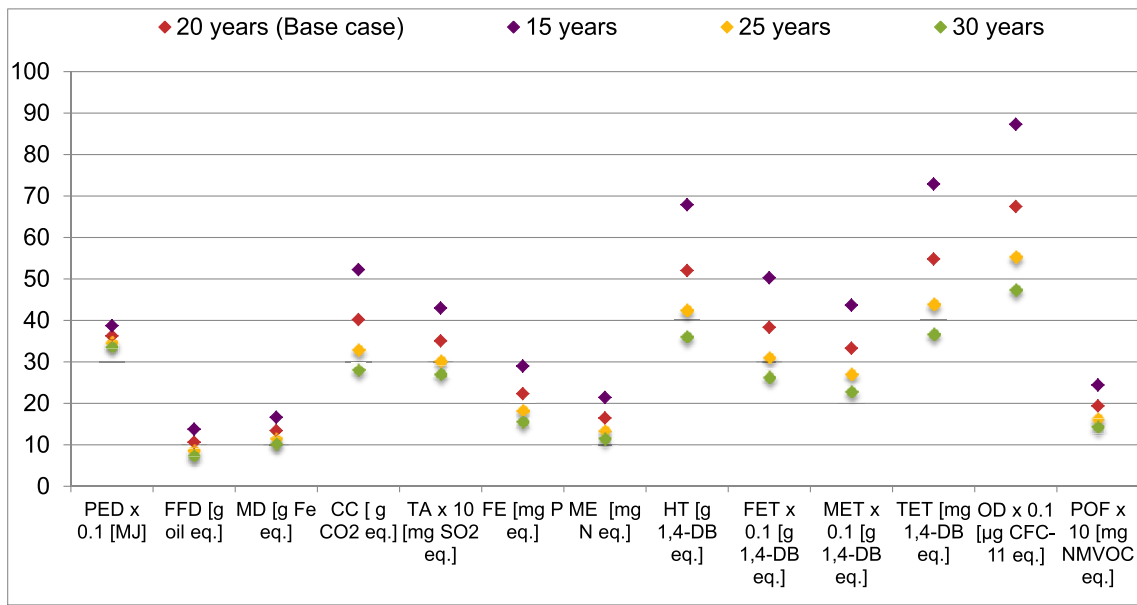


Fig. 8. Sensitivity analysis for a different lifespan of the PV system. [All impacts are expressed per 1 MJ] of effective energy delivered by hydrogen, taking into account stove efficiency. Some impacts have been scaled to fit; to obtain the original values, multiply with the factor shown against relevant impacts. For the acronyms, see Fig. 4].

also depletes 2.7 times less fossil fuel resources than charcoal and half the amount depleted in the life cycle of firewood. Hydrogen also has 8% and 2.4 times lower human toxicity, respectively. In comparison to charcoal, the hydrogen system requires three times less primary energy but, compared to firewood, its energy demand is 3.5 times higher.

Relative to LPG, hydrogen has 4.6 times lower fossil fuel depletion, four times lower ozone depletion and 6% lower potential for summer smog formation. For all the other categories, it is worse than LPG, with impacts being between 36% (terrestrial acidification) and 6.7 times higher (freshwater eutrophication).

Therefore, while hydrogen is by far the best option for climate

change, its environmental performance is worse than that of LPG for most impact categories considered, apart from the three mentioned above. It is also less environmentally sustainable than charcoal and firewood for four and five impacts, respectively.

3.5. Scenario analysis

This section analyses the environmental implications of a potential replacement of conventional cooking fuels with hydrogen, considering different levels of its penetration into the fuel mix. In addition, the health implications related to the emissions of particulates are also discussed. The analysis is based on the total

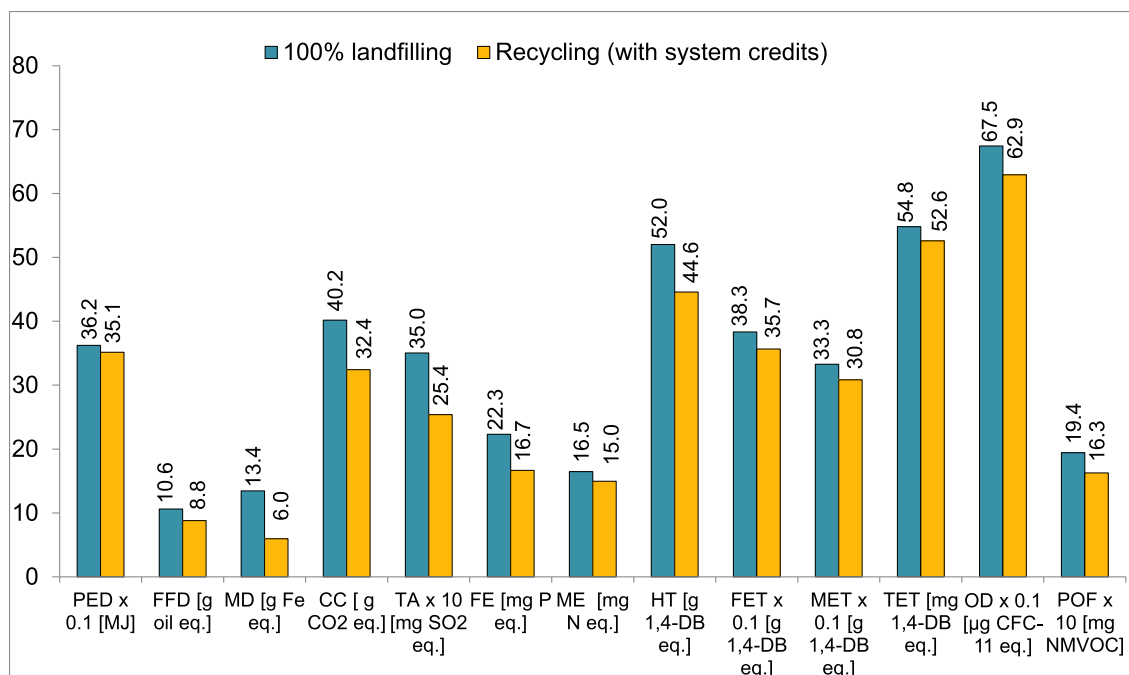


Fig. 9. Sensitivity analysis comparing the impacts of recycling and landfilling. [All impacts are expressed per 1 MJ of effective energy delivered by hydrogen, taking into account stove efficiency. Some impacts have been scaled to fit; to obtain the original values, multiply the value shown on top of the bars with the factor shown against relevant impacts. For the acronyms, see Fig. 4].

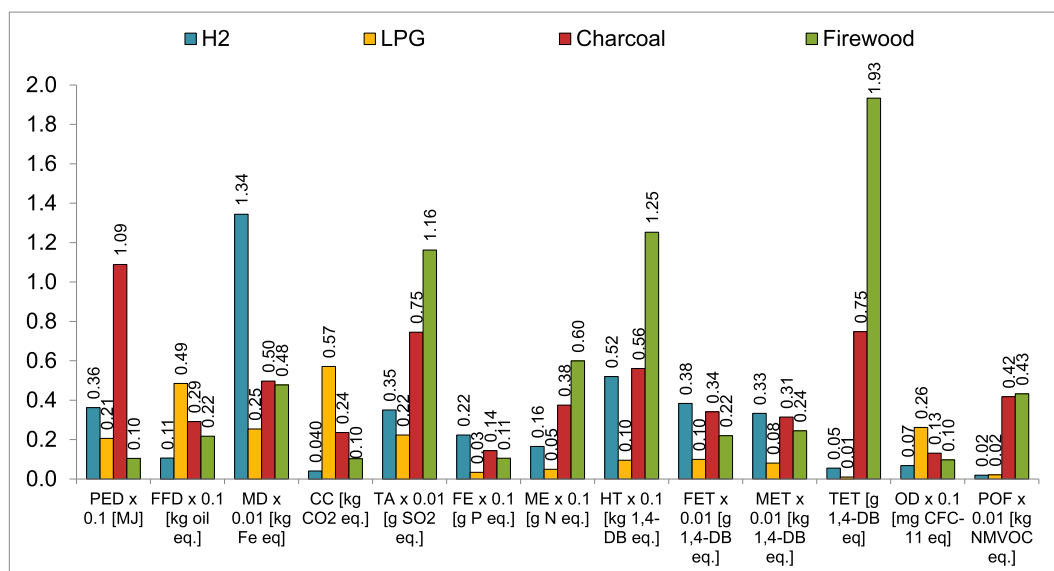


Fig. 10. Comparison of life cycle environmental impacts of hydrogen with conventional cooking fuels (LPG, charcoal and firewood). [All impacts are expressed per 1 MJ of effective energy delivered by fuels, taking into account stove efficiencies. Some impacts have been scaled to fit; to obtain the original values, multiply the values shown on top of the bars with the factor shown against relevant impacts. For the acronyms, see Fig. 4].

effective cooking energy of 1314 GJ used over 20 years by a community comprising 20 households. The impacts are compared to both BAU situations (high and low penetration of LPG) in the next sections.

3.5.1. Business as usual (BAU)

3.5.1.1. BAU 1: high penetration of LPG. As shown in Fig. 11, LPG is the main contributor to seven impacts: depletion of fossil fuels and metals, climate change, eutrophication, freshwater and marine ecotoxicities and depletion of the ozone layer; it also has a notable

contribution to primary energy demand and acidification. Charcoal is the main cause of primary energy consumption and firewood of acidification, human toxicity, terrestrial ecotoxicity and summer smog.

The total primary energy demand over 20 years is estimated at 4.25 TJ. LPG and charcoal share this impact almost equally, with 45% and 51%, respectively. This is due to the use of fossil fuels in their life cycles, and in the case of charcoal, worsened by a low production efficiency. Non-renewable sources account for 55% of the total primary energy demand, with the rest being from renewable

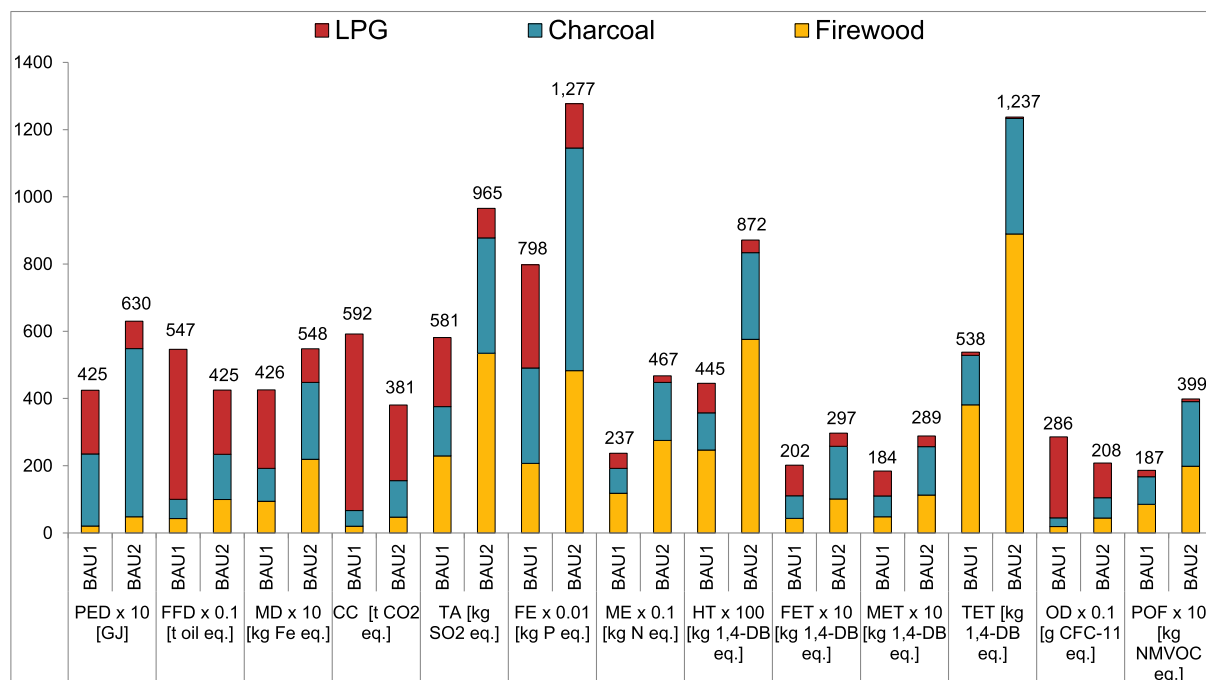


Fig. 11. Life cycle environmental impacts from conventional cooking fuels for business as usual (BAU). [Total impacts for 1314 GJ of effective energy delivered to 20 households for cooking over 20 years. For the definition of BAU, see Section 2.2.3. Some impacts have been scaled to fit; to obtain the original values, multiply the value shown on top of the graph bars with the factor shown against relevant impacts. For the acronyms, see Fig. 4.].

sources, mainly biomass.

Unsurprisingly, LPG is almost entirely responsible for the depletion of fossil fuels, contributing 82% to the total of 54.7 t oil eq. It also depletes 55% of metals, which is estimated at 4.3 t Fe eq. This is mainly due to the consumption of iron, manganese, nickel and chromium in the life cycle of steel used for the cylinders and for the construction of LPG refinery. Iron and copper used in the charcoal and firewood life cycles (production of machinery and transportation vehicles) add the remaining 45%.

The climate change impact, estimated at 592 t CO₂ eq., is also largely from LPG (89%). Emissions of CO₂, N₂O from its combustion and leakage of CH₄ across the LPG life cycle are the main contributors (~90%), followed by CH₄ emissions from charcoal production and wood combustion (5.6%), with the rest being due to CO₂ emissions from charcoal production and wood transportation (4.6%).

Terrestrial acidification has an almost equal contribution from LPG and firewood, with each causing ~40% of the total of 581 kg SO₂ eq. This is due to the emissions of SO₂ from the processing of petroleum used in the production of LPG and from ammonia from burning the firewood. The remaining 25% is from charcoal, owing to ammonia emissions during its use. Moreover, emissions of nitrogen oxides from the life cycle of crude oil and from burning charcoal and wood also contribute to this impact.

LPG is also the main contributor to freshwater eutrophication, causing 39% of the total of 7.98 kg P eq. This is due to phosphate emissions during the processing of petroleum and LPG. Charcoal contributes a further 36% and firewood the remaining 25%, also because of phosphate emissions in their respective life cycles, mainly from charcoal processing and both charcoal and firewood transport.

For marine eutrophication, estimated at 23.7 kg N eq., the main contributor is firewood (50%), followed by charcoal (31%) and LPG (19%). Emissions of nitrogen oxides are the main contributors, coming from the petroleum's life cycle in the case of LPG and from

combustion of all three fuels during cooking.

Firewood is also the greatest contributor to human toxicity, causing half of the estimated 44.5 t 1,4-DB eq. The main sources are emissions to air of formaldehyde and furan from wood burning and leakage of chlorine to soil related to maintenance of roads used for firewood transport. LPG and charcoal contribute the remaining half of the impact. The former is due to arsenic and zinc emissions from the life cycle of petroleum, while the latter is related to formaldehyde emissions to air and manganese emissions to waterways from burning the charcoal as well as soil emissions of chlorine related to transport.

Freshwater and marine ecotoxicity are estimated at 2 and 1.8 t 1,4-DB eq., respectively. The main contributors to both are LPG (40%–45%) and charcoal (~33%). This is mainly due to the emissions of zinc to water (85%) from the life cycles of petroleum used for LPG and electricity used for the production of charcoal. Firewood adds the remaining (22%–26%), mainly due to its transport.

Firewood is the main cause of terrestrial ecotoxicity, contributing 72% to the total of 538 kg 1,4-DB eq., largely due to the emissions of chlorine in the life cycle of transportation. Charcoal adds a further 27%, also due to the chlorine emissions from transport. LPG accounts for just 2%, mainly because of phosphorus emissions from the life cycle of petroleum.

Ozone depletion is equivalent to 28.6 g CFC-11 eq. and is related mainly to halon emissions. Halon is used as a fire retardant in the life cycle of LPG, which dominates this impact with a contribution of 84%. Halon emissions associated with the use of oil-derived products in the machinery and transport contribute 9% to the impact from charcoal and 7% from firewood.

Almost half (46%) of the 1.9 t NMVOC eq. of photochemical oxidants are due to firewood, followed closely by charcoal (44%). Emissions of carbon monoxide and ethylene from fuel combustion are the main cause of this impact (~50%). Nitrogen oxides and formaldehyde are also important contributors (~22%). LPG adds only 9%, mainly from nitrogen oxides and NMVOC emissions in the

life cycle of petroleum; LPG combustion also generates methane emissions, which increase its contribution to this impact by 2%.

However, it is important to note that some impacts from LPG, including human toxicity, ecotoxicities and summer smog, may be underestimated due to a lack of data: as shown in Table 8, only GHG emissions have been available for LPG while the data for the solid fuels are much more extensive.

3.5.1.2. BAU2: low penetration of LPG. Fig. 12 also shows the environmental impacts of the BAU2 scenario which assumes low penetration of LPG into the fuel mix. As could be expected, in this scenario solid fuels are the main contributors to 10 out of the 13 impacts. Charcoal uses the majority of the primary energy (79%), estimated at 6.3 TJ. It also causes over a half of freshwater eutrophication as well as freshwater and marine ecotoxicities; firewood contributes over a third to these impacts.

Firewood is the main source of human toxicity (55%) and terrestrial ecotoxicity (71%), which are estimated at 87.2 and 1.3 t 1,4-DB eq., respectively. Charcoal is the second largest contributor, adding over 30%. A similar trend is found for terrestrial acidification and marine eutrophication, with firewood being responsible for nearly a half and charcoal for a third of these impacts.

Photochemical oxidants and metal depletion are equivalent to 4 kg NMVOC eq. and 5.5 t Fe eq., respectively. Both impacts are contributed equally by charcoal and firewood, which are together responsible for over 80% of the impacts. Finally, as expected, LPG is the main cause of fossil fuel depletion (45%), climate change (59%) and ozone depletion (50%). The charcoal adds around a third with the rest being attributed to firewood.

The burdens contributing to the different impacts are the same as discussed in the BAU1 section and are hence not considered further in this section.

The results in Fig. 12 also indicate that the scenario with a high LPG share (BAU1) has 22% to 2.3 times lower impacts than BAU2 for most categories. The only exceptions are fossil fuel depletion, climate change and ozone layer depletion, which are 22%–36% higher for BAU1.

3.5.2. Different penetration of hydrogen into the fuel mix

The environmental implications of replacing conventional cooking fuels with hydrogen, assuming its different penetration into the fuel mix (scenarios SC1–SC5), are discussed first in comparison with BAU1, followed by BAU2. For the definitions of hydrogen-related scenarios, see Section 2.2.3.

3.5.2.1. BAU 1: high penetration of LPG. As can be seen in Fig. 12 and Table 10, some impacts are reduced relative to the BAU1 scenario and others are higher across the different scenarios. The only impacts that reduce in all the hydrogen scenarios are fossil fuel depletion, climate change, ozone depletion and formation of photochemical oxidants. For climate change, the best option would be the full replacement of the conventional fuels with hydrogen (SC5) which would reduce this impact by 11 times. The next best option is SC3, with a 50% replacement of LPG and a 100% substitution of solid fuels, reducing contribution to climate change by two times. The lowest improvement in this impact (4%) would be achieved if half of the solid fuels were replaced with hydrogen, keeping the LPG at the current level (SC1).

The other three impacts mentioned above follow a similar trend. The best scenario is SC5, which reduces these impacts between 3.2 (ozone depletion) and 7.3 times (photochemical oxidants). High reductions are also seen for the scenarios with a high replacement of LPG, namely SC3 and SC4, with the exception of photochemical oxidants, for which SC4 is similar to BAU1. SC1 and SC2 exhibit the lowest improvements in fossil fuel depletion and ozone depletion, mainly due to their high share of LPG.

The relative change for the rest of the impacts varies depending on the scenario. For example, terrestrial acidification, marine eutrophication and terrestrial ecotoxicity would be reduced for all the scenarios but SC4, with the reductions ranging respectively between 20% and 41%, 9%–2.2 times and 47%–17.5 times. This is due to the reductions in sulphur dioxide and nitrogen oxides emissions. However, for SC4 (50% replacement of LPG, keeping the current share of solid fuels), these impacts would increase by 4% for terrestrial ecotoxicity to 18% for marine eutrophication relative to BAU1. Furthermore, replacing solid fuels (SC1 and SC2) would

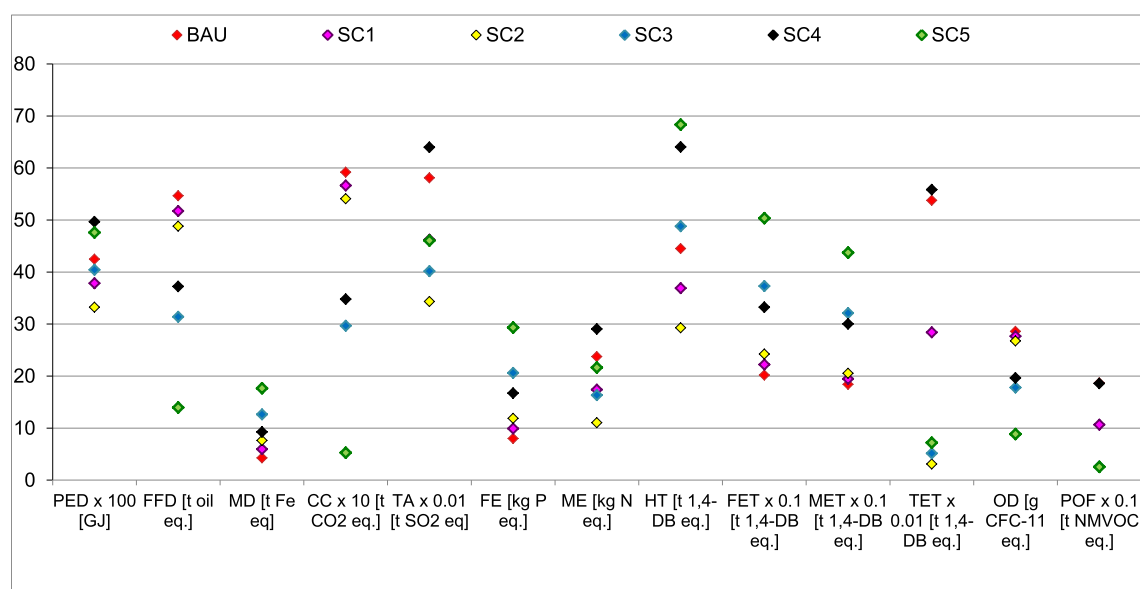


Fig. 12. Life cycle environmental impacts for different levels of hydrogen penetration into the fuel mix compared to business as usual with high penetration of LPG (BAU1). [Total impacts for 1314 GJ of effective energy delivered to 20 households for cooking over 20 years, taking into account stove efficiencies. For the definition of scenarios, see Section 2.2.3. Some impacts have been scaled to fit; to obtain the original values, multiply the values shown on top of the bars with the factor shown against relevant impacts. For the acronyms, see Fig. 4.]

Table 10
Comparison with BAU1 of the environmental impacts of different scenarios for hydrogen penetration into the fuel mix ^a.

Impacts	SC1	SC2	SC3	SC4	SC5
Primary energy demand	-11%	-22%	-5%	14%	11%
Fossil fuel depletion	-5%	-11%	-43%	-32%	-3.9%
Depletion of metals	28%	44%	3x	2.2x	4.2x
Climate change	-4%	-9%	-2x	-2x	-11x
Terrestrial acidification	-20%	-41%	-31%	9%	-21%
Freshwater eutrophication	20%	33%	2.6x	2.1x	3.7x
Marine eutrophication	-27%	-2.2x	-31%	18%	-9%
Human toxicity	-17%	-34%	9%	31%	35%
Freshwater ecotoxicity	9%	17%	1.8x	39%	2.5x
Marine ecotoxicity	5%	10%	43%	39%	2.4x
Terrestrial ecotoxicity	-47%	-17.5x	-10.5x	4%	-7.5x
Ozone depletion	-3%	-6%	-38%	-31%	-3.2x
Photochemical oxidants	-43%	-7x	-7x	-0.3%	-7.3x

^a The negative values mean that the scenarios evaluated have lower impacts than BAU1. The "x" against some values indicates how many times those impacts are lower (-ve values) or higher (+ve values) than for BAU1. The bold font denotes that the impacts for the scenarios considered are higher than for BAU1.

decrease human toxicity by 17%–34%. However, the replacement of LPG (SC3–SC5) would increase this impact by 9%–35%, respectively.

The remaining four impacts – depletion of metals, freshwater eutrophication and freshwater and marine ecotoxicities – would increase on the BAU1 values across the scenarios considered (Fig. 12 and Table 10). The largest increments are found for depletion of metals, going up by 44% (SC2) to 4.2 times (SC5). The increases in the other three impacts are also significant, ranging from 5% to 3.7 times.

Overall, SC4 is the worst option, which worsens nine out of the 13 impacts considered on the BAU1 values; this is largely because no solid fuels are replaced by hydrogen. The next worst alternative is SC5, where all the conventional fuels are replaced by hydrogen, which increases six impacts. The best scenarios are those that replace 50%–100% of solid fuels, which reduce between nine (SC1 and SC2) and eight (SC3) impacts on the BAU1 values.

3.5.2.2. BAU2: low penetration of LPG. As seen in Fig. 13 and Table 11, the comparison of the BAU2 (low penetration of LPG) with the hydrogen scenarios exhibits a similar trend as seen in the BAU1 analysis. Only four impacts – fossil fuel depletion, climate change, ozone depletion and photochemical oxidant formation – decrease across all the scenarios proposed. The greatest reductions are found for the formation of photochemical oxidants, with over 15 times lower impact relative to BAU2 in scenarios SC2–SC5. When all conventional fuels are replaced with hydrogen (SC5), the climate change impact is reduced by 7.2 times on the BAU2 levels while fossil fuel depletion and ozone depletion are three and 2.4 times lower, respectively. Overall, for these four impacts, the highest improvements are seen in SC5, followed by SC3.

The opposite picture can be observed for metal depletion, freshwater eutrophication and marine and freshwater ecotoxicities. For these four impacts, none of the hydrogen scenarios would help to improve the environmental impacts. For instance, the high penetration of hydrogen (SC3 and SC5) increases depletion of metals and freshwater eutrophication by up to 3.2 and 2.3 times, respectively. A similar effect is noticed for freshwater and marine ecotoxicities, which increase by up to 1.7 and 1.5 times.

The remaining five impacts (primary energy demand, terrestrial acidification, marine eutrophication, human toxicity and terrestrial ecotoxicity) improve in all the scenarios. The only exception is SC4, for which they are higher on average by 4%. The main reason for the increase is that LPG performs better for these impacts than hydrogen, meaning that hydrogen would improve these impacts

only when replacing solid fuels. The other scenarios, especially the ones with lower or non-solid fuels, such as SC2 and SC3, improve these impacts by up to 22.8 times (terrestrial ecotoxicity).

3.5.3. Local health and environmental impacts

The following impacts are generated at the point of use of conventional fuels and can affect the local environment and the health of local population: terrestrial acidification, marine eutrophication, human toxicity, terrestrial ecotoxicity and photochemical oxidants formation (summer smog). In addition, the combustion of charcoal and firewood emits particulates which can have serious health effects; these have been estimated here in terms of DALYs (the disability-adjusted life year), following the ReCiPe endpoint method (Goedkoop et al., 2009). These impacts are compared in Fig. 14 for the conventional fuels and hydrogen. Climate change is also included due to the local air emissions of GHG from LPG. To put the local (direct) impacts into perspective, the (indirect) impacts generated in the rest of the life cycle are also shown. The other impacts discussed in the previous sections are not affected by the use stage for any of the fuels and are hence not considered here. The discussion is based on the functional unit defined as "provision of 1 MJ of effective energy for cooking".

As can be seen in Fig. 14, charcoal and firewood are the only fuels for which the use stage contributes to all the impact categories while the use of LPG affects only climate change and summer smog. Firewood has the highest emissions of particulates and the related impact on health (6×10^{-7} DALYs/MJ), 7.6 times higher than charcoal on a life cycle basis and 29 times greater in terms of local emissions. Assuming a replacement in BAU2 of all solid fuels by hydrogen (SC5) and the annual energy demand by 20 households considered in this study (1324 GJ/yr), a total of 0.75 DALYs/yr would be avoided locally and 0.86 on a life cycle basis. Thus, switching to hydrogen would lead to significant health benefits as the emissions of particulates would be eliminated.

Using hydrogen would also eliminate GHG emissions locally, with a particular benefit if it were to replace LPG. The overall life cycle emissions would also be reduced significantly, as discussed earlier. There would also be substantial benefits in replacing charcoal and firewood by hydrogen in terms of terrestrial acidification. This impact generated locally by the combustion of firewood is 2.5 times higher than the total life cycle impact from hydrogen; for charcoal, the local impact is equivalent to the whole life cycle impact of hydrogen. A similar trend is found for marine eutrophication.

Replacing firewood with hydrogen would reduce local human toxicity significantly while also reducing the impact slightly elsewhere in the supply chain. The benefit of replacing charcoal would be small as its local impact is low; the life cycle impacts of these two fuels are also quite similar.

Local terrestrial ecotoxicity of both charcoal and firewood is relatively low compared to the rest of the life cycle (3% and 6%, respectively), hence the local benefit of using hydrogen would be limited. However, the savings on the life cycle basis would be very significant (13 and 35 times, respectively). Finally, replacing the two solid fuels by hydrogen would benefit the local environment substantially with respect to the reduced summer smog formation, while also reducing the impact in the rest of the life cycle (Fig. 14).

Nevertheless, LPG is still a better option than hydrogen, both locally and on a life cycle basis for all the impacts bar the particulate matter formation and climate change. However, as mentioned earlier, it should be borne in mind that the emissions data for LPG combustion are incomplete and hence its impacts may be underestimated.

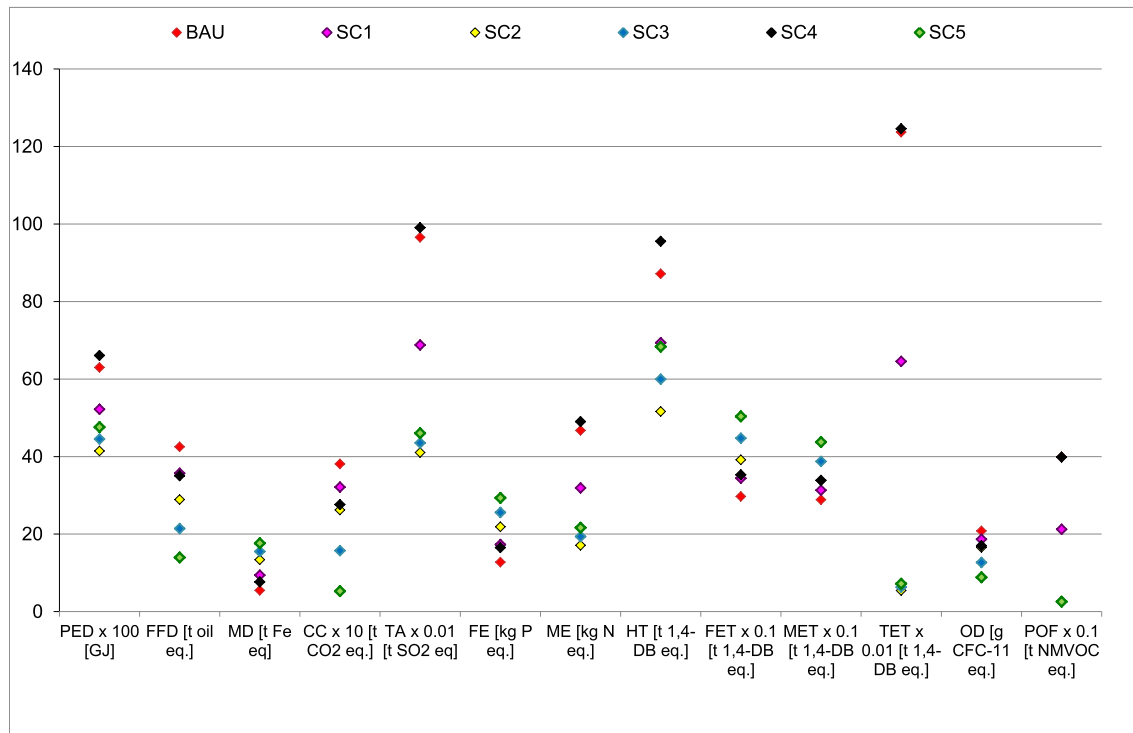


Fig. 13. Life cycle environmental impacts for different levels of hydrogen penetration into the fuel mix compared to business as usual with low penetration for LPG (BAU2). [Total impacts for 1314 GJ of effective energy delivered to 20 households for cooking over 20 years, taking into account stove efficiencies. For the definition of scenarios, see Section 2.2.3. Some impacts have been scaled to fit; to obtain the original values, multiply the values shown on top of the bars with the factor shown against relevant impacts. For the acronyms, see Fig. 4.].

Table 11

Comparison with BAU2 of the environmental impacts of different scenarios for hydrogen penetration into the fuel mix ^a.

Impacts	SC1	SC2	SC3	SC4	SC5
Primary energy demand	-17%	-34%	-29%	5%	-24%
Fossil fuel depletion	-16%	-32%	-2.0x	-18%	-3.1x
Depletion of metals	1.7x	2.4x	2.8x	28%	3.2x
Climate change	-16%	-31%	-2.4x	-27%	-7.2x
Terrestrial acidification	-29%	-2.4x	-2.2x	3%	-2.1x
Freshwater eutrophication	26%	1.7x	2.0	23%	2.3x
Marine eutrophication	-32%	-2.7x	-2.4x	5%	-2.2x
Human toxicity	-20%	-41%	-31%	9%	-22%
Freshwater ecotoxicity	14%	24%	34%	16%	1.7x
Marine ecotoxicity	8%	15%	26%	15%	1.5x
Terrestrial ecotoxicity	-1.9x	-22.8x	-19.6x	1%	-17.2x
Ozone depletion	-10%	-21%	-39%	-18%	-2.4x
Photochemical oxidants	-1.9x	-15.3x	-15.5x	-0.1%	-15.6x

^a The negative values mean that the scenarios evaluated have lower impacts than BAU2. The "x" against some values indicates how many times those impacts are lower (-ve values) or higher (+ve values) than for BAU2. The bold font denotes that the impacts for the scenarios considered are higher than for BAU2.

4. Conclusions

This study has evaluated the life cycle environmental impacts of hydrogen produced by a solar-powered PEM electrolyser and used as a cooking fuel. Its impacts have been compared with the conventional cooking fuels used in developing countries: LPG, charcoal and firewood.

The results show that the main contributor to all the impacts from the hydrogen system is the solar PV system. The share of the PEM electrolyser and transport is notable for terrestrial acidification; transport also contributes to ozone depletion and the formation of photochemical oxidants (summer smog). The impacts

would be reduced significantly by recycling the end-of-life system components and improving the efficiency of solar panels. The insolation levels considered here have no significant effect on the impacts.

In comparison with the conventional fuels, hydrogen is the best option for four impacts: fossil fuel depletion, climate change, ozone depletion and summer smog (the last, jointly with LPG). The greatest difference is noticed for climate change which is between 2.5 and 14 times lower than for the other fuels. However, hydrogen is also the worst option for four other environmental impacts – depletion of metals, freshwater eutrophication, freshwater and marine ecotoxicity – which are between 6% and 6.7 times higher than for the conventional fuels.

The results of the scenario analysis for different penetration of hydrogen into the cooking fuels mix, considering both low and high penetration of LPG, show that only four impacts are improved across the scenarios: fossil fuel depletion, climate change, ozone depletion and summer smog. Thus, if these, and in particular climate change, are deemed a priority, then replacing conventional cooking fuels by hydrogen is warranted. However, climate change would be mitigated at the expense of four other impacts – depletion of metals, freshwater eutrophication, freshwater and marine ecotoxicity.

Switching to hydrogen would also help to reduce local health and environmental impacts as it generates no pollution at the point of use. The greatest benefits would be achieved by replacing firewood with hydrogen; this could also help to avoid deforestation and related impacts on forest ecosystems. However, LPG is still environmentally a better option than hydrogen, both at the point of use and on a life cycle basis, for most of the impacts. The exceptions to this are the emissions of particulates and related health impacts,

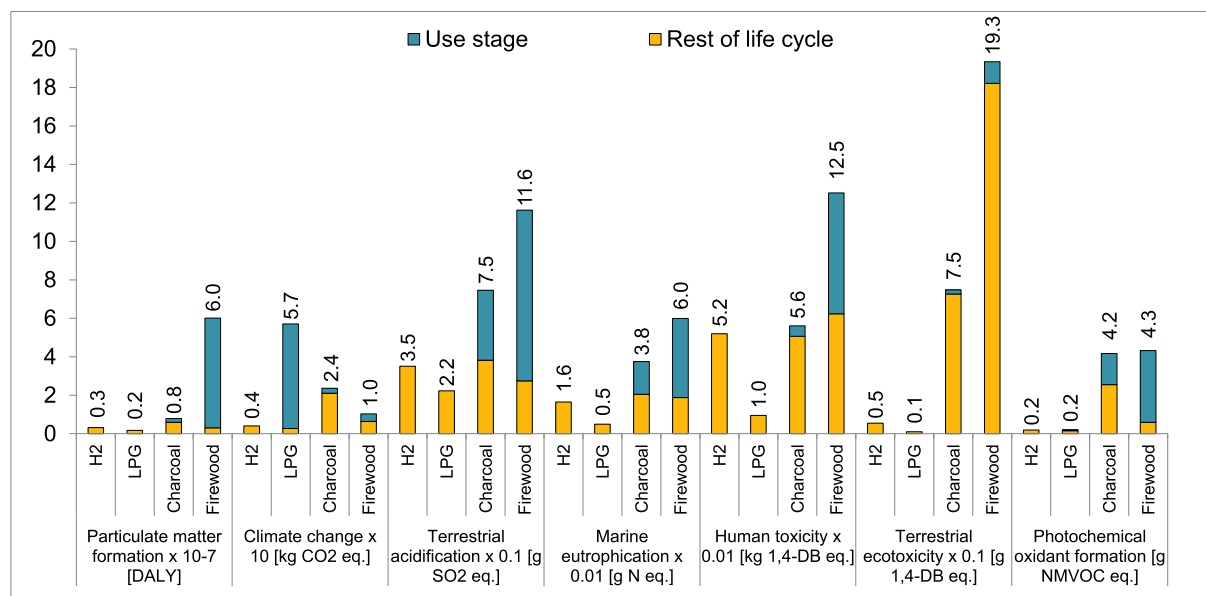


Fig. 14. Contribution of the use stage to the environmental impacts of different fuels. [All impacts are expressed per 1 MJ of effective energy delivered by fuels, taking into account stove efficiencies. Only impacts affected by use stage are shown. Some impacts have been scaled to fit; to obtain the original values, multiply the values shown on top of the bars with the factor shown against relevant impacts. For the acronyms, see Fig. 4.]

depletion of fossil fuels and ozone layer as well as climate change, for which hydrogen is the preferred alternative.

While hydrogen offers both environmental and health benefits over solid cooking fuels, its deployment in developing countries may be difficult due to costs, complexity of the technology, lack of skilled labour, safety and consumer acceptance. It is recommended that these issues be explored as part of future research.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at <https://doi.org/10.1016/j.jclepro.2018.06.033>.

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