

Review study on the Hydrogen Transition and Cooking

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March 2023

'This material has been funded by UKaid from the UK government and is implemented by the Department of International Development; however, the views expressed do not necessarily reflect the UK government's official policies.'

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1. Introduction

Globally, there are still about 2.4 billion people without access to clean cooking (IEA et al., 2022). This report looks at the state and future cost of cooking with green hydrogen based on a modified Liquefied petroleum gas (LPG) stove design (Mukelabai et al., 2022; E. Topriska et al., 2016). It is discussed if and when the green hydrogen transition could play a role in clean cooking in India, Morocco, and South Africa based on an analysis of the ecosystems and cost.

Green hydrogen means the production of hydrogen from electricity generated with renewables. In general, one can discern two low-carbon pathways for generating hydrogen: abated fossil fuels (such as blue or turquoise hydrogen) or electrolysis (such as renewable or green hydrogen) (IRENA & RMI, 2023). Green hydrogen is a lower carbon alternative rather than a no-carbon solution. There are two reasons why this is the case. When hydrogen is lost to the atmosphere, methane is generated which is a potent greenhouse gas (GHG) (Bertagni et al., 2022). A second reason is that in a strict sense one would also need to account for emissions embodied in the manufacturing processes of making the solar panels, electrolyzers and other equipment.

The report investigates the potential for green hydrogen to reduce or compete on cost with current cooking fuels such as LPG or electricity in the near future. Currently, LPGs such as Butane are already widely used in Morocco and India, while they play a secondary role in South Africa as backup to the weak power grid. While LPG offers a wide array of benefits in comparison to solid fuels (i.e., firewood, coal) recent studies have shown that it still significantly adds to indoor pollution leading to increases of respiratory diseases (i.e., Asthma) (Gruenwald et al., 2022). This report concludes that green hydrogen has the potential to replace dirty and unhealthy cooking practices or allow to leapfrog towards clean cooking. A future success of green hydrogen depends on innovations in stove design, availability of cheap green hydrogen both on and off the grid, and its safe application in households.

The study looks at policy discussions and hydrogen projects in the Maghreb, Southern African Development Community (SADC), and South Asia to understand the potential of scaling green hydrogen production. In addition, the spatiality of cost for electric cooking and LPG in comparison with green hydrogen based on an LPG stove-design is assessed for South Africa, Morocco, and India. Furthermore, the technological readiness and the lifecycle of hydrogen stoves and financing options in establishing green hydrogen production as part of off-grid solar home and mini-grid development are discussed.

The current energy crisis triggered by the Russian invasion of Ukraine has led to a geopolitical shift in energy security and the politics of carbon both for the Global North and South. In this context green hydrogen is seen as a strong contender for decreasing dependence on liquified natural gas (LNG), both for industrial (i.e., green steel and chemicals) and residential applications (heating and cooking). On the one hand, the European Union (EU) and its member states are leading efforts in building new energy partnerships between the Global North and South to access cheap and dependable green hydrogen. Developing countries on the other hand could profit from this shift in demand towards green hydrogen both, in their domestic economy and through revenues from exports. It is particularly heavy European industries that are supporting the establishment of partnerships with countries such as Morocco, South Africa, and to some extent India. Such North-South partnerships typically promote the establishment of on-grid demonstration facilities for green hydrogen production in partner countries and the installation of required renewable energy (Lindner, 2022).

In the context of the residential sector, blending imported green hydrogen with natural gas is already a practice in the EU and UK. Today, the permitted concentration of hydrogen in the gas grid across EU

countries ranges from 0.1 Vol.% to 14 Vol.%. However, injections above 15% would require additional investments to adapt the infrastructure, including monitoring and maintenance measures, and upgrading due to the lower durability of materials when exposed to hydrogen. In addition, there are so far no European standards setting a common admissible concentration of hydrogen in the natural gas network. (Quintero et al., 2022, p. 127)

As the global demand for green hydrogen is rising, it becomes an opportunity for countries that can manufacture and export green hydrogen at scale. Morocco is in a good position to benefit from the decarbonization efforts in Europe due to its proximity to the EU, relative political stability, and high potential for renewable energy – both solar and wind (Nuñez-Jimenez & De Blasio, 2022a). For these reasons, the country did conclude bilateral partnerships with Portugal and Germany to advance its green hydrogen sector (Lindner, 2022).

India and South Africa are also likely partners for the EU and UK as they are seeking to build green hydrogen export industries. In the case of South Africa, green hydrogen could help to decarbonize the heavily coal-reliant power grid based on the Just Energy Transition Partnership (JETP) between South Africa and the EU and UK.¹ Similar to South Africa, India is seeking to champion renewable energy and green hydrogen production in order to decrease reliance on coal imports. In difference to the other two cases, India has launched internal initiatives through the national green hydrogen mission and concluded several partnerships with European countries to develop green hydrogen projects (Lindner, 2022). The goal of India's hydrogen mission is to build capacities to produce at least 5 Million Metric Tons (MMT) of Green Hydrogen per annum by 2030 (Government of India, 2023).

The projected declining cost for green hydrogen production in Africa and India by 2030 could make it an alternative for cleaner and safer cooking. Recent review studies show that there is increasing attention for the green hydrogen transition and its potential application to cooking (Kozhukhova et al., 2021; Mukelabai et al., 2022). Earlier studies argued that there is a potential in sub-Saharan Africa for reducing the cost of hydrogen to USD 1.4-2.0/kg by 2030 depending on declining solar module and electrolyzer costs (IEA, 2022). Also, the Indian green hydrogen mission has defined a goal of USD 1/kg by the mid-2030s (Government of India, 2023). Green hydrogen might possibly help to solve current health considerations related to emissions from LPGs (Nix et al., 2022).

A first option to benefit from green hydrogen in cooking is blending hydrogen into gas pipelines. In general, blending hydrogen with piped natural gas (PNG) is not new. Until the 1960s, the UK used 'town gas' – a blend of 50% hydrogen with methane and carbon monoxide – which was then replaced with 100% methane.² Similar to the UK, blended hydrogen could become a relevant alternative for domestic cooking and heating applications in the Global South. However, opinions differ on the cost for adapting existing gas networks to cope with such a new blend of green hydrogen and PNG. So far, a few studies have evaluated the feasibility of blending between up to 20% and 50% of hydrogen into piped gas networks in India and South Africa (Government of India, 2021; Kozhukhova et al., 2021; Mukelabai et al., 2022).

A second option is to introduce blended or pure green hydrogen in cylinders similar to LPG for cooking. As discussed in chapter 2 and 4, hydrogen is stored in pressurized cylinders that are sold to the end-user to be connected to a hydrogen stove. The advantage of bottled green hydrogen is that it is relatively easy to

¹ https://ec.europa.eu/commission/presscorner/detail/cs/ip_21_5768

² <https://www.hy4heat.info/general>

transport and the required stove and equipment in the household are comparable to already available LPG. In comparison with LPG, bottled hydrogen could have benefits in terms of reducing household pollution and GHG emissions. However, there are several disadvantages to utilizing green hydrogen in the household such as the need for training in the safe use of green hydrogen discussed below or the need to sufficiently pressurize cylinders.

A third option is to use hydrogen through fuel cells for the later generation of electricity for cooking. In this context solid state storage of hydrogen bound in non-pyrophoric formulated storage material could be a viable option.³ The advantages lie in a longer-term storage solution and the reduced need to pressurize cylinders. A potential disadvantage is the energy loss from converting electricity to hydrogen and back to electricity that requires further research and innovation (Schöne et al., 2022).

Green hydrogen presents an opportunity to complement the use of LPG and electricity via blending or using green hydrogen where LPG is not available for cooking. Electricity was found to be the cheapest option for cooking when using an induction stove and electric pressure cooker (EPC). Calculations for cooking with hydrogen are comparable with LPG which is common in India, Morocco and to an increasing extent South Africa.

In all three country cases electricity for cooking faces challenges such as blackouts, cost of grid connections and electricity, and limited availability of electricity during peak consumption times during the day. Here, LPGs and potentially green hydrogen could play a role as a backup or primary cooking fuel. In India 56.2% of the population use LPG or PNG as the primary cooking fuel⁴ while it is 95% in Morocco (Nakanwagi, 2021) and about 3% in South Africa.⁵ Despite the currently low numbers, there is initiative to promote LPG in South Africa due to rolling blackouts and limited grid availability.

As demonstrated by previous research, several safety concerns need to be considered for the application of hydrogen. A recent study by Climate Compatible Growth (CCG) argued that there is only limited likelihood that green hydrogen will be adapted as a cooking fuel due to security concerns (Collett et al., 2022, p. 20). Hydrogen is more flammable than natural gas and there is a higher likelihood of severe explosions than with using natural gas in the household. (Hy4Heat, 2021b, 2021a) Furthermore, safety considerations include aspects of storage and transport such as fire resistance of storage tanks or safety at refueling stations. Safety issues also include the need for safe release and dispersion of liquid hydrogen indoors, requirements for ventilation systems, and teaching tactics for extinguishing hydrogen jet fires indoors and outdoors to fire fighters. (Kotchourko et al., 2014) Therefore, it is crucial to design safe hydrogen stoves (e.g., Fumey et al., 2016) and the appropriate safety standards to govern safe cooking.

Several examples for developing hydrogen stoves were found in the literature. This included a project by Brunel university and the Technical University of Jamaica (Schmidt Rivera et al., 2018; E. Topriska et al., 2015, 2016; E. V. Topriska, 2016). Beside this initiative, there was some evidence for experimentation in India (Department of Science and Technology, 2020), and the development of a hydrogen stove by the Swiss company EMPA (Fumey et al., 2016; Fumey & Vogt, 2014). From a design perspective, catalytic burner designs might offer an avenue for safely providing green hydrogen. A catalytic burner for LPGs was introduced by French Company Camping Gaz with some commercial success (Saint-Just & Etemad, 2016,

³ <https://www.harnyss.com/hydrogen-storage>

⁴ <https://www.orfonline.org/expert-speak/household-lpg-access-in-india/>

⁵ <https://www.iea.org/data-and-statistics/charts/south-africa-fuels-and-technologies-used-for-cooking-by-scenario-2018-2030>

p. 268). There is experimentation with blending hydrogen and LNG (Liquified Natural Gas) for urban cooking (Government of India, 2021) and a positive review of this purpose in South Africa (Kozhukhova et al., 2021). Lastly, several companies offer off-grid solar or wind-based green hydrogen plants: UK company ENGAS⁶, US company Harnyss⁷, Austrian company Fronius' Solhub⁸, Spanish company Desigenia⁹, and Indian company Hygenco¹⁰.

In this study, desktop research and an analysis of the cost of cooking was undertaken. The search strategy was based on research results acquired through google scholar, web of science, semantic scholar, PV magazine, and sun-connect.org. Keyword search chains followed the logic "region"+"hydrogen"+"cooking" and "country"+"Hydrogen"+"cooking". The search resulted in 110 documents that were further analyzed for the review (see references). Academic articles, official reports, grey literature (i.e., PowerPoint presentation style reports), and news articles were considered for this review. The method for the cost analysis is explained in more detail in Chapter 4. It must be acknowledged that there are some innovations and cookstove prototypes under development that were so far not reported in available literature.

The remainder of the report is structured as follows. Chapter 2 looks at hydrogen stove designs, the lifecycle of a green hydrogen ecosystem, and safety aspects of cooking with green hydrogen. Chapter 3 reviews the regional policy landscape and actors in India, South Africa, and Morocco based on the available literature. Chapter 4 presents an analysis of the spatiality of cost of cooking with electricity, LPG, and green hydrogen in India, South Africa, and Morocco. Chapter 5 discusses the potential of carbon credits in driving the emergence of off-grid green hydrogen applications.

2. Hydrogen stoves readiness and lifecycle

This section discusses experimentation with hydrogen stove development and companies offering off-grid solar/electrolyzer solutions. The feasibility of hydrogen stoves in developing countries was studied in the period of 2015 to 2018 through a project of Brunel university with the Technical University of Jamaica (Schmidt Rivera et al., 2018; E. Topriska et al., 2015, 2016; E. V. Topriska, 2016). This included research on Ghana and Indonesia (Fopah-Lele, 2022; E. V. Topriska, 2016). There is evidence for some experimentation with stove designs in the Indian context (Department of Science and Technology, 2020, p. 27).

2.1. Hydrogen stove designs

There is a variety of potential stove designs ranging from adapted LPG stove designs over catalytic combustion hydrogen stoves to hybrid stoves. Today, cost calculations based on a modified LPG design offer the best estimate for the cost of cooking with hydrogen based on the currently available data on stove efficiencies and stove cost. Catalytic combustion stove designs could be a game changer in modern cooking. However, there is so far only limited data available on their efficiency and cost. Further

⁶ <https://www.en-gas.com/products>

⁷ <https://www.harnyss.com/>

⁸ <https://www.fronius.com/en/solar-energy/installers-partners/products-solutions/commercial-energy-solutions/green-hydrogen-with-solar-energy-solhub>

⁹ <https://www.pv-magazine.com/2022/09/13/pv-powered-hydrogen-generation-tech-for-off-grid-areas/>

¹⁰ <https://fuelcellsworks.com/news/hygenco-installs-indias-first-of-its-kind-off-grid-solar-based-green-hydrogen-pilot-project-in-ujjain/>

experimentation with catalytic combustion hydrogen stoves and hybrid configurations will be necessary to determine if they can be cost-effective, healthy, and safe alternatives to other fuels and stoves.

The literature distinguishes catalytic hydrogen combustion cookers, direct hydrogen combustion cookers, and hybrid hydrogen cooking systems (Mukelabai et al., 2022). Figure 1 shows the different design options for cooking. A direct hydrogen combustion design draws on the conventional combustion of hydrogen. While this design promises an easier application in developing countries, there are so far not enough studies on the application of the design in households. Catalytic hydrogen combustion is considered a safer design compared with direct hydrogen combustion as it is a flameless combustion at lower temperatures between room temperature and 500°Celsius. A downside are the required rare metals which increase the cost of such stoves. A third option are hybrid hydrogen cooking systems which work through electricity generated from hydrogen combustion, or hydrogen cookers with thermal energy (waste heat) recovery systems. An advantage of hybrid systems is that they allow households to have electricity access at any time. (Mukelabai et al., 2022)

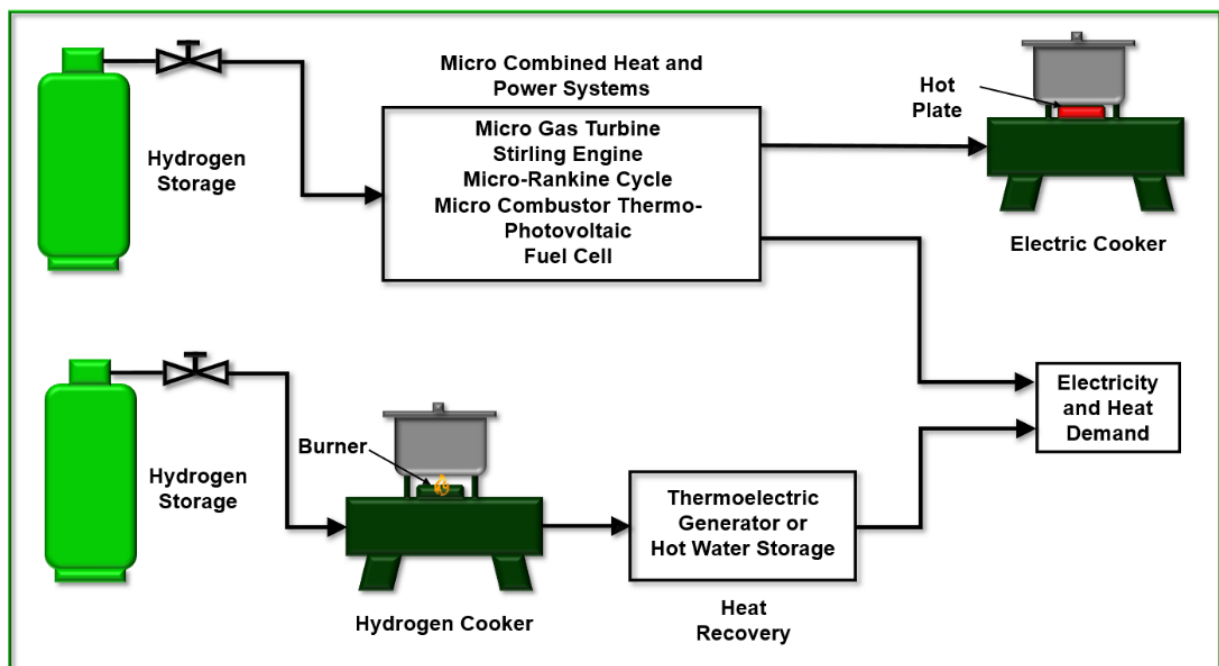


Figure 1: Schematic of three hydrogen stoves for developing countries, Source: Mukelabai et al., 2022, p. 11

Recent reviews of hydrogen as a cooking fuel considered catalytic burners as viable models. (Kozhukhova et al., 2021; Mukelabai et al., 2022). One pilot for a hydrogen stove was designed by the Swiss company EMPA (see Figure 2) in the context of a project on autarchic living (Fumey et al., 2016; Fumey & Vogt, 2014; Mukelabai et al., 2022). An interesting case for catalytic burner designs that could be applied to green hydrogen was a commercially successful camping stove by French Company Camping Gaz (Saint-

Just & Etemad, 2016, p. 268). Recently, Swiss research institute EPFL installed a demonstrator for a solar-hydrogen production system in Douala, Cameroon.¹¹



Figure 2: Assembled catalytic hydrogen combustion cooker (Source: Mukelabai et al., 2022, p. 9)

A catalytic combustion cooker design is seen as one way to solve issues with regard to household safety, heat efficiency, and reduced pollution (Kozhukhova et al., 2021; Mukelabai et al., 2022). Such a catalytic combustion stove would not expose the cook to an open flame while indoor emissions remain low (Kozhukhova et al., 2021). Previous studies have shown a maximum efficiency of 79.6% for catalytic combustion cookers (Mukelabai et al., 2022). A potential downside is the more complex design of the stove in comparison to a simple LPG design which might drive up cost (Kozhukhova et al., 2021, p. 21). A second downside to the design might be its susceptibility to errors (e.g., clogging up of air supply tubes) in non-laboratory context.

The cost calculations in this study (see chapter 4) rely on an adapted LPG stove design as shown in Figure 3 (E. Topriska et al., 2016). This direct combustion stove design has several advantages that make it a choice for studying cost. The design is similar to LPG stoves and would require only small changes to also be able to burn hydrogen. It is a lower cost option in comparison to a catalytic burner stove that could be made widely available.

¹¹ <https://www.epfl.ch/labs/lrese/sunhydrogencooking/>

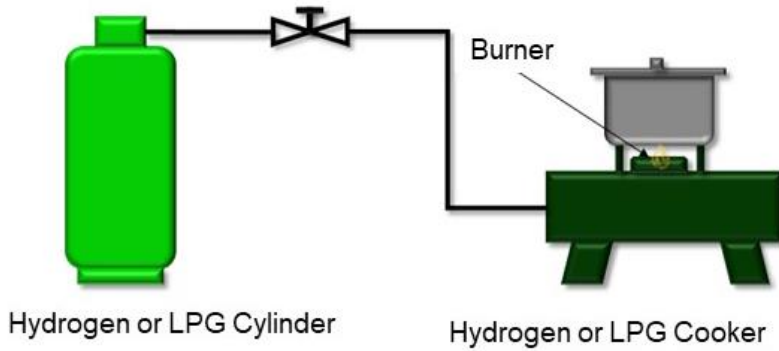


Figure 3: Schematic of a hydrogen stove for developing countries used in this study, Adapted from: (Mukelabai et al., 2022)

2.2. Electrolyzer lifecycle

Currently, the literature distinguishes between different colors of hydrogen based on the energy source for electrolysis. Figure 4 shows the current production costs for common types of hydrogen generation. Black or grey means the production of hydrogen from coal, natural gas, and lignite. Blue is used to produce hydrogen from fossil fuels with CO₂ emissions reduced using Carbon Capture and Storage. Green means the production of hydrogen from renewable electricity. (IEA, 2019, p. 34)

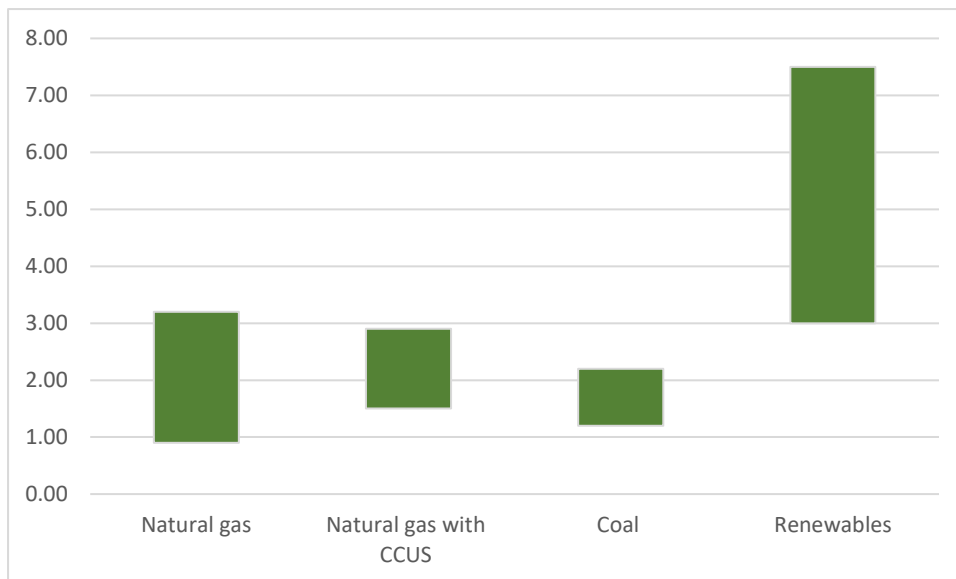


Figure 4: Comparison of hydrogen production costs in USD/kg Source: (IEA, 2023)

There are diverging findings about the best combinations between solar, batteries, and hydrogen. A recent study found that a combination of solar, batteries and power to hydrogen to power (P2H2P) could be a least cost option for storage and running mini-grids in sub-Saharan Africa (Schöne et al., 2022). An earlier study comparing a PV/Battery setup with a PV/Battery/fuel cell setup in East Malaysia concluded that a PV/Battery setup is more cost-effective (Das et al., 2017). Figure 5 shows the lifecycle of a solar-powered electrolyzer (Schmidt Rivera et al., 2018).

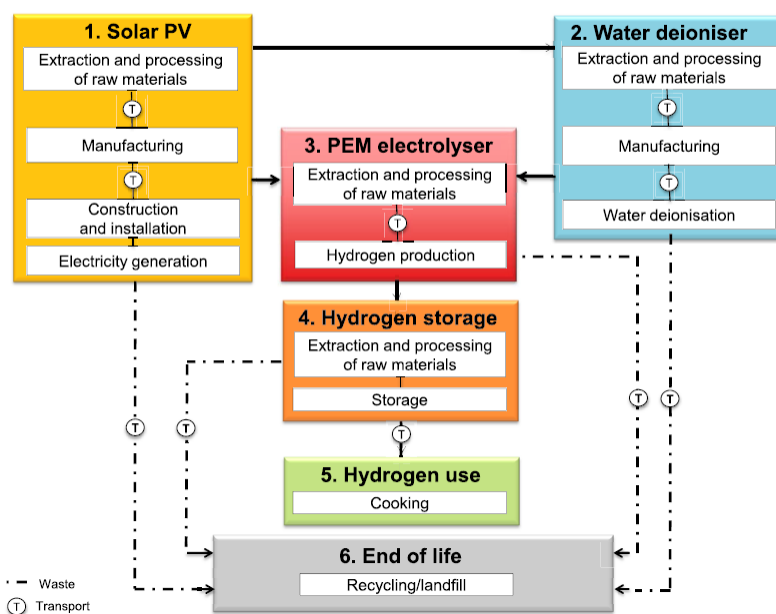


Figure 5 the life cycle of a solar-powered electrolyzer system. Source: Schmidt Rivera et al. 2018: 865

Several companies offer solutions for decentralized green hydrogen production. Examples include UK company ENGAS¹², Austrian company Fronius' Solhub¹³, Spanish company Desigenia¹⁴, and Texan company Harnyss¹⁵. Harnyss is so far the only company that also provides a cookstove solution currently under development that will be based on a catalytic combustion design. Indian company Hygenco¹⁶ has set up a research facility to study the use of off-grid solar for green hydrogen production.¹⁷ While Fronius focusses on mobility and fuel cells, Desigenia offers equipment for communications towers.

Concentrated Solar Power (CSP) companies such as solarspace.io¹⁸ might offer a longer-term perspective for generating the required electricity for green hydrogen or generating green hydrogen directly by reaching 1000°C with new mirror technology and motors developed by NASA for the international space station. However, studies in India reported that CSP technology achieved a maximum temperature of only up to 200°C. (Kumar et al., 2019).

There are several safety considerations that need to be considered but could be addressed through a catalytic combustion design. A first issue is that hydrogen is more explosive than comparable LPGs or LNGs. In an interview, the comparison was described as follows. Natural gas explodes at an atmospheric density of around 14% and has a flash point of 1500 degree Celsius. Hydrogen already at a range of 4-75%

¹² <https://www.en-gas.com/products>

¹³ <https://www.fronius.com/en/solar-energy/installers-partners/products-solutions/commercial-energy-solutions/green-hydrogen-with-solar-energy-solhub>

¹⁴ <https://www.pv-magazine.com/2022/09/13/pv-powered-hydrogen-generation-tech-for-off-grid-areas/>

¹⁵ <https://www.harnyss.com/>

¹⁶ <https://fuelcellworks.com/news/hygenco-installs-indias-first-of-its-kind-off-grid-solar-based-green-hydrogen-pilot-project-in-ujjain/>

¹⁷ <https://www.pv-magazine-india.com/2022/05/12/hygenco-commissions-green-hydrogen-pilot-plant-powered-by-off-grid-solar/>

¹⁸ www.solarspace.io

of atmospheric saturation can be explosive and has a low flash point of 500 degrees Celsius. Therefore, hydrogen might be already ignited by dropping a metal plate. (Interview 1) A second issue is that it is hard to add smells to hydrogen. (Interview 1) Difficulties to add additives to color hydrogen and the low radiation of heat beyond the hydrogen flame constitute a third safety issue. Overall, these issues complicate the application of green hydrogen in a domestic environment. (Interview 2)

3. Geographic aspects of low carbon and green hydrogen cooking

This section presents an overview on green hydrogen transitions and cooking applications in the Maghreb, Southern African Development Community (SADC), and South Asia. The section will discuss regional implications and country-focused findings in India, Morocco, and South Africa. The discussion looks at the role of green hydrogen in on-grid and off-grid environments. A review of organizations showed that there is a growing number of stakeholders involved in green hydrogen. The case study sections are structured by looking at the future role of the green hydrogen transition, potential growth of blending hydrogen with piped gas, as well as current and planned off-grid experimentation with green hydrogen.

3.1. India

The Indian green hydrogen transition focusses on a domestic expansion of green hydrogen production and cost reduction. In 2021, a National Hydrogen Mission was announced which shall boost India's hydrogen economy (MNRE & PIB, 2021). The goal of the National Hydrogen Mission is based on a '1-1-1' formula of USD 1 per 1 Kilogram in 1 decade (Shankaranarayanan & Kaushal, 2022). The mission targets the production of 5 million tons of green hydrogen annually by 2030 (PBNS, 2022). A recent report on green hydrogen published by Niti Aayog, the Indian government's think tank, sees hydrogen's potential as cooking fuel as inferior to electrification given the distributed nature of cooking demand. Limited hydrogen blending is seen as an option, while the lack of hydrogen specific furnaces and stoves outside of prototypes was seen as a disadvantage. (Niti Aayog 2022:36)

As shown in Figure 6 electricity for cooking remains limited in India but could play an increasing role due to the high air pollution. There is growing interest in eCooking amongst key stakeholders in India where the Indian government launched the Go Electric campaign.^{19,20} A study by the Indian NGO the Council for Energy, Environment, and Water (CEEW) found that in 2020 17% of households in Delhi and Tamil Nadu had adopted some form of electric cooking (Agrawal et al., 2021). Due to the high air pollution associated with cooking in India, the transition to low-emissions and carbon-neutral cooking solutions is desirable (Faizan & Thakur, 2019; Kushwah, 2022; Nagpure et al., 2021).

¹⁹ <https://pib.gov.in/PressReleasePage.aspx?PRID=1699386>

²⁰ <https://economictimes.indiatimes.com/news/india/delhi-tamil-nadu-lead-indias-transition-to-electric-cooking-with-17-adoption-ceew-study/articleshow/87107173.cms>



Figure 6: Proportion of population with primary reliance on fuels and technologies for cooking in India, by fuel type (%), based on a population of 1,370 million Source: (WHO, 2022)

Gas and biomass are the two dominating cooking fuels in India (see Figure 6).

LPG plays a key role in the transition towards clean cooking in India. Subsidized access to LPG is provided through the Indian Government LPG program (Union Government, 2019). The LPG share in primary cooking fuels increased from 28.5% in 2011 to 71% in March 2020 (Mani et al., 2021, p. ii). In April 2021 India achieved 99.8% LPG coverage. But there are persisting issues such as refilling, distribution, and consumer adaptation leading to fuel stacking persistence (Nagpure et al., 2021). Therefore, biomass and kerosene are still widely used in households across India as both primary and secondary cooking devices. (MECS, 2022, p. 5)

There is a range of subsidies to promote the adoption of LPG as a clean cooking fuel in India. At the beginning of the 2000s ‘under recovery’ subsidies for LPG were introduced. In 2006, about INR 120 billion (USD 2.7 billion) were invested to this end. (Sankhyayan & Dasgupta, 2019) Overtime the ‘under recovery’ subsidy was phased out and replaced with the Direct Benefit Transfer for LPG (DBTL) scheme introducing criteria for eligibility and caps in purchasable subsidized LPG. From 2012 to 2014 the Indian government increased the number of subsidized cylinders per household per year to 12.²¹ In 2014, the Pradhan Mantri Ujjwala Yojana (PMUY) scheme for low-income household was introduced to incentivize poor households to switch to LPG. The poor household subsidy was phased out in the budget covering the April 2023-March 2024 fiscal year while the DBTL remains in place. The government was criticized for the currently low budget allocation of INR 1.8 billion in the DBTL that might not reflect the potential oil price fluctuations and recent price increases for LPG (see Figure 7). To further ease the burden on the government budget, the ‘give it up’ campaign tries to convince Indians to buy non-subsidized LPG.²²

²¹ <https://www.iisd.org/story/cooking-with-gas-in-india/>

²² <https://www.givitup.in/about.html>

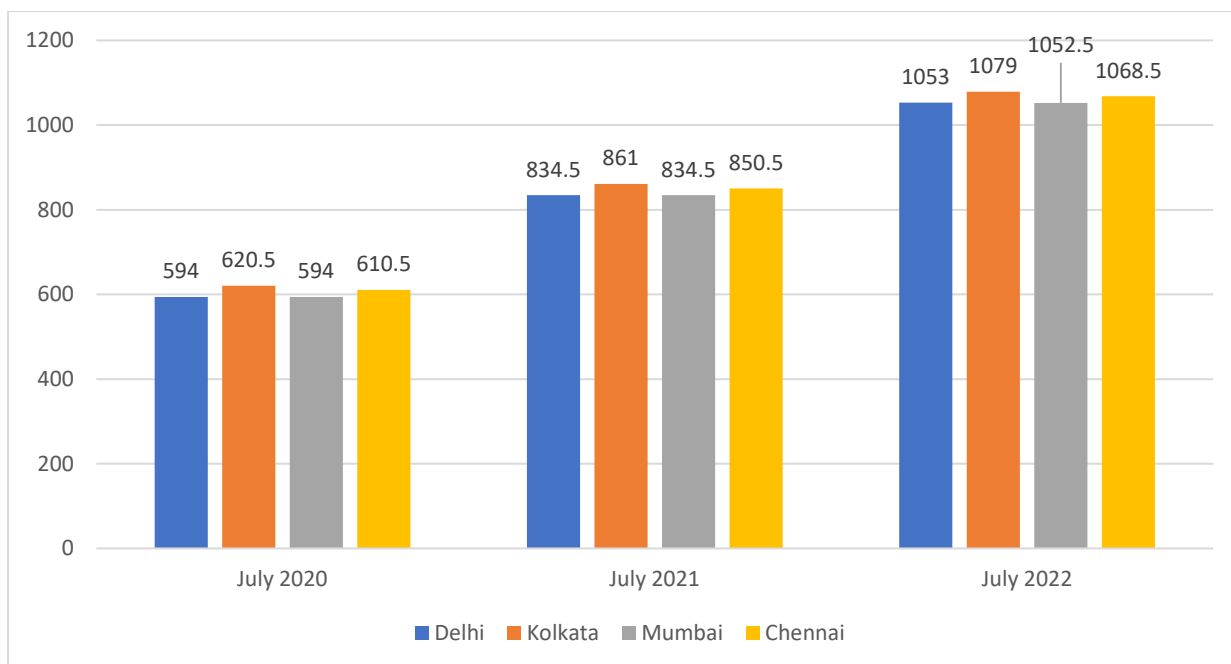


Figure 7: Non-Subsidized Prices of Indane LPG in Metros (INR/14.2 kg cylinder), Source: (Indian Oil, 2023)

Concerning on-grid strategies, experimentation with blending hydrogen and LNG (Liquified Natural Gas) for urban cooking (Government of India, 2021) has started in the beginning of 2023.^{23,24} Utility NTPC in cooperation with Gujarat Gas plans to produce green hydrogen for cooking using electricity from the existing 1 MW floating solar project of NTPC Kawas. The blended cooking fuel will be supplied to 200 homes and used for cooking applications in NTPC Kawas Township. The hydrogen content is around 5% at the beginning and might be increased to up to 20%. (Baruah, 2022; PBNS, 2022) A recent study by Ernest and Young underlined the potential for blending hydrogen with piped gas (PNG) in India (EYG - Ernst & Young Global Limited, 2022, p. 15).

On the grid, Indian enterprises focus on industry and mobility applications. INR 250 million will be provided by the MNRE for R&D activities in hydrogen. Reliance industries will invest USD 8 billion into giga-factories for fuel cells and electrolyzers. (EYG - Ernst & Young Global Limited, 2022, p. 17) Companies such as Reliance Industries Ltd., or Larsen & Toubro have signed agreements to implement green hydrogen projects²⁵.

Currently, costs of green hydrogen are not competitive with grey hydrogen according to ratings agency ICRA. From the industrial off-taker's perspective, Green Hydrogen is currently estimated to remain costlier by about USD 3.5-4 /Kg against Grey Hydrogen (see also Chapter 2.2.). In projects where an electrolyzer and renewable energy capacity are located in proximity, cost is estimated to decline by USD 0.5-1.0 /Kg due to savings in intra-state open access charges.(ICRA, 2022; Uma Gupta, 2022b)

²³ <https://www.indianarrative.com/india-news/in-a-first-ntpc-starts-supplying-hydrogen-blended-cooking-gas-to-houses-91150.html>

²⁴ <https://www.pv-magazine-india.com/2023/01/04/ntpc-starts-indias-first-green-hydrogen-blending-in-png-network/>

²⁵ <https://www.electronicandyou.com/blog/top-5-green-hydrogen-energy-companies-in-india-listed-in-stock-market.html>

From an off-grid perspective, a study on the Indian mini-grid sector argued that decentralized hydrogen production will be cheaper than on-grid production by 2030 (Hall et al., 2020). Costs are projected to fall to USD 2 per kg in 2030 (Uma Gupta, 2022a). While on-grid electrolyzers are estimated to be able to supply at a levelized cost of hydrogen (LCOH) of about INR 300/kg, off-grid electrolyzers were estimated to supply at a LCOH of about INR 180/kg in 2030 (Hall et al., 2020). Looking at the production cost trends for Jamnagar, the CEEW estimates a LCOH of about USD 2.4/kg in 2030 and a further decrease to about USD 1.7/kg by 2040 (Ghosh & Chhabra, 2021, p. 15).

Assessing off-grid solar green hydrogen applications is currently at a feasibility and piloting stage. A simulation on feasibility found economic viability for a university building (Singh et al., 2017). Pal and Mukherjee (2021) found that an off-grid solar green hydrogen fuel cell system can be cost effective in North-eastern Indian states. Indian company Hygenco has set up a pilot project for India's first off-grid solar hydrogen plant²⁶. Hygenco recently got funding by the NeeV fund which is backed by FCDO²⁷.

The wide adaptation of LPG for cooking might be beneficial for gradually switching to bottled green hydrogen by 2040, if cost and safety concerns are met. This is due to the advantages of green hydrogen such as its lower impact on GHG emissions and the similar approach to LPG cooking. Also, green hydrogen could lift the subsidy burden for the Indian government's budget through the implementation of carbon markets. There are already business cases such as KOKO networks in Kenya that have successfully pursued such a carbon credits-based model. Additional benefits such as the production of oxygen in electrolyzers could tilt the needle in favor of green hydrogen due to the impact of respiratory diseases (i.e., COVID-19) on the oxygen supply.

Overall, there is potential for green hydrogen in increasing access to cleaner cooking that might be driven by private sector companies and state utilities rather than the central government. If green hydrogen cost decreases and safety considerations are met, green hydrogen might play a role in the Indian market for cooking.

3.2. Maghreb and Morocco

Despite North Africa and the Maghreb being part of the solar belt, there is little done so far to use this potential. North African countries greatly exceed their emission targets (Fadlallah et al., 2022, p. 2). Morocco, however, due to its proximity to Europe and its renewable energy potential, is seen as a potential champion of the green hydrogen transition (Nuñez-Jimenez & De Blasio, 2022b). There are few studies covering renewable and hydrogen outside of Morocco in the region such as a simulation on a university building in Algeria (Mokhtara et al., 2021).

Currently, LPG is the dominant cooking fuel in Morocco. As shown in Figure 8, More than 90% of households use Gas or LPG as the primary cooking fuel. This dominance can be largely attributed to the high subsidies on LPGs. As will be further discussed in section 4, a 12 kg bottle of Butane which is one of the most common LPGs in Morocco costs about USD 4 while its unsubsidized price is USD 8. The

²⁶<https://fuelcellsworld.com/news/hygenco-installs-indias-first-of-its-kind-off-grid-solar-based-green-hydrogen-pilot-project-in-ujjain/>

²⁷ <https://yourstory.com/2022/10/neev-fund-green-hydrogen-haryana-startup-hygenco>

dominance of bottled LPG could allow for comparable approaches for distributing green hydrogen. A report by the German development cooperation (GIZ) considered cooking applications for green hydrogen as part of a long-term perspective for synthetic methanol after 2040 that might be the key to reduce the use of LPG in Morocco (GIZ, 2021).

Bennouna (2021) argued that subsidized Butane creates market inefficiencies in comparison to solar energy electricity-based cooking. In 2015/2016, electric cooking and other efficient household appliances were under 25% in Morocco (IEA, 2016).

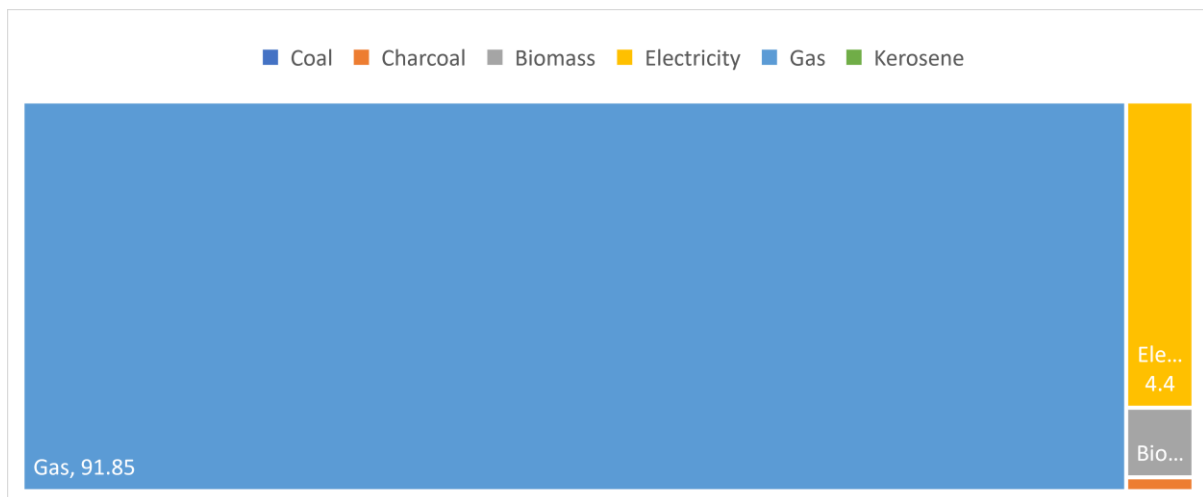


Figure 8: Proportion of population with primary reliance on fuels and technologies for cooking in Morocco, by fuel type (%), based on a population of 36.12 million, Source: (WHO, 2022)

From an on-grid perspective, Morocco has become one of the key examples for the potential of green hydrogen transitions. The country is considered as a future player in providing cost-competitive green hydrogen to the European Union (Lebrouhi et al., 2022; Nuñez-Jimenez & De Blasio, 2022). There are plans to establish 4-Terawatt hours (TWh) local and a 10 TWh export market, which would require 6 GW of additional renewable energy installed capacity that could create up to 15,000 direct and indirect jobs (IRENA, 2022, p. 48). The government aims to achieve a share of 52% total installed capacity by 2030 (Pflugmann & De Blasio, 2020, p. 26/27; Vagneur-jones, 2021). A national hydrogen roadmap was presented in January 2021 (Government of Morocco, 2021). The roadmap rests on three axes: ‘the appropriation of the necessary technologies, the development of the market and demand, and finally the investment and supply sector’ (Lebrouhi et al., 2022).

In an on-grid context, green hydrogen applications to cooking depend on the broader industrial strategy. Due to the focus on building industrial green hydrogen applications, a blending scenario where green hydrogen is blended into gas infrastructure is likely. This however depends on further investment into a natural gas transport infrastructure (World Bank Group, 2022, p. 31).

From an off-grid perspective, prefeasibility simulations with decentralized solar/wind and electrolyzers have taken place. First computer simulations estimated feasibility of a hydrogen hybrid PV System in isolated settings (Boukhris et al., 2018; Hatti et al., 2011) and recommended further research. A solar/battery-based simulation was conducted for a remote village in the Fez-Meknes region (El-houari et al., 2020). In a computer simulation, the levelized cost of hydrogen in a wind-powered and a

concentrated photovoltaic thermal system was assessed for the Tangier region finding wind power to be more cost-effective (Khouya, 2020). Touili et al. found in a simulation on different solar setups that hydrogen could be provided at a price of USD 5.57/kg compared to USD 5.96/Kg in Southern Spain and USD 6.51/Kg for South Africa (Touili et al., 2020). Another study argued that southern Morocco is potentially cost competitive with locations in Chile or Argentina (Ennassiri et al., 2019). There is some reporting on pilot projects with decentralized solar in Morocco where two companies teamed up to provide energy access for remote communities in Id Mjahdi.²⁸

Similar to India, cooking is not the primary consideration of Morocco's green hydrogen ambitions. The proximity to the EU in combination with its renewable energy potential might allow for the provision of cheap green hydrogen at USD 2/kg by the 2030s. The main energy source in the market for cooking fuels are subsidized LPGs. As gas networks are not sufficiently dense, bottled distribution of LPGs plays an important role. As shown in Figure 8, electricity does not play an important role in cooking at the moment. The data presented in Figure 8 shows that subsidized bottled Butane is primarily used. Due to the high subsidies, LPG are a large burden on Morocco's budget due to rising prices in the world market.

Overall, bottled green hydrogen could be a relevant alternative in the cooking sector in the future that could allow to reduce subsidies based on carbon finance. Green hydrogen could also play a role were eCooking does not make economic sense (i.e., off-grid or under the grid households). So far, experimentation with off-grid generation of green hydrogen is limited to prefeasibility assessments and computer simulations.

3.3. SADC and South Africa

In the SADC region many countries have set up programs for improved cookstoves (REN21, 2018). However, hydrogen technology is still rare (Fopah-Lele, 2022). In the context of the SADC, export of green hydrogen could be used to finance clean cooking projects rather than directly generating energy for cooking (Bhagwat & Olczak, 2020, p. 14; IEA, 2022, p. 136). Together with South Africa, Namibia is considered as an important future producer of green hydrogen in the SADC region (von Oertzen, 2021). Outside of SADC, research on hydrogen cookstoves took place in Ghana (Fopah-Lele, 2022; E. Topriska et al., 2016).

So far, the Southern African Development Community (SADC) lacks clear policy frameworks for green hydrogen South Africa and Namibia being the exceptions (Imasiku et al., 2021). Namibia launched its green hydrogen strategy at COP 27 in Egypt. It aims to produce 10-12 million tons of hydrogen per year by 2050. A currently constructed pilot project by Hyphen²⁹ Tsau Khaeb has set a Hydrogen production target of 300,000 tons per year. The electrolyzer capacity target for the Hyphen Tsau Khaeb project is 3 GW. Consultancy McKinsey estimates that Namibia could be producing green hydrogen at USD 1.5/kg by 2030.³⁰

Achieving access to clean cooking remains a challenge in South Africa which is why the country could benefit from considering green hydrogen for cooking. Here, improved cookstoves could make a difference for marginalized groups (Aktas et al., 2022). But vested interests and dysfunctionalities in energy access have to be overcome (McKay & Hendricks, 2022). As shown in Figure 9, 81.7% of South

²⁸ <https://www.ecmag.com/section/green-building/morocco-home-africas-first-solar-powered-village>

²⁹ <https://hyphenafrika.com/projects/>

³⁰ <https://gh2.org/countries/namibia>

Africans cook primarily with electricity while the bad economic state of the state utility ESCOM, continuing rolling blackouts and load shedding make clean cooking difficult (The Economist, 2023).

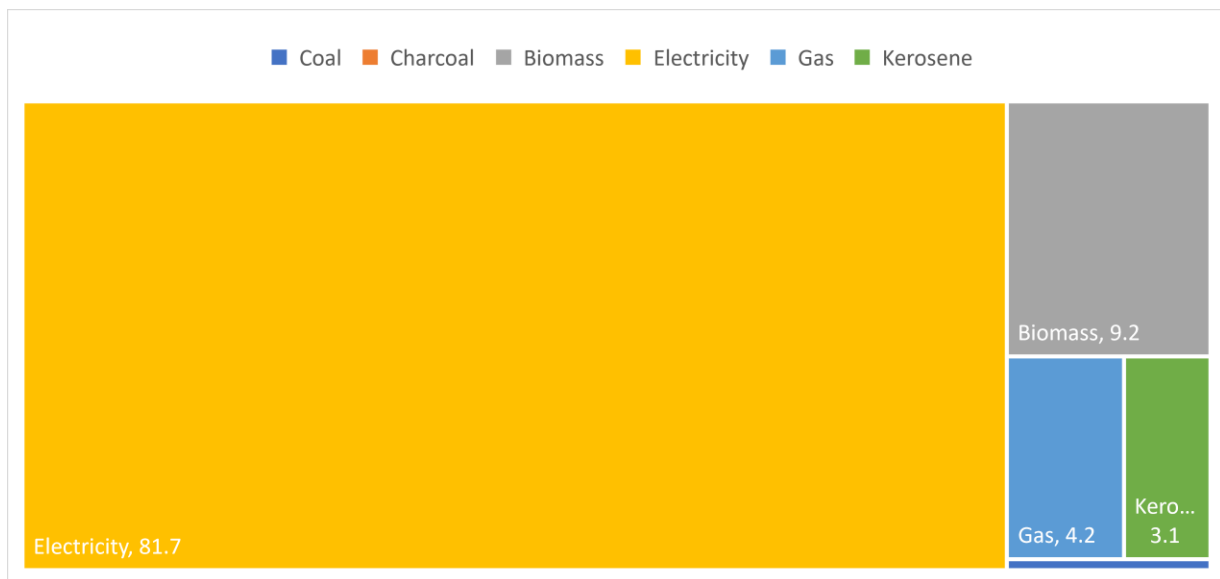


Figure 9: Proportion of population with primary reliance on fuels and technologies for cooking in South Africa, by fuel type (%), based on a population of 57,9 million, Source: (WHO, 2022)

From an on-grid perspective, scenarios aiming for blending green hydrogen with natural gas are considered. South Africa has a national program to promote hydrogen production: HySA (Hydrogen South Africa) (Ayodele & Munda, 2019, p. 17670). A recent study by HySA covers hydrogen applications for cooking. The study reviews the options for blending H₂ with natural and petroleum gas (Kozhukhova et al., 2021). Green hydrogen is also a part of the JETP, a multilateral partnership to allow South Africa to transition away from coal (IEA et al., 2022, p. 156; REN21, 2022, p. 183). South Africa is the 14th largest emitter of GHG due to high coal consumption (IRENA, 2022, p. 89; Lebrouhi et al., 2022, p. 7037; Salma, 2022, p. 3)

Mini- and off-grid scenarios are soon to be tested for feasibility in Namibia and to a more limited extent in South Africa. In Namibia, a cooperation by Enersense Energy Namibia, Windwise, University of Stuttgart, and NGHRI (UNAM) aims to create Africa's first green and carbon-neutral village that shall help to understand feasibility of green hydrogen use cases. The project aims to look at the feasibility of off-grid production of green hydrogen and ammonia-based fertilizer. Euro 15.1 million are earmarked for a pilot phase where 500 kg of Anhydrous Ammonia shall be produced per day. In subsequent phases up to 350,000 tons of ammonia per year shall be produced. (Daures Green Hydrogen Consortium, 2021) In South Africa, HySA was earlier involved in the development of more efficient fuel cells (Pollet et al., 2014). Another study investigated the economic feasibility of a solar/wind hybrid system with hydrogen to power applications in a health clinic for a South African village (Ayodele et al., 2021).

So far, the role of the green hydrogen transition is limited to Namibia and South Africa in the SADC region. Here, Namibia and South Africa stand out as they have established partnerships with European stakeholders to promote green hydrogen and setup piloting facilities. There was some exploration on the feasibility of blending hydrogen with piped gas in South Africa. There is an on-grid initiative in South

Africa to build three hubs for green hydrogen that were planned to be connected through pipelines in the context of the hydrogen valley project (Engie, 2021).

In Namibia, mini-grid experimentation is taking place through the Daures project. Here it is particularly German and Namibian stakeholders who want to develop a village that is completely powered by renewable energy and green hydrogen. The goal of the Daures project is to produce green hydrogen for export.

3.4. The green hydrogen transition and cooking in a regional perspective

Overall, India, Morocco, and South Africa represent very different ecosystems for cooking and a potential role for green hydrogen. Green hydrogen initiatives in Morocco and South Africa are driven by partnerships with stakeholders in the Global North. In difference, India has set national goals in building up a local green hydrogen industry. While cooking with electricity plays a minor role in India and Morocco, it is the dominant energy source for cooking in South Africa. In South Africa, issues such as blackouts, cost of grid connections and electricity, and limited availability of electricity during peak consumption times during the day are a problem. It can be argued that while LPG is not the primary cooking fuel in South Africa, it acts as a backup to frequent blackouts and limited availability of electricity during peak hours (Kimemia & Annegarn, 2016). In India and Morocco LPGs are highly subsidized and are a considerable burden to government budgets.

The analysis of the spatiality of cost of hydrogen in section 4 is based on the prevalence of LPG in cooking in Morocco and India and a still limited role of electricity. Due to the wider adaptation of LPG cookstoves, it makes sense to compare a similar stove configuration for green hydrogen. As similar cooking equipment is required and the infrastructures for making LPG and green hydrogen are similar, it can be assumed that cost structures do follow similar patterns. Therefore, the following section will consider cost based on a green hydrogen stove that consists of a cylinder, regulator, and adapted LPG stove.

4. Comparison of the spatiality of cost for green hydrogen and cooking fuels in South Africa, Morocco, and India

This section discusses the cost of green hydrogen for cooking and concludes with a comparison of the cost of cooking with LPG, electricity, and green hydrogen. The cost of cooking will be discussed in the context of India, South Africa, and Morocco. Section 4.1. looks at the assumptions for the calculation of the cost of green hydrogen, electricity, and LPG. Section 4.2. discusses the Levelized Cost of Hydrogen and the required capital expenditure as well as the cost of renewable electricity as the major operation cost. Section 4.3. presents information on the cost of transport and storage of hydrogen. Lastly, section 4.4. analyses the cost of cooking with green hydrogen, LPG, and electricity.

4.1. Assumptions for the calculation of cost in India, South Africa, and Morocco

This section presents information on the basis for calculating the cost of green hydrogen in the case studies. It also offers reflections on limitations. An overview on the data is presented in Annex 1 and includes information on the cost of cooking with electricity (EPC+Induction, Induction only), LPG (subsidized and unsubsidized), and green hydrogen (lower and higher cost scenarios).

The cost analysis is based on the properties of a direct combustion hydrogen stove. While catalytic combustion stoves are promising in terms of increased efficiency, further data is required to better understand the cost of making and using such stoves. Also, there are risks related to the use of catalytic combustion stoves in the field. Clogging of air ventilation etc. could be a serious downside to such designs that might threaten overall operability. Field testing results are required that cover long-term end-user experiences. Evidence gained through a demonstrator for a solar-hydrogen production system in Douala, Cameroon might help to understand such risks of catalytic combustion stoves.³¹

Two green hydrogen scenarios were calculated. Both are based on the direct combustion of green hydrogen rather than catalytic combustion or gaining electricity from fuel cells. The calculations for the required green hydrogen were based on the daily consumption of a household in Ghana of 4.20kWh/day or 0.107kg of hydrogen based on four household members as suggested in the literature (E. Topriska et al., 2016). Transport and storage costs for a pressurized cylinder were approximated based on data provided in earlier studies and are discussed in more detail in section 4.3. (Griffiths et al., 2021).

Storage of hydrogen creates higher costs due to higher pressurization and the necessary materials to contain such higher pressure. It is assumed that this leads to an increased cost of up to 10% compared to LPG cylinders. Weight and pressurization play an important role in higher transport and storage cost estimates (Collis & Schomäcker, 2022).

Scenario 1 reflects an optimistic scenario for the calculation of cost for cooking with green hydrogen by the mid-2030s. Calculations were based on the demand of a household of 4 members. In this scenario a pressurized cylinder containing 2.7 kg of hydrogen was used to store and transport the hydrogen. The production cost of the cylinder was based on available data on the likely least LCOH/kg in local currency and 2022 USD by the early 2030s and the size of the cylinder. The transport cost was based on two data sources. More specific estimates on the cost of transport in India were used (Hall et al. 2020). For South Africa and Morocco, a more general estimate on the cost of transport was used (BNEF, 2020, p. 6). The total cost of a cylinder was then calculated based on the least LCOH and the transport cost. Lastly, an estimate on annual cost was provided in local currency and 2022 USD.

Scenario 2 reflects a more pessimistic scenario on the calculation of cost for cooking with green hydrogen by the early 2030s. Household size remained the same for the calculation. The scenario is based on a 4.2 kg cylinder based on the same assumptions as in scenario 1. The production cost of one cylinder reflects a high estimated LCOH by the mid-2030s as found in the literature on the three case studies. Transport costs were based on the higher weight of the cylinder. Calculations for the total cost per annum were provided in local currency and in 2022 USD.

Since there were no hydrogen stoves found in the studied markets this study assumes that the cost might be up to 100% higher than a gas stove based on discussions in the European context.³² One reason for the higher cost is that near-term manufacturing costs will be higher before economies of scale are reached.³³

³¹ <https://www.epfl.ch/labs/lrese/sunhydrogencooking/>

³² <https://cleantechnica.com/2021/10/14/hydrogen-heating-cooking-would-cost-homeowners-100000-extra-over-15-years/>

³³ This reflects discussions about the need for developing hydrogen stoves. A possible alternative is adapted LPG stoves or multi-burners that were not considered in this review.

It can be argued that due to the relative ease in converting an LPG stove to using 100% hydrogen such initially higher costs will come down fairly quickly and potentially already by the mid-2030s.³⁴

The comparison of upfront cost was based on internet research on available appliances in markets and relevant case studies. Online research found one example for a hydrogen stove with a cooking plate at a price point of USD 165.³⁵ For India, the cost for eCooking with Induction + EPC and LPG cooking were based on an earlier cost comparison in the Modern Energy Cooking Services (MECS) program (MECS, 2022, p. 14).

The following limitations need to be considered. As shown by Mukelabai et al. (Mukelabai et al., 2022), there is so far only theoretical and limited experimental evidence for the feasibility of off-grid green hydrogen generation and cooking. Therefore, there is a need for further data to understand similarities and differences between the studied locations in terms of cost. A closer examination of real-time data for Rabat³⁶ could be a next step in better understanding consumption of electricity for cooking in Morocco at least in urban areas. Currency fluctuations make it harder to translate cost from one context to the other. Subsidies were found to have a large impact on the cost of cooking and significantly alter prospects for using green hydrogen for cooking. This is particularly the case when comparing the cost of LPG and green hydrogen (see Annex 1). Variations in household size between urban and rural areas, and in socio-economic status require a more granular examination of cooking demand per household.

4.2. Levelized Cost of Hydrogen (Cost of electrolyzers and renewable electricity)

Looking at the levelized cost of hydrogen (LCOH) in 2022, Bloomberg New Energy Finance (BNEF) has assumed a cost of Chinese alkaline electrolyzers at USD 0.25/W, Western alkaline electrolyzers at USD 0.93/W, and polymer electrolyte membrane (PEM) electrolyzer costs at USD 1.11/W. Based on the BNEF data, using wind energy in India had an LCOH between about USD 2/kg and USD 4.2/kg in 2022. Using solar energy, South Africa had an LCOH of approximately USD 2.5/kg to USD 5.9/kg. (BNEF, 2022, p. 19) In comparison, largescale project announcements for green hydrogen such as Helios Green Fuels in Saudi Arabia or Western Green Energy Hub in Australia project a cost of hydrogen around USD 2.55/kg³⁷. Simulations on the LCOH in several Moroccan locations and large scale fixed PV plants resulted in a cost range between USD 5.57 and USD 6.05/kg (Touili et al., 2020, p. 26795).

Studies on the cost of decentralized production of green hydrogen came to varying results. One study estimated the levelized cost of electricity (LCOE) generation in a wind/solar hybrid mini-grid for green hydrogen production at USD 2.34/kWh (Ayodele et al., 2021). A study looking at the case of Northern Africa in a simulation for an off-grid home arrived at a LCOE of USD 0.54 /kWh in 2008. The study was based on a combination of a PV-panel, battery, electrolysis cell, fuel cell and a converter. A high cost was calculated for an off-grid community in South Africa drawing on a simulation of a PV and wind, electrolyzer, fuel cell, and converter for an off-grid community. The study arrived at a cost USD 21.02 /kWh in 2018. (Mukelabai et al., 2022)

³⁴ <https://www.hy4heat.info/appliances>

³⁵ <https://hydrogenatm.com/product/hho-stove/>

³⁶ <https://moredataset.github.io/MORED/>

³⁷ Source: John Poljak/Keynumbers: <https://www.linkedin.com/pulse/which-country-produce-cheapest-green-hydrogen-john-poljak/?trackingId=kCCtDP4UT6OktXbM5uO9w%3D%3D>

4.3. Transport and storage

As shown in Table 1, cost for transporting hydrogen can vary greatly. This includes the need for higher compression of hydrogen during transportation and the increased weight of green hydrogen storage tanks due to the higher pressurization. Distribution of green hydrogen is a challenge due to the cost and carbon-intensity of delivery through trucks. A potential remedy could be to use hydrogen fueled trucks which raises further questions about cost in building a wider hydrogen infrastructure in remote areas. (Griffiths et al., 2021) In India, trucks are considered as the major transport option for hydrogen to remote areas. The cost of trucking ranged from INR 11.8 (USD 0.16) /kgH₂ assuming 50 km distance and 700 kg capacity to Rs 40.0 (USD 0.53)/kgH₂ assuming 50km distance and 200 kg capacity. (Hall et al., 2020)

	Distribution pipelines (0-10 km)	Distribution pipelines (10-100 km)	Trucks (0-10 km)	Trucks (0-10km, larger capacity)	Trucks (10-100km)	Trucks (10-100 km)
Volume/day	10-100 tons	10-100 tons	0-1 ton	1-10 tons	0-1 ton	1-10 tons
Cost	0.05-0.06	0.06-0.22	0.65-0.76	0.65-0.76	0.68-1.73	0.68-1.73

Source: BNEF 2020 p.6 (Numbers are based on compressed hydrogen)

Hydrogen storage remains one of the most critical issues where innovation needs to take place. Table 2 gives an overview of the available storage options and cost (Griffiths et al., 2021, p. 20). What becomes clear is that storage in geological formations is limited to specific geographies. Also, time plays a crucial role in storing green hydrogen. The two most interesting types of storage for cooking applications are pressurized containers and metal hydrides.

While the physical limits for the storage density of compressed and liquid hydrogen were reached, there is still potential for solid materials for hydrogen storage (e.g., metal hydrides) (Ball & Wietschel, 2009, p. 622). Compressed gas and cryogenic liquid storage are the most common approaches. Compression requires 350–700 bar and cryogenic liquid storage temperatures of -253 °C and below. At 700 bar hydrogen’s volumetric density can be increased to 37 kg/m³ (Kozhukhova et al., 2021, p. 4). LPG is typically stored in cylinders at about 20 bars. Butane has a density of 571.8±1 kg/m³.³⁸ Indian Oil Corporation Limited (IOCL) and IIT Kharagpur are working on 800 bar pressure tanks which increases the energy storage density over existing cylinders. (Hall et al., 2020)

³⁸ <https://science.lpnu.ua/istcmtm/all-volumes-and-issues/volume-80-no3-2019/lpg-accounting-specificity-during-its-storage-and>

	Salt Caverns	Pressurized Containers	Liquid hydrogen	Ammonia	Metal hydrides
Capacity	300-10,000 t H ₂ per cavern	5-1,100 kg H ₂ per container	0.2-200 t H ₂	1-10,000 t H ₂	0.1- 20 kg H ₂
Duration	Weeks to months	Daily	Days to weeks	Weeks to months	Days to weeks
Benchmark LCOS (\$/kg)	0.23	0.19	4.57	2.83	Not evaluated
Forecast LCOS (\$/kg)	0.11	0.17	0.95	0.87	Not evaluated
Geographical availability	Limited	Not limited	Not limited	Not limited	Not limited
Hydrogen carrier	No	No	No	Yes	Yes

Adapted from Griffiths et al., 2021, p.20 (Table 5)

4.4. Could green hydrogen become cost competitive?

This section provides an analysis on the cost for cooking appliances and cooking fuels in India, South Africa, and Morocco. This section first presents take-aways on the cost of required cooking appliances across the cases, then looks at the annual fuel costs, and finally concludes with a review on the potential for cooking with green hydrogen in the three cases. The results are based on the assumption of 100% green hydrogen provided in pressurized cylinders and on-grid production of green hydrogen to be transported over a distance between 10 and 100 km. Cost is presented in US-Dollars and exchange rates were retrieved on 7 December 2022. More information on the data is available in Annex 1.

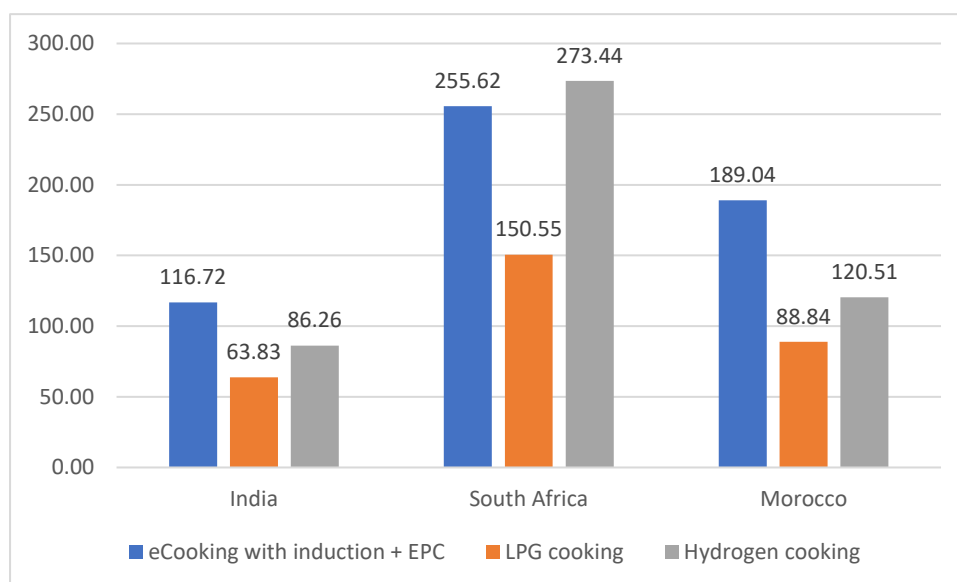


Figure 10: Cooking upfront cost in USD. Source: Annex 1

India has clear advantages in the upfront cost for cooking compared to South Africa where appliances were most expensive and Morocco which took a middle ground on expenses (see Figure 10). Upfront cost for cooking is significantly higher in South Africa than in Morocco or India. This higher upfront cost in South Africa might reflect the overall lack of locally manufactured appliances. The lower cost in Morocco

compared to South Africa might be due to the proximity to the European market for kitchen appliances. The cost for eCooking with EPC varied widely, which is mostly due to the different price points for EPCs found through an online search and in the relevant literature (MECS, 2022).

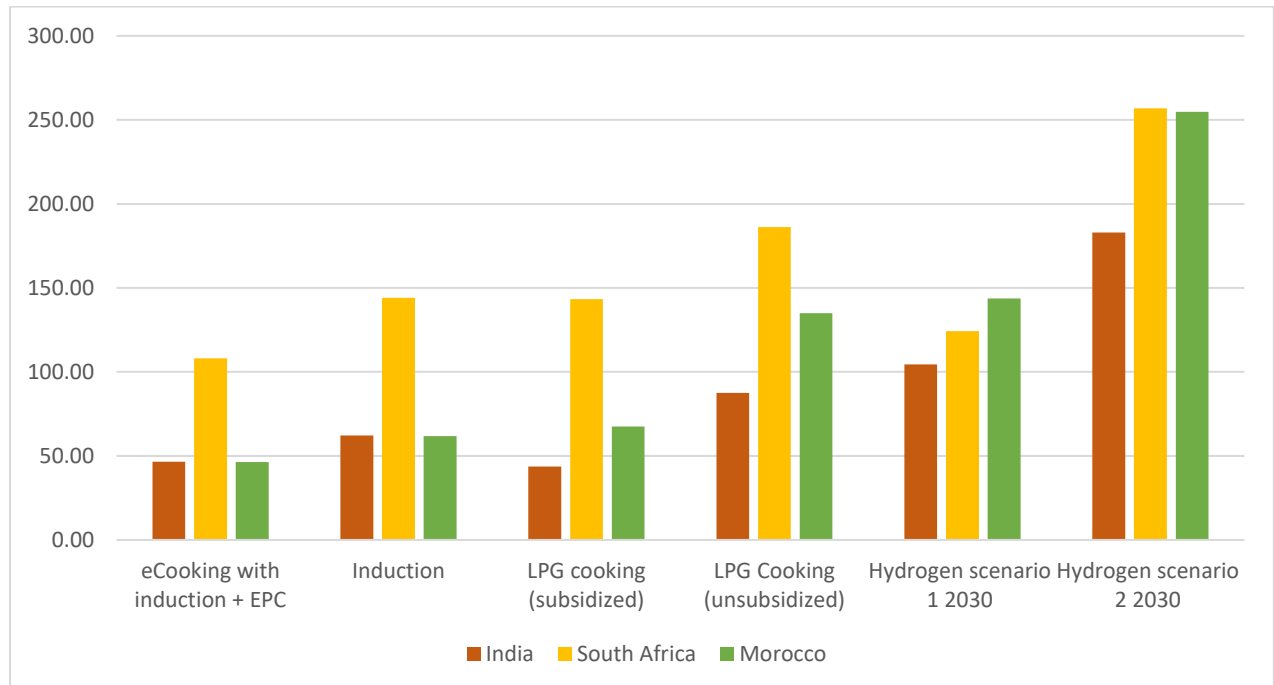


Figure 11: Cost of cooking fuels in India, South Africa, Morocco (in USD/year), Source: Annex 1

Concerning cooking fuels, Morocco and India were significantly cheaper than South Africa as shown in Figure 11. Interestingly, the South African hydrogen scenario 1 was only slightly more expensive than eCooking with induction and an EPC. This made it potentially one of the cheapest options in the cooking fuel market. However, hydrogen scenario 2 provided the highest cooking fuel estimate across the three case studies. eCooking with induction and an EPC was found to be the cheapest solution except for subsidized LPG in India. Cooking fuels were most expensive in South Africa, while they were least expensive in India. It is remarkable that hydrogen scenario 1 did comparably well on cost in comparison with unsubsidized LPG in South Africa and in India. Also, hydrogen scenario 1 was only slightly more expensive than unsubsidized LPG in Morocco.

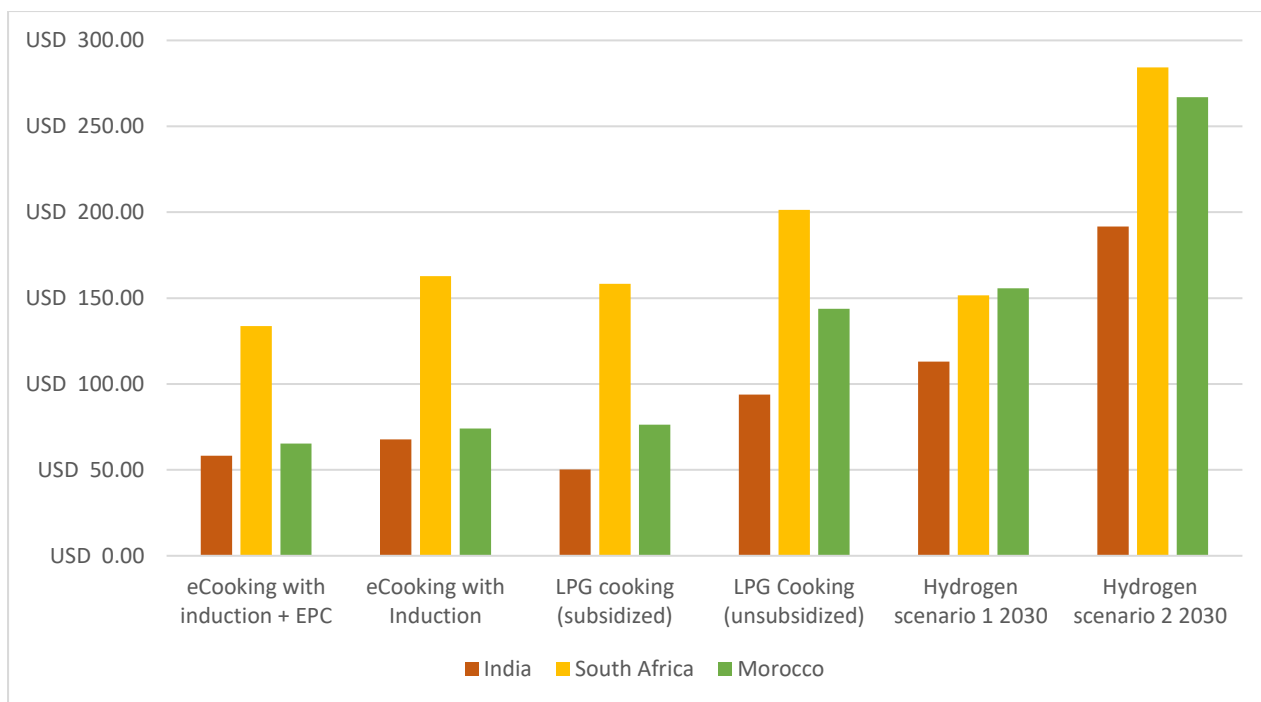


Figure 12: Annual cost of cooking (appliances and cooking fuels) in India, South Africa, Morocco (in USD/year), Source: Annex 1

Accounting for both, fuel, and upfront cost of purchasing appliances did not significantly shift the ranking of the single cases. Figure 12 presents the annualized cost for the appliances based on the assumption of linear investment depreciation over ten years and the annual fuel costs. The depreciation is likely on average due to the different depreciation rates of the stove, cylinder, the EPC and cooking utensils.

The overall annual cost of cooking shows that it makes a difference to account for the purchase of appliances. However, the overall story about the cost of cooking in India, South Africa, and Morocco remains widely unchanged. While hydrogen scenario 1 lands in the range of unsubsidized LPG, hydrogen scenario 2 renders the adoption of green hydrogen in the investigated scenario unlikely.

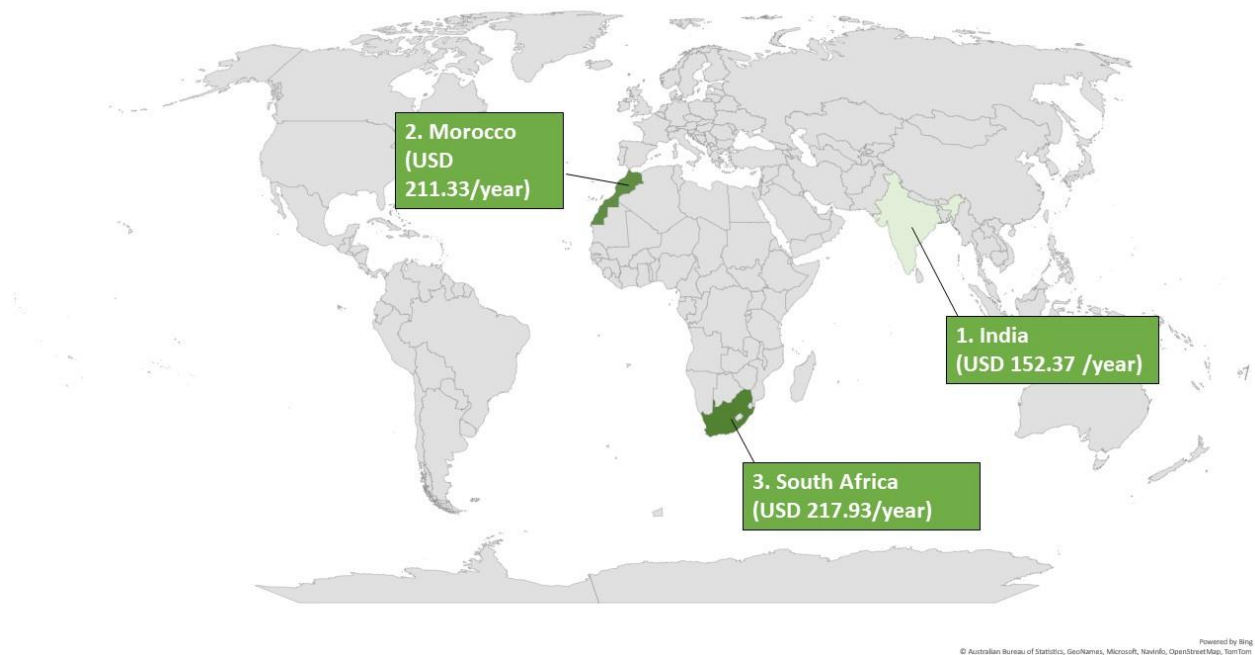


Figure 13: Ranking of average expected annual cost including green hydrogen appliances and cooking fuel in India, South Africa, Morocco based on Scenario 1 and 2 (in USD/year) by 2030s. Source: Annex 1

An overall comparison of the average cost for cooking with hydrogen shows that India clearly takes the lead. Figure 13 shows an average annual cost of cooking with green hydrogen based on the two scenarios and the cost for appliances in US-Dollar. The average cost for cooking with green hydrogen in Morocco and South Africa was significantly higher than in India. Both countries were relatively close on the overall cost, while India had clear advantages in providing green hydrogen at low cost. Therefore, one can conclude that the circumstances for using green hydrogen in cooking in India might become favorable for adoption first.

It can be concluded that some prerequisites of achieving the price points found in this chapter were already met across the three cases. The wide availability of LPG in India and Morocco and to some extent in South Africa as a secondary cooking fuel could benefit the adoption of cooking with green hydrogen. This is due to the low-cost changes required to use green hydrogen as a cooking fuel for an LPG stove. There are also potential benefits in carbon finance that might help to move away from the current approach in subsidizing LPG in India and towards lowering the burden on public budgets, both in India and Morocco through emission trading. Chapter 5 discusses some of the aspects that could benefit the adoption of carbon finance-based business models in green hydrogen.

While the cost calculation implies some potential for further developing green hydrogen, arriving at such low cost by the 2030s could be a challenge. This is due to the priority for industrial applications and export of green hydrogen as well as the clear policy priority for LPG and electricity in residential applications in India, South Africa, and Morocco. Continued shortages in renewable energy technology and electrolyzer capacity might be two of the most unpredictable factors in moving towards the LCOH projected in the two hydrogen scenarios. Such shortages could be triggered by efforts to decarbonize the energy systems of the EU and USA based on large-scale public procurement programs that might dry up the market particularly for Morocco and South Africa.

5. Hydrogen in an off-grid solar setting based on carbon finance

The calculations on the cost of green hydrogen undertaken in the last chapter raise the question of viable avenues for financing the use of green hydrogen in cooking. This chapter introduces three potential options for financing green hydrogen projects and discusses the Daures project as an example on how infrastructures could be set up to enable cost-efficient cooking with green hydrogen.

A first financing option could be based on directly leveraging carbon markets to move from subsidized LPG to green hydrogen. In India and Morocco, carbon credits generated through green hydrogen could be an interesting way of decreasing cost of green hydrogen for better-off households relying on subsidized LPG. Koko Networks is one concrete example of how such a business model can be successful.

A central question on this first option of finance is related to tying green hydrogen to global or national markets for carbon offsets. A global approach could trigger a higher demand at the cost of higher volatility due to uncertainties related to political and economic stability in other world regions and GHG output. In a national carbon market, demand might depend on the presence of polluting industries which is a given in all three case studies. In Morocco this relates to raw material extraction, while South Africa and India host further hard to abate for heavy industries.

A second financing option might be based on longer-term public-private partnership in developing an international green hydrogen sector. Here, the longer-term goal would be to provide targeted off- and on-grid green hydrogen solutions for a water-food-energy nexus ecosystem. Such a financing solution would involve public money to carry initial risk of adapting green hydrogen solutions in India, South Africa, and Morocco. This would also require public finance for startups and SMEs in the initial stages of market development and later stage financial support for crowding in private investors. Such a sectoral approach could draw on the evidence in the off-grid solar sector (Galan, 2022a, 2022b).

A third financing option could emulate the LPG success story in India in combination with carbon credits, and longer-term sector development as seen in the off-grid solar sector. A hybrid option between financing options 1 and 2 is to initially rely on public sector support to stimulate both supply and demand for green hydrogen based on the reallocation of LPG subsidies. Here, the exit strategy would be at a later stage to crowd in carbon finance investors. In India and Morocco, this would mean limited cost for households as existing LPG cooking appliances would only need a slight adaptation. As LPG is also used as a backup fuel in South Africa, green hydrogen could potentially be also a greener alternative or even a way to leapfrog to cleaner cooking.

A central issue is to finance the required low-cost hydrogen which would need a rapid expansion of green hydrogen on-grid production or low cost off-grid electrolyzers. Both on- and off-grid production require significant investment in renewable energy and electrolyzer development. (BNEF, 2020)

A hybrid option of combining public funding with carbon financing presents an opportunity for off-grid solar and clean cooking companies. Companies such as Solstroem, allow access to carbon financing by aggregating and generating micro-credits for companies directly, avoiding the high transaction costs implied for smaller companies (ESMAP et al., 2022). Here, carbon credit technology platform Carbon Clear offers an interesting case for carbon credits that could connect the off-grid solar sector with clean

cooking applications.³⁹ The platform brings together off-grid solar stakeholders such as Sun King or Engie Energy Access.

From a private sector perspective, an interesting case is the company Koko networks which offers ethanol-based cookstoves that might be similar to methanol made from green hydrogen in terms of combustion dynamics and related costs. KOKO sells carbon credits to a subsidiary of Korea Electric Power Corp., South Korea’s coal-burning power utility, and is preparing to expand sales of the instruments to Europe.⁴⁰ Further organizations such as Atmosfair offer carbon offsets for clean cooking (e.g., EPCs).⁴¹

There are pilot projects emerging which explore how green hydrogen could be used to decarbonize and decentralize production. One such example is the Daures Green Hydrogen Village project in Namibia (see Figure 14). The project aims to explore applications of green hydrogen in the water-energy-food nexus and to create the first Net Zero village in Africa. Sustainable production of green hydrogen and ammonia from renewable sources form the core of the project. The goal of the project is to demonstrate green hydrogen applications and export of green hydrogen. Also, the project explores sustainable production of Net Zero agricultural produce from green houses that create local employment. (Daures Green Hydrogen Consortium, 2022)

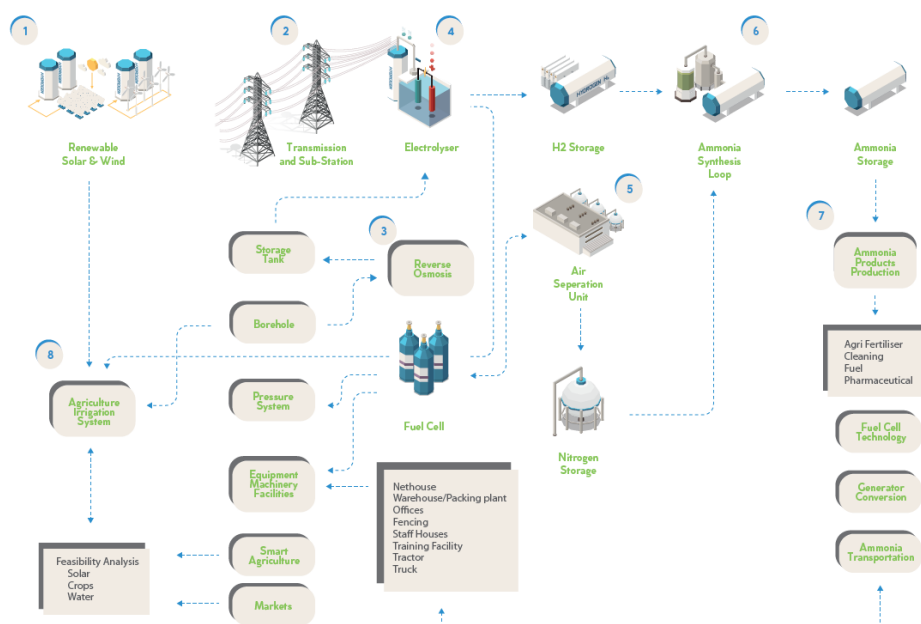


Figure 14: Mini-grid water-food-energy nexus. Source: Daures Green Hydrogen Consortium, 2021

6. Conclusion

The report discussed challenges and opportunities in enabling clean cooking through the transition to green hydrogen. Chapter 2 and 3 showed that there is an increasing number of stakeholders and literature that engages with green hydrogen and opportunities for cooking and other off-grid or on-grid applications. Looking at the cost of cooking in India, South Africa, and Morocco, Chapter 4 showed that

³⁹ <https://www.carbonclear.earth/>

⁴⁰ <https://www.bloomberg.com/news/articles/2022-01-26/koko-aims-to-replace-charcoal-in-47-billion-cooking-fuel-market?leadSource=verify%20wall>

⁴¹ https://www.atmosfair.de/en/climate-protection-projects/energy_efficiency/malawi-electric-cooking/

green hydrogen could become cost competitive. However, this would require significant cost reduction in all three cases. The high subsidies for LPG also limit the potential of green hydrogen in emerging as a competitive alternative in the clean cooking sector. One opportunity lies in considering a wider ecosystem within the food-water-energy nexus when it comes to green hydrogen.

As shown by the proposal for the Daures project in Chapter 5, green hydrogen should not be seen just as a fuel for cooking, but in addition as a way of improving agriculture and mobility for people living in off-grid environments. While this comes with additional complexities, it could also help to solve the many challenges in energy and food security. From a financing perspective, voluntary offsetting markets might be an opportunity to finance off-grid green hydrogen projects. As shown by other examples such as Koko networks, carbon finance can play a central role in expanding cleaner cooking. It remains however unclear how far green hydrogen can stand up to its promises in terms of offsetting carbon emissions.

There are several barriers that need to be overcome. A first barrier is the capital cost of electrolyzers. The high capital cost of conventional electrolyzers contributes about 70-80% of the overall cost of hydrogen in small to medium scale (5kW-100kW) configurations. A second barrier is the lack of suitable compression for smaller configurations that makes localized H₂ production difficult. A third barrier is access to purified water for hydrogen production where sea water could be a near future alternative (Farràs et al., 2021). A fourth potential barrier emerges around the question of business models for green electrolyzers. It remains open if electrolyzers can be best provided based on a leasing model or selling complete systems. In addition, this raises questions about licensing fees and the involved intellectual property rights. A fifth barrier refers to after sales maintenance and training of mechanics to operate a green hydrogen infrastructure. A sixth barrier are approaches to longer term storage of pressurized hydrogen or further development of storage efficiency through fuel cells or ammonia. A seventh barrier emerges around the question of tracking the green electricity for electrolyzers.

The results of this study show that despite the barriers, green hydrogen offers opportunities in further decarbonizing the cooking sector and making cooking healthier in developing countries. When solutions for technical and economic issues outlined above are found, green hydrogen could replace or complement highly subsidized LPGs or offer a backup solution to patchy electricity access for cooking.

The results of the study are not only relevant to the cases, but present transferable findings of how developing countries might connect to the ongoing green hydrogen transition to improve cooking. The lessons learned about future cost structures are applicable to other countries hosting large populations without access to clean cooking. This includes the 20 countries that are home to most of the 2.1 billion people who will lack access to clean cooking by 2030 (EA, IRENA, UNSD, World Bank, 2022). As LPG is a widely used cooking fuel beyond the three cases, this study also offers valuable results for other countries of the MECS program. Here, the report allows to draw lessons on how to best combine the dominant clean cooking technologies and fuels. Lastly, the report presented the state of knowledge on three countries that will likely act as hubs in the global green hydrogen ecosystem. Therefore, the report is a relevant starting point for evaluating how cost structures might create spillover effects in wider regions for clean cooking and which kind of stakeholders and policies are relevant to this end.

Looking at the role of green hydrogen in cooking, on-grid production could potentially lead to lower cost earlier than off-grid generation. Recent studies on green hydrogen show that there is still a large variation in generation costs for off-grid electrolyzers (Mukelabai et al., 2022). The ambitious plans to scale green hydrogen on the grid described in this study might lead to cheap green hydrogen sooner. Therefore, a

potential middle ground might emerge where green hydrogen is produced on the grid and transported to more remote locations. Here blends of green hydrogen with natural gas might emerge as a new type of cooking fuel.

Future research should further investigate cost elements that play a role in designing projects for green hydrogen for clean cooking. We should aim to understand avenues to reduce subsidies or connect them to new subsidy models based on carbon finance. Also, studies should look at potential co-benefits from green hydrogen such as applications for oxygen gained in the production process as well as applications in agriculture or providing clean water.

Further research should look at the following aspects:

- The development of business models in off-grid solar, green hydrogen, and cooking based on carbon finance.
- Projects that promote co-benefits between applications of hydrogen in the food-water-energy nexus.
- Further data should be collected on the cost of production, storage, and transportation of green hydrogen and the development of suitable appliances for cooking.
- Collect evidence on field-tested catalytic combustion stoves to establish proof of concept.
- The establishment of safety standards in developing green hydrogen stoves.

7. References

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Annex 1

Table 1: Cooking upfront cost in India (in INR)					
eCooking with induction + EPC****		LPG cooking****		Hydrogen cooker***	
Induction stove	1600	Cylinder + regulator	1450	Cylinder + regulator*	1595
Steel Cooking Utensils	3000	Cooking Utensils	2100	Cooking Utensils	2100
Electric Pressure Cooker	5000	Gas stove	1700	Hydrogen stove**	3400
Total	9600	Total	5250	Total	7095
In 2022 USD (7/12/2022)	116.72	In 2022 USD (7/12/2022)	63.83	In 2022 USD (7/12/2022)	86.26
<p>* Assuming a 10% higher cost compared to LPG ** Assuming double the cost due to lack of market ready stoves *** Own calculations **** (MECS 2022)</p>					

Table 2: Cost of cooking in India (in INR)											
eCooking with induction + EPC**		eCooking with induction**		LPG (subsidized)**		LPG (unsubsidized)**		Hydrogen scenario 1*		Hydrogen scenario 2*	
Household-kwh/year	766	Household-kwh/year	1022	Household-kwh/year	1592.5	Household-kwh/year	1592.5	Household-kwh/year	1533	Household-kwh/year	1533
Price electricity/year	5	Price electricity/year	5	Refills LPG (14.2kg)	8	Refills LPG (14.2kg)	8	Refills per year (2.7kg)	14.5	Refills per year (4.2 kg)	9.3
				Cost of refill	450	Cost of refill	899	Cost cylinder (INR/2.7)	486	Cost cylinder (INR/4.2)	1450.89
								Transport cost (INR/kg)	108	Transport cost (INR/kg)	168
								Final cost one cylinder	594	Final cost one cylinder	1618.89

Total per annum	3832	Total per annum	5110	Total per annum	3600	Total per annum	7192	Total per annum	8592.1	Total per annum	15053.8
In 2022 USD (7/12/2022)	46.59	In 2022 USD (7/12/2022)	62.13	In 2022 USD (7/12/2022)	43.77	In 2022 USD (7/12/2022)	87.44	In 2022 USD (7/12/2022)	104.46	In 2022 USD (7/12/2022)	183.02
<p>* Own calculations based on Toprisk et al. 2016 ** (MECS 2022) LPG transport cost assumed to be part of final price per cylinder.</p>											

Table 3: Cooking upfront cost in South Africa (in Rand)					
eCooking with induction + EPC *		LPG cooking***		Hydrogen cooker*	
Steel Cooking Utensils	699	Cylinder + regulator	100	Cylinder + regulator	110
Induction stove	2500	Cooking Utensils	385	Cooking Utensils	385
Electric Pressure Cooker (5L)	1190	Gas stove	2100	Hydrogen stove	4200
Total per annum	4389	Total per annum	2585	Total per annum	4695
In 2022 USD (7/12/2022)	255.62	In 2022 USD (7/12/2022)	150.55	In 2022 USD (7/12/2022)	273.44
<p>*Own calculations ** (Kimemia & Annegarn, 2016)</p>					

Table 4: Cost of cooking in South Africa (in Rand)											
eCooking with induction + EPC**		eCooking with induction**		LPG (subsidized)***		LPG (unsubsidized)***		Hydrogen scenario 1*		Hydrogen scenario 2*	
Household - kwh/year	667.74	Household - kwh/year	890.32	Household - kwh/year	1374.93	Household - kwh/year	1374.93	Household - kwh/year	1533	Household - kwh/year	1533
Cost of electricity Rand/kWh	2.78	Cost of electricity Rand/kWh	2.78	Refills per year (9kg)	12	Refills per year	12	Refills per year (2.7kg)	14.5	Refills per year (4.2kg)	9.30
Efficiency increase from Induction to induction and pressure cooker	3/4	Efficiency increase from hot plate to induction	3/4	Cost of refill (Rand/9 kg cylinder)	205	Cost of refill (Rand/9 kg cylinder)	266.5	Production Cost cylinder (Rand/2.7kg)	115.90	Production Cost cylinder (Rand/4.2kg)	425.47
								Transport cost (Rand/kg)	31.52	Transport cost (Rand/kg)	49.04
								Total cost cylinder	147.42	Total cost cylinder	474.51
Total per annum	1855.64	Total per annum	2474.19	Total per annum	2460	Total per annum	3198	Total per annum	2132.43	Total per annum	4412.38
In 2022 USD (7/12/2022)	108.07	In 2022 USD (7/12/2022)	144.10	In 2022 USD (7/12/2022)	143.27	In 2022 USD (7/12/2022)	186.26	In 2022 USD (7/12/2022)	124.19	In 2022 USD (7/12/2022)	256.98
<p>*Own calculations based on (Topriska et al. 2016) ** Based on (Masebinu & Kambule, 2022) *** based on (Kimemia & Annegarn, 2016) LPG transport cost assumed as part of final price per cylinder.</p>											

Table 5: Cooking upfront cost in Morocco (in DH)					
eCooking with induction + EPC *		LPG cooking*		Hydrogen cooking*	
Induction stove	550	Cylinder + regulator	350	Cylinder + regulator	385
Cooking Utensils	750	Cooking Utensils	290	Cooking Utensils	290
Electric Pressure Cooker	700	Gas stove	300	Hydrogen stove	600
Total	2000	Total	940	Total	1275
In 2022 USD (7/12/2022)	189.04	In 2022 USD (7/12/2022)	88.85	In 2022 USD (7/12/2022)	120.51
*Own calculations					

Table 6: Cost of cooking in Morocco (in DH)											
eCooking with induction + EPC*		eCooking with induction*		LPG (subsidized) *		LPG (unsubsidized)*		Hydrogen scenario 1*		Hydrogen scenario 2*	
Household - kwh/year	514.64	Household - kWh/year	686.18	Household - kwh/year	2859.88	Household - kwh/year	2859.88	Household - kwh/year	1533	Household - kwh/year	1533
Cost of electricity (DH/kWh)	0.953	Cost of electricity (DH/kWh)	0.953	Refills per year	17	Refills per year	17	Refills per year (2.7 kg)	14.5	Refills per year (4.2kg)	9.30
Efficiency increase from Induction to induction and pressure cooker	3/4	Efficiency increase from hot plate to induction	3/4	Cost per refill (DH/12 kg bottle)	42	Cost per refill (DH/12 kg bottle)	84	Production cost cylinder (DH/2.7kg)	85.70	Production cost cylinder (DH/4.2kg)	247.51
								Transport cost (DH/kg)	19.42	Transport cost (DH/kg)	42.45
								Cost one cylinder	105.12	Cost one cylinder	289.96

Total per annum	490.45	Total per annum	653.93	Total per annum	714.00	Total per annum	1428.00	Total per annum	1520.58	Total per annum	2696.24
In 2022 USD (7/12/2022)	46.36	In 2022 USD (7/12/2022)	61.81	In 2022 USD (7/12/2022)	67.49	In 2022 USD (7/12/2022)	134.97	In 2022 USD (7/12/2022)	143.72	In 2022 USD (7/12/2022)	254.84
*Own calculations LPG transport cost assumed as part of final price per cylinder.											

Annex 2 Interviews

	Role	Organisation
Interview 1*	Consultant	Consultancy on Electrification
Interview 2*	Business developer	Large technology corporation
Interview 3*	Director Climate Change	Energy company in East Africa
*Contact details upon request		