Proceedings of ECOS 2022 - The 35th International Conference On
Efficiency, **C**ost, **O**ptimization, **S**imulation and Environmental Impact of Energy Systems
3-7 July, 2022, Copenhagen, Denmark

Importing renewable energy to EU via hydrogen vector: Levelized cost of energy assessment

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Abstract:

European Green Deal sets the EU's target towards becoming the world's first climate-neutral continent by 2050. To achieve the 2050 Green Deal target, multi-combined actions are required, such as increasing renewable energy (RE) production in the EU, enhancing efficiency, and importing RE. The limited area, high population density, and geographical position constrain the EU's RE self-sufficiency; in fact, the energy import dependency of the European Union (EU-27) reached 58.4% and 60.7% in 2018 and 2019, respectively. Interestingly, the final energy consumption by fuel comprises 23% of electricity and 77% of molecules. Consequently, a sustainable energy system requires not only green electricity but green molecules as well to move from fossil to electrified chemical industry (chemistree).

In this context, the work analyses the LCOE of importing RE from Morocco, Algeria, Egypt, and Saudi Arabia to selected locations in the EU namely Rome, Madrid, and Cologne, since they have both a well-established energy importing/exporting network with the EU and a high potential of RE sources. A promising LCOE of H_2 is found in all importing scenarios with an average of 5.20 €/kg$_{H2}$. Hydrogen transport via pipelines (0.14 €/kg/1000 km) is found to be the optimal solution for the studied cases. Further investigation is required for importing RE via other types of molecules and e-fuels such as ammonia, methanol, and methane from the Middle East and North Africa (MENA) to the EU.

Keywords:
E-fuel, hydrogen, LCOE, renewable energy, Sustainability, transport.

1 Introduction

European Green Deal sets the EU's target towards becoming the world's first climate-neutral continent by 2050 [1]. To achieve the 2050 Green Deal target, multi-combined actions are required, such as increasing renewable energy (RE) production in the EU, enhancing efficiency, and importing RE [2]. The limited size, population density, and geographical position constrain the EU's RE self-sufficiency; in fact, the energy import dependency of the European Union (EU-27) reached 58.4% and 60.7% in 2018 and 2019, respectively [3, 4]. Interestingly, the final energy consumption by fuel comprises 23% of electricity and 77% of molecules [3]. Consequently, a sustainable energy system requires not only green electricity but green molecules as well to move wisely from fossil to electrified chemical industry (chemistree) [5].

Interestingly, the enormous total solar energy reaches the earth is 3,400,000 exajoules annually, which counts for 7000 to 8000 times the global energy demand [6]. However, on one hand, the worldwide solar energy potential is estimated at 1098 exajoules annually after considering constraints such as solar irradiation, suitable land, solar to electric technology, and net delivered energy to the end-user [7]. On the other hand, RE production is intermittent and varies temporally and spatially, which requires energy storage technologies, such as Power-to-X [8]. Hydrogen is considered as one of the primary energy vectors [8] and chemicals as well in the e-chemistree (electrified chemical industry) [5, 8]. The hydrogen is mainly produced via water electrolysis methods [9] which has a comparable water consumption to fossil-based hydrogen production (steam methane reforming) ~20 kg_{H2O}/kg_{H2} [10]. Despite the fact that green hydrogen is two times more expensive than large-scale fossil-based hydrogen (1.5-2.5 €/kg_{H2}); the continuously achieved improvements, enhanced efficiency and decreased cost per kW of photovoltaic panels and electrolysers are leading to breakeven price of green hydrogen by 2025 [11, 12]. Moreover, PV energy systems can be coupled directly with an electrolyser using DC-DC converter, which simplifies the system, reduces the cost and transmission loss [13-16]. Sayedin et al. optimize the PV-electrolyser system to maximize the Levelized cost of energy (LCOE) and minimize energy loss [15]. Coppitters et al. optimized the directly coupled PV-electrolyser system under techno-economic uncertainty to avoid a suboptimal coupling and obtained optimal $LCOE_{H2}$ of 10.5, 7.2 and 6.3 €/kg_{H2} in Bern, San Francesco and Johannesburg, consequently; without considering the H_2 transportation [16].

Dupont et al. studied the energy return on investment (EROI = facility's energy output/energy input over the facility's lifetime) for PV panels and concentrating solar power (CSP) power plants; the solar energy potential was assessed by taking into account net energy, solar to electric technology, solar irradiation and land use [7]. Using mono-si-PV as a PV technology, there are a few regions (e.g. regions in Chile, Algeria, Namibia, Libya, Egypt, Saudi Arabia, Oman, Yamen, Australia, Sudan, and Chad) where the EROI≥9 and only 15% of the solar potential worldwide can be harvested [7]. Despite the importance of EROI index and the clear energy return on energy invested, another index such as LCOE is required to assess the energy production economically.

Transportation counts a major share of the energy's final cost. The total cost of production and shipping RE from Morocco, Oman, Chile, Australia to Zeebrugge, EU was studied by the H_2 import coalition [17]. Morocco's scenario has minimal H_2 and NH_3 importing LCOE (60~90 €/MWh) [17]. However, the report does not reveal the used design variables and model parameters. Additionally, importing RE from other Mediterranean neighbourhoods (e.g. Algeria, Egypt) and Gulf countries (i.e. Saudi Arabia) was not studied. Even though the pipelines networks of natural gas and hydrogen are well established and being developed in EU-27, Mediterranean neighbouring countries, and the middle east [18, 19], there is a scarcity of comprehensive studies that consider the interconnection of these pipeline networks which can be used to transport green hydrogen via retrofitted existed pipelines and/or installing new pipelines. The European Hydrogen Backbone proposes retrofitting existing gas infrastructure, along with installing new dedicated hydrogen pipelines and compressor stations [18]. The interconnected dedicated H_2 transport infrastructure will be stretched to 11600 and 39700 km by 2030 and 2040, subsequently [18, 20, 21]. Moreover, there is already a gas pipeline network in North Africa and middle East (Trans-Saharan, Maghreb-Europe, Medgaz, Galsi, Trans-Mediterranean, Green stream, Others) between Spain, Algeria, Italy, Morocco, and Tunisia [22]. And hydrogen ''South-Nord stream'' from Egypt to Italy via Greece with a similar capacity as the Nord-stream, length of 2,500 km and with a 66 GW capacity, consisting of 2 pipelines of (900 mm) 48 inches each would connect pipelines infrastructure in Egypt and Saudi Arabia to the pipeline's infrastructure in Italy, the EU; this would bring the cost of H_2 transportation down to 0.005 €/kWh or 0.2 €/kg H_2. This work analyses the LCOE of importing RE from these countries, since they have both a well-established energy importing/exporting network with the EU and a high potential for RE sources [7, 23]. The LCOE covers the LCOE of production ($LCOE_{H2}$) and LCOE of transporting ($LCOE_{trans.}$).

2 Method and procedure

The PV-electrolyser system models consist 5 MW PV system array, DC-DC converter, and electrolyser (Figure 2). A SunPower PV array is considered in this study (model: SPR X22 470 COM [24]) to convert solar energy into electricity based on hourly measured ambient temperature and solar irradiation. A single PV cell is considered based on a single diode model and the current of PV cell I_{PV} is a function of photocurrent (I_L), the diode current (I_0), and the series resistance (R_s):

$$I_{PV} = I_L - I_O\left[exp\left(\frac{q(U_{PV}+I_{PV}R_S)}{n_d K T_{amb}}\right) - 1\right], \tag{1}$$

(q) is the electron charge, (k) is the Boltzmann constant, and (n_d) is the diode ideality factor. The PV model is described in detail in a previously published article by Coppitters et al. [25].

2.1 Proton Exchange Membrane (PEM) electrolyser:

The hydrogen is produced from the intermitted supplied electricity using a Proton Exchange Membrane (PEM) electrolyser was considered. The experimentally validated model by Garcia-Valverde et al. is adopted, and the applied PEM electrolyser's operating voltage (U_{elec}) is calculated (Eq. 2):

$$U_{elec} = U_{rev} + U_{electrodes} + U_{ohm}, \tag{2}$$

(U_{rev}) is the reversible potential, ($U_{electrodes}$) is the overpotential at the electrodes, and (U_{elec}) is the ohmic overpotential. The current ($I_{stack}= N_p \cdot I_{elec}$) and voltage ($U_{stack}=N_s \cdot U_{elec}$) of the electrolyser's stack depend on the number of combined electrolysers in parallel (N_p) and series (N_s). The hydrogen production is a function of Faraday efficiency (η_F), several electrolysers in series (N_s), and current (I_{stack}).

$$\dot{\mathrm{m}}_{\mathrm{H}_2} = \frac{N_s I_{stack}}{2000F} \eta_F, \tag{3}$$

Further details are explained extensively in the published work by Garcia-Valverde et al. and Coppitters et al. [15, 16].

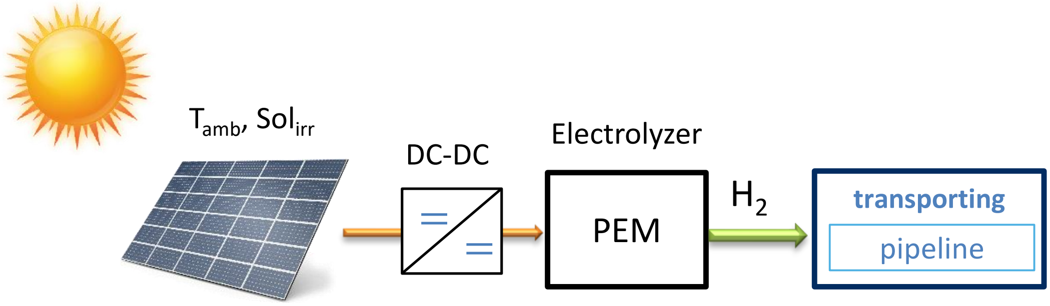

Figure 1 The flow chart of the photovoltaic-PEM electrolyser power to the Hydrogen plant

2.2 Levelized Cost of Energy

The LCOE is quantified to analyse the techno-economic performance of the system; the LCOE of H_2 production for each case (city) is calculated and the LCOE of transporting via pipeline is calculated based on the European hydrogen backbone (EHB) study [18]; EHB distinguishes three scenarios to transport H_2 via 1. new infrastructure [0.16-0.23 €/kg/1000 km], 2. retrofitted infrastructure [0.07-0.15 €/kg/1000 km] or 3. A mix of new and retrofitted infrastructure [0.09-0.17 €/kg/1000 km] [18]. In this study, the $LCOE_{trans.}$ is considered to be 0.15 €/kg/1000 km on average, 0.07 €/kg/1000 km for the best scenario (retrofitted infrastructure), and 0.23 €/kg/1000 km for the worst scenario (new infrastructure) (Table 1).

Table 1: PV-electrolyser system model decision variables of the NSGA-II algorithm.

Parameter	Deterministic value
$CAPEX_{PV}$	466 €/kWp [26]
$OPEX_{PV}$	17.5 €/kW/y [27]
n_{PV}	25 y [27]
$CAPEX_{elec}$	1300 €/kW (avg. 2022) [11, 28]
$OPEX_{elec}$	4% [29]
n_{elec}	8000 h [29]
G	hourly data for one year [30]
T_{amb}	hourly data for one year [30]
r	6% [16]
μ_{ISC}	0.065 A/K [16]
μ_{UOC}	0.08 V/K [16]
I_{SC}	3.8 A [16]
U_{OC}	21.1 V [16]
A_m	50 cm^2 [16]
t_m	0.0051 cm
η_F	99.5% [16]
U_{degr}	6μV/h [16]
T_{elec}	design parameter[16]
i_{lim}	2 A/cm_2 [16]

$\text{CAPEX}_{\text{new,Pipeline}}$	2.75 M€/km [20]
$\text{CAPEX}_{\text{retrofit,Pipeline}}$	0.5 M€/km [20]
$\text{CAPEX}_{\text{new/retrofit, compressor, station}}$	3.4 M€/MW [20]
Electricity price	50 €/MWh [20]
Depreciation period pipelines	42.5 y [20]
Depreciation period compressors	24 y [20]

By 2030, the CAPEX of PV and PEM electrolyser are projected to 340 €/kWp and 800 €/kW; which will reduce the LCOE drastically.

2.3 Optimal trade-off between hydrogen production and LCOE_{H2} (Knee/elbow)

The increased hydrogen production leads to increased LCOE_{H2}, since the electrolyser efficiency drops with the increase in operating I, V [31]. The maximum H_2 production leads to the highest LCOE_{H2} and vice versa, it is important to find the trade-off point between hydrogen production and LCOE_{H2}. Satopaa et al. proposed a method to detect knee (trade-off) points in system behaviour [32]. Besides Satopaa's method, in this work, the critical point of maximum H_2 production and LCOE_{H2} is considered as a reference point and an index is proposed "$\text{Gain\_LCOE}_{\text{H2}} = \text{LCOE}_{\text{max}} - \text{LCOE}_{\text{i}}$" which represents the gain of LCOE_{H2} due to operating below the critical point. Applying the proposed $\text{Gain\_LCOE}_{\text{H2}}$ and Satopaa's method [32, 33] results in defining the ideal domain of LCOE_{H2} and (hydrogen production) m_{H2}. Finally, the average of LCOE_{H2} is considered as a trade-off point.

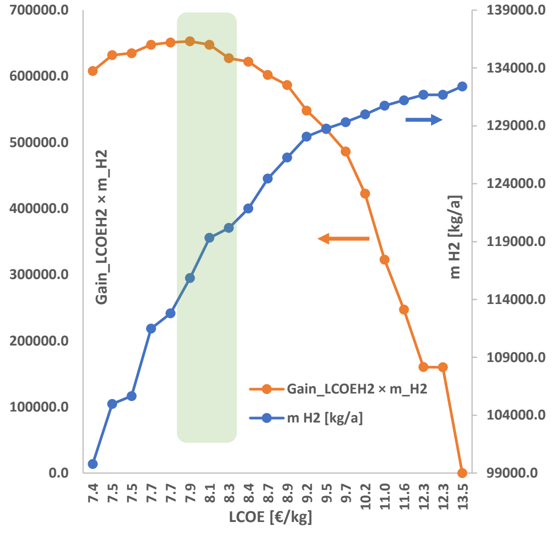

Figure 2 The domain of the trade-off points between hydrogen production and LCOE_{H2}

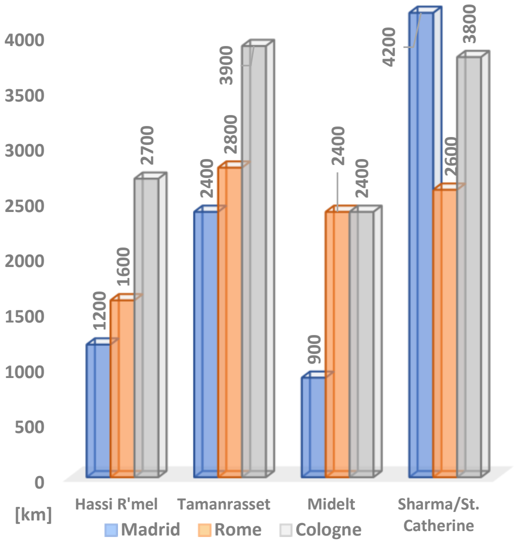

Figure 3 The pipelines/distance between H_2 production and consumption locations

Finally, similar to the way of PV's maximum power point (MPP) calculation, the point of max. m_{H2} and max. $\text{Gain\_LCOE}_{\text{H2}}$ due to operating below the critical point, which corresponds to the max. LCOE_{H2}, is calculated as shown in Figure 2.

2.4 Identifying practical potential importing and exporting locations and input data

Three EU countries, namely Italy, Spain, and Germany, are chosen as importers of green hydrogen due to their high net imports of energy (>90 Mtoe) and high energy import dependency (>60%). Madrid and Rome are chosen for Spain and Italy cases due to their central topographic position, but Cologne is chosen for the Germany case due to intensively centralised industry in North Rhine-Westphalia.

The theoretical PV power production is measured according to the amount of energy physically available (considered Level 0), which is not enough to select the ideal area to install PV panels [34, 35]. *Level 1* considers constraints such as complex terrain, large water bodies, forests, uninhabited areas, and intra-urban areas, and *Level 2* of PV power production potential considers excluding protected areas and cropland [7, 34, 35]. The following countries are chosen (Morocco, Algeria, Egypt, and Saudi Arabia) due to their high PV power output (≥5.0 kWh/kWp), practical potential zonation (Level 1 and 2) [36], and high EROI [7]; besides the short distance to EU which allows interconnection of gas pipelines networks (Table. 2).

Table. 2. Exporting areas of high practical potential solar power in North Africa and the Middle East

Country	City	EROI	Latitude and Longitude
Spain	Madrid	≥5	40.4168° N, 3.7038° W
Italy	Rome	≥5	41.9028° N, 12.4964° E
Germany	Cologne	<5	50.9375° N, 6.9603° E
Algeria	Hassi R'mel	≥7.5	32.9276° N, 3.2713° E
Algeria	Tamanrasset	≥9	22.7903° N, 5.5193° E
Morocco	Midelt	≥7.5	32.6799° N, 4.7329° W
Saudi Arabia	Sharma	≥9	28.0313° N, 35.2383° E
Egypt	St. Catherine	≥9	28.5609° N, 33.9480° E

For comparison reasons, the $LCOE_{H2}$ in Madrid, Rome, and Cologne are calculated. The hourly ambient temperature and solar irradiation are obtained from an online renewable energy dataset [30]. Figure 3 shows the distance (pipelines length) between the H_2 production and consumption locations. Based on this distance, the LCOE of transportation is calculated ($LCOE_{trans.}$); subsequently, the overall LCOE ($LCOE_{trans.}$+ $LCOE_{H2}$) is calculated.

2.5 Optimization algorithm

In this work, the Python framework (RHEIA) [37] is used to perform design optimisation. The Non-dominated Sorting Genetic Algorithm (NSGA-II) is implemented to optimise the PV-electrolyser system to find the optimal design (e.g. Design sample’s Pareto set). Latin Hypercube Sampling is used to initiate the first design sample for NSGA-II, detailed description of the framework and optimisation model can be found in the published literature [16, 37]. The population samples are carried out in parallel on Intel(R) Core(TM) i7-10610U CPU @ 1.80GHz 2.30 GHz PC.

3 Results and discussion

After applying the optimisation algorithm on the system model, the design optimisation results are presented and discussed.

3.1 Levelized cost of H_2 production ($LCOE_{H2}$)

By applying the optimization algorithm, the $LCOE_{H2}$-m_{H2} (Pareto front) for each location has been determined (Figure 4). All considered production (exporting) locations in MENA have lower $LCOE_{H2}$ and higher H_2 production compared to consumption (importing) locations viz. Madrid, Rome, and Cologne in the EU. The trade-off points between H_2 production and $LCOE_{H2}$ results of intermediate solution (highlighted points, Figure 4) are based on the illustrated procedure in section 2.3. The optimal $LCOE_{H2}$ ranges from 4.65 to 4.93 €/kg for the production/exporting locations, in contrast, the $LCOE_{H2}$ for Madrid, Rome, and Cologne cases are 5.37, 5.77, and 7.01 €/kg, consequently, which is comparable to those obtained results by Sayedin et al. [38]. The best PV-electrolyser system performance is found to be in Tamanrasset, Algeria where the optimal $LCOE_{H2}$ is 4.65 €/kg at 208994 kg/year. The performance of the system in St. Catherine is close to the one in Tamanrasset with $LCOE_{H2}$ is 4.77 €/kg at 210767 kg/year. Despite the short distance between Sharma and St. Catherine, the $LCOE_{H2}$ is 0.08 €/kg higher in Sharma. $LCOE_{H2}$ of Midelt is in the same range and below 5 €/kg. In the aim of compression of the overall LCOE, two cities in Algeria with different solar irradiation and distance from the EU are considered namely Tamanrasset and Hassi RMel. The $LCOE_{H2}$ in Hassi RMel is found to be 0.28 €/kg cheaper compared to Tamanrasset.

The maximum achievable H_2 production exceeds 200000 kg in all exporting locations in MENA. On the other hand, the highest H_2 production (186041 kg) in the European studied locations is found in Madrid, Spain which is 40%, 12% higher than Cologne and Rome, accordingly.

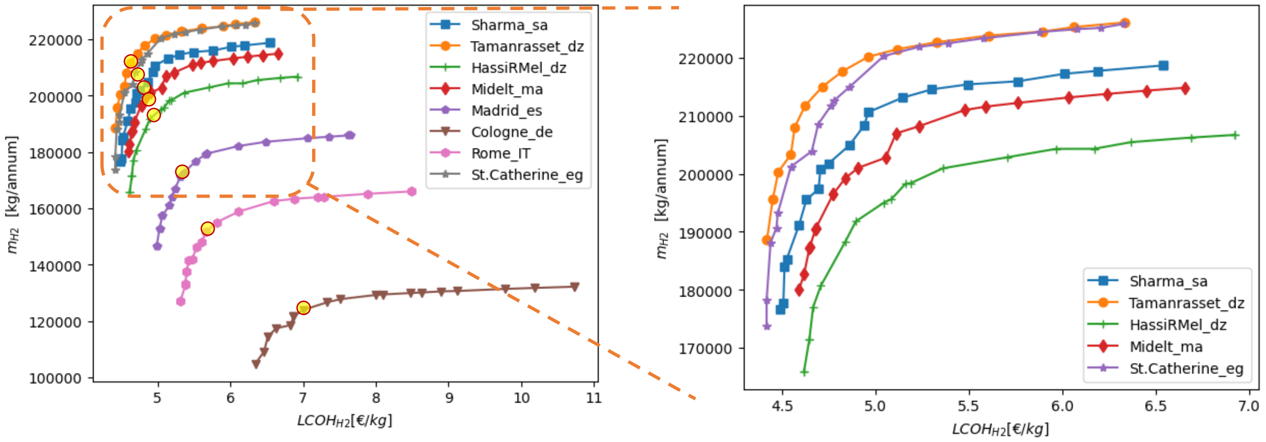

Figure 4 Pareto front of the hydrogen production and minimising the Levelized Cost of Energy (Hydrogen) ($LCOE_{H2}$) in Sharma, Saudi Arabia; Tamanrasset and Hassi RMel, Algeria; Midelt, Morocco; Madrid, Spain; Cologne, Germany; Rome, Italy; and St. Catherine, Egypt.

By 2030, the $LCOE_{H2}$ will decrease significantly e.g. in Hassi RMel $LCOE_{H2}$ will decrease from 4.93 to 3.5 €/kg. and in Cologne, will decrease from 7.01 to 5.0 €/kg. This decrement is attributed to the decreased CAPEX of PEM electrolyser and PV from 1300 €/kW to 800 €/kW; and from 466 €/kWp to 340 €/kWp by 2030 (Figure 5).

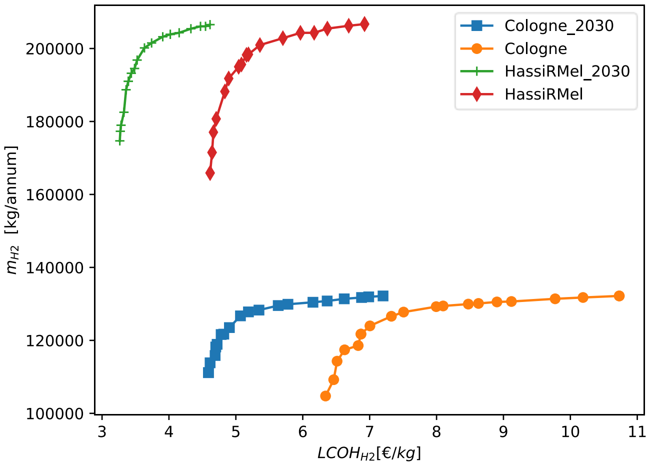

Figure 5 Pareto front of the hydrogen production and minimising the Levelized Cost of Energy (Hydrogen_2030) ($LCOE_{H2\_2030}$) in Hassi RMel, Algeria and Cologne, Germany.

3.2 Levelized cost of transport (Pipelines)

A pipeline network is considered for H_2 transportation in this study due to two facts firstly there is already an existing natural gas pipeline network that can be retrofitted; secondly, establishing a new pipeline network between MENA and EU is technically visible [20]. There are several factors that affect the $LCOE_{trans.}$ Via pipelines such as the distance, operating pressure, depreciation period of compressors and pipelines, CAPEX and OPEX of compressors and pipelines which vary depending on the size (diameter: <700mm, 700-900mm, and >900mm). For instance, the CAPEX of a small pipeline (<700mm) is (1.5 M€/km) almost 50% less than the CAPEX of a large pipeline (1.5 M€/km at D >900mm); but the final $LCOE_{trans.}$ for small [0.05-0.14 €/kg/1000km] and large pipelines are comparable to each other [0.058-0.16 €/kg/1000km]. interestingly, retrofitting the existing natural gas pipeline network would reduce the $LCOE_{trans.}$ by 55±10% compared to the newly installed pipelines. The average $LCOE_{trans.}$ for 1000 km is 0.14 €/kg and deviates ±0.088 €/kg between the worst and the best scenarios. Figure. 6 shows the $LCOE_{trans.}$ additionally, to the $LCOE_{H2}$ for exporting locations namely Tamanrasset, Sharma, St. Catherine, Midelt, and Hassi Rmel. The $LCOE_{trans.}$s for 1000, 2000, 3000 and 4000 km range [0.05, 0.23], [0.10, 0.46], [0.16, 0.68] and [0.21, 0.91], consequently. Compared to H_2 transport via pipelines (48”), shipping H_2 via Liquid organic hydrogen carriers (LOHC) and ammonia vectors could be competitive for distances longer than 3300 and 4400 km consequently [21]. In the study, all transporting scenarios go through on-shore land mainly which justifies H_2 transport from MENA to EU via pipelines rather than shipping.

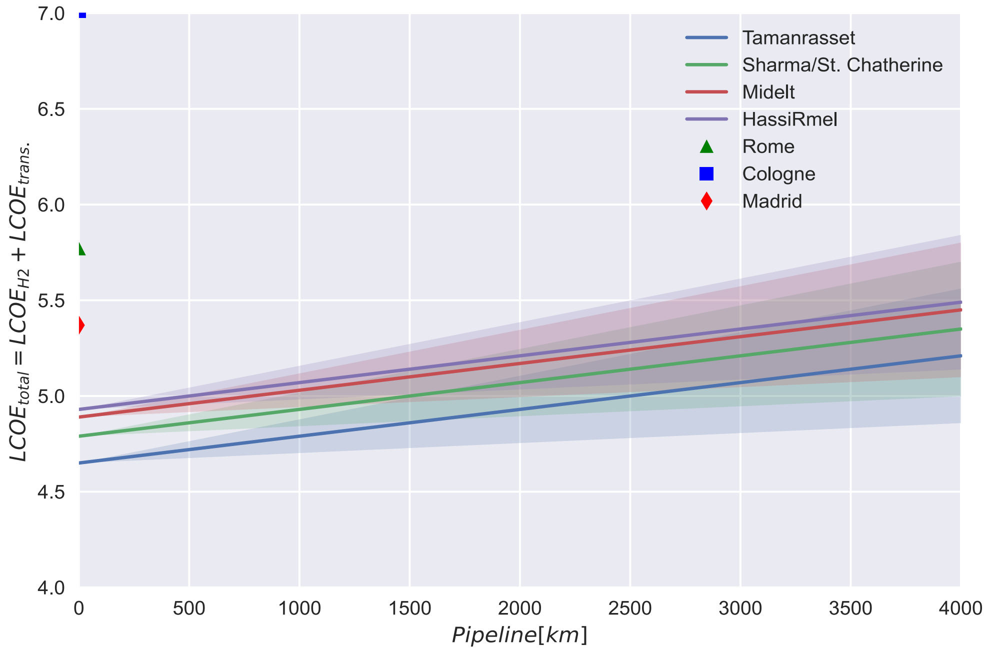

Figure. 6 The mean $LCOE_{total}$ increment with pipeline transport distance and the deviation due to $LCOE_{trans.}$ uncertainty from Sharma, Saudi Arabia; Tamanrasset and Hassi RMel, Algeria; Midelt, Morocco; and St. Catherine, Egypt compared to $LCOE_{total}$ of locally produced H_2 in Madrid, Spain; Cologne, Germany; and Rome, Italy.

3.3 Total Levelized Cost of Energy ($LCOE_{total.}$)

In all studied cases, the $LCOE_{total.}$ of imported H_2 from MENA to the EU ranges between 4.7 and 5.6 €/kg which gives importers the flexibility to diversify H_2 sources without risking a high difference in the $LCOE_{total.}$. However, considering the $LCOE_{total.}$ mean and deviation of the best and worst scenarios for each case is important in matching exporting-importing locations. For instance, $LCOE_{total.}$ for importing H_2 to Madrid from Hassi Rmel, Midelt and Tamanrasset are 5.10±0.11 €/kg, 5.02±0.08 €/kg, and 4.98±0.21 €/kg, consequently.

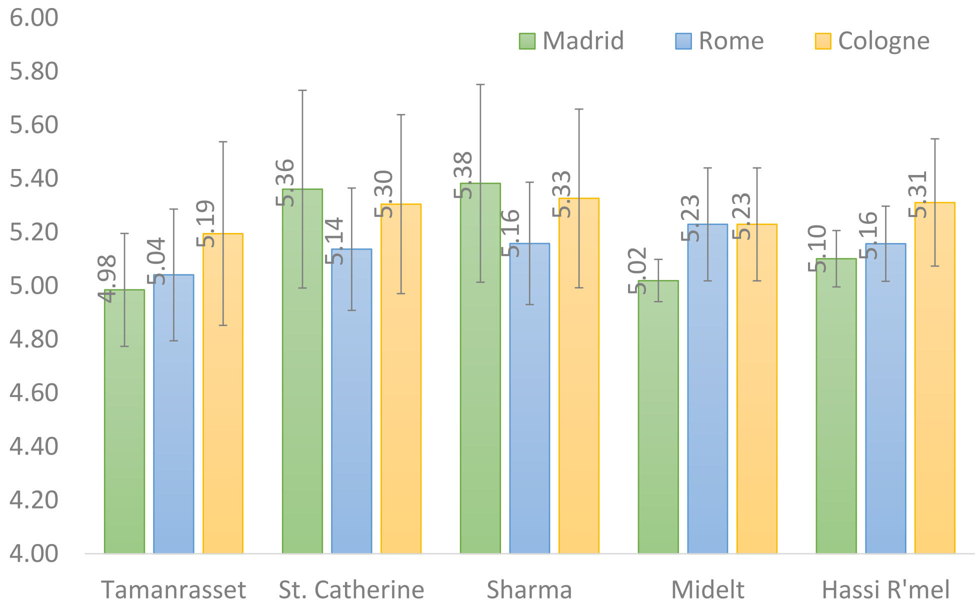

Figure. 7. The $LCOE_{total}$ of importing H_2 to Madrid, Spain; Cologne, Germany; and Rome, Italy from Sharma, Saudi Arabia; Tamanrasset and Hassi RMel, Algeria; Midelt, Morocco; and St. Catherine, Egypt.

For the Rome case, the optimal $LCOE_{total.}$ is associated with importing H_2 from Tamanrasset (5.04±0.25 €/kg) and Hassi Rmel (5.16±0.11 €/kg), followed by Sharma (5.16±0.23 €/kg), St. Catherine (5.14±0.23 €/kg) and finally Midelt (5.23±0.21 €/kg).

Considering 48” pipelines for H_2 transport to Cologne gives an advantage of import from Tamanrasset; in contrast, considering 36” pipelines gives an advantage of import from Midelt. Figure. 7 shows an interesting similarity of exporting locations namely Sharma and St. Catherine which is attributed to the close locations that lead to the similarity in $LCOE_{H2}$ due to the likeness of PV-electrolyser system’s operating conditions and similarity $LCOE_{trans.}$.

4 Conclusion

Producing H_2 using directly coupled photovoltaic-electrolyser systems in MENA and H_2 transport to EU via pipelines is promising. And from a techno-economic perspective, such a connected export-import network should achieve a Levelized cost of hydrogen of 5.20±0.13 €/kg. The lower $LCOE_{H2}$ compared to published results [16] is attributed to the decreased $CAPEX_{elec.}$ mainly. In the studied cases, H_2 transport via pipeline is favored over shipping, meanwhile, shipping could be the only option and more economic for H_2 import from remote overseas locations such as Chile and Australia. The $LCOE_{H2}$ counts for the major part of $LCOE_{total}$ with 92.6±2.7%. The research and development on PV and electrolyser technologies decrease their CAPEX and OPEX continuously which would lead to lower $LCOE_{H2}$, which would give the higher weight of the $LCOE_{trans.}$ in the final $LCOE_{total}$ compared with the current scenario. In this study, importing H_2 molecules is considered only, further investigation is required on other molecule/e-fuel types such as ammonia, methanol, and methane.

ACKNOWLEDGEMENTS

This project has received funding from the European Union’s Horizon 2020 research and innovation programme under grant agreement No 884157.

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