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Greening an Oil Exporting Country: Libyan Hydrogen, Solar and Gas Turbine Case Study

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Abstract

To decarbonize human activities a wide range of economic sectors need to coordinate and integrate their efforts and investments at a very high level. In the present research, a techno philosophical novel country-level quantitative thinking and foundation technique is offered to influence national policy and practice, aiming to set the decarbonization agenda for a complex economy. Libya has been chosen as a case study, a major oil exporter and the home of two of the authors. The principles presented here are valid to set decarbonization agendas worldwide. Official and unofficial country-level energy statistics were compiled, integrated, converted, and collated to start the exercise. The philosophical basis of the study is a decarbonization platform that comprises electricity, hydrogen, and gas turbines. The resulting analytical model incorporated consumption in different sectors, geographical data, meteorological patterns, solar illumination, consumption patterns and other information. Some inconsistences and gaps were bridged with reasonable assumptions and projections. This model provided a useful basis on which to examine replacement scenarios to decarbonize and influence production and user engagement with a realistic precision. The objective was to retain the benefits of the current energy consumption, coupled with a growth rate of 2% and to evaluate the resulting change in energy consumption arising from a fully green economy. Although there is an element of speculation and uncertainty in the results some very relevant qualitative and quantitative observations and conclusions emerge. Key in these scenarios is the use of hydrogen and a vast increase in electricity demand. Two scenarios were examined based on solar photovoltaic renewable systems working alongside hydrogen fueled gas turbines. In the first case the energy requirement was based on replacing fossil fuels with renewables and in the second the requirements included energy exports at a similar level as those delivered in the past, where past exports were oil and future exports are based on hydrogen. The results clearly show that the transition will require vast changes and investment. The core requirements are 4900 or 12000 km^2 of solar photovoltaic farms, for self-sufficiency and exports respectively plus 54 single shaft 600 MW combined cycle gas turbines.

Keywords: Oil Exporting; Hydrogen Fueled Gas; Decarbonization; Solar Photovoltaic Farms; Environmental Sustainability

Abbreviations: FCV: Fuel Calorific Value; GJ/T: Gigajoules/tonne; H_2: Hydrogen; H_2 TGTCC: Hydrogen fueled gas turbine combined cycle; kTonne: Kilo Tonne; MT: Mega Tonnes; MTOE: Million tonne oil Equivalent; NOx: Nitrogen Oxides; PJ: Petajoules; TJ: Terajoule

Introduction

The urgency, global nature, and necessity for substantial investments for decarbonization are widely recognized [1,2]. These investments are crucial to preserve the significant progress achieved over the past century in reducing global poverty [3]. Hence, environmental preservation, sustained economic growth, and the wise use of natural resources are inextricably linked. Major investors are already gearing up for this transition [4]. The philosophy of concurrent economic and environmental sustainability, the recognition of the issue's global nature, and the urgency to engage young talent are paramount [5]. Collaborative efforts spanning multiple sectors in large economic entities can yield significant economies of scale and experiential learning. This necessitates comprehensive and coordinated transition strategies that span across many economic sectors. In this study, a knowledge gap is addressed by introducing a novel techno philosophical approach [6] providing a clear understanding of the challenges and requirements, thereby informing these strategies.

A comprehensive and quantitative country-level replacement analysis of this kind has not been previously reported in public literature. Libya, a leading oil exporter and the home country of one of the authors, has been selected, here, as a case study for decarbonization by 2050. A key question for an oil exporter is how to decarbonize and, simultaneously, create energy-based wealth for its citizens and the world. Given its size and the planned replacement of hydrocarbon exports with green energy, Libya is a suitable candidate for such an evaluation, permitting an analysis that is both useful and representative. The volatile political situation in the country posed challenges in selecting a baseline for the study. However, in hopeful anticipation for the country's journey towards peace and prosperity, national and international data were accessed to estimate future energy demands and daily consumption patterns [7-14].

Renewable Energy Decarbonization

Many decarbonization studies have been carried out. However, no evaluation was found at a country level and comprising full replacement of socioeconomic benefits encompassing economic growth considerations in the timeframe of the move away from fossil fuel energy. The studies found were sometimes for individual population or economic units, sometimes for generation method. The focus on the present study is for wind energy alone, but the search was conducted for a range of decarbonization methods. Combining solar heat and photovoltaics emerges as a promising avenue for industrial decarbonization, emphasizing optimal integration for enhanced performance, cost-effectiveness, and environmental impact [15]. In Italy, the transition to 100% renewable energy unfolds with challenges, met by proposals such as utilizing energy-dense polysaccharides for storage. High installed capacities of renewable power plants and energy storage systems become focal points, alongside exploring consumer willingness to pay for green energy [16]. Global studies spanning California, Wisconsin, and Germany underscore the significance of a balanced portfolio of zero- and low-carbon resources.

The primary focus is placed on the achievement of cost-effective electricity generation and the reduction of carbon emissions. This includes addressing challenges related to integrating renewable energy into existing systems and understanding the impact on electricity rates, grid stability, and local industries [17]. Power-to-gas systems play a crucial role in absorbing excess renewable electricity, particularly in Germany, where they capture surplus wind and solar power. The integration of these systems with natural gas grids is deemed essential for the large-scale integration of renewable energy [18]. In the United States, the Markal nine-region model analyses various technology options for decarbonizing the power sector, emphasizing the technical feasibility of reducing greenhouse gas emissions. Through this analysis, insights are gained into the influence of different policies on electricity generation mix, emissions, and costs, enabling informed decision-making [19,20]. When examining policies for resilient decarbonization of the power sector in the United States, a tradeable performance standard and a hybrid Clean Electricity Standard emerge as advocated solutions. These solutions are highlighted for their cost-effectiveness and the urgent need for significant cost reductions in zero and near-zero-carbon technologies [21]. Strategies for managing variable electricity loads in wind and hydrogen systems take center stage, particularly in the context of a wind farm in Spain. Comparative analyses that encompass wind-hydrogen systems and battery storage provide valuable insights into addressing fluctuations in renewable energy production [22]. The importance of heat pumps in decarbonizing heating systems is emphasized, with a specific focus on their potential for reducing CO2 emissions in China. The integration of air-source heat pumps into district heating systems and the replacement of urban central heating systems with heat pump heating are proposed as means to achieve sustainable outcomes [23].

In smart cities of China, the role of electrolytic hydrogen in integrating with distributed renewable energy sources is explored. A focal point becomes the cost-competitiveness of electrolytic hydrogen production using wind power, along with its potential contributions to industrial transformation and sustainable development [24]. Hydrogen, positioned as a versatile energy carrier, takes center stage in discussions surrounding the decarbonization of oil-exporting nations, offering solutions to leverage untapped hydrocarbon reserves and stabilize grids in regions with renewable resources [25]. Strategies for decarbonization and the integration of renewable energy into West African nations are examined through Energy Plan modeling. The synergy between natural gas and renewable energy sources is emphasized, and the impact of cross-border electricity trading on generation costs and carbon emissions is discussed [26]. The potential for renewable electrolytic hydrogen in Algeria is assessed, with a specific focus on solar photovoltaic and wind resources. Feasibility discussions revolve around the use of solar energy for hydrogen production and the optimization potential of wind power for electrolysis [27].

Power-to-hydrogen projects in Morocco are scrutinized, simulating hydrogen production from wind and photovoltaic plants. Comparative assessments that consider production rates and costs shed light on the potential of wind-based hybrid energy systems [28]. Studies exploring the intersection of wind energy and hydrogen production in Iran delve into assessing the potential of wind power for electricity and hydrogen generation. Strategic locations for harnessing wind energy and producing hydrogen are proposed to achieve sustainable outcomes [29]. A critical review evaluates the challenges associated with alternative vehicular fuels, including electricity, hydrogen, and biofuels.

The discussion centers on the restrictions, such as the scarcity of resources, difficulties associated with infrastructure, and the expenses linked to battery-powered and fuel-cell-powered vehicles. The potential of biofuels is examined, considering the availability of feedstock and the dilemma of food versus fuel [30]. The primary focus is on the decarbonization potential of sustainable propulsion in road transportation. This exploration encompasses the utilization of renewable fuels, e-fuels, hydrogen, and electric vehicles to achieve carbon-neutral mobility. Special attention is given to the comprehensive data regarding the techno-economic performance of alternative fuels [31]. In the context of Uzbekistan's cement industry, studies concentrate on

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evaluating decarbonization pathways. These routes encompass carbon capture, storage, and utilization, the use of alternative fuels, electrification, and the integration of waste heat. Techno-economic assessments are conducted to analyze the performance and cost of various decarbonization systems, thereby providing valuable insights into the challenges and opportunities for the cement industry [32,33].

Thus, the analysis conducted here stands out because of its comprehensive approach that includes coverage of national and multi-economic sectors. Despite the assumptions and simplifications, it provides a comprehensive vision for decarbonizing any country. The authors emphasize that the single-source electrical supply (solar energy) is intended for visualization purposes. The authors aim to study the magnitude of the requirements resulting from solar energy decarbonization. Results are shown for illustrative purposes, without a recommendation for this source solution. A similar study was conducted by the authors regarding wind energy [34] , and closed cycle helium gas turbine [35], which adds another dimension to the analysis. The next step is to combine the studies on three into one comprehensive analysis, exploring the potential synergies and trade-offs between these sources.

Analysis Method

The present analysis can be divided into six steps. The first three steps focus on the process to define energy demand patterns. The final three aim to match demand and supply. The first step is an evaluation of the energy needs of the country in 2050, assuming a continuation of present trends, with a large emphasis on hydrocarbon fuels. The second step is the evaluation of the energy requirement to provide (via hydrogen and electricity) the same 2050 social and economic benefits using energy sources that do not emit carbon. The third step is using present daily and seasonal consumption patterns to produce the estimated equivalent and decarbonized daily and seasonal consumption patterns for 2050. The year is assumed to consist of four seasons, each represented by 91.25 ‘standard’ days of 24 hours. This third step includes adjustments to ensure that daily and seasonal energy consumption patterns match the annual scenarios of step 2.

The fourth step is the collection of information to evaluate solar energy potential in different geographical areas of the country. The fifth step is the conversion of this energy potential into electrical power and hydrogen from electrolysis using up to date equipment information. This includes the performance of solar panel, electrolysis, storage requirements, global transmission requirements, etc. The sixth step is an iterative process where the (solar energy in this investigation) single source energy supply is adjusted to meet the energy demand of the country. Two scenarios are examined. In the first the energy demand is matched for a critical season and in the other seasons some energy (hydrogen in this case) exports are made. In the second scenario the energy demand includes hydrogen exports to replace oil exports on the same basis; in the present analysis this is 2100 PJ of hydrogen calorific value. A holistic and quantitative country-level replacement analysis of this kind has not been found by the authors in the public domain. In hopeful anticipation of the country finding a path to peace and prosperity, national and international data were used to estimate future energy demands and daily consumption patterns.

Energy Demand Prediction for Libya in 2050

The need to decarbonize action is urgent and will require vast resources [1]. However, the authors advocate very strongly that these investments are necessary to protect the great strides made in the last 100 years to mitigate global poverty [3]. So, protecting the environment, continuing economic growth and careful use of natural resources must go hand in hand. This philosophy of parallel economic-environmental sustainability, the need to make this a global issue and the imperative to join the young is very important [5]. Major investors [4] are already preparing for these changes. Coordinated efforts encompassing a range of sectors in large economic units will bring important economies of scale while achieving the above goals. This requires the provision of detailed transition strategies across economic sectors. In the present investigation, the authors offer a techno philosophical view of what such strategies could look like. The vision offered here offers a clear view of challenges and requirements. Naturally, there are inaccuracies arising from inconsistencies in the data, gaps in the information and reasonable assumptions that the authors had to make. These enabled the completion of the present exercise that offers a clear view of the opportunities and challenges. A more detailed analysis could change some quantitative outputs, but it would not alter the main conclusions.

The unit to decarbonize by 2050 has been chosen to be Libya, a major oil exporter and the native nation of two of the authors. Libya is a sufficiently large country to decarbonize, especially considering the replacement of hydrocarbon exports with green energy, for the analysis to be useful and representative. The selection of a baseline for the study was not easy given the volatile political situation in the country. Nonetheless, hoping and expecting that the country will succeed to find the path to peace and prosperity the authors sought national and international information to estimate energy demands and daily consumption patterns for such a future [7-13]. From this information and publications regarding the use of renewable sources of energy [36,37] it was possible to produce an estimate of Libyan energy demand and consumption. Then with an exploration of age demographics [38] and optimism on the future of Libya, a growth rate of 2% was estimated. As expected, there were gaps and inconsistencies in the data, so an integration exercise followed where the authors exercised their judgement and experience to produce a baseline for 2020 and a scenario for 2050.

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The decarbonization analysis was carried out in two steps. The first one is the assessment of annual demand and the second is adapting demand to the daily requirement considering current consumption patterns. The premise of the study is to install solar farms that are utilized to their maximum capacity considering illumination and availability factors. This is one of many possible greening alternatives and the objective here is to produce a view of the outcomes of this single scenario, not to offer it as the best solution. Column 1 of Table 1 shows the baseline of 2020 resulting from the compilation and integration exercise outlined above. The Total requirement value calculated for Column 1 (809.47 PJ) does not include the last two items (Gas electricity and liquid fossil fuel for electricity) because these are already included in the fuel energy input (Gas for electricity and liquid fossil fuel for electricity). Column 2 shows an interim step for energy requirements based on the consistent annual growth of 2% used for this investigation. Items 5 and 6 have been removed on the premise that fossil fuels would not be used for electricity. The total of Column 2 now includes the electricity demand delivered by fossil fuels even though this would be produced differently.

Table 1: Decarbonized Libyan Energy Consumption for 2050 based on current energy needs.

Libya Energy Panorama in 2050											
	Column	1	2	3	4	5	6	7	8	9	10
Item		Current Energy Use PJ 2020	2050 Energy Demand PJ	Replacement Factors to Decarbonize	Need to Replace PJ	Replace with	Electricity PJ To satisfy direct electrical demand	Electricity for Hydrogen - PJ	H_2 FCV PJ	H_2 kTonne	H_2 % of use
1	Motor gasoline	227.01	410.9	0.8	328.7	Electricity	70.44				
				0.2	82.2	H_2 Gas		58.7	41.09	342.4	28.28
2	Diesel for transport	165.6	299.7	0.8	239.8	Electricity	85.64				
				0.2	59.9	H_2 Gas		71.37	49.96	416.3	34.38
3	Jet Fuel	24.49	44.3	0.15	6.6	Electricity	2.85				
				0.85	37.7	L H_2		75.36	41.45	345.4	28.53
4	Other (Marine, etc)	2.87	5.2	0.7	3.6	Electricity	1.56				
				0.3	1.6	H_2 Gas		2.23	1.56	13	1.07
5	Liquid fossil fuel for electricity	9.66	0	Replaced with Wind power in electricity demand							
6	Gas for electricity	337.5	0	Replaced with Wind power in electricity demand							
7	Gas-Domestic	21.6	39.1	1	39.1	Electricity	39.1				
8	Gas other	20.7	37.5	0.7	26.2	Electricity	11.24				
				0.3	11.2	H_2 Gas		16.06	11.24	93.7	7.74
9	Solar PV	0.04	0.1		0.1	Electricity	0.07				
10	Electricity from gas	104.83	189.7		189.7	Electricity	189.75				
11	Electricity from liquid fossil fuel	3.46	6.3		6.3	Electricity	6.26				
	Total Requirement	809.45	1032.7				406.86	223.7	145.29	1210.7	100
	Total Electricity	108.32	196.1			Total 2050	630.59				

Columns 3, 4 and 5 show the replacement philosophy to retain the same level of benefit. So, for example, the energy delivered by jet fuel would be replaced by electricity (15%) for short-range flights and hydrogen for medium and long-range flights (85%). For aviation the assumption is made that post-Covid, the industry will need to convert to non-carbon fuels and will grow given the vast cultural, economic and social benefits it brings in particular on business and tourism [39]. Based on the evaluation in [40] and [41] 15% of the aviation jet fuel energy requirement would be delivered by electric propulsion and the remaining 85% by hydrogen gas turbine propulsion systems. These replacement factors are shown in Item 3 Col 3. In 2050 the Libyan jet fuel requirement would be (Item 3, column 2) 44.328 PJ of fuel energy. 15% of this (columns 3 and 4) would be replaced by electricity and the remaining 85% by hydrogen. However to deliver the same service the amounts of energy required would change. 15% of the jet fuel energy requirement is 6.649 PJ. If the same benefit were to be delivered by electricity the energy requirement would be much smaller, 2.85 PJ.

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This is because the conversion from fuel energy to propulsive power is low due to the need to use a thermodynamic cycle (the gas turbine) to convert the heat input of the fuel into propulsive power. In the present analysis, a levelized average value of 30% is used. If electrical power is used, the conversion from electrical power at source, allowing for larger weight, transmission losses, and electrical equipment losses were evaluated at 70%. Hence the electrical power needed to deliver the same propulsive power as 6.649 PJ of fuel energy (Item 3, Col4). is much lower 2.850 PJ (Item 3, Col6). On the other hand, the amount of energy delivered by hydrogen would rise. Based on the evaluation in [40], airliners of the first innovation wave would have more voluminous bodies, resulting in higher drag. Hence the hydrogen energy needed would be larger, in this analysis by 10%. So to replace the service of 37.678 PJ of conventional fuel (Item 3, Col4), 41.446 PJ of hydrogen would be needed (Item 3, Col8). This hydrogen in the present analysis is produced using seawater electrolysis and needs to be liquefied with a combined efficiency of electrolysis and liquefaction, estimated here, of 55%. So the production of 41.446 PJ of hydrogen, 345.39 kilotonnes per annum (Item 3, Col 9) would require 75.357 PJ (Item 3, Col 7). In conclusion, to provide the 2050 propulsive power requirement for aviation 44.328 PJ of conventional fuel energy would be needed. In a decarbonized scenario the same requirement would be delivered by 2.850 PJ of electrical energy generation and 41.446 PJ of hydrogen. This hydrogen, in turn, would need 75.357 PJ of electrical energy generated.

Similar evaluations were carried out throughout the list of items. It was thus possible to evaluate the electrical requirements and the hydrogen requirements. The hydrogen requirements in turn produced their electrical requirement (column 7). It was assumed that aviation would require exclusively liquid hydrogen while all other sectors would use hydrogen gas. According to [42,43], the global liquid production of hydrogen is slightly more than 100 ktonnes p.a. i.e., about 0.15% of global hydrogen production so this approximation is of useful precision of the current analysis. Table1 shows (col 10) that 28.5 percent of the hydrogen produced is liquid hydrogen for aviation. This proportion will be kept constant for the rest of the study and then the global efficiency of hydrogen production is kept at 0.65 because the proportion of the hydrogen produced is liquid. So for a 2050 Libyan decarbonized future, without compromising economic growth, the total energy needed would be 638 PJ of electrical energy, 487 PJ used directly as electrical energy and the remainder used to produce hydrogen. It is interesting to note that decarbonizing a country yielded a great reduction (809 PJ to 638 PJ) of primary energy and a vast increase (108 PJ to 638 PJ) in electrical energy requirement. The primary reason for the reduction of primary energy is that a large proportion of fossil fuel energy is used today in thermodynamic cycles with thermal efficiencies of 0.15-0.6 that result in large rejections of thermal energy that is frequently wasted. Later this may change when additional hydrogen production requirements are included.

Adjustments for Daily Demand Considerations

When replacing fossil fuel conventional energy sources with solar PV energy consideration needs to be given to the need to satisfy demand when the sun is not shining. In the present scenario, this consideration is dealt via the use of Hydrogen Combined Cycle Gas Turbines (H_2 CCGTs); burning hydrogen using the low NOx designs being evaluated in ENABLE H_2 (2020). The current state of the art thermal efficiency is 62-64% (Siemens 2023, General Electric 2023, Mutsibishi 2023). By 2050 it is expected machines with an efficiency of 65%+ should be available. This coupled with electrolyze efficiencies of 70+ % can deliver efficiencies from electricity to electricity of 0.45 to 0.5. Furthermore, H_2 CCGTs deliver a large stream of thermal energy that can be gainfully employed in many areas, including desalination. This benefit is not included here. The combustors of these H_2 CCGTs will need to be designed with very low NOx objectives, as explored in Enable H_2. (2020). It is anticipated that these H_2 CCGTs will be located near the electrolyzing stations and use gaseous hydrogen. In the present study, the H_2 CCGTs are assumed to be 600 MW single shaft units delivering on average 500 MW (to account for hot days, off-design performance, degradation and availability in operation) with a thermal efficiency of 60%.

Therefore in addition to the hydrogen produced for the replacement scenario illustrated in Table 1, additional hydrogen will need to be produced for use in these gas turbines. It can be argued that other energy storage mechanisms could be used instead of H_2 CCGTs. However, for this scenario evaluation, H2 CCGTs are a very suitable alternative and will be the only ones considered here. In addition to the hydrogen required for these H_2 CCGTs the analysis has included a standby 4% energy backup. This satisfies the need to store enough hydrogen to run the H_2 CCGTs for 2 weeks assuming no solar energy is available. Figure 1 shows the demand curves for this study. The patterns used are from Libyan operating information (Rawesat and Sannuga 2021); they have been adjusted to give the 2050 total annual requirement of 406.89 PJ evaluated in section 3 and shown in Table 1. In total the grid evaluated here needs to deliver:

a) The electricity demand of 406.89 PJ in the patterns shown in Figure1

b) The 1210.7 ktonnes of hydrogen (3.32 ktone/day, liquid & gas) requiring 223 PJ annually

c) The additional Hydrogen to use in H_2 CCGTs to produce electricity at night

d) The 4% H_2 margin (2 weeks of operation) for the H_2 CCGTs peak and dark day demand duty

Assessment of Requirements Based on the Winter Season

The broad assumption of this study is that solar farms would be installed and operated at their maximum capacity, allowing for location and illumination characteristics. Desert locations

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situated in Libya at a latitude of 25N were chosen. These are nearly deserted locations and in the southern region of the country. The demand patterns of Figure 1 were used approximating the year to 4 seasons of 91.25 equal days. The first season to be analyzed was the winter because it is the 'pinch' season where demand is the highest and solar energy the least due to the low inclination of the sun and the shorter days. The initial step was an iterative process to find the area of the solar farm needed to provide the total electricity supply. This was found to be 4900 km2 based on estimations of:

PV Efficiency	0.14	Spacing Factor	0.75	Contingency	0.8
Weather Factor	0.7	Availability	0.9	Fouling	0.8

The PV efficiency used is conservative and some of the other factors may be higher than expected, but the assumption is that it will be possible to schedule much cleaning and maintenance work at night, enhancing availability. A key item is shown in the bottom row of column 5. This is the daily hydrogen requirement of 3.32 ktone/day augmented by 4% (as stated above) to 3592 tonnes/day to provide a buffer for peaks and long spells of sunless days. Column 1 of Table 2 shows the electrical power demand, also shown in Figure 1 for the winter season. Column 2 shows the energy required as a consequence of this demand. Column 3 shows the solar illumination for each hour of the day using a standard base figure of 1000 W/m^2. This was adjusted finding the sunrise, noon and sunset times from Omnicalculator [44] for a latitude of 25N, considering that the zenith in the winter solstice results in a solar inclination from the vertical of approximately 48 degrees and making an adjustment of solar inclination for the time of day. Column 4 shows the power delivered using the solar farm of 4900 km^2 and the adjustments outlined above. Of course, a solar farm only produces electricity during the day and it is assumed that at the edges of the sunlit period, there is no useful output. At night, the demand is satisfied using the H_2 CCGTs (col 14) that consume hydrogen produced during daylight hours (column 10). Column 15 shows the number of 600 MW single shaft H_2 CCGTs (delivering an effective 500MW to allow for several operational factors) [45,46].

Table 2: Analysis for the winter season.

Column	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Winter Hour	Power Demand GW	Energy Demand for Hour TJ	Solar illumination W/m^2	Solar Power Produced GW	Solar Energy produced for the hour TJ.	Supply-demand TJ	Solar PV Energy for H_2 - TJ	Electrical Power for H_2 - GW	H_2 Energy TJ of FCV	Tonnes H_2 Produced	Tonnes H_2 in storage	H_2CCGT Fuel Energy needed TJ	Tonnnes H_2	H_2 CCGT GW consumed	No 600 MW Single shaft GTs needed.
0:00	10.99	39.57	0	0	0	-39.56	0	0	0	0	8849.4	65.94	549.54	10.99	21.98
1:00	8.81	31.72	0	0	0	-31.72	0	0	0	0	8408.8	52.87	440.57	8.81	17.62
2:00	8.19	29.48	0	0	0	-29.48	0	0	0	0	7999.3	49.14	409.51	8.19	16.38
3:00	8.52	30.66	0	0	0	-30.66	0	0	0	0	7573.4	51.11	425.9	8.52	17.04
4:00	11.87	42.72	0	0	0	-42.72	0	0	0	0	6980	71.21	593.4	11.87	23.74
5:00	15.55	55.99	0	0	0	-55.99	0	0	0	0	6202.4	93.32	777.65	15.55	31.11
6:00	23.37	84.12	0	0	0	-84.12	0	0	0	0	5034	140.21	1168.38	23.37	46.74
7:00	26.56	95.63	0	0	0	-95.63	0	0	0	0	3705.8	159.38	1328.14	26.56	53.13
8:00	25.71	92.54	334.6	69.8	251.3	158.8	158.8	44.1	103.2	860	860.1	0	0	0	0
9:00	24.65	88.74	473.1	98.7	355.4	266.7	266.7	74.1	173.4	1445	2304.7	0	0	0	0
10:00	22.9	82.44	579.5	120.9	435.3	352.9	352.9	98	229.4	1912	4216.3	0	0	0	0
11:00	19.4	69.84	646.3	134.9	485.6	415.7	415.7	115.5	270.2	2252	6468.1	0	0	0	0
12:00	20.66	74.39	669.1	139.6	502.7	428.3	428.3	119	278.4	2320	8788	0	0	0	0
13:00	23.21	83.54	646.3	134.9	485.6	402	402	111.7	261.3	2178	10965.5	0	0	0	0
14:00	20.95	75.43	579.5	120.9	435.3	359.9	359.9	100	233.9	1949	12915	0	0	0	0
15:00	18.14	65.31	473.1	98.7	355.4	290.1	290.1	80.6	188.6	1572	14486.6	0	0	0	0
16:00	19.13	68.87	334.6	69.8	251.3	182.5	182.5	50.7	118.6	988	15475	0	0	0	0
17:00	19.77	71.18	0	0	0	-71.18	0	0	0	0	14486.3	118.64	988.64	19.77	39.55
18:00	19.59	70.52	0	0	0	-70.52	0	0	0	0	13506.8	117.54	979.49	19.59	39.18
19:00	18.32	65.96	0	0	0	-65.96	0	0	0	0	12590.7	109.94	916.13	18.32	36.65
20:00	18.38	66.16	0	0	0	-66.16	0	0	0	0	11671.8	110.26	918.87	18.38	36.75
21:00	17.13	61.67	0	0	0	-61.67	0	0	0	0	10815.3	102.79	856.58	17.13	34.26

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22:00	15.03	55.07	0	0	0	-55.07	0	0	0	0	10050.4	91.78	764.81	15.3	30.59
0:23	13.03	46.91	0	0	0	-46.91	0	0	0	0	9398.9	78.18	651.53	13.03	26.06
Total		1548.49			3558		2856.9		1857	15475	213753	1412.3	11769.13		
H_2 Produced K-tonnes	15475.02	H_2 for CCGT	11769	Other H_2	3693.7	H_2 Exports	12.18				Solar PV Farm	4900 sqkm			

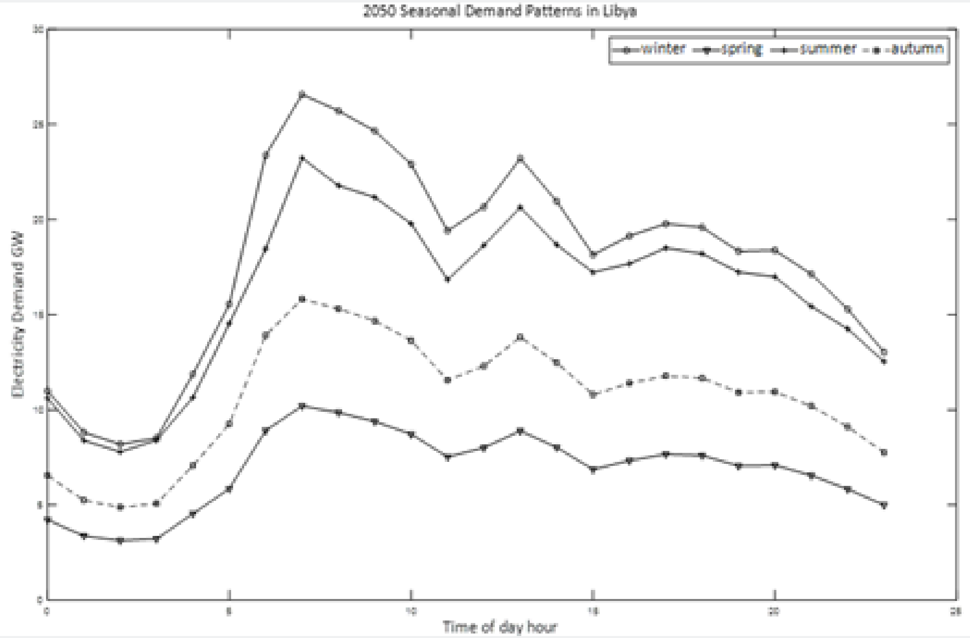

Figure 1: Demand curves for 2050 used in the study.

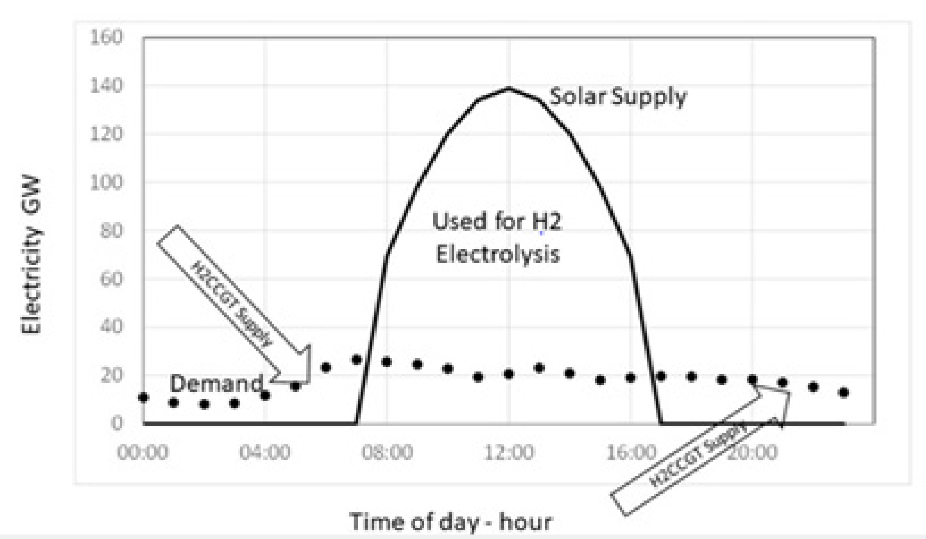

Figure 2: Electrical Supply and demand in a winter day.

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The largest value in column 15 indicates the number of these powerplants needed, 54 (arising from the value of 53.1 rounded up). One of the constraints of the evaluation is the hydrogen production of 3592 tonnes/day explained above. The bottom row shows that for a winter day, 15.361 ktonnes of hydrogen are produced, 11.77 of these are consumed by the H_2 CCGTs to satisfy the demand experienced during the sunless hours and the remainder is the 3592 tonnes/day requirement. Column 8 offers a view to estimating the electrolysis capacity and Column 11 offers information helpful for storage requirements. A particular assumption in this study is that the 3592 tonnes of hydrogen needed every day is consumed very quickly just before sunrise. This assumption simplifies the calculations, includes the availability of this hydrogen for most of the day and offers a useful numerical buffer for storage requirements. Figure 2 shows the electrical supply and demand patterns. The dotted line is the demand. This demand is satisfied at night with the H_2 CCGTs. During the day, the very large excess of supply over demand is used to electrolyze hydrogen for use in other economic sectors and to produce the hydrogen needed for the night operation of the H_2 CCGTs [47].

Spring, summer and autumn seasons

The evaluation of the other seasons ensued. In these, the solar PV farm was assumed to continue to deliver its maximum output, now larger because the sun is closer to a vertical inclination. For a latitude of 25 N, the inclination in the equinoxes is 25 degrees and during the summer solstice it is less than 2 degrees from the vertical. Table 3 shows the details of the spring season. This season has a lower demand (Figure 1) and more solar illumination (this I evident when comparing columns 3 of Table 2 & 3). There is a surplus production of hydrogen that can be exported, 16.6 ktonne/day. Like the daily need, this is assumed to be removed from storage at daybreak. Tables 4 & 5 show the results for the other seasons (Figure 3).

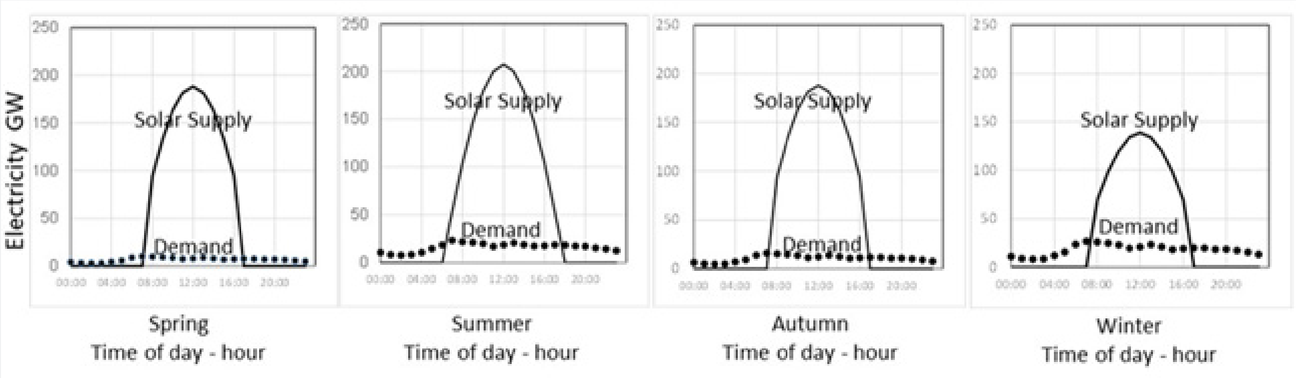

Figure 3: Electrical Supply and demand for the year.

Table 3: Analysis for the spring season.

Column	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Spring Hour	Power Demand GW	Energy Demand for Hour TJ	Solar illumination W/m²	Solar Power Produced GW	Solar Energy produced for the hour TJ	Supply-demand TJ	Solar PV Energy for H_2 - TJ	Electrical Power for H_2 - GW	H_2 Energy TJ of FCV	Tonnes H_2 produced.	Tonnes H_2 in storage	H_2CCGT Fuel Energy needed TJ.	Tonnnes H_2consumed.	H_2 CCGT GW	No 600 MW Single shaft GTs needed
0:00	4.21	15.16	0	0	0	-15.2	0	0	0	0	22100	25.27	210.58	4.21	8.42
1:00	3.38	12.16	0	0	0	-12.2	0	0	0	0	21931	20.26	168.82	3.38	6.75
2:00	3.13	11.27	0	0	0	-11.3	0	0	0	0	21775	18.78	156.46	3.13	6.26
3:00	3.23	11.62	0	0	0	-11.6	0	0	0	0	21613	19.37	161.38	3.23	6.46
4:00	4.54	16.34	0	0	0	-16.3	0	0	0	0	21386	27.23	226.93	4.54	9.08
5:00	5.86	21.09	0	0	0	-21.1	0	0	0	0	21093	35.16	292.98	5.86	11.72
6:00	8.91	32.07	0	0	0	-32.1	0	0	0	0	20648	53.45	445.43	8.91	17.82
7:00	10.2	36.71	0	0	0	-36.7	0	0	0	0	20138	61.18	509.84	10.2	20.39
8:00	9.85	35.46	453.2	94.6	340.4	305	305	84.7	198.2	1652	1652	0	0	0	0

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9:00	9.38	33.78	640.9	133.7	481.4	447.7	447.7	124.4	291	2425	4077	0	0	0	0
10:00	8.72	31.39	784.9	163.8	589.6	558.2	558.2	155.1	362.9	3024	7101	0	0	0	0
11:00	7.52	27.09	875.4	182.7	657.7	630.6	630.6	175.2	409.9	3416	10516	0	0	0	0
12:00	8.01	28.83	906.3	189.1	680.9	652	652	181.1	423.8	3532	14048	0	0	0	0
13:00	8.89	32.01	875.4	182.7	657.7	625.6	625.6	173.8	406.7	3389	17437	0	0	0	0
14:00	8.03	28.9	784.9	163.8	589.6	560.7	560.7	155.8	364.5	3037	20474	0	0	0	0
15:00	6.86	24.7	640.9	133.7	481.4	456.7	456.7	126.9	296.9	2474	22948	0	0	0	0
16:00	7.33	26.39	453.2	94.6	340.4	314	314	87.2	204.1	1701	24649	0	0	0	0
17:00	7.67	27.6	0	0	0	-27.6	0	0	0	0	24266	46.01	383.39	12.78	25.56
18:00	7.6	27.35	0	0	0	-27.4	0	0	0	0	23886	45.59	379.88	7.6	15.2
19:00	7.05	25.37	0	0	0	-25.4	0	0	0	0	23534	42.29	352.42	7.05	14.1
20:00	7.09	25.52	0	0	0	-25.5	0	0	0	0	23179	42.53	354.42	7.09	14.18
21:00	6.55	23.57	0	0	0	-23.6	0	0	0	0	22852	39.28	327.32	6.55	13.09
22:00	5.83	21	0	0	0	-21	0	0	0	0	22560	35	291.65	5.83	11.67
0:23	4.99	17.98	0	0	0	-18	0	0	0	0	22311	29.96	249.66	4.99	10.99
Total		593.36			4819		4551		2958	24649	456175	541.3	4511		
H_2 Produced K-tonnes	24649	$H_2$for CCGT	4511	Other H_2	3693.7	H_2 Exports	16444				Solar PV Farm	4900 sqkm			

Table 4: Analysis for the summer season.

Column	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Summer Hour	**Power Demand GW**	**Energy Demand for Hour TJ**	**Solar illumination W/m^2**	**Solar Power Produced GW**	**Solar Energy produced for the hour TJ.**	**Supply-demand TJ**	**Solar PV Energy for H_2 - TJ**	**Electrical Power for H_2 - GW**	**H_2 Energy TJ of FCV**	**Tonnes H_2 produced**	**Tonnes H_2 in storage**	**H_2CCGT Fuel Energy needed TJ.**	**Tonnnes H_2 consumed**	**H_2 CCGT GW**	**No 600 MW Single shaft GTs need**
0:00	10.61	38.2	0	0	0	-38.2	0	0	0	0	21452	63.67	530.56	10.61	21.22
1:00	8.39	30.21	0	0	0	-30.2	0	0	0	0	21033	50.35	419.56	8.39	16.78
2:00	7.79	28.03	0	0	0	-28	0	0	0	0	20643	46.72	389.33	7.79	15.57
3:00	8.4	30.25	0	0	0	-30.3	0	0	0	0	20223	50.42	420.16	8.4	16.81
4:00	10.65	38.35	0	0	0	-38.4	0	0	0	0	19691	63.92	532.64	10.65	21.31
5:00	14.54	52.35	0	0	0	-52.3	0	0	0	0	18964	87.25	727.06	14.54	29.08
6:00	18.46	66.45	0	0	0	-66.4	0	0	0	0	18041	110.74	922.85	18.46	36.91
7:00	23.22	83.6	258.7	54	194.3	110.7	110.7	30.8	72	599.7	600	0	0	0	0
8:00	21.78	78.41	499.7	104.3	375.4	297	297	82.5	193	1608.6	2208	0	0	0	0
9:00	21.16	76.17	706.7	147.5	530.9	454.7	454.7	126.3	295.6	2463	4671	0	0	0	0
10:00	19.78	71.2	865.5	180.6	650.2	579	579	160.8	376.4	3136.3	7808	0	0	0	0
11:00	16.83	60.59	965.3	201.4	725.2	664.6	664.6	184.6	432	3600	11408	0	0	0	0
12:00	18.64	67.1	999.4	208.6	750.8	683.7	683.7	189.9	444.4	3703.3	15111	0	0	0	0
13:00	20.63	74.28	965.3	201.4	725.2	650.9	650.9	180.8	423.1	3525.9	18637	0	0	0	0
14:00	18.67	67.2	865.5	180.6	650.2	583	583	161.9	379	3157.9	21795	0	0	0	0
15:00	17.23	62.01	706.7	147.5	530.9	468.9	468.9	130.2	304.8	2539.7	24335	0	0	0	0
16:00	17.68	63.64	499.7	104.3	375.4	311.8	311.8	86.6	202.6	1688.7	26023	0	0	0	0
17:00	18.5	66.58	258.7	54	194.3	127.7	127.7	35.5	83	691.9	26715	0	0	0	0
18:00	18.2	65.54	0	0	0	-65.5	0	0	0	0	25805	109.23	910.23	18.2	36.41

19:00	17.24	62.05	0	0	0	-62.1	0	0	0	0	24943	103.42	861.81	17.24	34.47
20:00	16.99	61.15	0	0	0	-61.1	0	0	0	0	24094	101.91	849.27	16.99	34.97
21:00	15.43	55.56	0	0	0	-55.6	0	0	0	0	23322	92.6	771.67	15.43	30.87
22:00	14.25	51.31	0	0	0	-51.3	0	0	0	0	22609	85.52	712.67	14.25	28.51
0:23	12.53	45.11	0	0	0	-45.1	0	0	0	0	21983	75.19	626.59	12.53	25.06
Total		1395			5703		4932		3206	26715	442113	1040.92	8674.41		
H_2 Produced K-tonnes	26715	H_2 for CCGT	8674	Other H_2	3693.7	H_2 Exports	14347				Solar PV Farm	4900 sqkm			

Table 5: Analysis for the autumn season.

Column	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Autumn Hour	**Power Demand GW**	**Energy Demand for Hour TJ**	**Solar illumination W/m²**	**Solar Power Produced GW**	**Solar Energy produced for the hour TJ.**	**Supply-demand TJ**	**Solar PV Energy for H_2 - TJ**	**Electrical Power for H_2 - GW**	**H_2 Energy TJ of FCV**	**Tonnes H_2 produced**	**Tonnes H_2 in storage**	**H_2 CCGT Fuel Energy needed TJ.**	**Tonnnes H_2 consumed.**	**H_2 CCGT GW**	**No 600 MW Single shaft GTs need**
0:00	6.54	23.56	0	0	0	-23.5	0	0	0	0	19899	39.26	327.17	6.54	13.09
1:00	5.25	18.89	0	0	0	-18.8	0	0	0	0	19636	31.48	262.31	5.25	10.49
2:00	4.88	17.56	0	0	0	-17.5	0	0	0	0	19392	29.26	243.82	4.88	9.75
3:00	5.07	18.26	0	0	0	-18.2	0	0	0	0	19139	30.43	253.59	5.07	10.14
4:00	7.07	25.44	0	0	0	-25.4	0	0	0	0	18786	42.4	353.31	7.07	14.13
5:00	9.26	33.33	0	0	0	-33.3	0	0	0	0	18323	55.56	462.97	9.26	18.52
6:00	13.91	50.08	0	0	0	-50	0	0	0	0	17627	83.47	695.6	13.91	27.82
7:00	15.81	56.93	0	0	0	-56.9	0	0	0	0	16836	94.88	790.68	15.81	31.63
8:00	15.3	55.1	453.2	94.6	340.4	285.3	285.3	79.3	185.5	1545.6	1546	0	0	0	0
9:00	14.68	52.84	640.9	133.7	481.4	428.6	428.6	119.1	278.6	2321.6	3867	0	0	0	0
10:00	13.63	49.08	784.9	163.8	589.6	540.6	540.6	150.2	351.4	2928	6795	0	0	0	0
11:00	11.55	41.58	875.4	182.7	657.7	616.1	616.1	171.1	400.5	3337.1	10132	0	0	0	0
12:00	12.3	44.29	906.3	189.1	680.9	636.6	636.6	176.8	413.8	3448.1	13580	0	0	0	0
13:00	13.81	49.73	875.4	182.7	657.7	607.9	607.9	168.9	395.2	3293	16873	0	0	0	0
14:00	12.47	44.9	784.9	163.8	589.6	544.7	544.7	151.3	354.1	2950.7	19824	0	0	0	0
15:00	10.8	38.88	640.9	133.7	481.4	442.6	442.6	122.9	287.7	2397.2	22221	0	0	0	0
16:00	11.39	41	453.2	94.6	340.4	299.4	299.4	83.2	194.6	1621.9	23843	0	0	0	0
17:00	11.77	42.38	0	0	0	-42.3	0	0	0	0	23254	70.64	588.63	19.62	39.2
18:00	11.66	41.99	0	0	0	-41.9	0	0	0	0	22671	69.98	583.16	11.66	23.33
19:00	10.91	39.27	0	0	0	-39.2	0	0	0	0	22126	65.45	545.43	10.91	21.82
20:00	10.94	39.38	0	0	0	-39.3	0	0	0	0	21579	65.64	546.98	10.94	21.88
21:00	10.2	36.71	0	0	0	-36.7	0	0	0	0	21069	61.19	509.92	10.2	20.4
22:00	9.11	32.78	0	0	0	-32.7	0	0	0	0	20614	54.64	455.3	9.11	18.21
0:23	7.76	27.93	0	0	0	-27.9	0	0	0	0	20226	46.54	387.87	7.76	15.51
Total		922			4819		4402		2861	23843	419859	841	7007		
H_2 Produced K-tonnes	23843	H_2 for CCGT	7006	Other H2	3693.7	H_2 Exports	13142.6				Solar PV Farm	4900 sqkm			

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A View of the Whole System

An examination of the above information reveals a great deal of useful detail to provide foundation knowledge for, among other things, policymaking and national investments. The size of the solar farm is 4900 km^2, this is shown in Figure 4 as three farms of 1633 km^2 each on the Libyan territory on the 25th parallel. The number of the H_2 CCGTs is determined by the maximum requirement (column 15, winter at 0700). This number will need to be rounded up to 54 units. The electrolyser requirement is determined by the maximum that takes place in the summer at 1200, shown in column 8, this is 189 GW. The Hydrogen storage requirement is determined by the maximum taking place in the summer at 1700 (column 11); it is 26 000 tonnes. Similarly, the grid capacity needed is for the summer maximum at 1200 (column 4) and is 207 GW. Table 6 shows a summary of these requirements with the electrolyser requirement adjusted by an availability factor of 0.95 and the Storage and transmission requirements adjusted by an availability factor of 0.9. These factors may seem high, but the periodicity and seasonality of solar energy should permit scheduling most of the maintenance when the sun is not shining and in seasons where there is excess capacity.

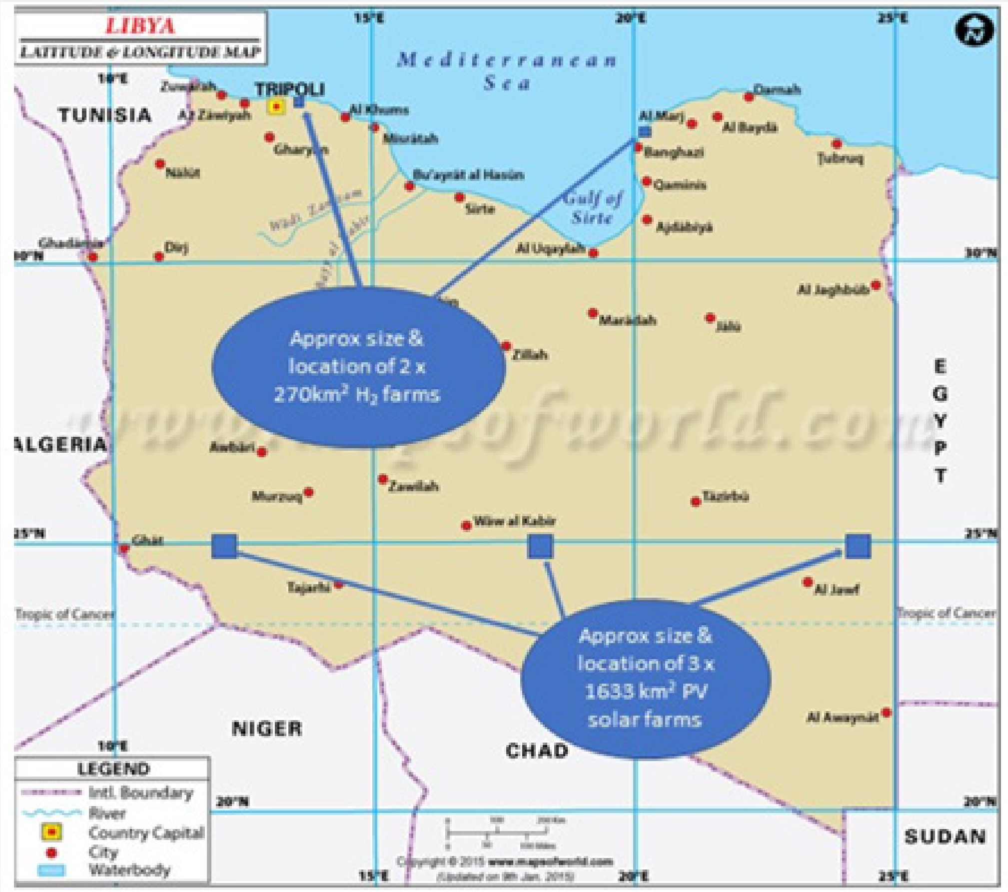

Figure 4: Location of facilities in Libya courtesy mapsoftheworld.com, annotated by the authors.

Table 6: National requirements – two scenarios: meeting winter demands and using Solar PV farms to their full capacity and exporting yearly 2100 PJ of hydrogen using Solar PV farms to their full capacity.

Scenario	Solar Farm GW	Solar Farm km^2	600MW H_2 CCGTS	Electrolyze GW	Storage H_2 tonnes	Transmission GW	H_2 Export PJ
Winter Self Sufficient	268	4900	54	199	28889	218	481
Export 2100 PJ of H_2	655	12100	54	519	78614	539	2100

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The geographic location of the solar farms is in the southern region of the country to bring them closer to the equator offering better illumination and more productive use of the solar farms. It is beneficial to locate the hydrogen grid very close to the coast on the premise that seawater will be used for electrolysis. An evaluation is needed to select between direct seawater electrolysis or to desalinate seawater and electrolyse it subsequently. The use of seawater to produce hydrogen is a necessity given the scarcity (or geographical maldistribution) of fresh water. The location of electrolysers, H_2 CCGTs and storage farms can be placed near the coast to minimize hydrogen transmission inland. So in this scenario, the electrical grid would be distributed throughout the country while the hydrogen grid would be concentrated near the Mediterranean coast.

The authors propose it is logical to group the hydrogen infrastructure in hydrogen farms by the Mediterranean coast to capitalize on economies of scale and integration; also reducing hydrogen transmission costs. These hydrogen farms were located close to the main cities, Tripoli and Benghazi where an important fraction of the demand is located. These cities also have the largest airports in the country where the vast majority of the liquid hydrogen will be used, noting that hydrogen for aviation will comprise 28% of the hydrogen demand (Table 1). These hydrogen farms would comprise the electrolysers, if adopted the desalination plant, the H_2 CCGTs, the storage facilities and where appropriate the liquefaction plant. Reviewing electrolyser and associated technologies Herzog [48]; ITM [45]; Mohammed-Ibrahim & Moussab [49]; H_2 Future, 2022; REFH. The authors concluded that two hydrogen farms of 270 km^2 each would meet the requirements of the demand and the solar energy produced. Figure 4 shows the proposed location of the hydrogen farms and the solar farms.

In the scenario evaluated here, the premise is that this hydrogen-electrical green grid meets the winter requirements of the nation. In the present scenario, the assumption is that solar farms are utilized to the maximum. The higher illumination experienced in the other three seasons delivers excess electrical energy that is used to produce hydrogen for export. The excess hydrogen produced daily is shown in column 7 at the bottom of the table for each season. The values are: 16392, 14266, 13090 tonnes for spring, summer and autumn. This delivers a total of 3.992 Megatonnes of Hydrogen each year, which equates to 479 TJ each year, exported in three seasons. North Africa is seen to have great potential for energy exports [50], green and conventional. In 2021 Libya used exported slightly over 1 million Barrels/day [51] this is approximately 49 Megatonnes of oil each year with an energy content of 2100 PJ per year. A reasonable ambition would be to retain Libya's international position as an energy exporter. Then a similar analysis can be carried out using this method for a scenario where Libya is exporting 2100 PJ of Hydrogen each year. This could be exported by tankers [52] or by pipeline. The corresponding results for this energy export scenario are shown in the lower row of Table 6. This type of analysis could be used for different levels of export to deliver the appropriate quantitative results. One more detail to highlight is that the total solar electricity generated is much larger than the 630 PJ (407 PJ of electrical demand plus 223 PJ for hydrogen) required to satisfy the national demand. This is because of the need to produce additional Hydrogen for the H_2 CCGTs and exports. In the two scenarios examined the total solar electricity produced is 1714 PJ and 4200 PJ.

Foundation Analysis for Policy and R&D Investments

The present study has the appropriate accuracy for setting research and financial agendas. A key outcome is the cascading and evaluation of research requirements. For example, a key R&D issue that arises is how to produce hydrogen from seawater. Advances are taking place in seawater electrolysis Mohammed-Ibrahim, & Moussab [49]. Another alternative is to do this in two steps, first desalination, followed by electrolysis of the resulting water stream. Another important source of water in the hydrogen farms is the combustion products of hydrogen in the H_2 CCGT exhaust. A techno-economic analysis of the options is needed to make an appropriate selection. Solutions are likely to vary, dependent on the features of different geographic locations and it is likely that depending on circumstances, a portfolio approach will be needed. Within this context, there is also a choice to be made of the right electrolyser selection from the many options available.

Another area that will have a significant impact is the selection of alternative storage alternatives. The case proposed here, the use of H_2 CCGTs is very competitive [53-55] but not the only option. Technologies such as batteries, pumped storage compressed air storage [56,57] and others may be viable. Often different geographic areas will require different solutions and a portfolio approach may be the outcome. Similarly, there is a host of other areas to explore in terms of technoeconomic performance, these include the solar cell design and principle of operation, inclination, variable foundations, etc., [58]. The design of electricity and hydrogen storage systems is another area that is receiving and will continue to receive a great deal of attention. Demand management is an option that may yield cost benefits by reducing the size of the peaks and reducing equipment requirements. Furthermore, the assumption of this study is that the national energy export will be hydrogen. This is one option. Another option is the export of electricity or a combination of hydrogen and electricity.

Realistic assumptions were made for the redundancy needed, availability and other capacity-constraining factors for several inputs. These could be improved given the relatively low utilization (plus the cyclic nature of the operation) of the capital equipment. This, through careful maintenance scheduling, would permit some improvements. Improvements in these factors are expected arising from experience, volume and technology acquisition. So the present study offers a foundation for a more detailed techno economic optimization examining the opportunities and options outlined above. It also offers the ability to start costing the transition to a decarbonized economy.

Conclusions and the Future

This foundation level investigation is offered as an illustration, without judgements, recommendations, or optimization. There are many conclusions that emerge from this foundation study. The first one, notwithstanding many uncertainties and a single solution examination, is that the cost and infrastructure requirements will be vast. A cost estimate will be carried out in the near future, but even before that, Tables 6&7 show the enormous equipment needs; they will be very expensive. Even though the present investigation has been based on some single choices, these are competitive, so the order of magnitude of the requirement is considered valid. Another important conclusion is that, given the periodic and seasonal nature of sunlight illumination, the general utilization of the equipment is medium to low. This can be helped by demand management, improved technologies, adoption of advanced maintenance techniques and other means to provide some useful benefits. However, these may not match the benefits of the presence of a constant source of electrical power. The concept of the hydrogen farm deserves detailed future attention. It promises a useful reduction of costs, even though the order of magnitude of the decarbonising investment is not expected to change. Careful integration of the different elements will also yield savings. Furthermore, the stringent Health and Safety measures required for hydrogen operations will be confined to specific areas. A detailed Technoeconomic Environmental Risk Analysis is the next step in the investigation, this will be using the techniques described in Nalianda [59]. The greening process will require a vast amount of electrification. This foundation analysis can mark the beginning of the R&D, investment, and political agenda at the starting point of the road to decarbonization.

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