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Transition to Low-Carbon Hydrogen Energy System in the UAE: Sector Efficiency and Hydrogen Energy Production Efficiency Analysis

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Abstract: To provide an effective energy transition, hydrogen is required to decarbonize the hard-to-abate industries. As a case study, this paper provides a holistic view of the hydrogen energy transition in the United Arab Emirates (UAE). By utilizing the directional distance function undesirable data envelopment analysis model, the energy, economic, and environmental efficiency of UAE sectors are estimated from 2001 to 2020 to prioritize hydrogen sector coupling. Green hydrogen production efficiency is analyzed from 2020 to 2050. The UAE should prioritize the industry and transportation sectors, with average efficiency scores of 0.7 and 0.74. The decomposition of efficiency into pure technical efficiency and scale efficiency suggests policies and strategies should target upscaling the UAE's low-carbon hydrogen production capacity to expedite short-term and overall production efficiency. The findings of this study can guide strategies and policies for the UAE's low-carbon hydrogen transition. A framework is developed based on the findings of the study.

Keywords: hydrogen; sector coupling; efficiency; data envelopment analysis; UAE

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1. Introduction

The United Arab Emirates (UAE) has set clear climate goals. This includes a significant reduction in CO_2 emissions by 2030 and net-zero emissions by 2050 [1]. The UAE net-zero 2050 strategic initiative aligns with the Paris Agreement that calls for long-term strategies to reduce greenhouse gas (GHG) emissions and limit the global temperature to 1.5C compared to pre-industrial levels [2]. This goal means a significant transition for the UAE's energy, economic, and environmental system. A large share of the country's energy comes from natural gas and oil to produce electricity or industrial processes that require a vast amount of heat. The share of gas in power generation is 96.7%, while the share of low carbon sources is 2.7% [3]. For some sectors, they can easily switch to green electricity. However, for high-temperature heat applications, this may not be feasible. For example, at high temperatures, the efficiency of a solar-driven desalination unit drops [4]. These challenging sectors can be decarbonized by switching to low-carbon hydrogen [5,6].

Hydrogen is key to having a complete set of alternatives to decarbonize the current and future energy consumption [7] and a crucial component of supporting longer-term climate neutrality and strategic independence for several large countries [8]. Compared to the available energy sources, hydrogen has attracted significant interest as a contributor to the sustainable development of industries worldwide due to its sustainable and reliable characteristics [9]. Hydrogen is a growth enabler for the multisectoral transition to a low-carbon economy based on clean energy sources. Hydrogen could contribute to reaching Goal 7 of the United Nation's Sustainable Development Goals (SDGs), i.e., affordable and clean energy [10]. Hydrogen will allow the decarbonization of areas where electrification is not a solution, either for technical or economic reasons [11]—namely, heavy industry, heavy transportation, air transportation, sea transportation, and many industrial processes. Additionally, hydrogen could play a role in long-term electricity storage. The electricity storage potential has significant economic and technical advantages in improving the efficiency of renewable energy (RE) sources [12]. Hydrogen is also a valuable chemical feedstock in petrochemical and metallurgical processes, food, and microelectronics [13]. Despite the momentum behind hydrogen, there is some skepticism regarding adopting hydrogen energy compared to alternative sources. Midilli et al. [13] highlight two major concerns regarding hydrogen: First is the quick volatility of hydrogen when combined with air at low temperatures, which raises safety concerns. Secondly, hydrogen storage in liquid form requires low temperature, making it difficult to store and transport. In addition, the commercial attractiveness of hydrogen compared to alternative energy sources is also a concern due to the cost associated with production, storage, and transportation. Hydrogen's environmental and ecological impact is linked to potential leakage during transport [7]. Few studies have identified hydrogen as having indirect greenhouse gas potential; however, they are significantly lacking compared to fossil fuel-based energy sources [8]. These concerns regarding hydrogen are the key motivation of this study to identify the appropriate sectors for hydrogen implementation.

The renewed focus on hydrogen is a result of the convergence of multiple factors: improvement in the cost and efficiency of electrolyzers, the increased competitive cost of renewable energy technologies, increased global regulatory efforts on climate change, and the broader application of hydrogen [9]. As technology advances, it is expected that the cost of hydrogen will continue to drop. National governments are making a significant effort to transition into a sustainable energy system. This transition has an economic and environmental impact on multiple sectors of the country. The hydrogen economy is envisioned as a burgeoning phenomenon that would ensure economic and environmental sustainability [10]. This paper provides a two-phase efficiency analysis of sectoral hydrogen transition based on energy, economic, and environmental factors, and low-carbon hydrogen production efficiency. Subsequently, a framework for the uptake of hydrogen energy transition in the United Arab Emirates (UAE) is presented.

The Hydrogen Roadmap of Europe stated that accomplishing the European Union's energy transition will require upscaling hydrogen. Without establishing the projects, the EU would not fulfil the decarbonization objective. The fuel offers a diverse, sustainable, and scalable energy vector to achieve the transition objectives [11]. Concrete model calculations demonstrate that 'blue' hydrogen can temporarily supplement the needs-based supply of consumers via existing gas storage. A concomitant expansion of renewable electricity generation is necessary to raise the percentage of green hydrogen. To ensure the competitiveness of climate-neutral hydrogen on the energy market, standard and suitable framework conditions are required to build a hydrogen industry in line with the market [12]. Noussan et al. [9] discussed the market and geopolitical perspectives of hydrogen generation via green or blue pathways, transportation, storage, and final use in various sectors. In addition, they covered the critical aspects of implementing an energy system based on hydrogen technologies. Moreover, this hydrogen transition study towards a low-carbon society covered three analytical perspectives: an energy model, an economic model, and a socio-technical case study. The results showed that, in Norway, it is required to have access to renewable power and hydrogen to decarbonize transport and industrial sectors and that hydrogen will drive the momentum and maintain a high level of economic activity [13]. Considering the spatiotemporal fluctuations in energy demand and supply, the researchers developed a comprehensive methodology for co-optimizing infrastructure investments across the power and H_2 supply chains. The conclusion showed that the deployment of carbon capture and storage (CCS) for power generation is less cost-effective than its usage for low-carbon H_2 production due to the grid flexibility allowed by sector coupling [14].

Hydrogen Potential of the UAE

The UAE is a major player in the energy market and is positioned to lead the hydrogen energy transition in the region and globally. The UAE plans to decarbonize its system and increase the generation of low-carbon hydrogen by having half of its installed power capacity come from nuclear and renewable sources by the year 2050 [15]. The UAE plans to diversify from fossil fuels, and export renewable energy and clean hydrogen to foreign consumers [16].

To maximize the contribution of hydrogen to the attainment of net-zero emissions, consumption should increase to 212 million metric tons (mt) by 2030 [17]. The UAE declared its goal of capturing 25% of the global low-carbon hydrogen market by 2030 [18]. The UAE's national oil facility, Abu Dhabi National Oil Company (ADNOC), already produces more than 300 kt of hydrogen annually. Efforts are made to expand its reach and increase production to 500 kt annually [19], particularly for the decarbonization of high-polluting heavy sectors. The increased output of low-carbon hydrogen, which may be used in the domestic economy or transformed into exportable goods such as ammonia, may be achieved with relatively modest additional investment [20]. Policies are streamlined with international organizations to accelerate the growth of hydrogen in the country. For example, an agreement was established to jointly build a waste-to-hydrogen project in the UAE between the British waste-to-energy company Chinook Sciences and the Emirati waste management company Bee'ah [21]. The UAE could be the major exporter of green hydrogen to the South Asia market, which is close enough to be connected by a pipeline [22]. Therefore, large-scale solar application is a viable investment for the UAE to become the leading green hydrogen exporter in the future [22,23].

Based on electrolyzer cost assumptions, solar predictions, and learning rates, Gandhi et al. [24] highlighted the economic viability of green hydrogen production in UAE industries between 2032 and 2038 with production costs at USD 0.95/kg and USD 1.35/kg. The UAE is constantly rated among the cheapest producers of renewable energy. They recorded the lowest solar energy cost in Dubai in 2015 at USD 5.6/kWh and in 2016 at USD 2.99/kWh. The most recent record was in 2020 in Abu Dhabi for the 2 GW Al Dhafra project with an offer of just USD 1.35 kWh [25]. According to IEA, the Middle East has the lowest hydrogen production cost from natural gas for blue hydrogen production at USD 0.43 kg/h [26].

The UAE has several advantages in leading the hydrogen market. For blue hydrogen, advantages include reliable and affordable hydrocarbons, large-scale ammonia and hydrogen production facilities, and sizable, well-characterized underground formations for carbon dioxide storage [27]. The outstanding sun generation conditions and the low levelized cost of solar power generation are favorable for green hydrogen [28]. The existing infrastructure, such as port facilities, LNG export and import terminals (which could be modified to support hydrogen trade), gas pipelines, salt domes for hydrogen storage, a central geographic location between critical markets, and a steady, business-friendly, and innovative approach are all benefits for hydrogen projects. UAE also benefits from an advanced, extensive network of petrochemical and refining facilities, including the Ruwais ammonia plant, and future possibilities for manufacturing methanol and synthetic fuels [29].

The economic dimension of the hydrogen transition is imperative. The UAE is considered a reliable and sustainable investment environment with a solid track record of public–private collaborations with domestic and foreign companies across the energy and industrial sectors. The establishment of the Abu Dhabi Hydrogen Alliance by ADNOC, Mubadala, ADQ, and the Ministry of Energy and Infrastructure is a critical first step towards a coordinated effort to achieve the UAE's low-carbon economy. However, other strategic initiatives, such as creating carbon accounting guidelines and protocols for hydrogen production, usage, and trade are required [22].

The energy transition at the national or global level is a complex system to unpack, given the existing energy infrastructure. A transition would require many infrastructural upgrades or changes. Estimating the low-carbon hydrogen production efficiency and prioritizing the sector coupling to obtain maximum energy, environmental, and economic impact is imperative to the energy transition, hence the motivation of this study. Many studies have focused primarily on hydrogen energy transition in transportation without socio-economic and environmental basis. Few studies have looked into the UAE's H_2 economy potential. Kazim [30] performed a conceptual and techno-economic analysis of the UAE's potential to utilize hydrogen energy to satisfy its energy needs. Eveloy and Gebreegziabher [31] studied the UAE's excess electricity and power-to-gas potential. More recently, Gandhi et al. [24] quantified the potential of green hydrogen in the UAE for domestic use and energy exports. This contributes to the literature by presenting an efficient hydrogen sector coupling framework for the UAE by first performing an energy, economic, and environmental analysis of the UAE sectors to justify the notion of hydrogen sector coupling and identifying the sector that should be prioritized in the hydrogen energy transition. The so-called data envelopment analysis technique is employed to evaluate efficiency and create an empirical basis for the UAE's hydrogen energy transition sector (DEA). DEA is a robust performance analysis technique developed by Charnes et al. [32] based on the work of Farrel [33]. DEA has been applied in renewable energy [34] and hydrogen-related subjects [35]. For example, Chi et al. [36] evaluated the efficiency of hydrogen-listed enterprises in China using DEA and the Malmquist index. Huang and Liu [37] presented an analysis of China's potential for producing hydrogen using solar and wind energy. This paper takes a holistic view of the UAE's hydrogen energy transition. To the best of our knowledge, this study is the first to analyze the UAE's sector efficiencies and production efficiency in achieving its hydrogen transition target. Furthermore, the hydrogen energy transition framework introduced presents an empirical rationale for future hydrogen policy implementation strategies. Figure 1 illustrate a diagrammatic overview of the study. The remainder of the article is organized as follows: Section 2 details low-carbon hydrogen. Sector coupling is discussed in Section 3 with the analysis framework in Section 4. Section 5 presents the methodology of the study. The results and discussions are provided in Section 6 with the proposed UAE hydrogen transition framework. Finally, the summary and conclusions are presented in Section 7.

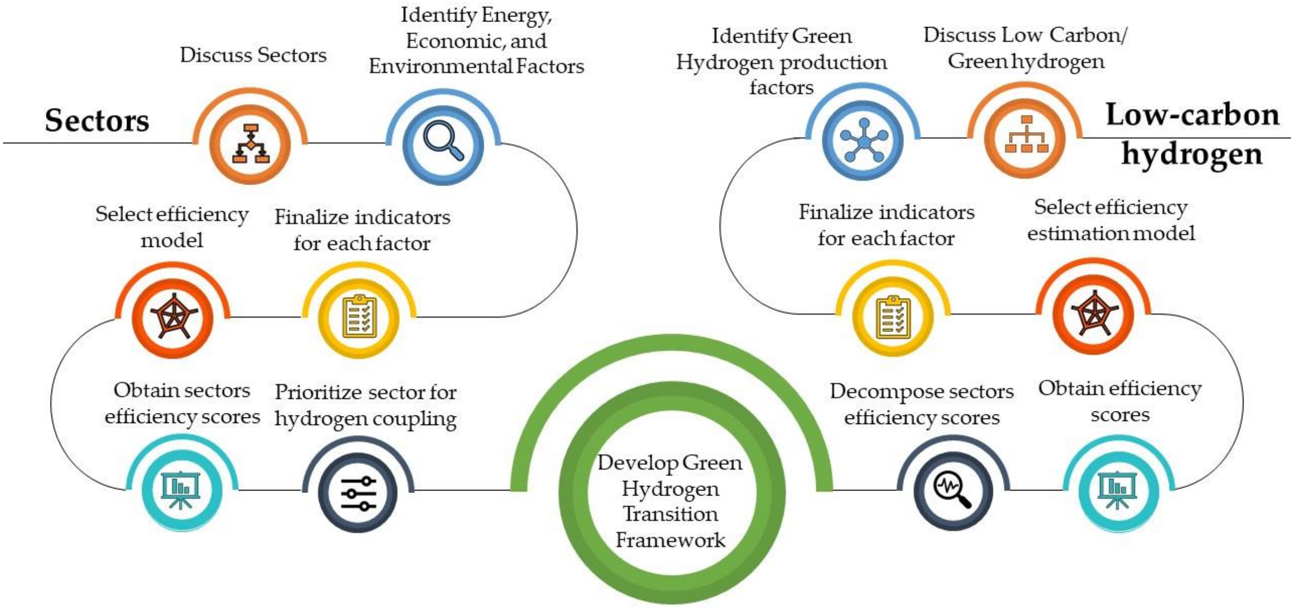

Figure 1. Research overview.

2. Low-Carbon Hydrogen Energy

The economic development pathways for many countries are increasingly influenced by the urgent need to tackle climate change. However, the success of environmental protection measures, such as GHG emission reduction, is being used to gauge economic growth [38]. Some countries are implementing efforts to assume leadership roles in the movement to create low-carbon economies as the international community works towards an effective global system to price the use of carbon [39]. The UAE has undertaken an ambitious national policy for energy saving and emission mitigation in response to international challenges to reduce its CO_2 emissions. The nation intends to lower its carbon intensity while expanding its industrial activities.

To minimize GHG emissions and decelerate climate change, the global energy system must fully transition to a decarbonized system [40]. Energy sustainable development is the only viable path [39]. The role of alternative fuels and technologies intended to support the energy transition are imperative. Studies have shown that hydrogen fits into several integrated energy system models as an alternative fuel in the low-carbon economy [13].

High costs and the availability of infrastructure have prevented hydrogen from having a significant impact on energy systems [38]. However, hydrogen is vital in the UAE's low-carbon pathway due to its versatility as an energy carrier and its potential to reduce emissions in hard-to-abate industries [41]. Hydrogen can be produced in several ways. The primary production method is steam methane reforming, but for hydrogen to be a low-carbon energy carrier, the existing generating methods need to be altered using renewable electrolysis [42]. Utilizing renewable electrolysis can help enhance the penetration of renewable energy [43].

Hydrogen is categorized according to colors based on the energy source used [24]. Hydrogen produced from fossil fuels such as petroleum, coal, and natural gas is denoted as 'black', 'brown', and 'gray' hydrogen, respectively. Low-carbon hydrogen includes blue hydrogen (hydrogen from fossil fuels with CO_2 emissions reduced by the use of carbon capture use and storage (CCU/S), green hydrogen (hydrogen from renewable electricity), and aqua hydrogen (hydrogen from fossil fuels via new technology) [44]. Natural gas reformation is currently used on a wide scale to produce hydrogen [45]. It is a well-developed industrial method that creates hydrogen using high-temperature steam. In this process, the steam reacts with a hydrocarbon fuel to produce hydrogen. Today, the steam reforming of natural gas produces 95% of global hydrogen [46]. Electrolysis is a potentially clean hydrogen generation process, although its environmental impact is well documented. As opposed to hydrogen from natural gas reforming, only low-carbon electrical sources such as hydro, solar, or wind power that enable a significant reduction in GHG emissions are utilized [47]. To produce green hydrogen, the energy source must be renewable energy. There are commercially available alkaline and polymer electrolyte membrane (PEM) electrolyzers. Both are secure and dependable [48].

To meet the enormous demand for low-carbon hydrogen, national and regional efforts are made to boost the electrolyzer capacity. Green hydrogen production is still limited due to renewable energy constraints due to geographical factors and electrolyzer capacity [49,50]. Wind power is a vital energy source for renewable energy [51] and green hydrogen production. Technological advancements such as wind power predictability will enhance renewable energy [52] to support green hydrogen production. To boost low-carbon production, Huang and Liu [53] recommend an integrated scheme of fossil-based hydrogen with CCSU/S and renewable energy hydrogen. Utilizing CCS as an option for low-carbon hydrogen production comes with challenges such as leakage. Selecting the appropriate underground natural gas storage could enhance energy transition and sustainable development goals [54]. To facilitate the permanent storage of CO_2, AlRassas et al. [55] developed an integrated static and dynamic modeling framework to tackle the challenge of CO_2 storage capacity.

The cost of hydrogen production is important in attaining a low-carbon hydrogen economy [13]. The Middle East has the lowest hydrogen production cost using natural gas, with and without carbon capture [3]. Various technical and economic considerations, with gas prices and capital expenditures, affect the cost of producing hydrogen from natural gas [49].

3. Sector Coupling

The sector coupling (SC) concept has been recognized since the turn of the 20th century. There is a broad spectrum of definitions of SC and sectors in the literature. Initial studies defined the sectors as power, heat, hydrogen, and natural gas [50]. Recent studies stated that sectors are not limited to energy sources but also cover the industry, energy economics, residential, commercial, and mobility fields. Figure 2 shows the sector coupling system for direct or indirect electrification; for indirect electrification, power-to-heat (P2H) techniques using combined heat and power (CHP) or electric boilers can be used (EBs). Another option is power-to-gas (P2G), which converts power into hydrogen through electrolysis which can then be processed to produce methanol or methane (CH_4) using a source of CO_2 (H_2) [51].

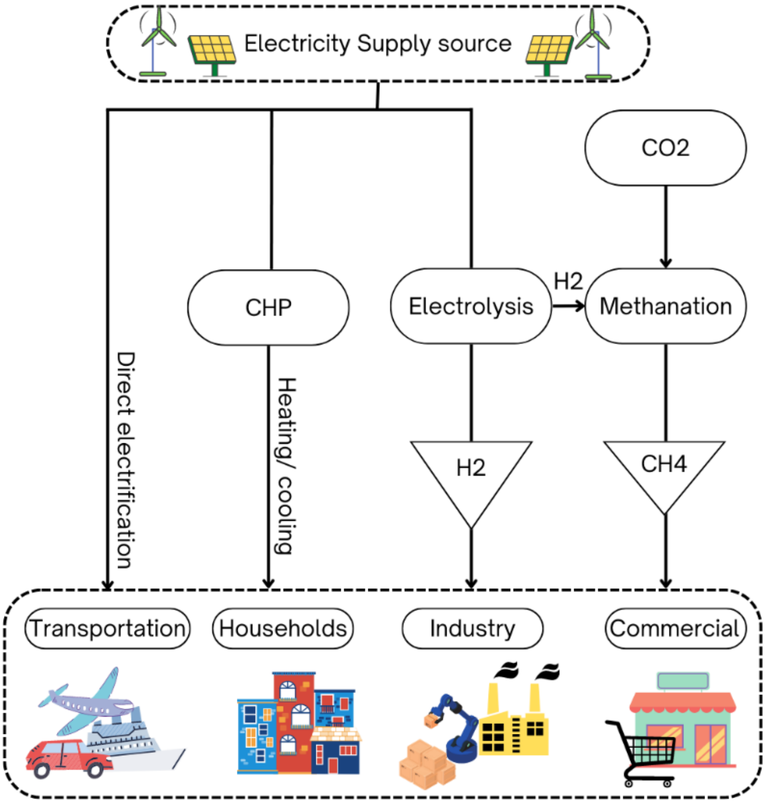

Figure 2. Sector coupling.

There are several definitions of SC, and the researchers described it based on the nature of the study [52]. Energy networks have previously been viewed independently, and only optimization interventions for a single network have been used. Instead, sector coupling enables the integration of all existing networks into a comprehensive energy system, typically referred to as a multi-carrier energy system (MCES). MCES is made up of various energy carriers such as hydrogen, heat, electricity or gas [53]. Economically, MCES lowers the integrated system's operational costs by 1.3% and potentially reduces the impact of wind power output unpredictability on operating expenses by 20% [54]. These benefits add to the growing support for SC in many countries.

SC primarily refers to electrifying end-use industries such as transportation and heating to increase the proportion of renewable energy in these sectors and offer balancing services to the power sector [55]. Supply-side coupling has been integrated into SC more recently through technologies such as power-to-gas that aim to incorporate the gas and electric power sectors [52,56]. The cost-effective decarbonization of the energy system depends heavily on electrifying end-use sectors, but efficient integration of the energy supply sectors can ensure flexibility and efficiency to meet the net-zero national and global target [57]. SC has been extended to include system adaptability with technologies such as electrolyzers for hydrogen production, which has increased demand [58]. This enables a flexible system integration with transportation, electrical, and thermal energy grids to optimize the whole operations as one system economically [59]. End-use SC and cross-vector integration are the two categories under SC [52]. End-use sector coupling strengthens the relationship between electricity supply and end-use while electrifying energy demand. Cross-vector coupling is the coordinated use of various energy infrastructures and vectors, particularly electricity, heat, and gas at the supply side, for example, when surplus electricity is converted to hydrogen, or at the demand side when residual heat from power plants or industrial processes is used for district heating. Sector coupling, according to numerous studies, can reduce the overall costs of the energy transition [57].

Direct electrification is problematic for end-use SC, such as heavy-duty transportation, where refilling time and the volume of energy density are essential factors in fuel selection. Studies show hydrogen energy is essential in the decarbonization of hard-to-electrify end-users [14]. Integrating renewable energy at a higher rate is demanding since passenger and freight transport vehicles require affordable replacements for all fossil fuels used in combustion engines. Additionally, alternatives to high-temperature industrial process heat are crucial. To effectively handle these difficulties and meet the 2050 decarbonization target, SC must expand rapidly, and renewable energy can play an increasingly important role in the hard-to-abate sectors, either directly or through the creation of hydrogen or synthetic fuels [60].

4. Analysis Framework

To adopt a holistic view of hydrogen energy transition, a two-phase efficiency analysis is applied. Figure 3 illustrates the conceptual analysis framework of the paper. First, the sector efficiency of the UAE's system is analyzed to prioritize the less efficient sector. We assume that early transition in the less efficient sectors will have more impact on the transition target rather than in the relatively efficient sector. Subsequently, the low-carbon hydrogen production efficiency is estimated for future planning and action.

The first phase measures energy, economic, and environmental efficiency for each sector. The sectors selected are transportation, industry, and electricity and heat producers. The sectors were considered according to IEA Energy Technology Perspectives' (ETPs) 2017 end-use sectors (industry, transportation, and buildings), which are integrated and linked robustly. The industrial sector covers mining and quarrying, construction, and manufacturing. Buildings cover residential, non-residential, commercial, and public service sectors that use cooling, water heating, lighting, and appliances that require electricity [61]. In our paper, this sector is referred to as electricity and heating deployed in the UAE. The third sector is transportation, which includes all primary motorized forms of transportation such as road, rail, shipping, and air services that offer passenger and cargo services [61].

The variables used to model the efficiency of sectors were applied as the dimensions of each sector. The final energy consumption by sectors represents the energy dimension, while the sector contribution to gross domestic product (GDP) represents the economic dimension [62,63]. The CO_2 emissions of each sector represent the environmental dimensions of the analysis [63]. The energy dimension is the input of the DEA analysis, while the environmental and economic dimensions are the output variables in the analysis. Total energy consumption has been used as an input variable in previous DEA studies [64]. Similarly, GDP [65] and CO_2 emissions [64] have been used to represent the economic and environmental outputs of DEA efficiency analysis. Data for sectoral total final energy consumption and CO_2 emissions were sourced from the IEA's World energy balance [66]. Sector contribution to GDP was sourced from the UAE's Federal Competitiveness and Statistics Center [67].

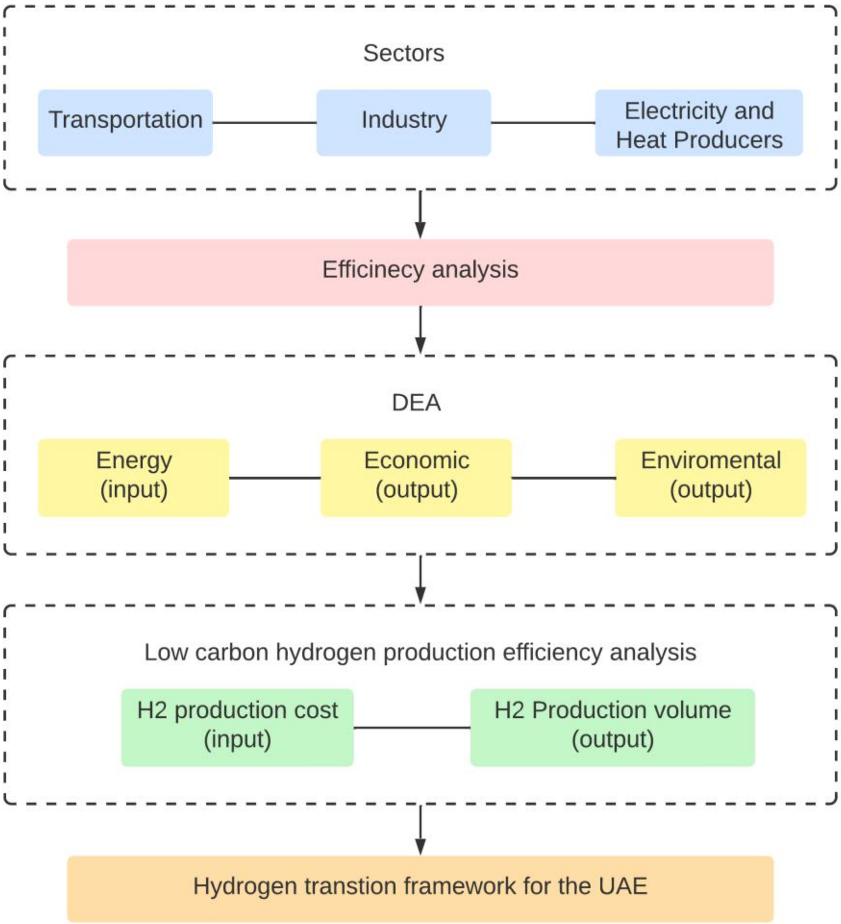

Figure 3. Analysis framework.

The second phase of the analysis looks into the efficiency of the UAEs' low-carbon hydrogen production potential. The results will contribute to developing a hydrogen energy transition strategy for the decarbonizing sectors identified in phase one. Two critical factors are considered to estimate the low-carbon hydrogen production efficiency of the UAE: low-carbon hydrogen production cost and the amount of hydrogen produced annually. A major concern for hydrogen decarbonisation is cost efficiency [68]. To estimate future low-carbon hydrogen production efficiency, we rely on the data from the recently published study of Gandhi et al. [24].

The study of Gandhi et al. [24] applied economics-based aggregate estimates of future demand for green H_2 in the UAE based on existing and planned uses. Our study considered the business-as-usual (BAU) data regarding the adoption across sectors. The BAU method presents a more realistic and less assumptive scenario. This practical perspective assumes the current situation is maintained. Based on the cost and adoption results of the scenarios, the UAE's green H_2 demand and production scenarios were visualized using growth trajectories across all sectors. We take into account capacity utilization, typical hydrogen requirements, and anticipated market growth rates to estimate annual hydrogen demand per industry. This estimate represents the entire green H_2 demand from the industries examined. The absolute demand is evaluated based on the current projections for domestic production rates and those in the future according to Equation (1).

$$ID_{H2,m} = IC_{UAE} \times U_{plant} \times CF_{H2} \tag{1}$$

ID_{H2} represents the industrial H_2 demand in a year in units of tonnes, while IC_{UAE} indicates the domestic industrial installed capacity in units of tonnes. Ultimately, CF_{H2} is the conversion factor from unity output to hydrogen tonnes.

5. Data Envelopment Analysis Efficiency Estimation

Data envelopment analysis is a data-driven, non-parametric technique that effectively evaluates the efficiency of systems known as decision-making units (DMUs). DMUs are a set of homogenous entities that carry out an input–output transformation process. DMUs are characterized by an input–output vector that comprises the amount of different inputs consumed and different outputs produced. The basis of DEA methodology is the derivation of the production possibility set (PPS) that contains all points of the input–output vectors that are considered feasible based on the observed DMUs.

DEA evaluates the efficiency of a set of $j = 1, 2, \ldots, n$ observed DMUs. These observations transform a vector of $i = 1, 2, \ldots, m$ inputs $x \in \Re^m_{++}$ Xer into a vector of $i = 1, 2, \ldots, s$ outputs $y \in \Re^s_{++}$ using the PPS of Equation (2), following constant return to scale, and Equation (3), following variable return to scale.

$$P = \{(x, y) | x \geq X\lambda, y \leq Y\lambda, \lambda \geq 0\} \tag{2}$$

$$P = \{(x, y) | x \geq X\lambda, y \leq Y\lambda,\ e\lambda = 1, \lambda \geq 0\} \tag{3}$$

where $X = (x)_j \Re^{s\times n}_{++}$, $Y = (Y)_j \Re^{m\times n}_{++}$ and $\lambda = (\lambda_1, \ldots, \lambda_n)^T$ is a semipositive vector.

An efficient DMU is derived with maximum outputs with constant inputs or minimum inputs with constant outputs. Apart from inputs and desirable outputs, undesirable outputs are also considered inefficient evaluation, especially in energy utilization systems. The undesirable outputs are related to the environment, such as CO_2 emissions [69], SO_2 emissions, and industrial waste [70]. Therefore, to take into account the undesirable outputs produced, DEA evaluates efficiency by finding the maximum desirable output and minimum undesirable outputs utilizing the same inputs. To estimate efficiency, this paper adopts the undesirable output direction distance function model (DDF). Compared to the traditional DEA model. The DDF model introduced by Chambers et al. [71] is a non-radial, non-oriented DEA model. The Chambers et al. [71] model estimates efficiency given technology T and a non-zero direction vector $(g^x, g^y) \in \left(\Re^m_+ \times \Re^s_+\right)$, and DDF $D_T(X_0, Y_0, g^x, g^y)$ is defined as:

$$\begin{aligned} D_T(X_0, Y_0, g^x, g^y) = {} & Max\ \beta \\ & s.t. \\ & \hat{X} = \sum_{j=1}^{n} \lambda_j X_j \leq X_0 - \beta g^x \\ & \hat{Y} = \sum_{j=1}^{n} \lambda_j Y_j \geq Y_0 + \beta g^y \\ & (\lambda_1, \lambda_2, \ldots, \lambda_n) \in \Lambda^T\ \beta\ free \end{aligned} \tag{4}$$

where Λ^T can be constant return to scale or variable return to scale. The first and second constraints of Equation (1) show that $D_T(X_0, Y_0, g^x, g^y)$ reduces the inputs and increases the outputs simultaneously using the direction (g^x, g^y) as a projection direction. Equation (4) corresponds to technical efficiency (TE) from the constant return to scale (CRS) assumption. Pure technical efficiency (PTE) with respect to variable return to scale (VRS) is calculated by adding the VRS constant, $\sum_{j=1}^{n} \lambda_j = 1$. Consequently, scale efficiency (SE) can be calculated as: $SE = TE - PTE$.

To simultaneously increase desirable output and decrease undesirable output in efficiency estimation, Chung et al. [72] introduce an undesirable output DDF model to ensure asymmetry between both types of production. Treating both sets of outputs differently requires the redefinition of the PPS as $P = \left\{\left(x, y^d, y^u\right) \middle| x \geq X\lambda, y^d \leq Y\lambda,\ y^u = Y\lambda,\ \lambda \geq 0\right\}$

where the outputs are separated into desirable and undesirable outputs as: $y = \left(y^d,\ y^u\right)$ with $y^d \in R^q_{++}$ and $y^u \in R^r_{++}$, respectively. Correspondingly, the directional efficiency measure of a DMU $\left(x_0,\ y^d_0,\ y^u_0\right)$ is projected along the direction output vector $g_y = \left(y^d,\ y^u\right) \neq 0_{m+s}$. To prevent inconsistency in the original approach, Álvarez et al. [73] present a robust undesirable output DDF model as:

$$\begin{aligned}
&\max_{\beta,\lambda} \beta \\
&\textit{subject to} \\
&\qquad X\lambda \leq x_0 \\
&\qquad Y^d\lambda \geq y^d_0 + \beta y^d_0 \\
&\qquad Y^u\lambda \leq y^u_0 + \beta y^u_0 \\
&\qquad \max\left\{y^u_i\right\} \geq y^u_0 + \beta y^d_0 \\
&\qquad \lambda \geq 0.
\end{aligned} \tag{5}$$

The solution of the linear program presents the efficiency score. If the optimal solution $\beta^* = 0$ with $\lambda_0 = 1,\ \lambda_j = 0\ (j \neq 0)$, then the unit is directionally efficient. Otherwise, $\beta^* > 0$ implies the unit is inefficient, and efficiency score is presented as: $1 - \beta^*$.

6. Results and Discussions

Table 1 present the descriptive statistics of the variables used in the first phase of the analysis. The result shows that the industry sector has the highest variation among all variables, which indicates that the values are spread out over a broader range. This variation may be attributed to the variability in industry activities compared to other sectors. On the other hand, the lowest standard deviation is the electricity and heat producers' sector. The electricity and heat producers' sector has a higher consistency and predictability in energy consumption and other factors than other sectors. In addition, the industry sector consistently has the highest mean among all the variables.

Table 1. Descriptive statistics for sector efficiency analysis.

Sectors		Total Final Consumption (TJ)	Sector GDP Contribution (Billion USD)	CO_2 Emissions by Sector (mt CO_2)
Industry	Mean	1,021,346.5	147.45	57.65
	Std. Dev	300,881.02	28.28	17.22
	Min.	606,997	90.24	34
	Max.	1,459,132	181.81	83
Transport	Mean	407,791.64	19.67	29.2
	Std. Dev	100,384.21	2.60	7.08
	Min.	226,644	14.88	16
	Max.	577,048	26.03	41
Electricity and heat producers	Mean	101,964.04	7.41	58.75
	Std. Dev	35,234.752	2.89	12.16
	Min.	39,107	3.21	32
	Max.	148,246.85	11.36	72

In estimating the sectors' energy, economic, and environmental efficiency, model (5) is applied using Matlab R2020a. The results are presented in Table 2. Total final energy consumption is considered as the input, sector contribution to GDP is the desirable output, and sector CO_2 emission is an undesirable output. Figure 4 illustrates the average efficiency scores in different time intervals. The electricity and heat producers' sector was the most efficient over time, with an efficiency score between 0.89 and 0.99. The average efficiency of electricity and heat producers improved over time, especially over the last 3–5 years.

Table 2. Sector efficiency scores.

Year	Industry	Transport	Electricity and Heat Producers
2001	0.66	0.99	0.99
2002	0.69	0.96	1.00
2003	0.77	0.94	0.77
2004	0.87	1.00	0.77
2005	0.92	0.94	0.78
2006	1.00	0.95	0.77
2007	0.88	0.97	0.79
2008	0.82	0.94	0.66
2009	0.67	0.97	0.89
2010	0.66	0.72	0.84
2011	0.69	0.74	0.90
2012	0.65	0.75	0.89
2013	0.64	0.70	0.90
2014	0.67	0.74	0.92
2015	0.64	0.82	0.97
2016	0.64	0.73	1.00
2017	0.71	0.70	0.98
2018	0.85	0.74	0.98
2019	0.74	0.79	1.00
2020	0.70	0.69	0.98

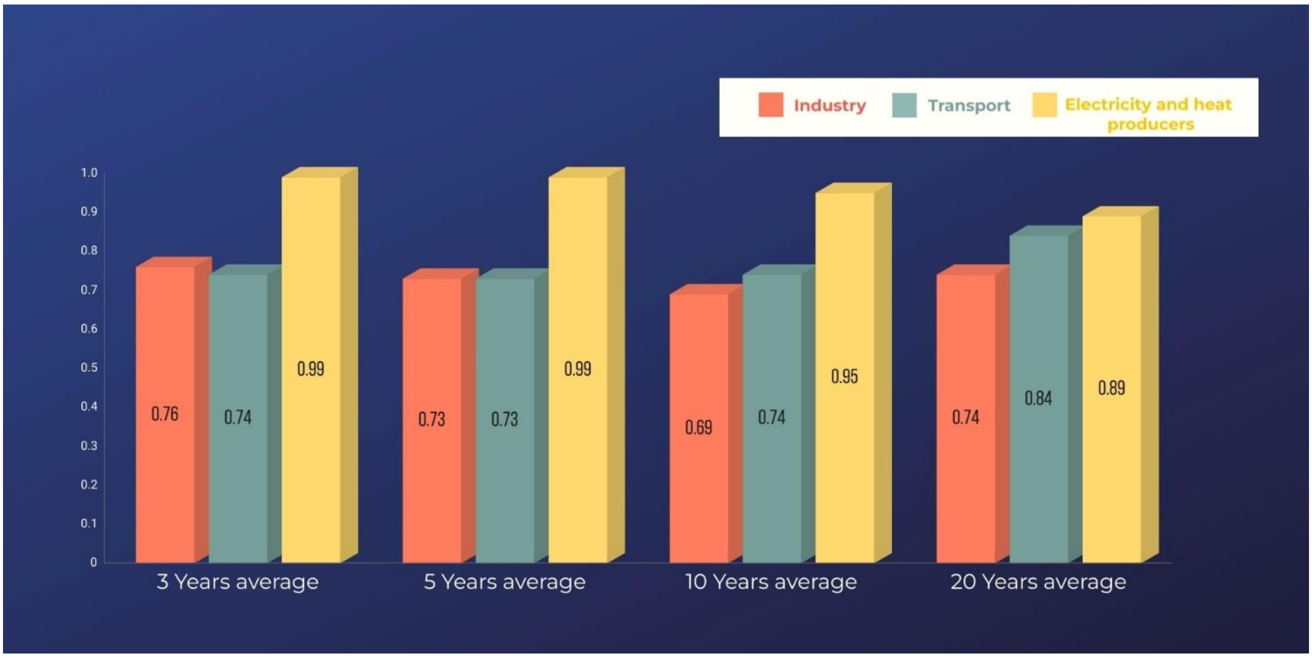

Figure 4. Average energy, economic, and environmental efficiency of UAE sectors.

Conversely, the industry and transport sector observed a relative decline in average efficiency. Average efficiency indicated the transport sector to be the least efficient in the last 3–5 years. Table 2 presents the detailed annual efficiency scores. Electricity and heat producers had three periods—2002, 2016, and 2019—identified as efficient. The transport (2004) and industry (2006) sectors had only one period identified as efficient. The efficiency of the transport sector in 2020 had the least efficiency scores of all periods in the transport sector. The industry sector showed a slight improvement over time. However, the last 3–5 years were relatively inefficient.

The results of the efficiency scores of the industry, transport, and electricity and heat producer sectors, therefore, suggest the transportation and industry sectors be prioritized in the hydrogen energy transition, given the relatively inefficient performance of the sectors. Coupling hydrogen energy with the transportation and industry sector could be more impactful, and the net-zero target could be efficiently attained.

The second phase of the analysis looks into the green hydrogen production potential of the UAE. Annual green hydrogen production cost is the input, while the output is the amount of green hydrogen to be produced. To estimate green hydrogen production efficiency, Equation (4) is applied. Figure 5 presents the estimated annual technical efficiency (TE) score of green hydrogen production. TE is decomposed into PTE and SE for further analysis. Figures 6 and 7 illustrate PTE and SE scores, respectively. TE is consistent with overall efficiency, which includes operational efficiency and scale efficiency. PTE corresponds to the operational aspect of efficiency. The relationship between TE and PTE is the scale efficiency, which refers to the utilization of capacity with respect to the input.

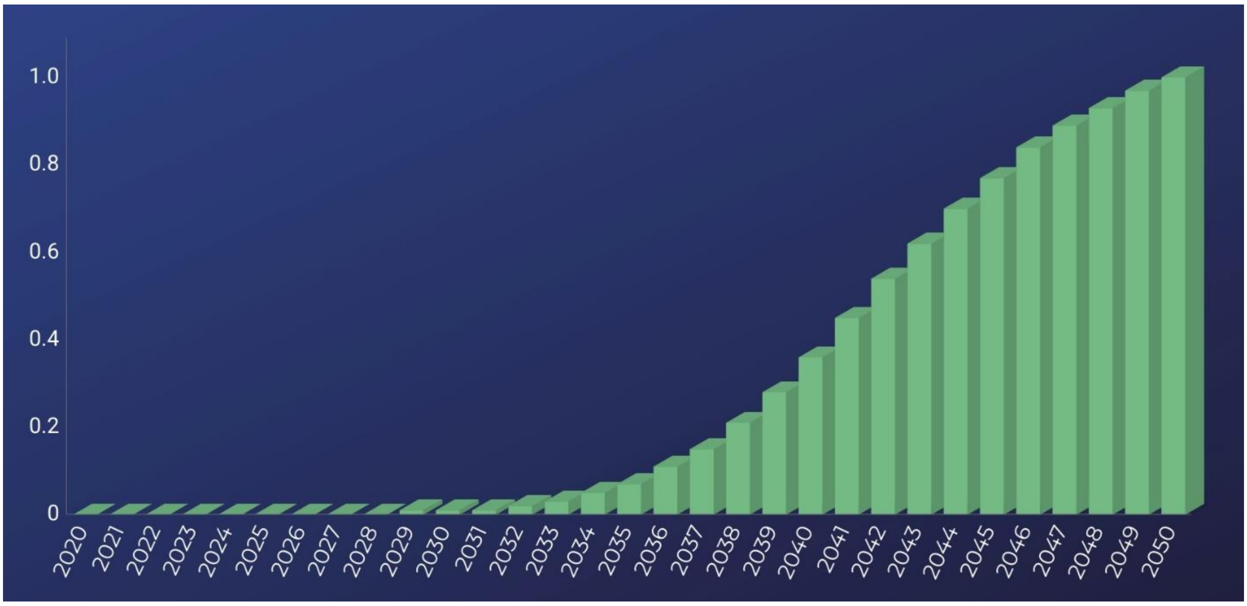

Figure 5. Technical efficiency (TE) of green hydrogen production in the UAE.

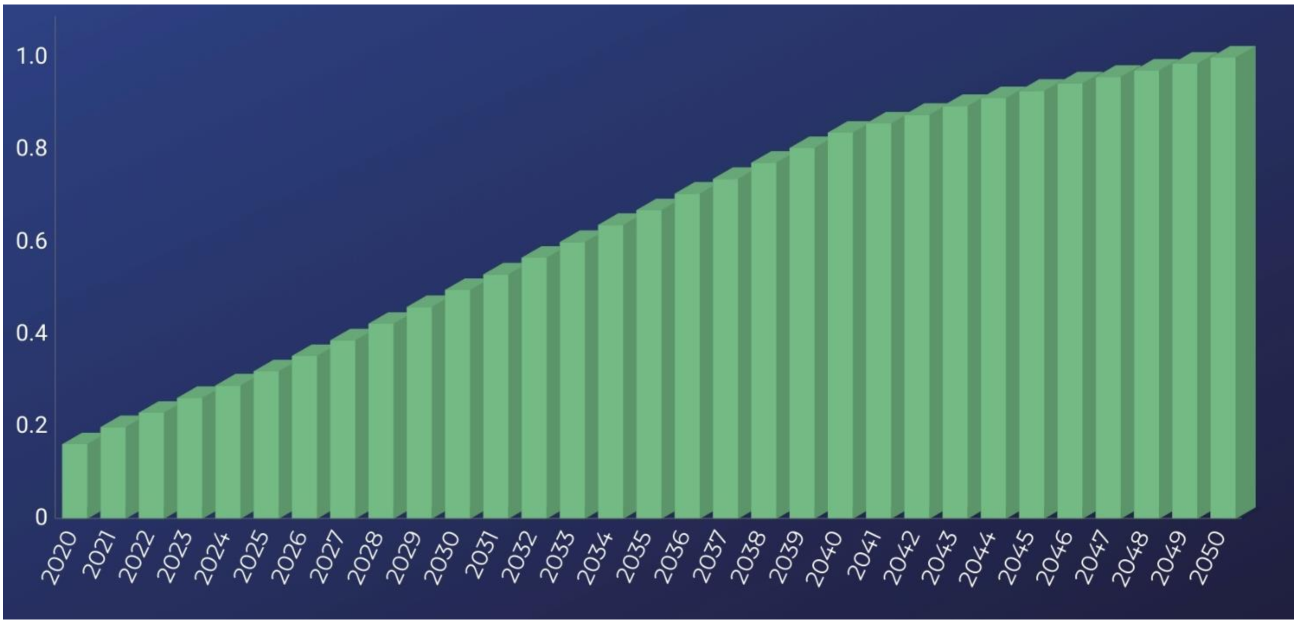

Figure 6. Pure technical efficiency (PTE) of green hydrogen production in the UAE.

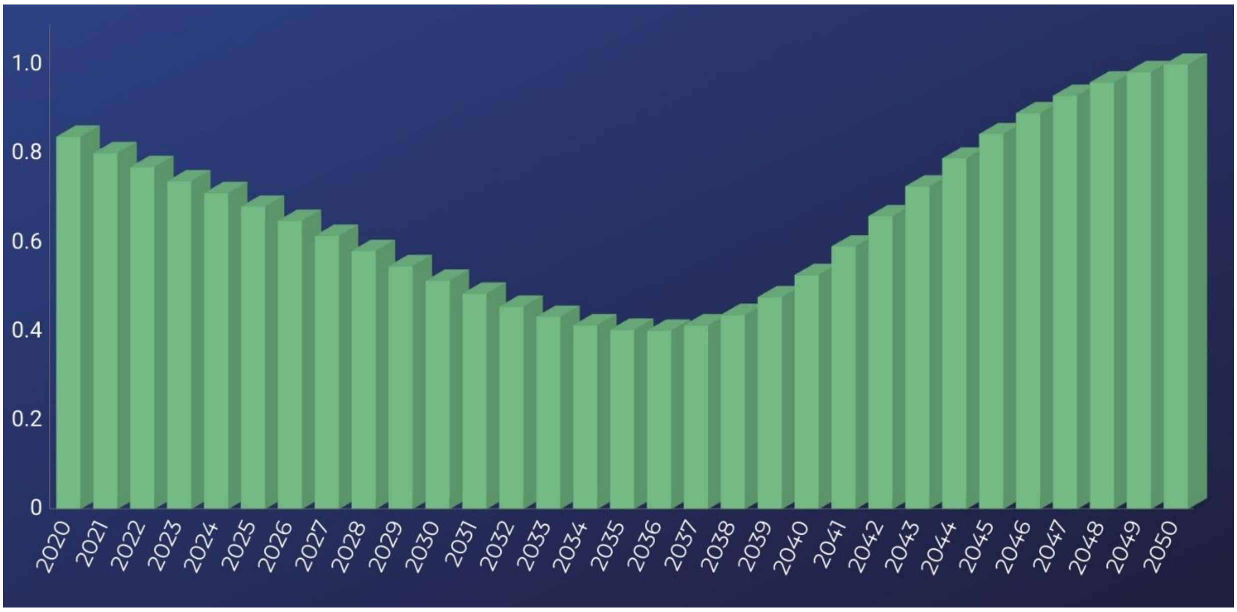

Figure 7. Scale efficiency of green hydrogen production in the UAE.

Results of TE indicate a steady growth in green hydrogen production efficiency in the UAE. For the next 10 years, the UAE will continue to experience an inefficient green hydrogen production system. This period can be considered a growth and capacity-building stage. Across the UAE, various projects are developed to improve production. In addition, the UAE is building operational competency for green hydrogen production, as observed in PTE efficiency. In 2030, the UAE will experience a boost in operational efficiency with a PTE score of 0.5. The result shows that the UAE is focused on building operational competency for the next ten years. There is a decline in scale efficiency, as observed in Figure 7. The decline is relative to the cost of hydrogen production. This decline in scale efficiency signifies that the amount of hydrogen produced does not complement the hydrogen production cost. The decomposition of the green hydrogen production efficiency results highlights the need to scale infrastructure for the storage and transportation of green hydrogen from both supply and demand sides. Since low-carbon hydrogen requires significant infrastructure for effective implementation, investment is needed to meet the short-term target. The results show a shortfall of technological advances to meet the growing technical efficiency of green hydrogen in the short term. Since the results point to short-term inefficiency in the UAE, the international hydrogen market is a viable alternative for the UAE to export low-carbon hydrogen to countries such as Japan, contributing to the global hydrogen energy transition by maintaining its role in the energy market. Therefore, the scale needs to be increased in these periods. This decline is projected to continue until 2036, when there will be a significant improvement in scale efficiency. This improvement in scale efficiency corresponds to the growth in the overall efficiency of hydrogen production in the UAE. Therefore, scale efficiency is imperative to the overall efficiency of the UAE's green hydrogen production system. Policies and strategies should, therefore, target upscaling the UAE's green hydrogen production capacity.

The low-carbon hydrogen transition is a global effort towards decarbonizing our energy systems. To our knowledge, no study has explored sector efficiency and green hydrogen production efficiency in the UAE. However, the findings of this study are consistent with a Chinese provincial study by Huang and Liu [42]. Their analysis points to a promising green hydrogen production for Chinese provinces using wind and solar energy up to 2030. Huang and Liu [37] recommend an integrated scheme to promote low production costs to boost low-carbon hydrogen production. Our study adds to the literature by further decomposing efficiency into pure technical and scale efficiencies, presenting an empirical improvement strategy combined with the sector efficiency analysis for an efficient hydrogen economy. Furthermore, the study provides a long-run efficiency estimation, offering technical and managerial insight toward attaining the 2050 target.

Hydrogen Transition Framework for the UAE

Developing a hydrogen-integrated energy system requires a broad and integrated set of changes, including infrastructure and technology; policies and incentives; regulations and codes; behaviors and habits; and investment patterns. Such broad changes are considered a “technological transition” from one sociotechnical system to another [74]. The dynamics of sociotechnical change are imperative in developing a framework for the hydrogen energy transition. The energy, economic, and environmental efficiency results indicate that the industry and transportation sectors should be the priority for the UAE’s hydrogen energy transition. Following the increase in low-carbon hydrogen production efficiency, the UAE shows competency in achieving its hydrogen energy transition through sector coupling. Based on global hydrogen transition strategies of leading hydrogen economies such as the United Kingdom [75] and Germany [76], a UAE hydrogen energy transition framework is proposed in Figure 8.

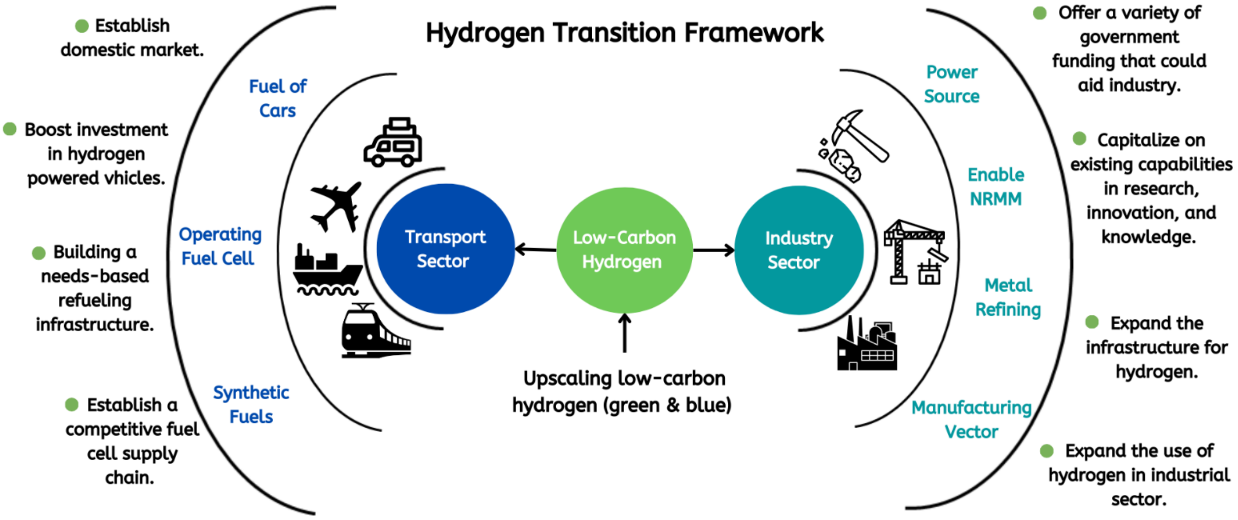

Figure 8. Hydrogen energy transition framework for the UAE’s transportation and industry sectors.

The sector efficiency analysis in phase one suggests the transportation sector be prioritized before the industry sector due to its lower average efficiency score. However, the infrastructural constraints of the transport sector necessitate the industry to come first. This strategy could improve the transition’s short-term inefficiency and achieve decarbonization by 2030. The low-carbon hydrogen strategy targets the decarbonization of transport and industry sectors through upscaling the production of blue and green hydrogen. The UAE transportation sector comprises cars, buses, metro, trams, airplanes, and marine transportation. The industry sector includes the manufacturing, mining, and construction operations [3], which are considered busy sub-sectors in the UAE.

Establishing a robust and sustainable domestic market for hydrogen production and domestic use is the first step that needs to be taken to accelerate the adoption of hydrogen technology. The following measures should be implemented to expedite the adoption of hydrogen technology between the public and private sectors to realize its full potential. The transition strategy should serve as a basis for private sector investment in hydrogen generation that is both commercially and environmentally feasible.

In the industry sector, the government has to offer a variety of funding that can help the industry make the transition to low-carbon technologies. Capital expenditure (CAPEX) support mechanisms and operating expenditure (OPEX) mechanisms need to be in place to support and boost the transition. The UAE has initiatives that encourage the use of hydrogen in production. However, this needs to be scaled to meet the net-zero target. Effective collaboration in a public–private partnership is key to a successful transition. To fully realize hydrogen's potential to aid in reducing carbon emissions, we must invest in the research and innovation of the hydrogen value chain [75]. Hydrogen might be used to reduce a significant amount of emissions brought on by using non-road mobile machinery (NRMM) such as diggers and excavators. Robust and scalable hydrogen infrastructure must be built with significant investments in CAPEX and OPEX to utilize it as a solution in various industry options [75]. Industrial users are anticipated to generate the majority of the new demand for hydrogen through industrial fuel switching, and the industrial sector is likely to pave the way for large-scale low-carbon hydrogen consumption. This is achieved by accelerating the industrial use of current hydrogen to decarbonize current processes. In order to expand into other sub-sectors of the industry and the larger energy system, the hydrogen economy must thrive. A rise in the number of locations having access to low-carbon hydrogen ongoing technological advancements to broaden the variety of processes that can use hydrogen, and a change in associated expenses, such as the price of carbon, would all contribute to the transition [76]. There is significant market demand for low-carbon hydrogen. International collaborations for hydrogen transport could enhance the hydrogen energy transition.

In the transport sector, hydrogen is an energy source that can be deployed to create synthetic fuels or used in fuel cells to power hydrogen-powered vehicles. Synthetic fuels are necessary for decarbonizing both sea and air transportation. For some mobility requirements, fuel cells and battery-powered drives may be an option in aviation and coastal and inland transportation. Despite the opportunities in this field, technological advancements are required to push transport development. Therefore, increasing financial investment in hydrogen-powered transportation (light and heavy trucks, buses, railroads, and cars) will boost the advances in the sector [76]. Building a needs-based refueling infrastructure is necessary for vehicles, particularly heavy-duty road haulers, vehicles used in public transportation, and local passenger rail services. The support for developing a competitive fuel cell supply chain includes the establishment of an industrial basis for large-scale fuel cell stack production for vehicle applications. Investigation of the feasibility of establishing a hydrogen technology and innovation hub will facilitate the emergence of hydrogen energy in the transport sector [76]. More importantly, financial investment is insufficient for private companies to collaborate and achieve the sector's transition [77]. The IEA recommends developing funding schemes, such as a capital expenditure tax decrease, to overcome the high cost of new technologies. Moreover, establishing emission restrictions, carbon pricing, and mandates for renewable energy adoption in the sector will encourage the higher adoption of hydrogen demand [78]. Approaches such as tax incentives for switching to hydrogen will be beneficial. Moreover, reducing investment risks will significantly enable infrastructure expansion and market penetration for hydrogen [79].

7. Summary and Conclusions

This paper takes a holistic view of hydrogen energy transition in the UAE. Using an undesirable output DDF DEA model, the energy, economic, and environmental efficiency of UAE sectors are analyzed in the first phase for the period of 2001–2020 to identify the sectors that should be prioritized in hydrogen energy sector coupling. The second phase of the analysis evaluates the production efficiency of low-carbon hydrogen, i.e., green hydrogen, in the UAE for the period of 2020–2050, using the business-as-usual (BAU) case of green hydrogen production cost and green hydrogen production volume in the UAE. The sector efficiency analysis result shows the transport and industry sectors are the most inefficient due to their declining efficiency averages. Therefore, the two sectors should be prioritized in the decarbonization strategy.

The green hydrogen production efficiency results show great potential in the long run. The relative underperformance of short-term hydrogen production efficiency is attributed to scale inefficiency. Therefore, to improve short-term efficiency and for the UAE to attain its

2030 hydrogen vision of capturing 25% of the global low-carbon hydrogen market, there is a need to scale low-carbon hydrogen production to meet the short-term target. The current trajectory shows that the UAE is on track to attain its 2050 green hydrogen energy vision.

The paper comes with some limitations. The low-carbon hydrogen production efficiency focuses primarily on green hydrogen production, and the model does not consider carbon emission in the production process. Process emissions during electrolyzer/PV manufacturing, construction, and transportation are, of course, present. However, the green hydrogen production process itself does not involve any emissions. Other low-carbon H_2 options, such as blue hydrogen, do involve GHG emissions. Future research should consider blue hydrogen production and GHG emissions in the model.

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