Thesis for the Degree of Master of Engineering

Green Hydrogen Economy and Sustainable Development: Overcoming Socio-Political Barriers

By

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The Graduate School

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DEDICATION

I dedicate my dissertation to my husband and children for their endless support and motivation.

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Alhamdulilah, for every blessing that our Creator (the most Merciful) has bestowed upon His creation. I would not be able to achieve anything if it were not for the strength that I solely gained by asking Him throughout graduation and my life.

I am highly obliged to my supervisor and advisor Prof. J. Jay Liu for providing me with an amazing opportunity to nourish myself, learn something innovative and enhance my research skills.

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ABSTRACT

As the global energy landscape undergoes a transformative shift, propelled by the imperative for sustainable solutions, this research embarks on a multifaceted exploration of the green hydrogen economy. Against the backdrop of escalating climate change challenges and an urgent need for sustainable energy sources, this research adopts a qualitative research approach, engaging in a systematic analysis and synthesis of existing literature, policies, and socio-economic data. In this context, the research motivation stems from the profound social, economic, and geopolitical implications the transition to a green hydrogen economy holds for achieving global sustainable development. The exploration encompasses key findings, challenges, and potential future works, presenting a comprehensive understanding of the evolving landscape.

Chapter 1 sets the stage by addressing global challenges, particularly climate change, and the need for sustainable energy sources. It emphasizes the crucial role of green hydrogen in tackling these issues and introduces the central themes of the thesis: the effects of the COVID-19 pandemic on energy transition, the socio-political aspects of the green hydrogen economy, and its contribution to realizing the SDGs. Chapter 2 delves into the complex relationship between the COVID-19 pandemic, South Korea's economy, and the hydrogen economy. It offers a comprehensive understanding of the pandemic's various impacts, from disruptions in the energy sector to broader economic consequences, laying the groundwork for grasping the immediate challenges and opportunities that emerged after the pandemic. Chapter 3 unravels the intricate web of socio-political and geopolitical challenges tied to global green hydrogen production and trade. It provides a deeper understanding of the complexities behind these processes and stresses the importance of a fair transition that ensures equitable benefits for all societies and nations. Chapter 4 focuses on how the green hydrogen economy aligns with the SDGs. It notably supports SDG 7 ('Affordable

and Clean Energy') and SDG 13 ('Climate Action'), making green hydrogen a crucial driver for clean energy and climate action. However, this alignment extends to the broader SDG agenda, exploring the nuances of synergies and trade-offs and highlighting green hydrogen's pivotal role in promoting holistic sustainability.

The key findings of this research reveal two pivotal aspects:

Alignment with SDGs: The green hydrogen economy emerges as a critical driver in achieving SDGs, notably SDG 7 ('Affordable and Clean Energy') and SDG 13 ('Climate Action'). The research explores broader implications for the SDG agenda, examining synergies and trade-offs, and positions green hydrogen as a linchpin for holistic sustainability.

Socio-political & Geo-political Complexities: The examination exposes crucial insights into socio-political and geopolitical challenges tied to global green hydrogen production and trade. This understanding emphasizes the need for a fair transition, ensuring equitable benefits and addressing potential power imbalances.

Chapter 5 concludes the thesis by emphasizing the paramount importance of holistic sustainability. Envisioning a future where the coexistence of humanity and the planet is imperative, the green hydrogen economy emerges as a catalyst. Aligned with ambitious SDG goals, it ensures a world characterized by clean energy, climate resilience, and social equity at its core. Despite these contributions, our examination primarily focuses on specific geographical and geopolitical contexts. While this specificity allows for a detailed exploration, the findings may not be universally applicable. As the green hydrogen economy continues to evolve, future research should broaden the geographical scope and delve deeper into specific socio-political contexts.

Additionally, exploring emerging technologies and their impact on green hydrogen production presents avenues for future investigation.

요약

전세계 에너지 환경이 지속 가능한 솔루션의 필요성에 이끌려 변화함에 따라, 이 연구에서는 녹색 수소 경제의 다양한 측면을 조사하고자 한다. 급격한 기후 변화와 지속 가능한 에너지원에 대한 긴박한 요구 속에서, 이 연구는 기존 문헌, 정책, 및 사회 경제 데이터를 체계적으로 분석하고 종합하는 정성적인 연구 방법론을 따른다. 이 맥락에서 연구의 동기는 세계적으로 지속 가능한 발전을 위한 녹색 수소 경제 전환의 사회, 경제 및 지정학적 영향에서 비롯된다. 이 조사는 현재의 에너지 환경에 대한 종합적인 이해를 제공하여 주요 결과, 도전 그리고 잠재적인 향후 연구 방향을 다룬다.

제 1 장에서는 특히 기후 변화와 지속 가능한 에너지원에 대한 전세계적 도전의 배경을 설정한다. 이 장에서는 이러한 문제에 대응하는 데 있어 녹색 수소의 중요한 역할을 강조하며 논문의 중심 주제 - COVID-19 대유행이 에너지 전환에 미치는 영향, 녹색 수소 경제의 사회 정치적 측면과 지속 가능한 발전의 실현에 기여 - 를 소개한다. 제 2 장에서는 COVID-19 대유행, 대한민국의 경제, 그리고 수소 경제 간의 복잡한 관계를 탐구한다. 이 장에서는 COVID-19 대유행이 에너지 부문의 붕괴에서부터 폭넓은 경제적 결과까지 다양한 영향을 종합적으로 이해하며, 대유행 이후 나타난 즉각적인 도전과 기회의 기초를

마련한다. 제 3 장에서는 전세계 녹색 수소 생산 및 무역과 연결된 복잡한 사회 정치 및 지정학적 도전을 파헤친다. 이는 이러한 과정의 복잡성에 대한 심층적인 이해를 제공하며 모든 사회 및 국가에 공정한 전환을 보장하고 잠재적인 권력 불균형에 대처하는 중요성을 강조한다. 제 4 장에서는 녹색 수소 경제가 지속 가능한 발전(Sustainable Development Goals, SDG)에 어떻게 일치하는지에 중점을 두고 있다. 특히 SDG 7 ('저렴하고 깨끗한 에너지')와 SDG 13 ('기후 조치')를 지원하여 녹색 수소를 깨끗한 에너지 및 기후 조치의 중요한 주도 요인으로 만들고 있다. 그러나 이는 더 광범위한 SDG 계획으로 확장되어 시너지와 트레이드 오프의 미묘한 측면을 탐색하고 녹색 수소의 중요한 역할을 강조한다.

이 연구의 주요 결과는 다음의 두 가지 중요한 측면을 드러낸다.

SDG 와의 일치: 녹색 수소 경제는 특히 SDG 7 ('저렴하고 깨끗한 에너지')와 SDG 13 ('기후 조치')에 대한 중요한 주도 요인으로 떠오른다. 이 연구는 SDG 계획의 넓은 영향을 탐색하며 시너지와 트레이드 오프를 조사하고 녹색 수소를 종합적인 지속 가능성을 촉진하는 중심 요소로 위치시킨다.

사회 정치적 및 지정학적 복잡성: 이 연구는 글로벌 녹색 수소 생산 및 무역에 관련된 사회 정치 및 지정학적 도전에 대한 중요한 통찰력을 제공한다. 이 이해는 모든 사회 및 국가에 공정한 전환을 보장하고 잠재적인 권력 불균형에 대응하는 필요성을 강조한다.

제 5 장은 종합적인 지속 가능성의 중요성을 강조하며 이 논문을 마무리한다. 인류와 지구의 공존이 필수적인 미래를 상상하면서, 녹색 수소 경제는 촉매제 역할을 한다. SDG 의 야심찬 목표와 조화롭게 어우러져 깨끗한 에너지, 기후 내성, 그리고 핵심적인 사회적 공정이 특징인 세계를 보장한다. 그럼에도 불구하고 이 논문은 특정 지리적, 지정학적 맥락에 중점을 두고 있다. 이러한 특수성은 자세한 탐험을 가능케 하지만 결과가 보편적으로 적용될 수 없을 수 있음을 의미한다. 녹색 수소 경제가 계속해서 진화함에 따라 향후 연구는 지리적 범위를 확대하고 특정 사회 정치적 맥락을 보다 깊게 탐구하야 한다.

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CHAPTER 1

1 INTRODUCTION

In recent years, the world has faced many global challenges, including climate change, as fossil fuels have contributed significantly to global warming. To mitigate climate change issues and achieve net zero targets, 196 parties adopted the Paris Agreement at the UN climate change conference, which became effective on 4 November 2016. As soon as nations across the globe became united behind decarbonizing their industrial and energy sectors, the COVID-19 pandemic hit the world severely, resulting in massive health and economic crisis. With lockdowns, energy demand plummeted, causing oil prices to fall. The most significant reduction in CO_2 emissions in history occurred in 2020, with a 6.4 percent decrease in global emissions [1]. The International Energy Agency (IEA) estimates that global CO_2 emissions will decline by 8% due to the pandemic in 2020 [1]. According to a study by Dincer et al., the coronavirus has paved a path for achieving the climatic goals that lie ahead by introducing the hydrogen economy replacing fossil fuels [2]. The harmful effects of fossil fuels are increasing and the countries are aggressively seeking clean and renewable energy sources, including wind, solar and biomass energy [3]. To mitigate the global warming issues and GHG emissions, countries around the globe are focusing on renewable energy transitions.

Hydrogen is emerging as a potential clean energy carrier and can be produced using several feedstocks (fossil fuels, water, biomass) as shown in Figure 1. [4]. Also, the production of hydrogen from renewable electricity (green hydrogen) is viewed as an essential enabler for achieving net-zero emissions and contributing to the global transition to sustainable energy. Green hydrogen presents numerous advantages, making it one of the most promising alternative energy

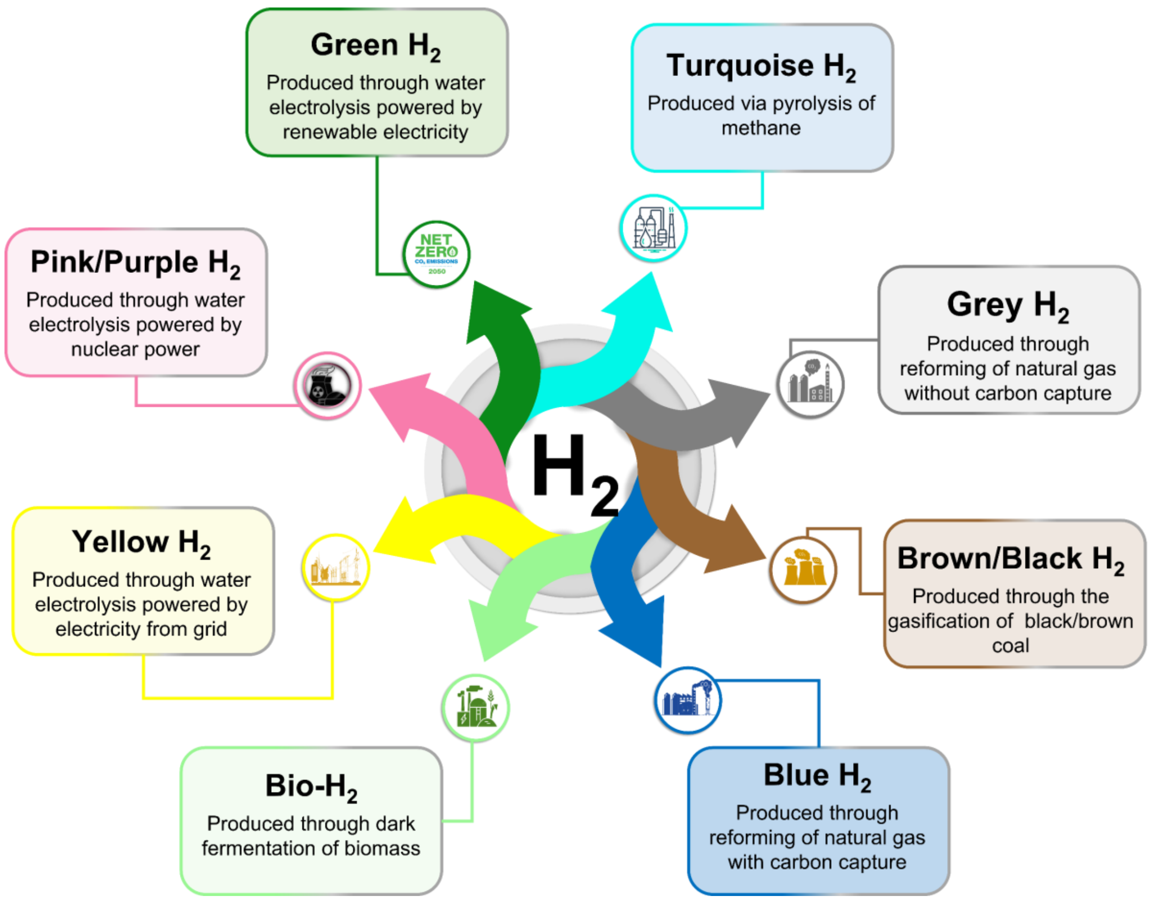

Figure 1. Types of hydrogen based on color spectrum and method of production.

sources, attracting many countries to consider their transition towards renewable energies. Transportation sector contributes 28% to the GHG emissions since it relies heavily on fossil fuels [5]. Hydrogen can be used as an energy carrier in the transport sector and can be helpful in gaining sustainable mobility [6]. Basic hydrogen strategy was first initiated by Japan in December 2017 and the Japanese government tends to reduce carbon emissions by 39% in the residential sector and 40% in the commercial sector by 2030 by introducing green hydrogen in the energy and the transport sectors [7–9]. Hydrogen fuel cell automobiles can be seen more attractive to public as it has shown advantages as compared to the electric vehicles in terms of cost and refueling time.[10].

The emergence of Russian-Ukraine war has expediate the need in green hydrogen economy deployment due to the dependency of European Union on Russian oil [11]. Therefore, many other countries are making ways to switch towards establishing clean energy industries, including Europe, the USA, China, Japan, and South Korea, with other oil and gas-producing countries such as Saudi Arabia, Oman, Kuwait, Qatar, and United Arab Emirates. Hydrogen economy requires various challenges to be addressed, including technological, economic, environmental, political, and social challenges. However, the research based on economic and environmental assessment of green hydrogen technologies is well-addressed [12–16].

In an agenda to be achieved by 2030, UN proposed a set of 17 sustainable development goals (SDGs) with 169 targets [17]. The basic idea which these goals represent is *the development of basic needs of human beings without compromising the ability of future generations to meet their own needs.* Green hydrogen plays a key role in supporting the goal 7 & 13 in the SDGs i.e., "affordable and clean energy" and "climate action", respectively. Falcone et, al. showed the importance of hydrogen in achieving the 7th goal of SDGs i.e., affordable and clean energy and a smooth transition towards hydrogen economy in the near future [18]. Moreover, owing to its decarbonization potential it significantly contributes to supporting the climate action targets (SDG 13). But the role of green hydrogen economy in realization of other SDGs is still unknown. Since implementing the UN 2030 Agenda demands a more comprehensive, coherent, and integrated strategy at global and national levels. Also, to achieve the net zero target, the goal must not focus on protecting the environment while also considering adhering to the principles of social justice, social equity, and sustainable development at a global scale. For the investors, states and communities, more effective policies are needed to democratize societal benefits and reduce conflicts between intra and inter countries' stakeholders. A low-carbon economy will require improved social indicators in order to make decarbonization synergistic with social justice. As a result, it is imperative to assess the impact of establishing a green hydrogen economy on the UN SDGs.

This research embarks on a multifaceted exploration of the green hydrogen economy, aiming to uncover its profound social, political, and geopolitical implications. The study is motivated by the need to understand how the green hydrogen economy impacts the realization of SDGs and its broader implications for global sustainable development. While acknowledging the impact of the COVID-19 pandemic on South Korea's economic landscape, energy sector, and Korea hydrogen economy roadmap 2040, this study delves into the intricate challenges linked to global green hydrogen production and emerging international socio-geopolitical challenges. The research methodology employed is anchored in rigorous qualitative methods, involving a systematic analysis and synthesis of existing literature, policies, and socio-economic data relevant to the green hydrogen economy, surpassing conventional literature reviews to offer a more nuanced understanding. Navigating through the complexities of this emerging field, the aim is to highlight socio-political barriers hindering the green hydrogen economy's supportive role in global sustainable development and provide impactful policy insights for decision and policymakers. This, in turn, positions green hydrogen as a pivotal tool for achieving SDGs, encompassing driving clean energy, climate action, and socio-economic development concurrently. This thoughtful understanding, coupled with actionable policy insights, constitutes the foundation of our research. It envisions a future where the harmonious coexistence of humanity and the planet is not just a possibility but an imperative. The transformative potential of the green hydrogen economy unfolds as a catalyst for sustainable global development, where the synergy of energy, environmental responsibility, and societal well-being becomes the cornerstone of our shared future.

This thesis navigates through five chapters, inaugurating with a contextualization of global challenges and the pivotal role of green hydrogen in Chapter 1. Subsequently, Chapter 2 delves into the intricate impacts of the COVID-19 pandemic on South Korea's economy and energy sector. Shifting the focus globally, Chapter 3 explores socio-political and geopolitical challenges in the production of green hydrogen. In Chapter 4, we delve into the alignment of green hydrogen with SDGs, underscoring its critical role in clean energy and climate action. In conclusions, chapter 5 underscores the transformative potential of the green hydrogen economy in achieving holistic sustainability highlighting key findings, research limitations, and potential future works.

CHAPTER 2

2- POST COVID-19 AND KOREA HYDROGEN ECONOMY ROADMAP 2040

This chapter is a modified version of the ongoing manuscript ‘*Post COVID-19 and Korea Hydrogen Economy Roadmap 2040: Challenges and the way forward’*. This chapter describes the impact of COVID-19 on the economy and energy transition in South Korea. Afterwards, these impacts were analyzed from a hydrogen economy perspective to identify potential challenges and determine a way forward. The chapter is divided into three sections, each of which addresses a different aspect of the topic. The first section, "Mapping the Journey: Hydrogen Economy Roadmap," describes the initiatives and developments that were planned when the hydrogen roadmap was announced in January 2019, but were impacted by the pandemic. The second section, "COVID-19 in South Korea and its Impact on Economy and Energy Transition," examines the situation in Korea during the pandemic and its impact on the country's economy and energy transition. The third section, "Challenges and the Way Forward: Hydrogen Economy Perspective," discusses the challenges facing the hydrogen economy in South Korea post COVID-19 and outlines a way forward for the country to become a global leader in this emerging industry.

2.1 Mapping the Journey: Hydrogen Economy Roadmap

The Korea Hydrogen Economy Roadmap 2040 was introduced in January 2019 with the goal of increasing the share of hydrogen in the transport and energy sectors by 2040 [19]. The roadmap outlines ambitious targets for the deployment of hydrogen vehicles, fuel cell power plants, and hydrogen refueling stations, as well as the production and supply of hydrogen. An overview of the targets set out in the roadmap and the progress achieved towards these targets as of May 2021 is

Table 1. Korea hydrogen economy roadmap targets and the progress achieved [19–24].

Targets set out in Korea Hydrogen Economy Roadmap 2040 (January 2019)							**Progress achieved**
Sector	**Type**	**2018**	**Transition (as of May 2021)**	**2022**	**2030**	**2040**	**Comments (Updates as of Dec 2022)**
Mobility	Passenger vehicles	1800 units	14,426 units	80,000 units	850,000 units	6.2 million units	29,733 units (37.16% achieved) 300,000 units (expected by 2030 given with help of subsidies)
	Bus	-	106 units	-	-	80,000 units	-
	Taxi	-	20 units as of May 2021	-	-	40,000 units	-
	Hydrogen Refueling Station	14 units	86 planned by Dec 2019 and 88 existing (as of May 2021)	310 units	660 units	1200 units	213 units (68.7% achieved)
Energy	Fuel Cell power plants	307 MW	Plants: 53 units (659 MW) Buildings: 7.1 MW (as of Dec 2020)	1.5 GW	2.0 GW	15 GW	As of IEA (2022), hydrogen was not one of the 10 energy sources that provided 99.75% of Korea's power in 2021.
	Residential Fuel Cells	7 MW		50 MW (940,000 Households)	70 MW	2.1 GW	
Hydrogen Supply	Hydrogen Supply Amount	130,000 T/Y	220,000 T/Y (as of Dec 2021)	470,000 T/Y	3.9 MT/Y	5.26 MT/Y (by 2040) 27.9 MT/Y (by 2050)	Share of clean hydrogen 0% (2022) to 2.1% (2030)
		By-product / SMR	Large-scale production	Electrolyser	share of green hydrogen 2.1% and large-scale electrolyser	Green hydrogen	
Hydrogen Cost	KRW/kgH_2	8,800	9,794 – 13,112 (HyNet)	5,500	4000	3000	-

provided in Table 1. The progress of the Korea Hydrogen Economy Roadmap in various sectors reveals a more nuanced picture when viewed in the context of the COVID-19 pandemic. Notably, the target for hydrogen-powered passenger vehicles, set at 80,000 units by 2022, shows a slower progress rate with only 37.16% achieved by May 2021. This lag indicates a significant impact on the roadmap's timeline due to the challenges posed by the pandemic, although it is important to acknowledge that these impacts or delays may be attributed not solely to the pandemic but are influenced by several factors. It is evident that the pandemic had a notable influence on the Korean economy and energy sector. The deployment of hydrogen refueling stations, while making significant headway with 213 units (68.7% achieved), also reveals the pandemic's potential to disrupt the timeline of these ambitious projects. In the energy sector, the roadmap's aspirations for hydrogen-based power generation, such as the 15 GW target by 2040, must be viewed with consideration of the challenges in integrating hydrogen as a primary energy source during global crises, including the COVID-19 pandemic. The progress in hydrogen supply, reaching 220,000 tons per year by December 2021, signifies forward momentum; however, long-term targets like achieving 5.26 million tons per year by 2040 remain a substantial challenge, especially in the wake of the pandemic's influence on the economy. The roadmap was developed in response to the need to reduce greenhouse gas emissions and address climate change. The Korean government has recognized the potential of hydrogen as a key driver of economic growth and a solution to climate change. The roadmap has been supported by various policies and initiatives, including the Hydrogen Law (Hydrogen Economy Promotion and Hydrogen Safety Management Law), which was passed by the National Assembly of Korea in February 2020.

Table 2. Coronavirus statistics as of September 30, 2023 [25].

Sr. No	Countries	Total Cases	Total Deaths	Total Recovered	Total cases per 1M population	Deaths per 1M population	Death/ Cases %
1	USA	108,749,266	1,177,281	106,508,074	324,813	3,516	1.08%
2	India	44,998,838	531,930	44,466,366	31,990	378	1.18%
3	France	40,138,560	167,642	39,970,918	612,013	2,556	0.42%
4	Germany	38,493,206	176,071	38,240,600	458,888	2,099	0.46%
5	Brazil	37,796,956	705,775	36,249,161	175,511	3,277	1.87%
6	S. Korea	34,571,873	35,934	34,535,939	673,523	700	0.10%
7	Japan	33,803,572	74,694	N/A	269,169	595	0.22%
8	Italy	26,082,645	191,715	25,736,785	432,815	3,181	0.74%
9	UK	24,704,113	229,089	24,468,622	360,655	3,344	0.93%
10	Russia	23,029,404	400,047	22,468,635	157,946	2,744	1.74%
11	Turkey	17,232,066	102,174	N/A	201,399	1,194	0.59%
12	Spain	13,914,811	121,760	13,762,417	297,840	2,606	0.88%
13	Australia	11,774,220	22,798	11,745,992	451,660	875	0.19%
14	Vietnam	11,623,698	43,206	10,640,809	117,466	437	0.37%
15	Taiwan	10,241,523	19,005	10,222,518	428,720	796	0.19%
16	Argentina	10,070,247	130,608	9,936,400	218,870	2,839	1.30%
17	Netherlands	8,617,412	22,992	8,594,420	500,679	1,336	0.27%
18	Mexico	7,649,199	334,472	6,899,865	58,141	2,542	4.37%
19	Iran	7,616,791	146,386	7,377,233	88,544	1,702	1.92%
20	Indonesia	6,813,429	161,918	6,646,827	24,409	580	2.38%
21	Poland	6,523,278	119,653	5,335,940	172,849	3,170	1.83%
22	Colombia	6,378,000	142,961	6,190,683	123,814	2,775	2.24%
23	Greece	6,101,379	37,089	6,064,290	591,412	3,595	0.61%
24	Austria	6,081,287	22,542	6,054,934	670,727	2,486	0.37%
25	Portugal	5,623,951	27,509	5,586,098	554,599	2,713	0.49%
26	Ukraine	5,557,995	112,418	5,445,577	128,681	2,603	2.02%
27	Chile	5,293,064	64,497	5,228,452	274,962	3,350	1.22%
28	Malaysia	5,125,900	37,172	5,077,516	154,483	1,120	0.73%
29	State of Palestine IOP by Israel	4,837,580	12,670	4,798,473	518,720	1,359	0.26%
30	Belgium	4,817,196	34,376	4,773,093	412,845	2,946	0.71%

31	North Korea	4,772,813	74	4,772,739	183,636	3	0.00%
32	Thailand	4,757,283	34,474	4,692,636	67,885	492	0.72%
33	Canada	4,728,375	53,793	4,655,065	123,172	1,401	1.14%
34	Czechia	4,651,495	42,848	4,605,310	433,230	3,991	0.92%
35	Peru	4,519,976	222,161	4,297,815	134,187	6,595	4.92%
36	Switzerland	4,413,440	14,452	4,395,295	503,034	1,647	0.33%
37	Philippines	4,174,101	66,643	4,103,828	37,100	592	1.60%
38	South Africa	4,076,463	102,595	3,912,506	67,095	1,689	2.52%
39	Romania	3,455,207	68,341	3,360,779	181,554	3,591	1.98%
40	Denmark	3,183,756	8,814	3,174,942	545,636	1,511	0.28%
41	Hong Kong	2,920,721	14,254	2,902,638	384,088	1,874	0.49%
42	Sweden	2,717,578	24,888	2,690,396	265,935	2,435	0.92%
43	Singapore	2,588,520	1,885	2,149,583	435,518	317	0.07%
44	Serbia	2,556,026	18,057	2,529,789	295,391	2,087	0.71%
45	New Zealand	2,469,587	4,843	2,463,270	504,182	989	0.20%
46	Iraq	2,465,545	25,375	2,439,497	58,474	602	1.03%
47	Hungary	2,204,488	48,881	2,152,155	229,485	5,088	2.22%
48	Bangladesh	2,045,671	29,477	1,998,448	12,185	176	1.44%
49	Slovakia	1,867,525	21,167	1,846,156	342,025	3,877	1.13%
50	Georgia	1,855,289	17,132	1,776,548	467,476	4,317	0.92%

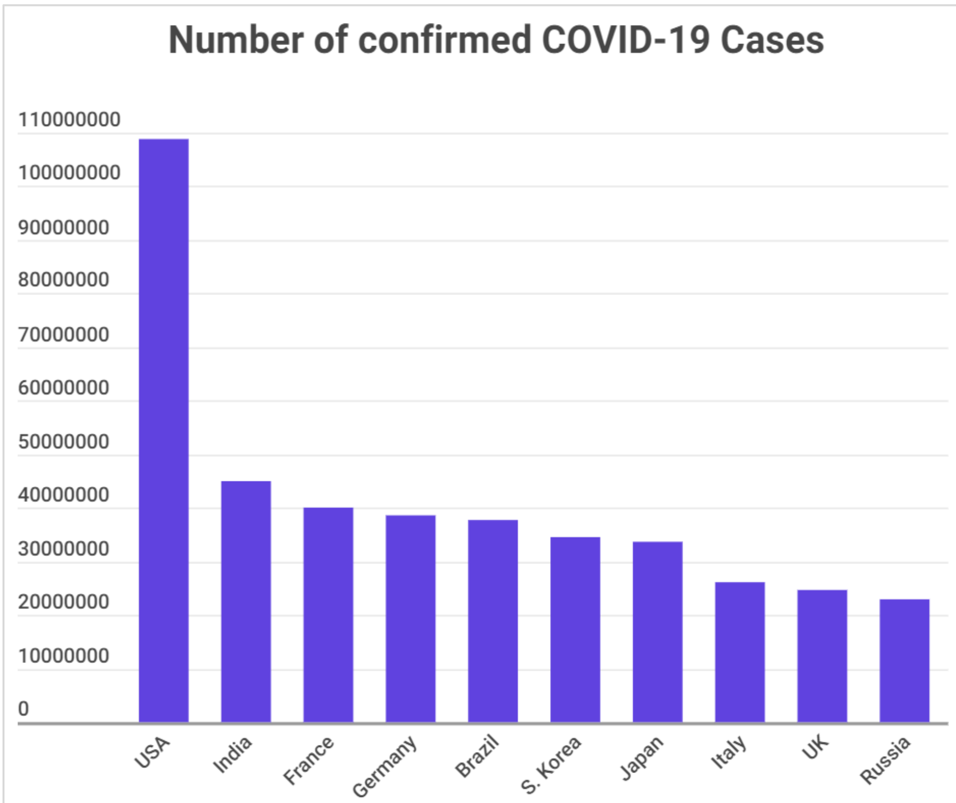

Figure 2. Top ten countries with the greatest number of COVID-19 Cases

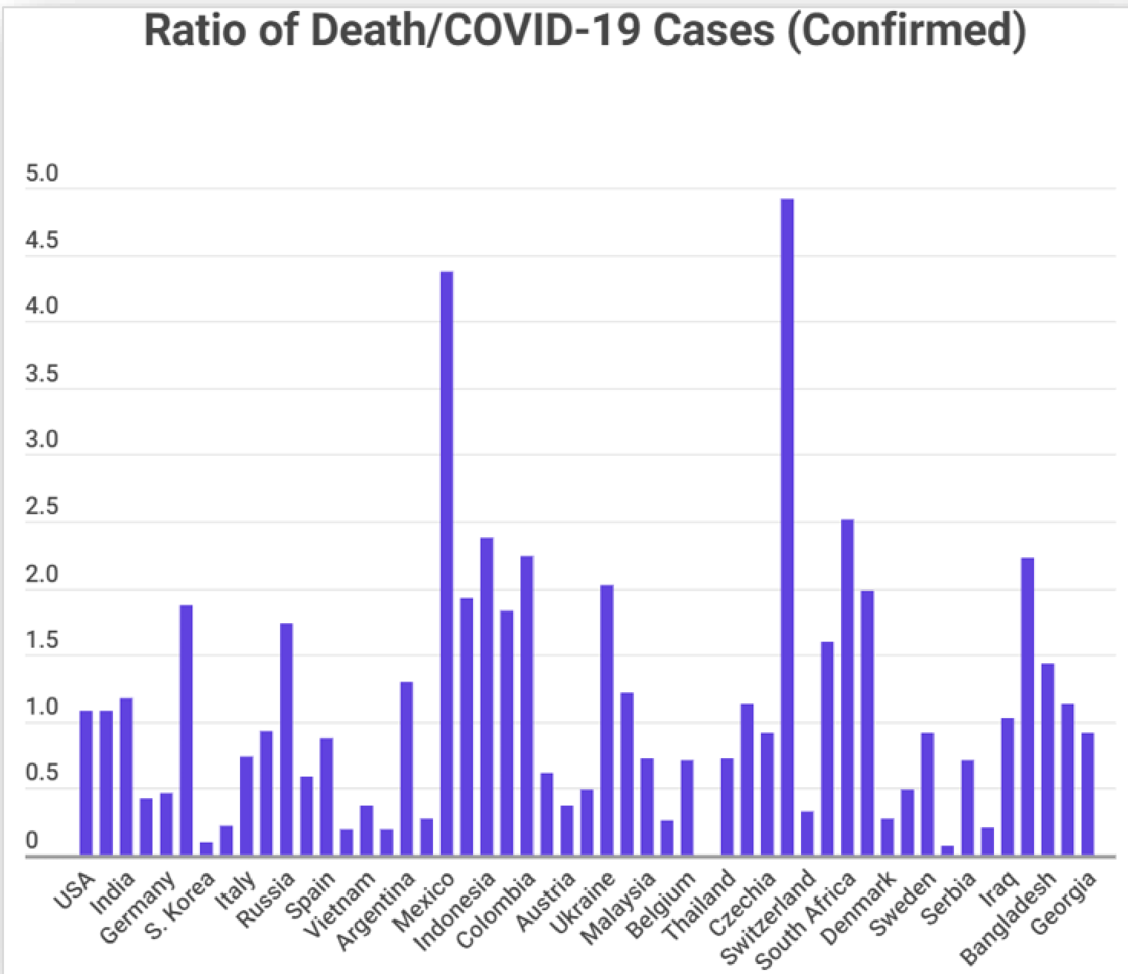

Figure 3. COVID-19 death rate of the countries.

Table 3. Impact of COVID-19 on Korean Economy [26] .

	Historical trend (A)	2020 (B)	Decline (=B-A)
GDP growth (%, %p)	2.8	-0.9	-3.7
Employment (1,000 persons)	238	-219	-457

Table 4. Main economic indicators for South Korea [27].

Main Indicators	2020	2021	2022 (E)	2023 (E)	2024 (E)
GDP *(billions USD)*	1,644.68	1,810.97	1,665.25	1,721.91	1,792.73
GDP *(Constant Prices, Annual % Change)*	-0.7	4.1	2.6	1.5	2.4
GDP per Capita *(USD)*	31,728	34,998	32,250	33,393	34,807
General Government Balance *(in % of GDP)*	-1.5	0.1	-0.9	0.2	-0.1
General Government Gross Debt *(in % of GDP)*	48.7	51.3	54.3	55.3	55.9
Inflation Rate *(%)*	0.5	2.5	5.1	3.5	2.3
Unemployment Rate *(% of the Labour Force)*	3.9	3.7	2.9	3.7	3.7
Current Account *(billions USD)*	75.90	85.23	29.83	37.11	50.41
Current Account *(in % of GDP)*	4.6	4.7	1.8	2.2	2.8

2.2 COVID-19 in South Korea

As the world remained busy fighting against climate issues, the covid-19 pandemic hit the world severely, resulting in economic and health crises. The first case of coronavirus (COVID-19) was detected in Wuhan, China in 2019 [28]. As soon as the virus spread globally, scientists failed to detect it, leading to a global crisis that prompted the World Health Organization (WHO) to declare it a pandemic on March 11, 2020 [29]. A nationwide lockdown was implemented in China after the immediate spread of the virus, and countries around the globe followed this to stem the spread [30]. Lockdowns around the world initially reduced the spread of the virus, but as most countries reopened, it began to spread again, forcing them to consider another lockdown [30]. The first case of COVID-19 in South Korea was officially announced on 20th January 2020 when a 35-year-old woman arrived at Incheon airport from Wuhan, China on 19th January 2020. The total number of confirmed cases recorded globally was greater than 565 million, and the total number of deaths was 6.3 million in July 2022, in a report conducted by WHO [31]. China took immediate measures to control the Covid-19. A total of twenty million people were restricted from moving around the area, all the international flights were ceased, a total of 1200 beds were arranged with individual nurses. Within 10 days, masks were imposed for all on the threat of imposing imprisonment in case of not wearing it. They were not the only steps taken during the virus outbreak in China of course, but these steps resulted in the reduction of 2331 cases to 437 within two weeks after the Chinese government implemented them. The latest statistics of the top fifty countries with most confirmed cases as of 30th September 2023 are shown in Table 2. South Korea continued to hold its position among the top three countries within the list of the top fifty, all while maintaining a remarkably low death rate of just 0.10%, despite being in the sixth position for the highest number of confirmed COVID-19 cases as shown in Figures 2 and 3.

2.2.1 Impact on economy

Since the coronavirus disease widespread over the globe, it has affected adversely on the country's economy. A study conducted by Choi et,al showed that compared to the countries like China and US, South Korea also suffered from the real pandemic economic crisis [26]. According to the Organization for Economic Co-operation and Development (OECD), the US, EU, and South Korea reported year-over-year real Gross Domestic Product (GDP) growth rates of -9.49%, -11.9%, and -3.7 %, respectively in Q2 2020 [26]. In Korea, the economy experienced an annual increase in Gross Domestic Product (GDP) of approximately 2.5% before COVID-19 but faced a decline of around 3.7% in 2020, as shown in Table 3. Furthermore, a loss of approximately 460 thousand jobs was also observed by the end of 2021 resulting in an unemployment rate of 3.7 [27,32,33]. The main existing and future estimated economic indicators for Korea are presented in Table 4. The budget surplus fluctuated, with a deficit in 2020, and is expected to stabilize around +0.3% in 2023 and +0.4% in 2024. Public debt rose to 54.1% in 2022 and is projected to reach 55.2% in 2024. Inflation is expected to be 3.8% in 2023, following 5.5% in 2022 and 2.5% in 2021 [27]. The Korea's tourism sector was previously negatively affected by Middle East Respiratory Syndrome (MERS), which resulted in a US$2.6 billion loss of revenue [34]. Researchers have reported that the past infectious disease outbreak like MERS and Severe Acute Respiratory Syndrome (SARS) have led the region's GDP, and income to a decline [35].

During the pandemic, the Korean government enforced strong social distancing rules with prohibition of gathering of three or more people at an indoor place including the religious places such as Church, Mosque etc. The pandemic has affected consumer behavior globally and similarly there have been several studies showing changes in Korean consumer behavior as well [36,37]. A study examined the consumer behaviors in Seoul the capital city of Korea, Since COVID-19 emerged the trade and distribution of goods decreased, while online purchases increased gradually via credit and debit cards [36]. Further, delivery businesses have expanded their services to groceries and errands, and as the pandemic continues, demand for these services will likely rise [36]. Sectors such as business, trade and education also got highly impacted by the sudden changes. Online classes and meetings also gained popularity over in-person meetings and classes, and online shopping experienced a boom from 2020 - 2022 [36]. In another study, it was shown that during the pandemic, the Korean consumers were becoming more health-conscious and were paying more attention to the nutritional value of the food they consume [37]. These changes are likely to have long-lasting effects on the Korean economy and businesses.

To stabilize the economy during pandemic successfully, the Korean government took initiative measures. Their success in dealing with the virus depended on having reliable tests and effective contact tracing. To achieve this, health authorities in the country worked closely with private labs from an early stage. They encouraged the labs to create tests and quickly approved them for use. South Korea also utilized advanced data analytics to support contact tracing efforts. These involved authorities accessing a diverse range of personal information about infected individuals, such as medical records, financial data, mobile phone location history, and closed-circuit television recordings. This comprehensive dataset enabled them to efficiently and accurately trace individuals who may have had contact with those who were infected. As part of its efforts to mitigate the economic impact of the pandemic, the Korean government implemented a fiscal stimulus of KRW 67 trillion (about 3.5% of GDP) in 2020 as shown in Table 5 [33]. Moreover, their long-term recovery plan, the Korean New Deal, focuses on advanced technology investments, workforce development, and positioning in the data and green economies [38].

Table 5. Fiscal expenditures and details of South Korea's new green deal and digital new deal. [33,38]

Green New Deal	**KRW: 42.7 trillion**
1. Implement a green transition for cities, spaces, and infrastructure (KRW 12.1 trillion)	a. Facilitate zero-energy in public facilities. b. Restore the green ecosystem of land, ocean, and cities. c. Build a clean and safe water management system
2. Expand low-carbon and distributed energy (KRW 24.3 trillion)	a. Build smart grids for efficient energy management. b. Create a foundation for renewable energy deployment and support a just energy transition. c. Promote green mobility, such as electric and hydrogen vehicles.
3. Establish an innovative ecosystem for green industries (KRW 6.3 trillion)	a. Develop promising green enterprises, establish low carbon, and green industrial complexes. b. Create a foundation for green innovation in the R&D and financial sector.
Digital New Deal	**KRW: 44.8 trillion**
1. Strengthen the ecosystem for data, networks, and artificial intelligence (KRW 31.9 trillion)	a. Build big data platforms and make them open to public. b. Promote convergence with 5G and artificial intelligence in the 1st, 2nd, and 3rd industries. c. Establish an intelligent government system based on 5G and artificial intelligence. d. Establish a Korean cyber quarantine system.
2. Digitalize educational infrastructure (KRW 0.8 trillion)	a. Build digital-based infrastructure in every elementary, middle, and high school. b. Promote online education in universities and vocational training centres nationwide.

According to an article, South Korea's economic response to the pandemic aligns with that of Organization for Economic Co-operation and Development (OECD) nations, employs fiscal measures to ease financial burdens on businesses and households [38]. They strategically allocate funds to hard-hit sectors and encouraged immediate spending by providing citizens with pre-paid cards or credit deposits for emergency cash transfers. Another news article showed Korean government introduced a groundbreaking support program aimed at stabilizing local financial markets amidst the new coronavirus outbreak. This comprehensive initiative, valued at 50 trillion won (approximately $38.9 billion), primarily targets assistance for small and medium-sized businesses and individuals with lower credit ratings [39]. Furthermore, the financial minister has extended the initial six-month loan maturity extension, originally designed for small and medium-sized enterprises, to encompass all lenders, including insurance companies and non-banking institutions. An article states, to combat the economic impact of COVID-19, South Korea took various steps to boost consumer spending [40]. These actions included distributing local business coupons, slashing automobile taxes by 70%, providing subsidized daycare when schools closed, offering welfare assistance, and granting direct relief payments of up to 1 million South Korean won (approximately $860) to support low-income individuals [40].

According to the statistics by the Bank of Korea, South Korea’s economy has dropped 1% in GDP growth over 2020 as shown in Figure 4. Though, it has not experienced the worst economic decline

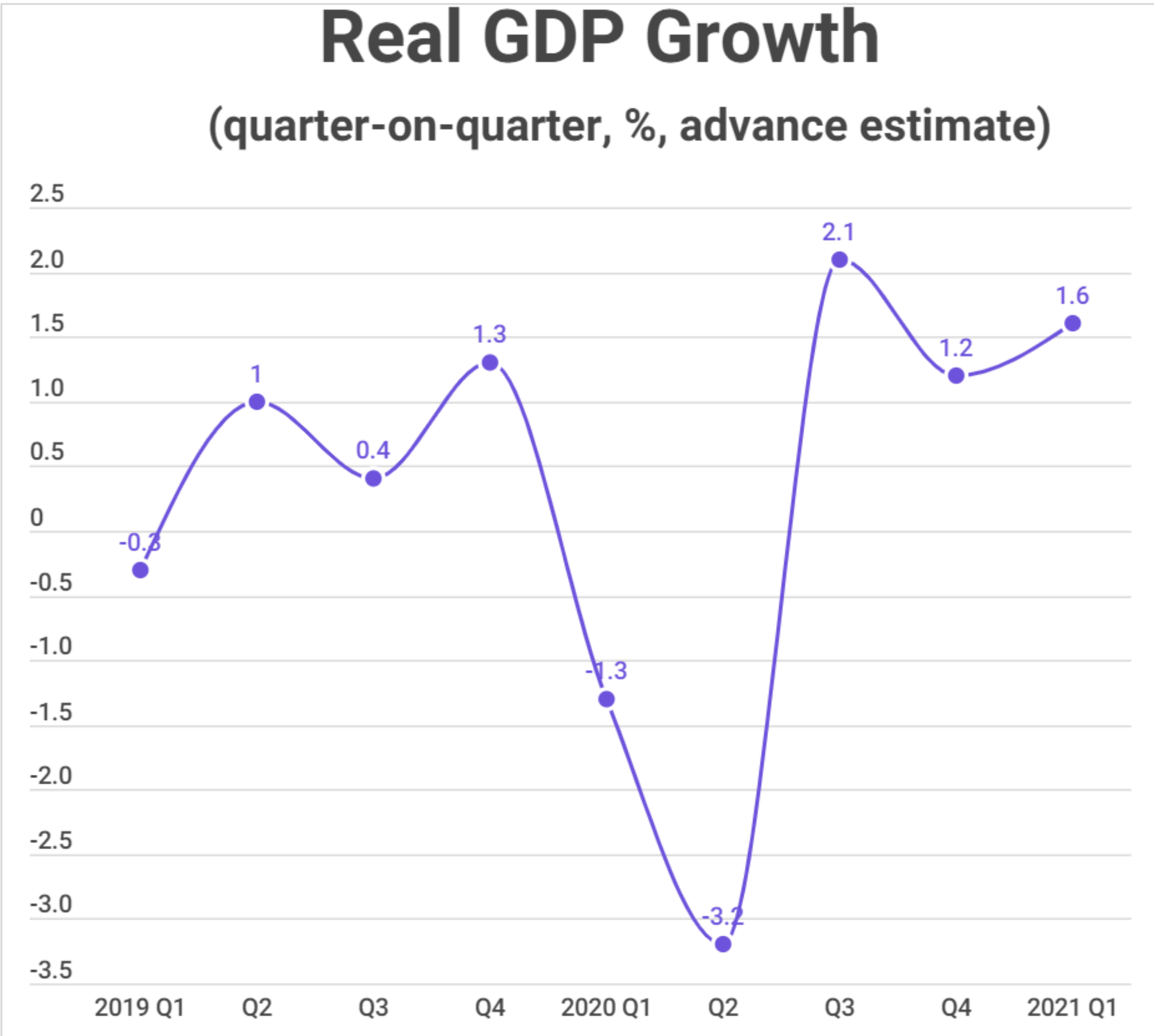

Figure 4. Existing and advance estimate of Korean GDP.

like other developing countries [41]. South Korea's economic rebound from the COVID-19 pandemic has exceeded expectations, with GDP expanding by 1.6 percent in the first quarter of this year compared to the previous quarter. Notably, this growth has surpassed pre-pandemic levels, as the country reported its first COVID-19 case in January 2020. South Korea's strong economic fundamentals and effective policy responses have led to a robust recovery from the pandemic, surpassing pre-crisis levels despite multiple waves of COVID-19 infections. Among the world's top 10 economies, only China and India, alongside South Korea, have managed to achieve this remarkable recovery [41,42]. However, concerns about stagflation risks have heightened due to the effects of Russia's invasion of Ukraine and related sanctions, including rising commodity prices, particularly in energy, driving inflationary pressures [43]. Another report released by the Bank of Korea shows that, in the first quarter of 2021, South Korea's economy made a faster-than-expected recovery from the COVID-19 pandemic. This increase of 1.6% in the GDP was driven by a 1.1% increase in private consumption and a significant 6.6% rise in facility investments [42].

However, according to the expert's opinion the future outlook for the Korean economy post-pandemic is mixed with potential challenges and opportunities. A report by S&P Global shows that in 2023, the Korean economy is anticipated to encounter ongoing economic challenges, primarily stemming from subdued export performance and the prolonged repercussions of the monetary policy tightening implemented by the Bank of Korea in 2022 [44]. Meanwhile, the latest forecast predicts that GDP growth will further slowdown, going from 2.6% in 2022 to 2% in 2023 mainly due to a decrease in exports, especially in the semiconductor sector, but it is anticipated to rebound with a 2.3% growth afterward [27,45,46]. In 2023, the nation's foremost challenge will be navigating a volatile international context, marked by the enduring health and economic impacts of a global pandemic, a European war, a cost-of-living crisis from persistent inflation, and a slowdown in China. Nevertheless, the country is well-equipped with robust economic fundamentals and appropriate policies to handle these challenges effectively [47]. Moreover, the relaxation of COVID-19 restrictions in mainland China presents a potential opportunity for South Korean exports [47]. Additionally, reducing dependence on fossil fuels not only enhances resilience but also helps South Korea move closer to achieving its ambitious climate targets [48].

2.2.3 Impact on energy transition

As the world's fourth-largest coal importer and third-largest investor in foreign coal projects, Korea, driven by its 2050 Carbon Neutral Strategy, necessitates a significant boost in clean technology to phase out or convert coal plants to liquefied natural gas by 2050 [49–51]. As its economy heavily relies on fossil fuels, with about 98% of its fossil fuel consumption being met through imports due to the scarcity of domestic resources [50]. In 2021, renewables made up just 3% of South Korea's primary energy consumption, but this was a significant increase from less than 1% in 2015, marking a consistent growth trend [50]. The Korean government aims to boost renewable electricity from less than 5% in 2018 to 20% by 2030 and 30-35% by 2040 [51]. It also plans to reduce the use of coal and nuclear energy, enhance energy efficiency, and develop the hydrogen industry. Under the Paris Agreement 2015, by 2030 Korea seeks to reduce 40% of its total national GHG emissions from 726 Mt CO_2-eq in 2018 [51].

As electricity prices are strongly connected with coal and natural gas prices, it has been indicated by Maeil Business Newspaper (2021) the consumer price index is expected to rise by 2.2% next year after increasing by 2.4% this year, surpassing the government’s 2% target [52]. This includes increased electricity and gas rates, indicating that global energy price fluctuations could make investing in renewables riskier. Boston Consulting Group (BCG) analyzed COVID-19's regional impact on energy transition and found that South Korea, along with China, Japan, Malaysia, and Singapore, is well-positioned to advance it's energy transition despite economic challenges faced by some parts of Asia. [53]

During the outbreak of pandemic in 2020, several sectors have been affected badly globally including economic, transport, and energy. [54][55][56] Consequently, COVID-19 has had an impact on South Korea's energy consumption. A study conducted by He et, al. concludes that the COVID-19 pandemic has exacerbated the decline in industrial production, the use of oil-related products, and reduced investment [57]. This shift towards non-oil products is likely due to changes in consumer behavior and economic challenges brought on by the pandemic. To cope with these challenges, companies have reduced their production and workforce, contributing to rising unemployment rates. [57]

As a result of lockdowns, restrictions, and changes in daily life, there was a global shift in energy demand. Similarly, in South Korea the pandemic resulted in reduced power transactions, affecting energy sources such as LNG, nuclear power, and bituminous coal, which continued to decline until May 2020, except for bituminous coal as shown in Figure 5 [58,59]. In the initial five months of 2020, South Korea experienced a noteworthy surge in its LNG imports, marking an increase of 14% compared to the prior year. This boost was mainly driven by direct importers seizing the opportunity presented by exceptionally low spot prices in the global market, along with the absence of the Asia Premium for a significant portion of this period [60]. Conversely, KOGAS (Korea Gas Corporation) found it necessary to formally request a deferment of long-term LNG deliveries, including those scheduled for 2021, from its main gas suppliers.[61] Furthermore, the company's substantial inventory at the end of the prior mild winter has placed constraints on its ability to

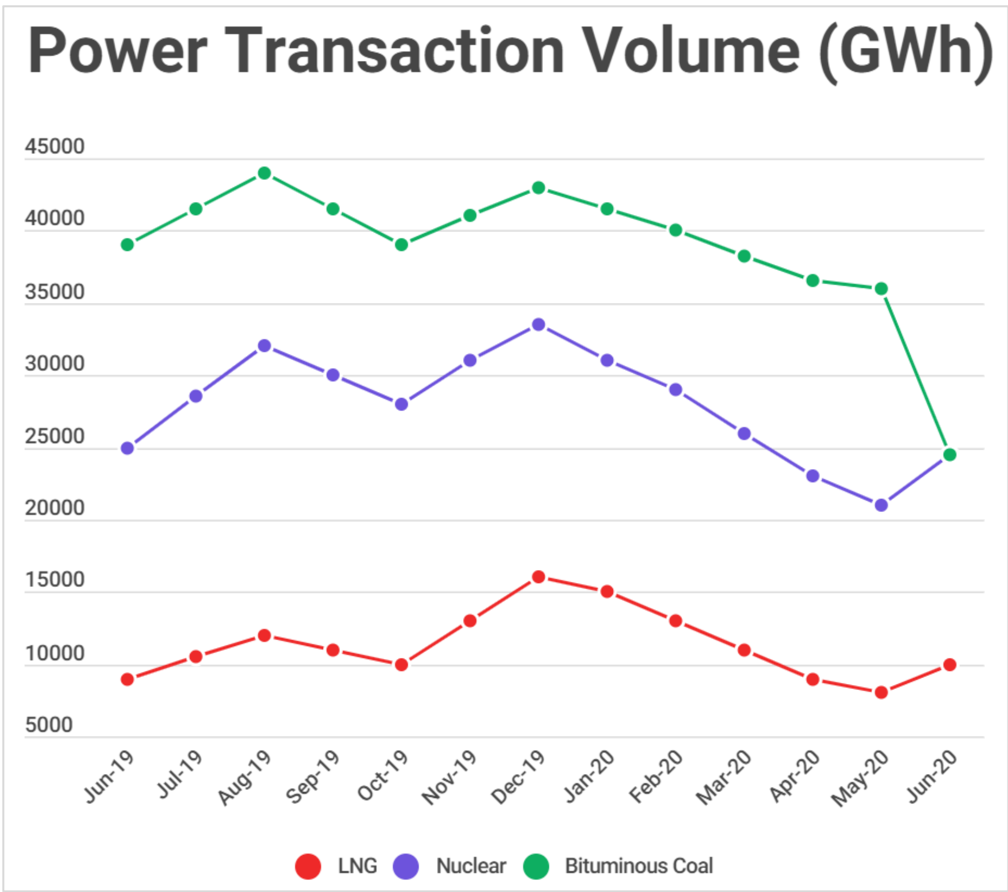

Figure 5. Power transaction volume of Korea.

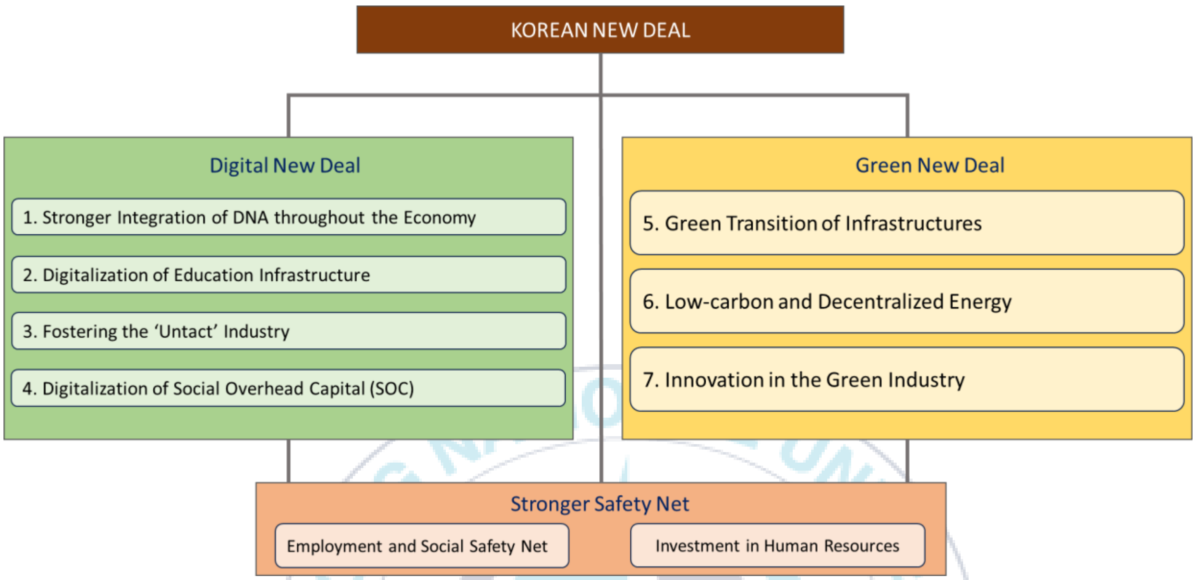

Figure 6. Three pillars of the Korean New Deal.

accumulate extra gas volumes at the accessible, highly favorable prices.[61]

Other precautionary measures like social distancing implemented during the COVID-19 pandemic in South Korea have had an impact on the country's energy mix, particularly in terms of energy consumption. The research shows that the social distancing measures implemented by Korean government due to pandemic in 2020, resulted in reduced energy consumption in the industrial, commercial and educational sectors while having an increase in residential energy consumption by 0.3% caused by a unit increase in the time-varying reproduction number of COVID-19 [62]. Another research conducted in 2020 examining the changes in building energy consumption has revealed that energy usage according to the building type, was impacted by social distancing measures leading to an average decrease of -4.46% in electricity consumption and -10.35% in gas consumption compared to the previous year (2019).[63]

South Korea's approach to the COVID-19 pandemic includes a commitment to "building back better." This strategy is embodied in the Korean New Deal, which is built on three key pillars: the Digital New Deal, Green New Deal, and the enhancement of employment and social safety nets as shown in Figure 4 [64]. Korea's Green New Deal is introduced as a part of COVID-19 recovery plan that aims to accelerate the energy transition through renewable energy, green infrastructure, industry support, and improved safety nets as shown in Table 4 and Figure 4 [64,65]. It involves a total investment of 160 trillion won (with 114.1 trillion won in fiscal investment) to generate 1,901,000 jobs by 2025 [66]. South Korea's Green New Deal involves a KRW 73.4 trillion investment, with the goal of creating 659,000 jobs by 2025. This comprehensive plan focuses on urban transformation, boosting electric vehicle adoption, and setting up 100 smart factories, emphasizing the use of renewable energy sources and clean industrial practices [66].

2.3 Challenges and the way forward: Hydrogen economy perspective

The COVID-19 pandemic has had a significant impact on the global economy, and South Korea has not been immune to its effects. The country's hydrogen economy roadmap, which was announced in January 2019, has faced several challenges due to the pandemic. However, despite these challenges, the Korean government has continued to prioritize the development of a hydrogen economy, recognizing its potential as a key driver of economic growth and a solution to climate change.

2.3.1 Challenges

1. Balancing economic recovery with sustainable development: The pandemic has highlighted the importance of resilience and sustainability in the face of global crises, and the Korean government has recognized the need to prioritize these goals in its hydrogen economy roadmap. However, balancing economic recovery with sustainable development can be challenging.

2. Ensuring the availability of renewable energy sources: One of the main challenges facing the hydrogen economy in South Korea post COVID-19 is the need to ensure the availability of renewable energy sources for hydrogen production. Currently, most hydrogen is produced from natural gas, which is not a sustainable solution in the long term.

3. Adapting to changing global energy markets: The COVID-19 pandemic has disrupted global energy markets, and the Korean government needs to adapt to these changes to ensure the success of its hydrogen economy roadmap. For example, the pandemic has led to a decrease in demand for oil and gas, which could impact

the development of hydrogen as an alternative energy source. The Korean government needs to monitor these changes and adjust its policies accordingly.

4. Ensuring the safety and security of hydrogen production, storage, and transportation: Hydrogen is a highly flammable gas, and there are concerns about the potential risks associated with its use.

2.3.2 The Way Forward

1. Investing in research and development: To overcome the challenges facing the hydrogen economy in South Korea post COVID-19, the Korean government needs to invest in research and development to reduce the cost of producing and transporting hydrogen, as well as to improve the safety and security of hydrogen production, storage, and transportation.

2. The Korean government has set a target of producing 6.2 million tons of hydrogen per year by 2040, with five million tons of that coming from renewable sources. Providing financial incentives for companies to invest in hydrogen technologies: The Korean government can provide financial incentives for companies to invest in hydrogen technologies, such as tax breaks or subsidies for research and development.

3. Promoting the use of hydrogen in transportation, industry, and power generation: The Korean government can promote the use of hydrogen in transportation, industry, and power generation by introducing policies to drive up demand, such as encouraging steel and chemical firms to shift to H2-based processes, promoting hydrogen-based transport technologies, and encouraging fossil power generators to blend H2 into their fuel mix.

4. Launching a public education campaign to raise awareness of the benefits of hydrogen: The Korean government can launch a public education campaign to raise awareness of the benefits of hydrogen and to encourage public support for its development. This can include promoting the use of hydrogen in transportation, industry, and power generation, as well as highlighting the potential environmental benefits of a hydrogen economy. In order to ensure the safety in hydrogen related activities. the Korean government has also promulgated the Hydrogen Economy Promotion and Hydrogen Safety Management Act in February 2020, which is now the central legislation regulating the hydrogen industry.

5. Ensuring energy security: The Korean government needs to ensure energy security by diversifying its energy sources and reducing its dependence on fossil fuels. This can include investing in renewable energy sources, such as solar and wind power, and promoting energy efficiency measures.

By addressing these challenges and continuing to invest in the development of a hydrogen economy post COVID-19, South Korea can be in a well-positioned scenario to become a global leader in this emerging industry. The government's hydrogen economy roadmap includes plans to expand the use of hydrogen in transportation, industry, and power generation, as well as to promote the development of fuel cell technologies. By investing in research and development, infrastructure, and public education, Korea aims to become a global leader in the hydrogen economy and to contribute to the fight against climate change.

CHAPTER 3

3- SOCIAL AND GEOPOLITICAL CHALLENGES AND IMPLICATIONS OF THE GREEN HYDROGEN ECONOMY

This chapter is a modified version of the book chapter (under publication) '*A review of social challenges of green hydrogen economy and its realization towards sustainable development goals'* by Khan et.al and the manuscript '*Green hydrogen and sustainable development – A social LCA perspective highlighting social hotspots and geopolitical implications of the future hydrogen economy'* by Akhtar et al. This chapter serves as a dedicated exploration of the intricate interplay between society and politics within the context of the green hydrogen paradigm. This chapter involves a comprehensive examination of the nuanced social and geopolitical challenges that have a profound impact on the global green hydrogen landscape. It delves into issues such as the dynamics of geopolitical instability, the role of diplomacy in shaping hydrogen affairs, and the intricate web of international hydrogen trade. Together, these insights illuminate the multifaceted relationships between social forces, geopolitical considerations, and the unfolding green hydrogen revolution. This chapter provides crucial perspectives on the wider implications for sustainable development and international collaboration.

3.1 Energy security and hydrogen

Hydrogen can enhance energy security by reducing import dependence, mitigating price volatility, and increasing energy system flexibility and resilience, with most benefits associated with green hydrogen [67]. Energy security also encompasses sustainability and equity, making imports of renewable hydrogen from areas lacking electricity access or relying on fossil fuels a complex issue.

The physical impacts of climate change pose a significant challenge, with energy infrastructure, including hydrogen facilities, increasingly vulnerable to destructive cyclones, flooding, and storms [68]. Considering energy security, green hydrogen can help in various dimensions as stated below:

- **Reducing import dependence:** Hydrogen, produced from domestic renewable energy sources, can help reduce energy import dependence by replacing the need for imported fuels [69]. This shift can enhance energy security, reduce a nation's vulnerability to global energy market fluctuations, and decrease its energy import expenses [70]. Utilizing natural gas as the feedstock for hydrogen production may lead to the extension or even an increase in the imports of natural gas. Countries that choose to manufacture hydrogen from natural gas may end up importing equivalent or greater amounts of natural gas via pipelines or LNG terminals, resulting as an increase in their import dependency [71].

- **Mitigating price volatility:** Green hydrogen offers stability to industrial consumers by shielding them from the volatility of fossil fuel prices, which can fluctuate significantly over time. This became evident in late 2021 when record-high gas and electricity prices prompted energy-intensive industries, such as fertilizer manufacturing, to temporarily curtail production [72].

- **Improving flexibility and resilience:** Hydrogen has the potential to bolster the flexibility and resilience of a transitioning, more electrified energy system. Yet, strategic planning is vital to optimize hydrogen deployment effectively. Therefore, electrolyzers can be strategically placed in areas with abundant variable renewable energy where surplus power cannot easily be transmitted through power lines or stored in batteries, such as Northern Chile or offshore wind zones in the North Sea [73]. Hydrogen possesses a unique competitive advantage in its capacity to store energy over extended periods and in massive quantities. Salt caverns are regarded as one of the most promising solutions for the long-duration storage of hydrogen [74]. In addition, hydrogen has the capability to improve the sustainability of remote and isolated communities, such as mountain villages and distant islands. These specific communities encounter unique energy security issues, frequently relying on imported fossil fuels for their energy needs. Furthermore, their energy grids are typically compact and often depend on diesel generators for backup power. Nevertheless, these communities possess access to some of the world's most abundant renewable energy resources [75].

3.2 Social and Geopolitical Challenges

An effective transition to a green economy requires a massive overhaul of social economic structures and reforming energy policy institutions. Before moving towards the implementation of hydrogen technology on a bigger scale there are multiple challenges that need to be focused on by the policy makers and stakeholders. An expanding body of research indicates that the long-term ecological consequences of wind power development are raising concerns, giving rise to territorial disputes, economic disruptions, and political reactions. Research conducted in UK by Bell et al. shows that the difference between public opinion is consistently accompanied by a "social gap" which has resulted in conflict during the installation of wind-based power projects [76]. Social acceptance is another key factor for understanding the contradictions between public support in the installation of renewable energy projects. Social acceptance of energy development projects has been considered in three dimensions: socio-political acceptance, market acceptance, and community acceptance [77]. It is imperative that environmental and social considerations are prioritized by investors and planners before focusing on wind quality and efficiency. In Brazil, several social conflicts have been indicated contributing to the energy injustice making the Brazil's wind development unsustainable [78]. It is evident that wind turbine noise can cause adverse effects on local communities and lead to lower acceptance of wind energy. In South Korea, local residents that live close to the project sites have shown opposition to the development of wind farms [79]. The onshore wind farm projects carried out in Netherland faced staunch issues in public acceptance due to their too much focus on the practical aspects resulting in leaving feeling of social injustice towards local communities. [80,81]

Solar energy projects have been opposed in the rural areas due to the lack of awareness and strong opposition from the local public in Pakistan despite of having rich renewable energy resources [82]. Public opinion regarding hydrogen energy in Wales have shown positive attitude in its acceptance without compromising safety for both environment and production with cost being the main consideration [83]. Policy makers need to emphasize these barriers with stronger community guidelines before the installation of renewable energy-based hydrogen energy projects in the present and the future. It is common for stakeholders involved in the hydrogen economy to have conflicting views and goals based on their involvement with hydrogen technologies. For example, some experts may be interested in cost competitiveness, while others might have different views regarding safety improvement, while others might be interested in industrial collaborations. To improve sustainability decisions and reduce conflicts, their diverse perspectives are of much importance. In a recent study by Romero et al. it is shown that Europe and Asia are leading in the research on green hydrogen [84]. Still in most of the countries, there is lack of awareness on several aspects of green hydrogen including production and storage, safety, involvement of indigenous communities in the policy making, and the participation of the local authorities in rural locations [84].

However, there are some aspects that need to be determined while considering green hydrogen technology in the transport sector. It should be cost competitive as compared to the other energy carriers like batteries, safety precautions must be equal or better than of fossil fuel-based energy sources, as hydrogen has low density property enhanced and easy storage process will be required. Also keeping in view, the sustainability requirements, the waste resulting from end-of-life solar PV panels, wind turbines, vehicles and their components must also comply with existing legal requirements, ensuring that these are reused, recycled, or recovered. To achieve hydrogen mobility in the market massively it should be made cost-effective which includes lowering the price of cars and refueling stations. Hydrogen engines must be designed very carefully to avoid combustion asymmetries. The cost effectiveness of green hydrogen is influenced by the location of its production plant, which, if located near renewable energy rich locations, may reduce its cost.

It is quite challenging to picture a carbon-neutral economy eventually. As fossil fuels are replaced with renewable energy sources, the energy industry as well as geopolitical dynamics are likely to be affected in the long run. In addition, the International Renewable Energy Agency points out that the shift to clean energy will change the balance of power in the world, affect how countries interact, influence the risk of conflicts, and impact the factors contributing to global instability, similar to how fossil fuels have shaped global politics for the past two centuries [85]. The near future is likely to witness the widespread adoption of a green hydrogen economy due to the implementation of diverse national hydrogen strategies by various countries. This transition is anticipated to reshape the global geopolitical landscape, redrawing the roles of hydrogen importers and exporters on the world stage.

Table 6. Seven critical aspects of climate change threatening political stability. [86]

Threat Description	Explanation	Examples
Local Resource Competition	Increased pressure on natural resources can lead to conflicts when disputes cannot be resolved.	Example: Villages fighting over water sources in a drought-affected region.
Livelihood Insecurity and Migration	Climate change can harm livelihoods, prompting people to migrate or resort to illegal activities.	Example: Farmers moving to cities due to unpredictable weather and failing crops.
Extreme Weather Events and Disasters	Extreme weather can worsen vulnerable situations, increasing grievances, especially in conflict zones.	Example: Hurricane displacement in an area with ongoing social conflicts.
Volatile Food Prices and Supplies	Climate change disrupts food production, leading to price volatility and the risk of protests and civil conflict.	Example: Rising food prices triggering protests in regions with damaged crops.
Transboundary Water Management	Shared water resources become a source of tension due to growing demand and climate-induced scarcity.	Example: Countries disputing water rights in a drying river.
Sea-level Rise and Coastal Degradation	Rising sea levels threaten coastal areas, leading to displacement and disputes over maritime boundaries.	Example: Coastal communities forced to relocate due to sea-level rise, sparking conflicts over new land.
Unintended Effects of Climate Policies	Climate policies can have unforeseen negative consequences, especially in fragile contexts.	Example: A policy causing job losses in an economically distressed region, leading to social unrest.

3.3 Geopolitical instability and role of hydrogen diplomacy

In this interconnected world, discussions of geopolitical shifts must consider diverse global threats. 'Human security' extends this discourse beyond traditional state security concerns to encompass non-conventional risks like climate change, poverty, and disease, which can undermine peace and stability within and among nations. The United Nations General Assembly, in 2012, endorsed this concept, shaping UN initiatives across peacebuilding, humanitarian aid, and sustainable development.

3.3.1 Reasons of geo-political instability

The reasons for the geopolitical instability are described below:

1. The global move towards cleaner energy has social and economic consequences. For instance, the adoption of technologies like electrolysers for clean hydrogen production is expected to create 2 million jobs worldwide by 2030, from a projected workforce of 137 million [87]. Policymakers need to consider this impact on jobs and inclusivity to ensure a fair energy transition. In contrast to this, green hydrogen can disrupt industries by risking stranded assets whereas blue hydrogen is considered safe because it uses existing natural gas resources. However, as green hydrogen costs drop and climate policies tighten, investments in fossil fuel-based hydrogen could become stranded and financially unviable as per the IRENA expectations until 2030 [88]. In countries like China, Brazil and India, green hydrogen is expected to undercut blue hydrogen costs even sooner than 2030, due to their cheap electrolysers, and affordable renewable energy [89].
2. Over the past decade, climate change has been considered as a "threat multiplier" because it worsens existing challenges, including persistent poverty, inadequate resource

management and conflict resolution institutions, historical tensions, limited access to information and resources, and mistrust among communities and nations. In essence, it magnifies the vulnerabilities associated with these pre-existing issues [90]. A report sponsored by the Group of Seven (G7) outlines seven interconnected climate-fragility risks that present significant threats to the stability of states and societies in the coming decades as shown in Table 5 [86]. Clean hydrogen is vital for deep decarbonization and climate change mitigation. It has the potential to enhance geopolitical stability. The global warming potential of hydrogen, when considered over a 100-year timeframe, is estimated to be less than one-fourth of that of methane [91]. However, effective policies are needed, especially for blue hydrogen due to methane risks and carbon capture standards. Also, the establishment of certificates of origin within a transparent and credible international framework will be critical for monitoring and managing hydrogen's role in climate change mitigation.

3. Another challenge, water stress, directly endangers human and environmental well-being. driving mass migrations and potentially sparking conflicts. These conflicts can emerge from local communities competing for scarce water resources to international disputes over shared transborder water sources. [92] Approximately 2 billion people lack safe drinking water, and nearly half of the world's population faces severe water scarcity at some point in the year [93]. Hydrogen production relies on substantial amounts of pure water as a feedstock. As climate change worsens water scarcity, more countries may need to question the long-term viability of hydrogen production. In the scenario set out by IRENA, which aims to limit global warming to 1.5°C and requires 409 million tonnes of green hydrogen by 2050, it would entail an annual water usage of approximately 7-9 billion cubic meters

[94,95]. IRENA's analysis demonstrates that by expanding their use of renewable energy sources and implementing more efficient cooling technologies, China and India can decrease their water consumption in electricity generation. Specifically, by 2030, this could result in a 42% reduction in water withdrawal intensity for electricity generation in China and an even more substantial 84% reduction in India, contributing to both sustainability and water conservation [94,95].

4. Hydrogen is essential for producing ammonia, which is a key component of synthetic fertilizers. Without hydrogen, ammonia production would be severely impacted, and this would lead to a significant reduction in agricultural productivity. As a result, food security for millions of people around the world would be jeopardized. The use of hydrogen in synthetic fertilizer production, often derived from fossil fuels, has environmental implications. The expansion of clean hydrogen production methods can help decarbonize the food supply chain, enhance environmental sustainability, and improve global food security by reducing the carbon footprint in fertilizer production. The advent of clean hydrogen may impact global food prices. Initiatives like India's proposed green hydrogen quotas for fertilizer producers can boost green hydrogen production. However, the effect on food security requires vigilant monitoring. Notably, natural gas costs currently make up a significant portion (60-80%) of variable input costs in nitrogen fertilizer production [96]. Fluctuations in gas prices often lead to corresponding changes in fertilizer prices. It became evident in 2021, when rising natural gas prices led several fertilizer manufacturers in Europe to scale back their production partially or completely.
5. Constraints do occur in deploying large-scale renewables-based electrolysis in regions characterized by high population densities or competing land use activities such as

agriculture or the preservation of protected areas. Nevertheless, the most substantial land impact will emanate from the extensive development of wind and solar PV farms required to meet the demand for renewable electricity and green hydrogen. One significant project in Australia, the Western Green Energy Hub, is set to span an extensive area of 15,000 km². This ambitious project aims to produce green hydrogen and ammonia for export. To minimize the potential for land use conflicts, renewable energy installations are being strategically located in sparsely populated desert regions and offshore zones.

The interplay of trade and economic partnerships is closely intertwined with broader political factors. The rise of hydrogen and clean fuels might reshape political alliances. Trade in oil and gas has been heavily influenced by the geographic distribution of hydrocarbon reserves, as these reserves are primarily concentrated in a limited number of countries. Interestingly, around 80% of the global population resides in countries that depend on importing fossil fuels [69]. While renewable resources are found in every country, the strength of wind and solar resources varies globally while some renewables like hydropower and geothermal energy are more region-specific. Given the widespread availability of renewable energy, countries have the opportunity to select their preferred trade partners in the upcoming clean fuel markets [97].

The growing hydrogen trade might raise strategic concerns. The expansion of hydrogen trade will elevate the importance of importing regions and impact the strategic planning of security and defense organizations. Some countries may need to import hydrogen from regions with which they lack strong alliances. Moreover, the process of adaptation may increase the risk of instability and conflict in petrostates such as Venezuela. For instance, Brazil and South Africa are poised to become notable green hydrogen exporters, whereas India may not . Russia's political isolation could constrain its hydrogen potential, but Turkey and Iran are predicted to play significant roles in the hydrogen market. Japan and South Korea, reliant on energy imports, may diversify their sources, with Australia emerging as a prominent hydrogen exporter [98]. As energy trade patterns shift, adjustments in security partnerships will follow. The United States' experience of reducing its Middle East involvement during the shale oil boom can provide valuable insights into the potential effects of the growing use of clean hydrogen on security dynamics. Therefore, major oil transit routes like the Strait of Hormuz might become less crucial for global energy security, even though they could still be important for the transportation of clean hydrogen from Middle East [67].

3.3.2 Developing world and hydrogen diplomacy

Many developing countries are still in the process of constructing essential infrastructure such as roads, residential buildings, educational institutions, factories, sewage systems, and electrical grids. This development stage necessitates a significant amount of energy and the use of materials that can have a substantial environmental impact, often acquired through imports. Meeting these infrastructure needs has the potential to significantly amplify the advantages of rapid progress. Since years, many countries believed that the most cost-effective path to development relied on fossil fuels, especially coal, which has been a major source of power globally. This reliance on coal has underpinned economic growth in several developing countries, The share of the world's coal generation in China increased from 44% in 2015 to 53% in 2020, and For Asia as a whole, it has now risen to 77%. Whereas, industries like cement, steel, and chemicals have remained deeply tied to fossil fuels [99]. Over the past decade, the increasing affordability of renewable energy sources has started to challenge the dependence on fossil fuels . The decreasing costs of technologies like solar photovoltaics, wind power, and energy storage have paved the way for new development opportunities. Consequently, the developing world currently has a unique opportunity to leapfrog fossil fuels and by making transition towards cleaner power systems. It is expected that transport leapfrog in emerging markets has the potential to greatly decrease the anticipated demand for the year 2030, by over 70% [100]. As countries like China leads the electric vehicle (EV) industry with remarkable statistics as 59% of bus sales and 61% of 2-wheeler sales in 2019 [100]. Meanwhile, India is also making significant strides, aiming for 30% of car sales to be EVs by 2030 [100].

Developing countries must build essential infrastructure, which demands significant energy and emissions-intensive materials, often imported. Clean hydrogen can open up new industrial opportunities, including the production of green steel, even in some of the world's poorest countries. By tapping into their renewable energy potential to produce green hydrogen locally, these nations can boost their economies and improve energy security. To make this a reality, international cooperation is needed to share resources, technologies, and expertise knowledge. At present, the costs associated with energy transition technologies pose a financial challenge for numerous developing countries, resulting in a disparity between those with the capacity to invest in clean hydrogen and those without such means. To bridge this gap and ensure a fair transition, it is essential to provide developing countries, especially the least developed, with access to technology, training, capacity building, and affordable finance for hydrogen adoption. This not only promotes fairness but also fosters international trade, cooperation, and energy security.

Where this much geopolitical instability exists, many governments are also making bilateral deals for cross-border hydrogen trade, ranging from feasibility studies to trial shipments. Countries like Canada, Chile, Germany, Italy, Japan, and Spain are exploring such relations in their national strategies, potentially leading to new energy trade routes. The emergence of these hydrogen trade routes could reshape energy geopolitics, and countries like Germany and Japan are pioneering "hydrogen diplomacy" to import hydrogen and zero-carbon fuels. Other nations are also following suit, making it a growing part of economic diplomacy [67]. Numerous nations are actively engaging in diplomatic initiatives to advance their hydrogen strategies. For instance, Germany has established bilateral hydrogen partnerships with several prospective supplier countries, which encompass Australia, Chile, Morocco, Namibia, Tunisia, and Ukraine. They have established hydrogen diplomacy offices in locations like Angola, Nigeria, Russia, Saudi Arabia, and Ukraine to facilitate international discussions on the global hydrogen market's geopolitical implications [67]. Japan is discussing hydrogen trade partnerships with Australia, Brunei, Norway, Saudi Arabia, and others to compete with LNG and gasoline. They also aim to export their low-carbon technologies and expertise abroad [101]. South Korea and Chile have signed an agreement to share technologies in the low-carbon hydrogen sector, with a focus on production, storage, transportation, and usage. The partnership aims to establish an economical hydrogen supply network and expand low-carbon hydrogen trade by combining South Korea's expertise with Chile's renewable energy resources [102]. The Dutch government is aiming for potential hydrogen suppliers from countries including Chile, Namibia, Portugal, and Uruguay [103]. Belgian industrial players are exploring large-scale hydrogen imports from Chile, Namibia, and Oman [104]. Germany plans to initiate partnerships with producers of cheap green hydrogen countries including Chile, Morocco and Australia [97].

3.4 Risks and vulnerabilities of international hydrogen trade

In the realm of international politics, there is a growing focus on addressing climate change. This raises concerns about the prospect of developed nations relocating their carbon-intensive operations to developing countries while simultaneously reducing emissions within their own borders and making use of the resources and workforce of these developing nations [67,85,105]. The adoption of hydrogen as an energy carrier has the potential to elevate energy security concerns, particularly when dealing with internationally traded hydrogen and its associated products.

3.4.1 Country investment risk

Establishing the essential infrastructure for hydrogen trade poses challenges for both suppliers and consumers. Due to the substantial capital demands of hydrogen trade value chains, reducing the associated investment risks will require the engagement of significant partnerships, active government support, and global cooperation. For an exporter, ensuring the security of revenue is of utmost importance. Without a guaranteed and steady stream of income, it becomes impossible to recover the initial capital expenditures invested in the development of hydrogen projects. This revenue needs to be substantial enough to cover various expenses, such as the costs associated with electrolysers (for green hydrogen), natural gas reformers (for blue hydrogen), solar and wind parks (for green hydrogen), gas reserve facilities (for blue hydrogen), as well as the infrastructure needed for the transportation and storage of hydrogen. Hydrogen export projects are sprouting in regions like Australia, the Middle East, North and Southern Africa, and South America, with the aim of producing substantial amounts of clean hydrogen for global markets. The future of these plans is uncertain due to emerging global demand and fierce competition for hydrogen sales. Importantly, more countries aspire to become hydrogen exporters than those planning imports.

For buyers gearing up to rely on hydrogen imports, guaranteeing a secure supply of hydrogen is a top priority. They must have confidence that hydrogen-exporting nations can sustain sufficient renewable electricity capacity for the electrolysis process. The challenge lies in the fact that many of these aspiring hydrogen-exporting countries are contending with an increasing demand for domestic power. This situation is particularly relevant in regions like the Middle East and North Africa, which are often seen as potential hydrogen suppliers. These regions' population is projected to double by 2050, according to the United Nations in 2019. Consequently, there will be a significant increase in electricity demand.[106] Renewable energy sources are under substantial pressure, as they are tasked with fulfilling multiple roles simultaneously. These roles include satisfying the growing electricity demands, substituting existing fossil fuel power generation infrastructure, and providing the energy required for operating hydrogen production through electrolysis, specifically for export markets. Greater investment risks can raise project financing costs, but they do not necessarily deter investments. The oil and gas industry shows that with clear revenue prospects, investments can proceed even in high-risk countries. For instance, in May 2021, an Australian renewable energy developer signed a USD 40 billion agreement with Mauritania to create a significant green hydrogen project, despite Mauritania's "high warning" status on the fragile states index [107].

3.4.2 Technical failures and political disruptions

Energy supplies can face disruptions due to a variety of factors, including technical issues (equipment or infrastructure failures), human errors or accidents, and natural disasters. Hydrogen infrastructure, due to its unique properties, also demands specialized safety measures [108]. However, well-established national and international standards can effectively mitigate hydrogen-related safety risks. For example, the U.S. National Fire Protection Association (NFPA) and the International Code Council (ICC) have established codes and standards for the safe design and operation of hydrogen storage systems. These standards provide guidelines on factors like ventilation, safety distances, and materials used to ensure the secure storage and handling of hydrogen. Adhering to these standards helps mitigate the safety risks associated with hydrogen storage.

Another reason for causing disruption occurs when states use energy trade and interdependence strategically to disrupt international relations, impacting energy flows, prices, and infrastructure to achieve their geopolitical objectives. There are numerous historical examples of states using energy trade and interdependence as tools for geostrategic purposes.[109] This includes actions such as implementing export boycotts or import bans, offering energy price discounts to allies, and constructing new oil and gas pipelines to advance their foreign policy objectives. In the future, hydrogen trade could be used for political leverage. This would be more likely when one country heavily depends on hydrogen from another and lacks alternative sources or reserves. This scenario is contingent on a concept called "asymmetric independence," where one party in an energy trade relationship is significantly more susceptible to the relationship's termination. This vulnerability may result from a lack of alternative trade partners or significant energy reserves, such as emergency stocks [110].

In the early phase of international hydrogen trade, there will be few trading partners, often locked into long-term contracts. If there are disruptions in these imports or exports, it could have a significant impact on the other side because there may not be a readily available and active market for hydrogen such as emergency stocks. The possibility of a hydrogen cartel forming, reminiscent of historical fossil fuel alliances, seems improbable. Cartels typically necessitate specific conditions, such as a limited number of dominant producers capable of market control and the enforcement of production constraints. The historical fossil fuel alliances, as exemplified by the "Seven Sisters," were comprised of a select group of multinational oil corporations that wielded significant market influence. In contrast, the hydrogen sector displays a decentralized structure, characterized by the involvement of a broader array of stakeholders (located in different regions) in hydrogen production, distribution, and utilization. This decentralization, wherein power and control are dispersed among multiple participants from different countries, presents a substantial obstacle to the emergence of a hydrogen cartel. Hydrogen is different and it is found naturally at several places, so it is hard to control who enters the industry or limit new players. Additionally, many countries want to export hydrogen, reducing the chances of one dominant exporters.

3.4.3 Access to critical raw materials

Access to critical raw materials is vital for hydrogen and other renewable energy technologies. About thirty raw materials are used in fuel cells and hydrogen storage technology, making material security a key concern for sustainable renewable energy development. Among these materials 13 are considered critical including cobalt, magnesium, rare earth elements (REEs), platinum, palladium, borates, silicon metal, rhodium, ruthenium, graphite, lithium, titanium, and vanadium.[111] While there are sufficient geological reserves of minerals and metals for now, rising demand and slow mining projects could tighten supply. New technologies may also compete for these materials. Even if countries produce their own hydrogen, they may rely on a few nations for raw materials. To address this, innovation, energy efficiency, recycling, and circular economy principles are crucial to avoid material shortages.

The fast growth of the hydrogen sector will increase the need for certain raw materials like nickel and zirconium in electrolyzers, as well as platinum-group metals in fuel cells [112]. This is because hydrogen adoption will drive the wider use of renewable energy technologies, such as solar and wind power. Furthermore, the integration of hydrogen will involve expanding electrical infrastructure and battery installations, which will, in turn, boost the demand for the minerals and materials used in these technologies. Several types of electrolysers and fuel cells have diverse material requirements. Alkaline electrolysers, which are currently the most common in the market, primarily use materials that are generally considered uncritical, including steel and nickel [113]. By comparison, Polymer-electrolyte membrane and solid-oxide electrolysers raise greater concerns due to their dependence on rare and environmentally impactful metals, such as platinum and iridium. The supply of these metals is also heavily demanded, with South Africa providing more than 70% of the world's platinum and over 85% of global iridium [114].

Platinum group metals, such as platinum, palladium, and rhodium, are commonly used in catalytic converters to reduce vehicle emissions. However, the shift to electric vehicles has reduced their demand. The platinum industry is looking to the rise of electrolysers and fuel cells to make up for this decreased demand. Solid oxide electrolysers, although currently at the laboratory development phase, hold the potential for enhanced efficiency and reduced electricity consumption. However, they face an even greater concentration of supply issues. Ninety-five percent of the critical materials essential for solid oxide electrolysers are sourced exclusively from China. The markets for these materials lack liquidity and are sensitive to even slight changes in supply and demand. Over the past 20 years, prices for materials like platinum, palladium, and iridium have fluctuated significantly by a factor of four, 15 and 70 consecutively , impacting hydrogen supply chains and equipment costs, as well as the revenues of miners and material exporters [115].

CHAPTER 4

4- GREEN HYDROGEN ECONOMY & SDGS – TOWARDS HOLISTIC SUSTAINABILITY

This chapter is a modified version of the book chapter (under publication) '*A review of social challenges of green hydrogen economy and its realization towards sustainable development goals'* by Khan et.al and the manuscript '*Green hydrogen and sustainable development – A social LCA perspective highlighting social hotspots and geopolitical implications of the future hydrogen economy'* by Akhtar et al [116].

Within the evolving landscape of sustainable development, this chapter serves as an informative guide through the intricate interplay between the green hydrogen economy and Sustainable Development Goals (SDGs). This chapter unfolds a journey that unveils the transformative potential of green **h**ydrogen while scrutinizing its profound alignment with pivotal SDGs, including "Affordable and Clean energy (SDG 7)" and "Climate Action (SDG 13)." Beyond the obvious connections, here, we delve into the intricacies of these relationships, recognizing the pivotal role of policymakers in balancing beneficial synergies and addressing potential challenges. This chapter illuminates the path towards holistic sustainability, offering insights into a greener, more inclusive, and harmonious future.

4.1 Green hydrogen economy and SDGs

Green hydrogen is considered as a clean, potential, and sustainable energy vector to decarbonize a variety of sectors. The promotion of sustainable development should not be limited to environmental concerns. Instead, it should encourage sustainable development for all humans. The promotion of sustainable development should not be confined solely to environmental matters; rather, it should encompass the goal of achieving sustainable development for all human beings. Sustainable development transcends economic and environmental considerations, extending its scope to encompass social concerns, which hold paramount importance for holistic sustainability. The interconnection between green hydrogen achieving SDG 7 i.e., affordable, and clean energy owing to its decarbonization potential has been made evident previously by the researchers.

Although green hydrogen is not cost effective until now but it is significance in mitigation the global warming issues is incontrovertible. The UN SDGs are integral to the achievement of the Paris Agreement by reducing global GHG emissions by 2030. Falcone et,al. argued hydrogen economy as a game changer in providing ways for decarbonization in industries and supporting SDGs [18]. A report by United Nations Industrial Development Organization (UNIDO) shows hydrogen being a zero emission energy carrier sufficient to fuel 250 million cars, and it's marketing through SDGs 7,9 and 13 [118]. The recent energy progress report in tracking SDG 7 with its indicators assessment shows their economic recovery plans targeting renewable energy market to get stronger than the before [119]. Until 2050, carbon emissions can be reduced by 90% using renewable energy solutions and efficiency measures together. Africa poses a challenge in achievement of SDG 7 due to being one of the least energized region, over 800 million African people lack access to clean technology and its acceleration towards renewable energy is required [120]. As we experience around the world, energy policies are interlinked with the SDG 7, but there is uncertainty in overcoming climate tipping points due to the disconnection between market, social, and infrastructure as well as social acceptance factors [121]. However, the remaining SDGs and the impact of hydrogen economy towards them has not been studied rigorously until now. A coherent action plan and effective policies on renewable energy can help catalyze progress on the other SDGs. Hydrogen energy is pivotal in supporting SDGs 1,2 & 3 i.e., *poverty, hunger, and Health* especially in the aftermath of Covid pandemic it has become more imperative to expand progress in energy market. As energy is crucial in ending hunger, poverty, and health crisis by running households, and healthcare facilities. The energy poor countries have limited financial space, and they are likely to face more economic constraints which may result in considerable risk of poverty and hunger. The expansion of cleaner use of energy sources has not made progress effectively in rural areas and their households [122]. In the least developed or rural areas, It is possible to create employment opportunities for both youth and women, through scaling up of renewable energy, including biogas solutions for clean cooking. The electrification of health facilities through clean energy sources can reduce the overall percentage of air pollution as many other health facilities use unreliable electricity supplies.

4.2 Holistic Sustainability and the Green Hydrogen Economy

The pursuit of comprehensive sustainability involves addressing multiple interconnected aspects, and the green hydrogen economy plays a crucial role in this transformation. By harnessing the abundant potential of renewable energy sources for hydrogen production, the green hydrogen economy provides a versatile solution that not only addresses environmental concerns but also aligns with social and economic imperatives. This alignment contributes to several SDGs, making it a central player in advancing ecological responsibility, social inclusivity, and economic viability. Two fundamental SDGs that benefit from the growth of green hydrogen are SDG 7, which focuses on "Accessible and Clean Energy," and SDG 13, aimed at "Action on Climate Change." In this research, we explore how the green hydrogen economy can promote comprehensive sustainability, considering the ways different SDGs can work together and the potential trade-offs between them.

4.2.1 Green Hydrogen and SDG 7: "Clean and Affordable Energy"

The most obvious way that the green hydrogen economy and the Sustainable Development Goals (SDGs) work together is seen in SDG 7, which focuses on "Affordable and Clean Energy." The main goal of the green hydrogen ecosystem aligns perfectly with this objective. By using clean energy sources like wind and solar power to produce hydrogen, we can significantly decrease our reliance on fossil fuels, leading to a substantial reduction in greenhouse gas emissions. This positions green hydrogen as a clean, efficient, and cost-effective energy carrier, which is vital for the transition to sustainable energy systems. A compelling statistic supporting this collaboration is the impressive reduction in carbon emissions achievable through the adoption of green hydrogen. Research shows that the methods used for green hydrogen production can cut carbon emissions by as much as 90% when compared to traditional hydrogen production methods, highlighting its potential to advance the goal of clean and affordable energy [14].

4.2.2 Addressing SDG 13: "Climate Action"

The global climate crisis stands as one of the most urgent challenges we face today. In this context, green hydrogen plays a vital role in advancing the goals of SDG 13, which emphasizes the need for immediate action to combat climate change and its consequences. When we replace traditional hydrogen production from fossil fuels with green hydrogen, the reduction in carbon emissions becomes quite clear. This shift towards environmentally sustainable practices makes significant contributions to the dual objectives of addressing climate change and its far-reaching effects. However, achieving comprehensive sustainability requires a thoughtful understanding of potential trade-offs and negative impacts when balancing the growth of the green hydrogen economy with other crucial SDGs. It calls for careful policymaking and strategic planning.

4.2.3 Navigating Trade-offs for Holistic Sustainability

1. SDG 6: "Clean Water and Sanitation":

    - Trade-off: Green hydrogen production often entails substantial water usage, raising concerns about water scarcity. Policymakers need to implement sustainable water management practices, such as water recycling, to mitigate this trade-off effectively.

2. SDG 2: "Zero Hunger":

    - Trade-off: Competition for land and water resources between green hydrogen production and agricultural needs may emerge. Policymakers must carefully navigate these trade-offs to ensure that agricultural productivity remains intact.

3. SDG 9: "Industry, Innovation, and Infrastructure":

    - Synergy: The green hydrogen economy fosters innovation, job creation, and sustainable economic growth. Policymakers should institute frameworks that support research and development while ensuring equitable employment opportunities.

4. SDG 8: "Decent Work and Economic Growth":

    - Synergy: Green hydrogen initiatives can generate employment prospects, particularly in regions hosting renewable energy and hydrogen production facilities. Policymakers must focus on skill development and equitable employment practices.

5. SDG 16: "Peace, Justice, and Strong Institutions":

- Synergy: By diminishing reliance on fossil fuels and mitigating geopolitical tensions, green hydrogen can stimulate international cooperation and promote peace. Policymakers should champion international agreements and collaborative endeavors to facilitate the growth of the green hydrogen sector.

4.2.4 Fostering Synergies for Holistic Sustainability

Understanding the positive synergies across various SDGs is equally crucial. These synergies serve as pillars of holistic sustainability in the context of the green hydrogen economy:

1. Synergy Between SDG 6, 9, and 14: Green hydrogen production that incorporates sustainable water management practices aligns with SDG 6 (Clean Water and Sanitation), SDG 9 (Industry, Innovation, and Infrastructure), and SDG 14 (Life Below Water) by preserving water resources and ecosystems.

2. Synergy Between SDG 2, 8, and 9: Investment in research and development for green hydrogen not only promotes innovation (SDG 9) but can also create jobs (SDG 8), while ensuring that employment opportunities are accessible to all, contributing to food security (SDG 2).

3. Synergy Between SDG 16 and Climate Action: Reducing greenhouse gas emissions through green hydrogen aligns with SDG 16 (Peace, Justice, and Strong Institutions) by diminishing geopolitical tensions and fostering international cooperation, which is instrumental in climate action (SDG 13).

4.3 Policy insights

To achieve holistic sustainability through the green hydrogen economy, a comprehensive and integrated policy approach is paramount:

1. Integrated Planning and Governance: The formation of multi-stakeholder task forces comprising governmental bodies, industries, and civil society is vital to oversee green hydrogen projects, ensuring alignment with sustainability objectives.

2. Integrated Sustainability Assessments: Life cycle sustainability assessments (LCSA) on economic, environmental, and social perspectives can provide us detailed insights and hotspots throughout the process value chain. The life cycle costing, environmental and social life cycle assessment can provide us hotspots that can lead us to improve our processes on the front of sustainable development as emphasized by Akhtar et al [116]. Therefore, in order to evaluate sustainability metrics of hydrogen production processes LCSA should be the methodology of priority globally.

3. Inclusive Decision-Making: Engaging communities, especially marginalized groups, in project planning and implementation is essential for equitable benefit distribution and a comprehensive understanding of local impacts.

4. Sustainable Siting: Encouraging the use of brownfield sites and repurposing abandoned industrial infrastructure is an effective means to reduce the environmental footprint and mitigate land competition with agriculture.

5. Cross-Sector Collaboration: Collaboration among the energy, water, agriculture, and transportation sectors is indispensable for optimizing resource use and minimizing conflicts, thereby embracing a holistic perspective.

6. Monitoring and Reporting: Robust monitoring and reporting mechanisms should be in place to continually assess the progress of green hydrogen projects concerning SDGs, facilitating necessary adjustments.

7. Research and Data Collection: Continuous investments in research and data collection are indispensable for evaluating the impacts of green hydrogen projects on SDGs, thereby informing adaptive management strategies in alignment with sustainable development objectives.

In summary, the green hydrogen economy serves as a powerful driver for comprehensive sustainability. Although it strongly aligns with SDGs focused on clean energy and addressing climate change, policymakers must carefully navigate the complex terrain of balancing various SDGs. By implementing well-informed and integrated policies and strategies, policymakers can harness the transformative potential of the green hydrogen economy, moving society closer to the realization of holistic sustainability.

CHAPTER 5

5- CONCLUSIONS

This work explores the significant impact of the green hydrogen economy within the ever-evolving global energy landscape and its relationship with the Sustainable Development Goals (SDGs). We delve into the economic, environmental, and socio-political aspects of green hydrogen in a post-COVID-19 world, highlighting both challenges and opportunities. In Chapter 2, the profound impacts of COVID-19 on various aspects of South Korea's economy, energy sector, and hydrogen economy roadmap are presented. For South Korea's success, policy consistency is critical for nurturing hydrogen as a viable power source, especially considering potential shifts in policy emphasis due to political transitions between different elected governments. Ensuring a steady, long-term commitment from both the government and industry is crucial for realizing the full potential of a hydrogen economy in South Korea. While the pandemic brought disruption, it also allowed us to envision a future where green hydrogen can be the linchpin for achieving sustainable, clean, and equitable energy systems.

Chapter 3 provides an in-depth exploration of the intricate socio-political and geopolitical complexities surrounding green hydrogen. The global production and trade of green hydrogen are not solely economic transactions; they are deeply entwined with complex geopolitical dynamics. The insights from this chapter hold substantial implications for global fairness, resilience, and power dynamics. It underscores the importance of a just transition, ensuring that the advantages of the green hydrogen economy are equitably distributed among societies and nations.

In Chapter 4, it becomes evident that green hydrogen aligns exceptionally well with key Sustainable Development Goals (SDGs), particularly SDG 7 ('Affordable and Clean Energy') and SDG 13 ('Climate Action'). It emerges as a beacon of hope in the journey toward a clean energy future and climate mitigation. However, this alignment is not isolated, and to fully realize the potential of the SDGs, efforts should be directed towards balancing trade-offs and fostering synergies across the SDGs agenda.

The transition towards a sustainable and resilient future depends on well-informed decisions, innovative policies, and collaborative efforts. The objective is to cultivate a world where energy, environmental responsibility, and societal well-being seamlessly intertwine, guiding the path of global sustainable development. While green hydrogen paves the way for clean energy and climate action, its significance transcends these domains. A sustainable future encompasses more than just environmental stewardship; it includes considerations of social equity, economic prosperity, and global resilience. In our pursuit of sustainability, we must remain vigilant about potential challenges and obstacles. Advancing one SDG should not inadvertently impede the achievement of another. An all-encompassing approach recognizes the intricate interplay among these goals and strives to navigate this terrain with wisdom and foresight. In conclusion, this research underscores that a sustainable future is a shared vision, where the harmonious coexistence of humanity and the planet is not only a possibility but an imperative. The transformative potential of the green hydrogen economy empowers us to envision and create such a future, one that aligns with the grand vision of the SDGs, ensuring a world that thrives with clean energy, climate resilience, and social equity at its core. The green hydrogen economy is not just a solution; it is a catalyst for transformative change, offering a glimpse of a future where the synergy of energy, environmental responsibility, and societal well-being becomes the cornerstone of global sustainable development.

Despite the comprehensive nature of this research, certain limitations should be acknowledged. This study is primarily based on an extensive review of existing literature, policies, and socio-economic data related to the green hydrogen economy which may introduce biases or gaps. It is crucial to acknowledge that the availability of comprehensive data varies across countries and regions. While efforts were made to gather as much information as possible, the specific policies addressing sociopolitical barriers in the green hydrogen economy in individual countries may not be uniformly represented due to data constraints. The limitations stem from the varying degrees of data availability and the challenge of obtaining detailed, country-specific information on sociopolitical aspects. Therefore, the findings should be considered with awareness of these data constraints, especially in regions where detailed information might be lacking. Future research should aim to address these gaps by conducting more in-depth, country-specific studies where comprehensive data are available.

CHAPTER 6

6- REFERENCES

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