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LCA of Mixed Generation Systems in Singapore: Implications for National Policy Making

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Abstract: The decarbonization of electrical power generation systems is one of Singapore's national political agendas to reduce national greenhouse emissions. LCA is applied to assess the trade-offs of national implementation of electricity generation from conventional fossil-fuel power plants, compared to low-carbon alternatives. The first aim of LCA is to quantify the emission inventory of national electrical generation within the geographical boundary of Singapore, and next to generate the potential environmental impacts of Global Warming Potential, Acidification, and Eutrophication. Various scenarios are tested for a projected diversity of fuel resource mixes considered for years 2030 and 2040 and a hypothetical scenario where 100% renewable energy is employed and imported as the nation transitions towards a low-carbon energy future. Further discussions on the additional LCA model indicators should be included for the potential of low-carbon hydrogen application.

Keywords: LCA; national fuel mix; environmental impacts; scenario analysis; policy implications

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Citation: Khoo, H.H. LCA of Mixed Generation Systems in Singapore: Implications for National Policy Making. *Energies* **2022**, *15*, 9272. https://doi.org/10.3390/en15249272

Academic Editor: Ali Nabavi

Received: 3 November 2022
Accepted: 3 December 2022
Published: 7 December 2022

1. Introduction

As a highly industrialized and urbanized nation, energy plays an important role in shaping Singapore's economic development. The increase in national electricity consumption for industrial and household needs has led to the need for obtaining various types of energy feedstock (e.g., fossil-based fuels and renewable energy resources), which may pose environmental or sustainability concerns. It is important to project the environmental profile of the changing landscape of the nation's electrical generation systems taking into account the diversity of the energy resource portfolio [1]. As a city-state with no fossil fuel resources, Singapore relies entirely on imports to meet its growing natural gas demands, used mainly for electrical power generation and petrochemical production. The major source of natural gas comes mostly from West Natuna's offshore gas field, other parts of Indonesia, and the rest from Malaysia. Besides natural gas, the second main fossil fuel resource imported is crude oil. Sources of crude oil are mainly shipped from Middle Eastern countries such as Saudi Arabia, Kuwait, Qatar, United Arab Emirates [2]. Another energy generation system is waste-to-energy (WTE) plants, or incineration facilities, which make use of heat generated from the calorific values of wastes to produce electricity [3]. As an important move toward the transition of a low-carbon nation, alternative sources of energy are sought.

To the best of our knowledge, no reported work has been conducted to evaluate the national trade-offs of energy mix portfolio—for the comparison of fossil fuels vs. renewable resources—via cradle-to-gate (resource supply-to-power) LCA application. The importance of this work is to provide implications for strategic policy making as the nation moves towards a low-carbon energy future.

1.1. Solar Power

With the aim to reduce greenhouse gas (GHG) emissions, Singapore is prompted to employ large-scale solar photovoltaic (PV) in the near future [4]. Over the past decades,

research breakthroughs in solar technologies have made giant leaps to enable higher conversion efficiency at lower cost, resulting in exponential increases in global installed capacities [5]. Solar energy is also considered to be a non-polluting source of energy; its use is not accompanied by the release of harmful gases (e.g., oxides of C/N/S and/or VOCs) and particles (e.g., soot, heavy metals, and dust) [6].

1.2. Liquefied Natural Gas (LNG)

With plans to diversify energy resources, liquefied natural gas (LNG) will begin to play a bigger role in power generation in the coming years. A graph predicting the increased volume of LNG imports is shown in Figure 1 [7]. LNG can be delivered by ocean tankers from neighboring countries to Singapore. This will help the options for fossil fuel requirements and, at the same time, help to safeguard the nation's future energy needs [8]. A vast volume of LNG is located in Western Australia, where the world's largest LNG project is situated [9]. Indonesia, another LNG producer, has established strategic national projects in the energy sector with the aim of exporting more LNG to Singapore. Among the LNG projects are the Indonesia Deepwater Development (IDD) and Jambaran-Tiung Biru Field in Java. Exports of LNG from Indonesia are expected to play a major part in Singapore's energy portfolio in the next coming years [10]. After the transportation of LNG to its destination, regasification is also required [11,12]. The specific work required for liquefaction can range from 907 to 1080 kJ/kg LNG [13,14]. Regasification of LNG to NG can require ca. 853 kJ/kg [15].

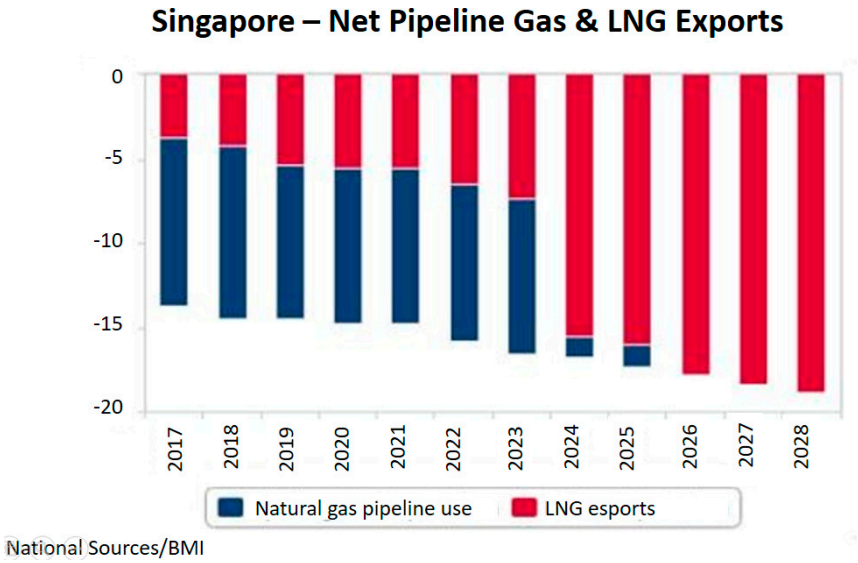


Figure 1. Expected increase in use of LNG [7].

1.3. Renewable Hydrogen and Bioenergy

The cleanest way to produce hydrogen is through water-splitting technologies coupled with renewable energy sources. In order to achieve large-scale hydrogen-to-electricity supply chains, reliable systems for hydrogen production, storage, and distribution are vitally important. As research and demonstration activities of hydrogen technology progress, one of the energy sources for the nation is expected to come from renewable hydrogen [16].

Agricultural by-products can be found in neighboring countries such as Malaysia or Indonesia. Rice husk contains about 30–50% of organic carbon and has a high heat value of around 16 MJ/kg [17]. The biomass resource can be used to generate fuel, heat, or electricity [18,19]. Most bioenergy plants use direct-fired combustion systems where the biomass is combusted directly to produce high-pressure steam that drives turbine generators to generate electricity.

1.4. Wind and Hydropower

Wind and hydropower are both regarded as renewable energy technologies that emit lesser emissions that pollute the environment [20]. Apart from greenhouse gas reductions, such renewable energy generation technologies can also help in reducing the dependency on fossil fuels [21]. It has been estimated that roughly 10 million MW of energy are continuously available in the earth's wind. Studies have already been performed to determine the environmental benefits of different types of hydropower concepts [22] and wind power technologies [23].

2. Materials and Methods

Life cycle assessment (LCA) is applied to demonstrate how the diversification of the fuel supply portfolio is an important factor that affects the impacts of electrical production systems within the geographical boundary of Singapore for the following:

(i) National inventory emissions for 2020 according to national fuel mix (compared to the year 2010), and next, the associated environmental impacts of electricity generation from different supplies of fuels for the functional unit of 1 MWh.

(ii) Environmental impacts of projected fuel mixes for 2030 and 2040; and a futuristic scenario where 100% renewable energy technologies are applied and imported. The projected scenarios serve to generate the impacts for 1 TWh.

The overall methodology is illustrated in Figure 2.

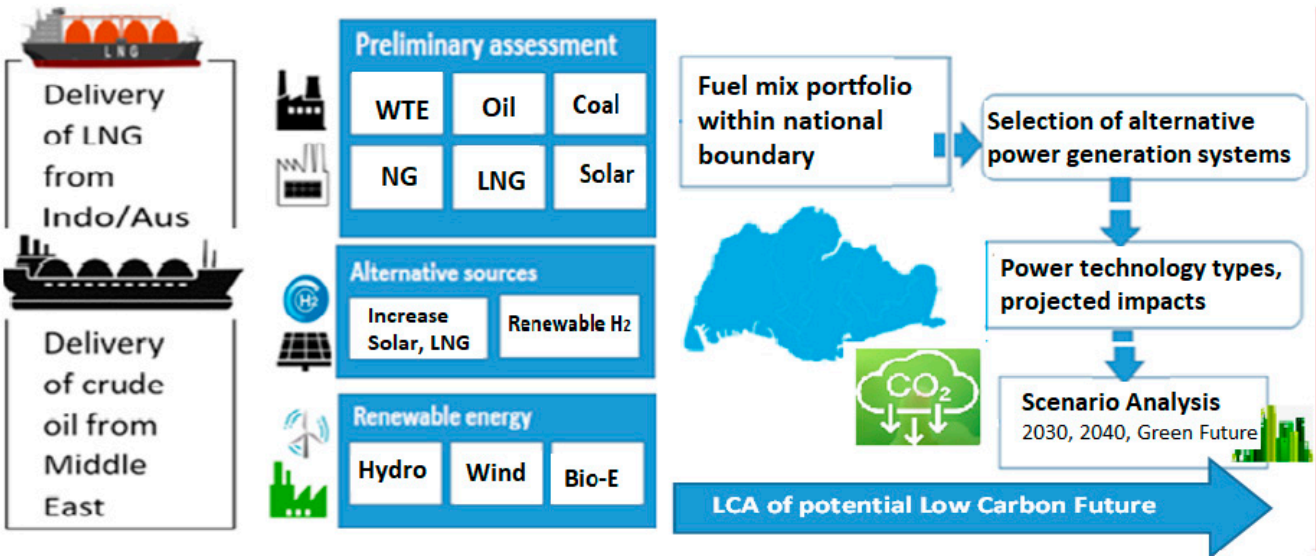


Figure 2. Overall methodology.

2.1. Life Cycle Assessment (LCA)

Life cycle assessment (LCA) studies of electricity supply play a central role in various nations and regions, especially in the aim of establishing low-carbon energy scenarios to aid in policy making. At a national level, structural LCA pathways are designed to connect the consumption of fossil resources to the electrical power production network, similar to the case of a previous cradle-to-gate LCA work [2].

2.1.1. Case Study Settings

The LCA investigation is conducted with the fuel mix for the year 2020 projected as 95.2% natural gas, 0.7% petroleum products, 1.2% coal, 1.45% WTE, and 1.45% Solar PV [24]. The stages addressed in the LCA method include the extraction and transportation of fossil fuels and end with the combustion of different fuel types to generate 1 MWh of electrical power. Life cycle inventory (LCI) data and information flow form the foundation of the LCA modeling structure. The material and energy flow associated with each life

cycle inventory (LCI) of power generation are collected from existing LCI databases and reports [25–27]. Unavailable information is extracted from other articles (e.g., [4,12,28]).

The calorific values of each fuel type are: 24–30 MJ/kg for coal, 43–46 MJ/kg for crude oil, 47–52 MJ/kg for natural gas (NG), and ~53.5 MJ/kg of LNG. Typical coal power plant efficiency ranges from 32% to 42%. Steam turbines can achieve ca. 45% efficiency. The power plant efficiency for the NGCC system is 48.8% [26]. An advanced LNG power plant is reported to achieve an overall efficiency of 55% [29]. The specific amount of fuel types and delivery parameters to Singapore is detailed in Table A1 (Appendix A). The associated gate-to-gate and cradle-to-gate LCI calculations for the year 2020 are compiled in Tables A2 and A3, respectively.

2.1.2. Annual Scenario Analysis

To further enhance energy security and, at the same time, reduce GHG emissions, a wide range of renewable energy technologies are expected to be employed. Scenario analysis will be performed for the projected diversity of fuel mixes along with increased use of renewable energy. The increase in LNG imports will replace the use of NG in the upcoming years [7,30]. Considered a "cleaner and greener fuel", plans and programs for LNG port receiving terminals are already ongoing [31,32]. Electricity generated by solar PV is also expected to play a more significant role in the future [33]. Since the rest of fossil fuel resources result in high GHG impacts, they will not be considered; moreover, with plans to proceed to become a zero-waste nation, WTE are also eliminated in future scenarios [34].

- Projected fuel mixes for years 2030 and 2040

It was reported that the "largest floating solar farm" would be constructed in Singapore. The solar farm located at Tengeh Reservoir in western Singapore—covering about 45 football fields—is expected to produce a maximum capacity of 60 megawatts of electrical power [35]. In addition, as one of the options to enhance energy security, Singapore aims to be "the premier LNG bunkering hub in Asia" [31]. An estimation of around 60% of LNG will be applied for the fuel mix in 2030 [32]. For the year 2040, a steady increase in solar-powered energy (from 10% to 20%) and LNG (from 60% to 70%) will be expected; with NG remaining as the rest of the fuel mix (10%). The remaining electrical power portfolio is expected to be fueled by NG. Apart from low-carbon initiatives, Singapore plans to be a zero-waste city-nation [34].

- Green Future: 100% renewable energy

Achieving long-term targets for GHG reductions will require a transition to energy low-carbon energy supply technologies. An ambitious target of 50% solar power is projected [36], along with renewable hydrogen (20%) [37]. A hypothetical scenario of energy imports to ensure a sustainable low-carbon future is investigated for a "100% renewable energy" scenario. The remaining 30% of electricity is supplied via imports of wind (10%), hydroelectric power (10%), and bioenergy (10%) from neighboring countries [19].

All the scenarios are compiled in Table 1.

The set of environmental impacts from the scenarios (Table 1) is projected for the total energy use for the years 2010, 2020, 2030, and 2040 and a "Green energy future". Based on the statistics from [24], the predicted annual national electricity consumption for the years 2010–2040 is displayed in Table A4 (Appendix A). The results of TWh/year are generated for energy use in the following sectors: 42.5% industry-related, 36.8% commerce and services, 14.5% households, and 6.20% of energy use in other sectors (e.g., transportation, heating/cooling systems, etc.).

Table 1. Projected Scenarios.

Scenarios	Fossil Fuels				Other		Renewables			
	NG	Oil	Coal	LNG	WTE	Solar PV	Renewable H_2	Hydro *	Wind *	Bio-Energy *
Year 2010	78%	20%	0	0	2%	0	0	0	0	0
Year 2020	95.2%	0.7%	1.2%	0	1.45%	1.45%	0	0	0	0
Year 2030	30%	0	0	60%	1%	10%	0	0	0	0
Year 2040	10%	0	0	70%	0	20%	0	0	0	0
Green Energy	0	0	0	0	0	50%	20%	10%	10%	10%

* Imported electricity.

3. Results

3.1. Preliminary Assessment

In the first set of preliminary assessments, five environmental impacts are projected for 1 MWh. Life cycle impact assessment method CML 2001 was applied to generate:

- Global Warming Potential (GWP), measured in kg CO_2-eq;
- Acidification Potential (AP), measured in kg SO_2-eq;
- Eutrophication Potential (EP), measured in kg phosphate-eq;
- Human Toxicity Potential (HTP), measured in kg DCB-eq.

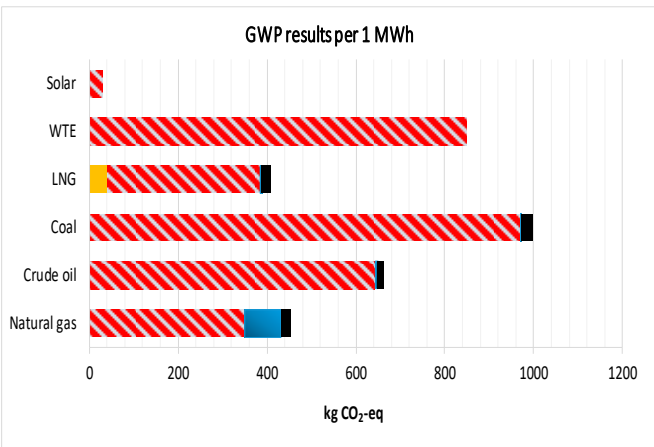
The five environmental impacts of GWP, AP, EP, and HTP for fuel extraction and transportation to combustion at the power plants to generate 1 MWh are reported in Figure 3a–d, respectively.

3.2. Scenario Test Results

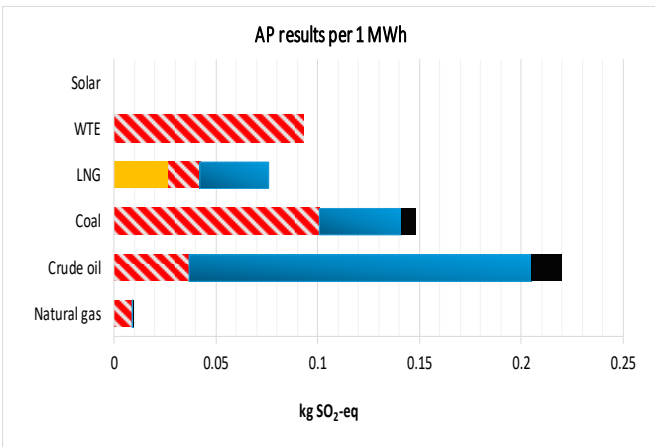
The projected results for annual TWh for the scenarios (displayed in Table 1) are reported in Figure 4a–d for GWP, AP, EP, and HTP, respectively.

3.3. Discussions: Preliminary Environmental Impacts for 1 MWh

From Figure 3a, the GWP impacts for fossil fuels to power combustion are 452, 664, 1000, and 205 for natural gas, crude oil, coal, and LNG kg CO_2-eq/MWh, respectively. The GWP results are reasonably comparable to the LCA study carried out by Garcia et al. [38] for NGCC (423 kg CO_2-eq/MWh) and coal-based power plants (1021 kg CO_2-eq/MWh). However, fuel oil power production was reported by the authors to be higher (912 kg CO_2-eq/MWh). It is observed that the GWP for WTE is 850 kg CO_2-eq/MWh.

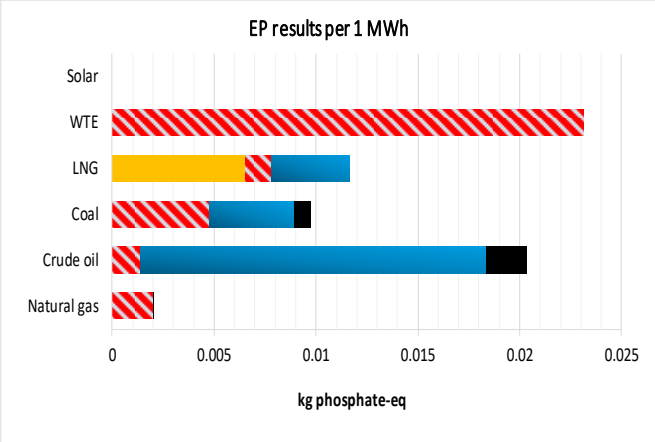


(**a**) GWP

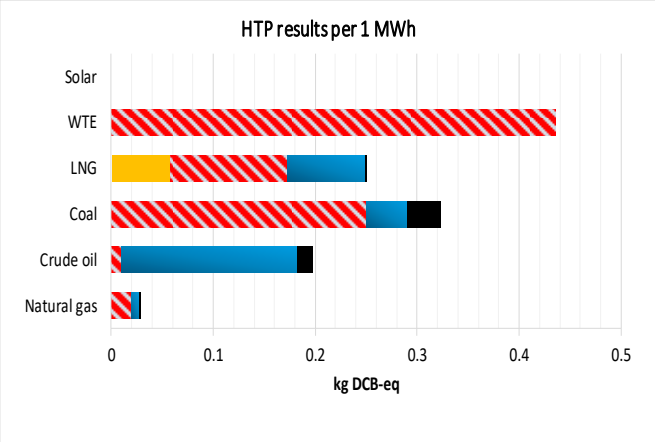


(**b**) Acidification Potential (AP)

Figure 3. *Cont.*

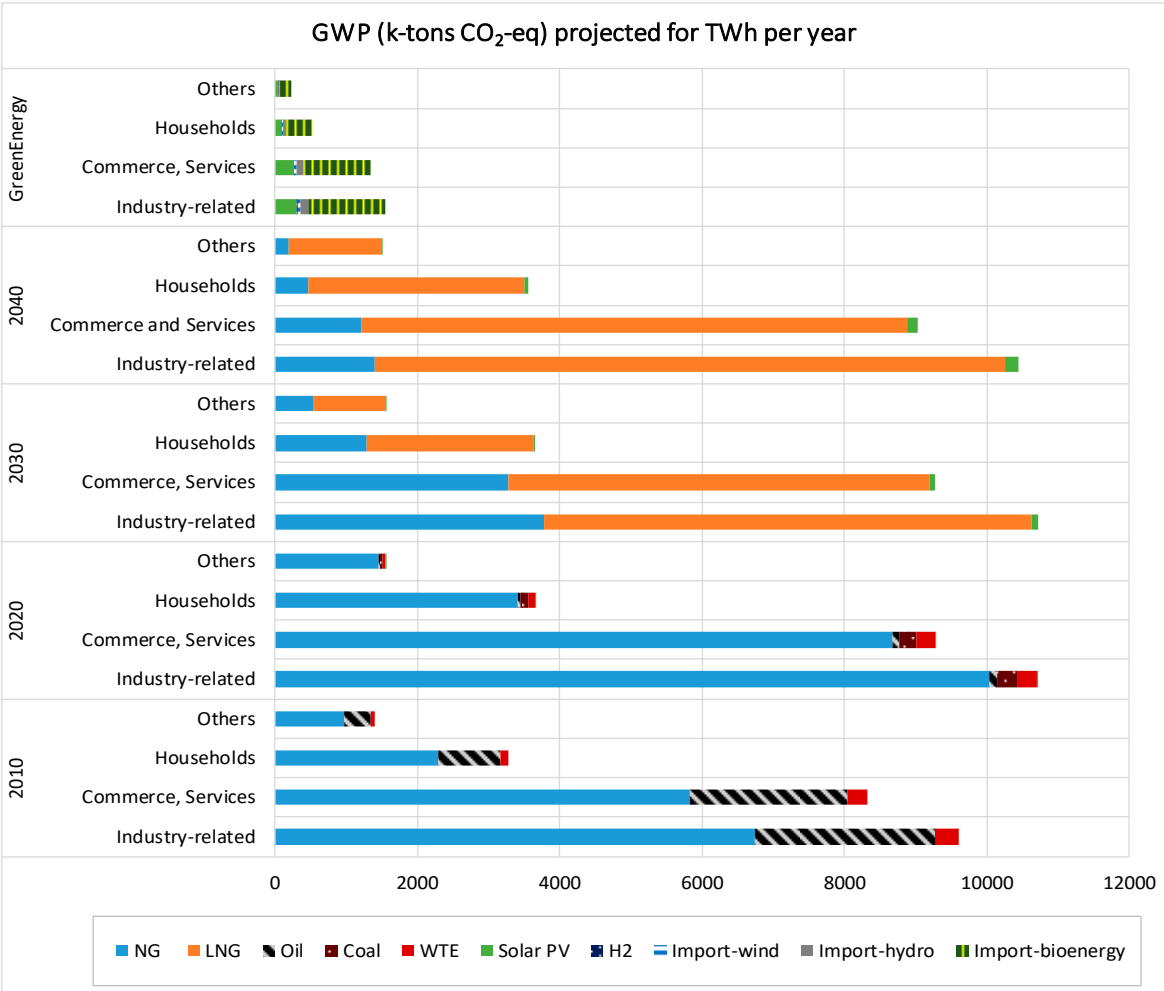


(**c**) Eutrophication Potential (EP)



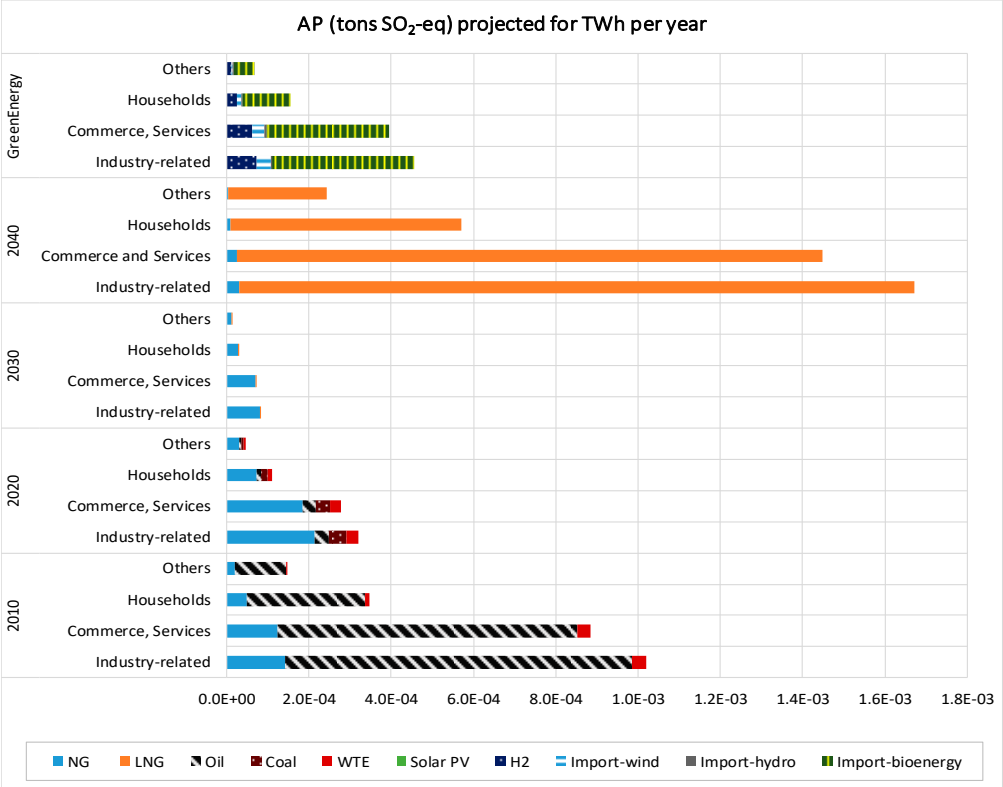
(**d**) Human Toxicity Potential (HTP)

Figure 3. Preliminary assessment: environmental impacts.

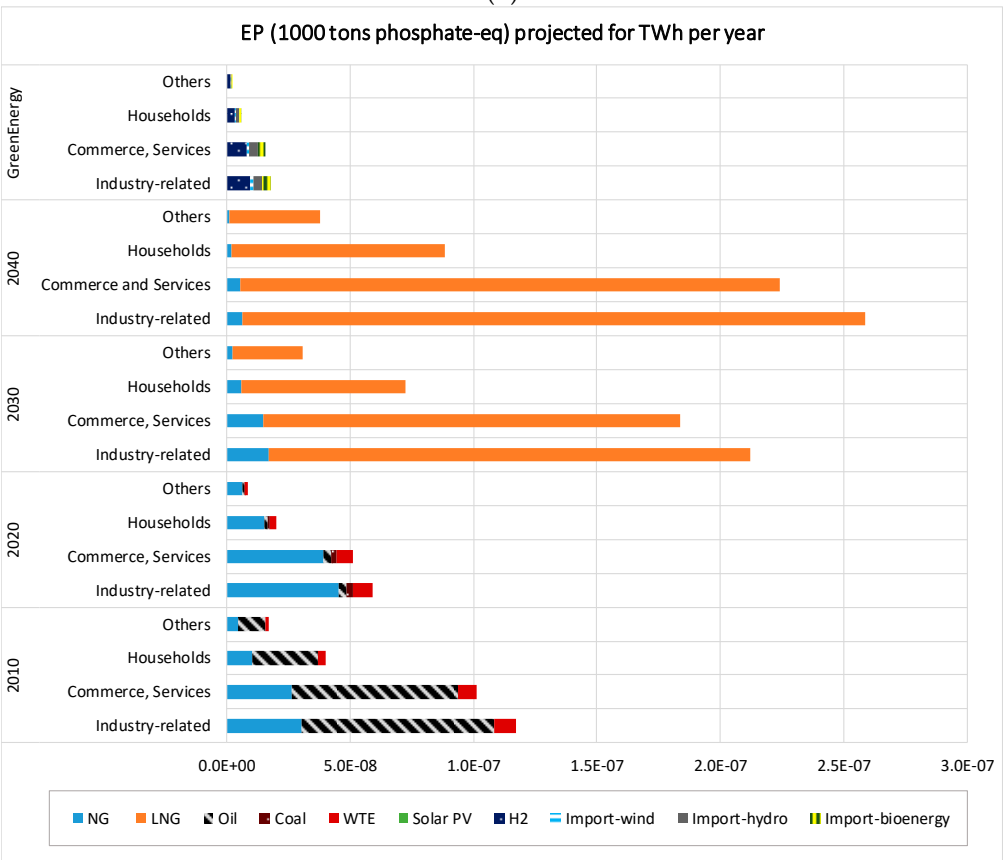


(**a**)

Figure 4. *Cont.*

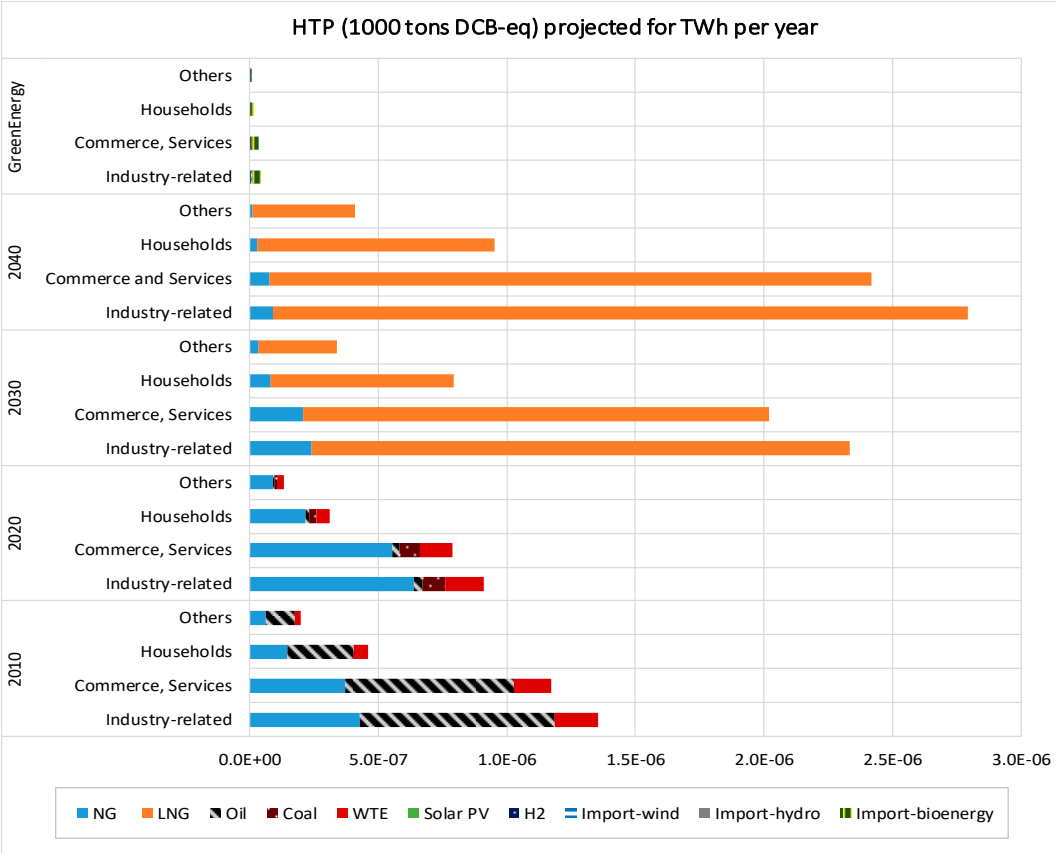


(**b**)



(**c**)

Figure 4. *Cont.*



(**d**)

Figure 4. (**a**) Projected GWP impacts for TWh/year. (**b**) Projected AP impacts for TWh/year. (**c**) Projected EP impacts for TWh/year. (**d**) Projected HTP impacts for TWh/year.

Jeswani and Azapagic [39] reported that an output of 519 net kWh and 452 kg CO_2 are generated from CO_2/MWh. Alternatively, EPA [40] stated that 2988 pounds of CO_2 is released for every 1 MWh generated from the incineration of MSW (i.e., 1355 kg CO_2 per MWh). The GWP results for solar is 30 kg CO_2-eq/MWh. Fthenakis and Kim [41] claimed that a range of 17–39 kg CO_2-eq/MWh can result from solar electric power. Another study carried out by Kim et al. (2019) estimated median values for PV technologies are below 50 kg CO_2-eq/MWh.

The types of power combustion that generate the highest AP and EP results are from WTE and coal-based power generation due to NOx and SO_2 emissions, as displayed in Figure 3b,c. The coal-fired electrical generation system contributes to up to 68% AP and 50% EP. In other related studies, high emissions of acidic gasses were also reported to be released by both WTE and coal-fired power plants. According to Chen and Christensen [42], emissions of 1.42 kg NOx and 0.45 kg SO_2 are emitted to the environment for every 1-ton MSW feed input at an incineration or WTE plant. As for coal-fired combustion, both AP and EP results are mostly contributed by significant emissions, which can be as high as 820 kg/MWh NOx and 940 kg/MWh SO_2 [43]. For the case of crude oil, significant results of AP and EP mainly come from ocean tanker transportation (76% AP and 84% EP). Emissions of SO_2 and NOx from long-distance ocean transportation are a growing environmental concern [44]. Programs to reinforce environmental regulations for shipping companies will potentially reduce the environmental footprint caused by marine transportation [45,46].

It can be observed from Figure 3d that the HTP impact for WTE is rather significant. Air pollutants from WTE or incinerator facilities can potentially lead to toxic impacts that negatively affect human health, as highlighted by Allsopp et al. [47]; however, various

environmental management options to control or reduce such pollutants already exist and can be carried out [48].

3.4. Projected Scenarios for Annual TWh

Figure 4a shows that all the results demonstrate that the highest GWP emissions are mostly from industry-related energy use—the GWP results dropped from 10,713 ktons/TWh CO_2-eq in the year 2020 to 3667 ktons/TWh CO_2-eq in the green energy scenario. The results in the years 2020 and 2030 also imply that an increase in LNG use has a significant effect on GWP. The total GWP decreased by merely 8.5% from 2010 to 2020, and 16.5% in 2030 when a fuel mix of 60% LNG, 30% NG, and 10% solar energy is employed. A noteworthy reduction of 85% is achieved from the year 2020 onward when 100% renewable energy is employed. This translates to an amount of ~ 21,540 kton of GHG reduction as the nation transits to a low-carbon future with renewable energy applications.

Figure 4b,c show that AP and EP impacts for 2010 are mainly caused by the crude oil production chain—the combined effects of oil extraction, ocean tanker, and combustion. Compared to years 2020 and 2030, higher AP and EP impacts for the year 2040 were observed due to the 70% use of Liquefied Natural Gas (LNG). The total combined AP impacts from the use of LNG for industry, commerce and services, households, and other sectors are 3,864,000 tons SO_2-eq in the year 2040, and for EP, 593,328 tons phosphate-eq. The emissions are mostly due to LNG transportation [45,46]. AP results for bioenergy are comparable to the total of AP impacts in the year 2020 for the renewable energy scenario. EP impacts caused by hydropower are not as significant as fossil fuel power generation systems.

Figure 4d depicts human health impacts caused by pollutants that affect air quality. The highest HTP impacts for electrical generation are basically from WTE and coal (i.e., Figure 3d); however, none of them are included in the fuel portfolio for 2030 and 2040. Considering a large portion of fuel comes from LNG production and its associated processing and transportation, significant HTP impacts are observed. HTP impacts are mostly due to additional power required for the activities involved in LNG regasification [11,12]; the annual amount of HTP resulted in 5,965,058 ton DCB-eq. Apart from HTP impacts, other types of investigations cautioned that safety measures should be carried out for LNG processing facilities [49]. HTP impacts for the case of renewable energy are minimal compared to all other scenarios.

3.5. Further Discussion: Low-Carbon H_2 production

With steadfast ambitions for the decarbonization of energy and fuels, Energy Market Authority announced that the potential of low-carbon hydrogen energy will account for up to 60% of Singapore's energy supply mix by 2050 [50]. It is suggested that along with the growing interest in implementing low-carbon hydrogen technology applications, extensive LCA investigation will have to be conducted to appropriately include additional safety standard [51,52] indicators. The following should be considered for LCA models of H_2 systems: (i) types of energy use; (ii) production methods; (iii) storage (with safety features); (iv) delivery and utilization. An illustration of the details in the system parameters that should be considered for the LCA of hydrogen production is shown in Figure 5.

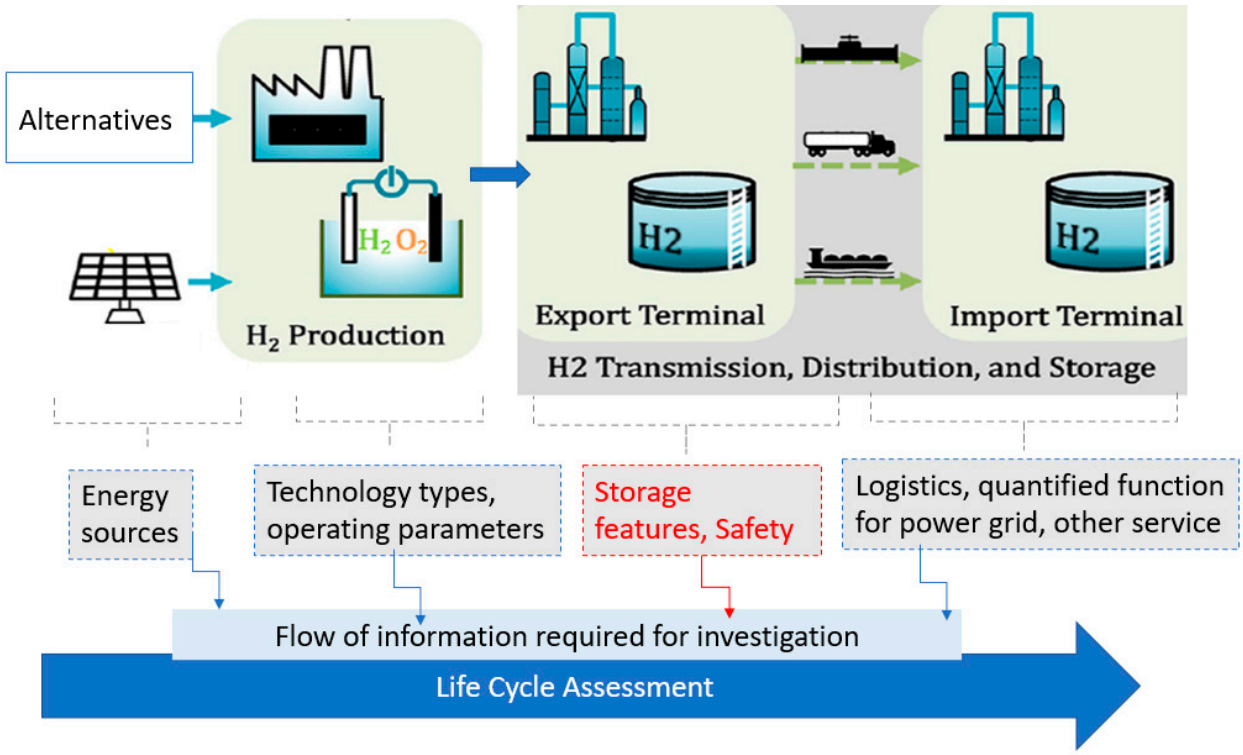


Figure 5. LCA stages recommended for hydrogen production (adapted/modified from Hong et al. [53].

4. Conclusions and Policy Implications

Sustainability is a key concern for fast-growing industrial activities, and more sustainable energy systems are crucial to modern nations such as Singapore. Many efforts are underway to shed light on different national energy portfolio scenarios and provide guidance on making decisions for policy makers. The aim to achieve long-term targets for GWP reductions and, at the same time, increase energy security prompts countries such as Singapore to diversify fuel supplies. The following highlights are given to aid in policy decision making for national energy sustainability and security:

- The highest GWP impacts were from coal and WTE.
- With 100% renewable energy employed ('Green Energy' future), a noteworthy reduction of 85% GWP was achieved.
- An increase in LNG supplies resulted in higher AP and EP impacts due to the transportation of ocean LNG tankers; higher HTP impacts were also observed due to the activities involved in LNG regasification activities.
- Future LCA model parameters should include safety indicators for the potential of low-carbon hydrogen application.

Author Contributions: All LCA process models and environmental impacts were performed by Hsien H. Khoo. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not Applicable.

Informed Consent Statement: Not Applicable.

Data Availability Statement: All data are available in Appendix A section.

Conflicts of Interest: There is no conflict of interest; this work was conducted according to strict scientific, ethical standards.

List of Nomenclature

AP	Acidification Potential
EP	Eutrophication Potential
GHG	Greenhouse gas
GWP	Global Warming Potential
HTTP	Human Toxicity Potential
LCI	Life cycle inventory
LNG	Liquefied Natural Gas
MWh	Megawatt-hour
NG	Natural gas
PV	Photovoltaic
TWh	Terawatt-hour
WTE	Waste-to-energy

Appendix A

Table A1. From fuel to Singapore.

Source	Fuel Type (ca. Calorific Value in MJ/kg)	Estimated Amount Required (kg) to Generate 1 MWh	Transportation Type	Brief Description	Distance Travelled (km)
Indonesia, Malaysia	NG (48 MJ/kg)	130	Offshore long-distance gas pipeline	Grissik-Batam-Singapore pipeline	468
Indonesia	Coal (21.5 MJ/kg)	295	Sea travel freight shipment	From Palembang port, South Sumatra, to Jurong terminal	559.3
Middle East countries	Crude Oil (35.5 MJ/kg)	178	Ocean tanker for oil	Saudi Aramco's Ju'aymah *Terminal* to Jurong terminal	6846.8
Australia	LNG (51 MJ/kg)	124	Ocean Tanker for LNG	50% from Barrow Island port, WA, to Jurong Terminal	3055.8
Indonesia			Ocean tanker for LNG	50% from Tanjung Emas port, Java, Indonesia to Jurong Terminal	1266.8

Table A2. Gate-to-gate LCI for 1 MWh.

Air Emissions (kg)	2010	2020
Carbon dioxide (CO_2)	455.6	361
Carbon monoxide (CO)	0.12	0.0303
Methane (CH_4)	n.a	8.7×10^{-6}
Nitrous oxide (N_2O)	Negligible	Negligible
Nitrogen oxides (NOx)	1.42	0.0168
Sulfur dioxide (SO_2)	5.18	0.0021
PM	0.068	0.0213
NMVOC	n.a	0.00021
VOC	0.033	0.0007

Table A3. Cradle-to-gate LCI for 1 MWh.

Air Emissions (kg)	2010	2020
Carbon dioxide (CO_2)	568.3	390.6
Carbon monoxide (CO)	0.19	0.0304
Methane (CH_4)	n.a	0.774
Nitrous oxide (N_2O)	0.06	0.000437
Nitrogen oxides (NOx)	1.965	0.0172
Sulfur dioxide (SO_2)	2.975	0.00289
PM	0.079	0.0218
NMVOC	n.a	0.000349
VOC	0.065	0.000485

Table A4. Annual TWh.

Year	TWh/Year
2010	45
2020	55
2030	66
2040	73
Green Energy Future	79

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