# ENVIRONMENTAL IMPACT ASSESSMENT OF A DOMESTIC WASTEWATER TREATMENT PLANT IN BANGKOK, THAILAND


**BY**

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# ABSTRACT

The Wastewater Treatment Plant in Thailand plays a crucial role in treating raw domestic wastewater. The wastewater treatment plant can also be integrated with the water reclamation system for sustainable reuse. This system integration promotes the circular economy principle and has already been implemented at the Bang Sue wastewater treatment plant. As the demand for treatment continues to increase, the energy requirements associated with these processes become increasingly significant. This study focuses on calculating environmental impacts, transportation, direct air emissions, water pollution, energy, and chemical consumption during the operation phase. In this research, the impact assessment is carried out using ReciPe 2016. The results of the study will be beneficial for government stakeholders in making a decision. To narrow the scope of the research, we specifically analyze the gate-to-gate aspects. The input output inventory data was examined through midpoint and endpoint impact assessments using Open LCA software. This study compared the environmental impact of two scenarios: current practices (Scenario 1) and a projection for 2037 (Scenario 2). The results show a positive environmental shift in Scenario 2. The impact on ecosystem quality decreased from $1.21\times10^{-9}$ species-years to $1\times10^{-9}$ species-years. Similarly, the impact on human health improved with a reduction in disability-adjusted life years (DALYs) from $5.77\times10^{-7}$ to $4.18\times10^{-7}$. There was a slight decrease in the impact on natural resources, with the cost dropping from $0.01697 (USD 2013) to $0.01692 (USD 2013). This study recommends implementing energy conservation and prioritizing the transition from lignite to renewable energy. A 5% reduction in energy consumption can lead to significant improvements across various environmental metrics, including a 4.74% reduction in impact on total ecosystem quality, a 4.65% reduction in impact on total human health, and a 4.79% reduction in impact on total natural resources.

**Keywords**: Wastewater treatment plant, Environmental impact, Energy, Impact assessment

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Ardhy Yuliawan Norma Sakti

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| Symbols/Abbreviations | Terms |
|---|---|
| AEDP | Alternative Energy Development Plan |
| ADFP | Abiotic Depletion (fossil fuel) Potential |
| AP | Acidification Potential |
| BFP | Belt Filter Press |
| BOD | Biochemical Oxygen Demand |
| CEB | Chemically Enhanced Backwash |
| CF | Characterisation Factor |
| COD | Chemical Oxygen Demand |
| DEDE | Department of Alternative Energy Development and Efficiency |
| DO | Dissolved Oxygen |
| EFB | Empty Fruit Bunch |
| EGAT | Electricity Generating Authority of Thailand |
| EP | Eutrophication Potential |
| EPPO | Energy Policy and Planning Office |
| ESM | Earth System Model |
| FEP | Freshwater Ecotoxicity Potential |
| GLO | Global |
| GWP | Global Warming Potential |
| HTP | Human Toxicity Potential |
| ILCD | International reference Life Cycle Data system |
| IPCC | Intergovernmental Panel on Climate Change |
| IPP | Independent Power Producer |

| | |
|---|---|
| JICA | Japan International Cooperation Agency |
| LCA | Life Cycle Assessment |
| LULC | Land Use/Land Cover |
| MWA | Metropolitan Waterworks Authority |
| ODS | Ozone-Depleting Substances |
| OLDP | Ozone Layer Depletion Potential |
| PDP | Power Development Plan |
| PV | Photovoltaic |
| RDF | Refuse Derived Fuel |
| RoW | Rest of the World |
| SCADA | Supervisory Control and Data Acquisition |
| SDGs | Sustainable Development Goals |
| SIIT | Sirindhorn International Institute of Technology |
| TEFs | Thai Eco Factors |
| TEQ | Total Ecosystem Quality |
| THH | Total Human Health |
| TKM | Tonne- kilometer |
| TKN | Total Kjeldahl Nitrogen |
| TN | Total Nitrogen |
| TNR | Total Natural Resources |
| TP | Total Phosphorus |
| TSS | Total Suspended Solid |
| TU | Thammasat University |
| UF | Membrane Ultrafiltration |
| VSS | Volatile Suspended Solids |
| WWTP | Wastewater Treatment Plant |

# CHAPTER 1
# INTRODUCTION

## 1.1 Problem statement

The water demand for domestic consumption, tourism, and industrial activities in Thailand continues to grow. Thailand will need 5 billion cubic meters of water in 2027 to meet the growing demand (Apipattanavis et al. 2018). As a major city in Thailand, the Bangkok Metropolitan Area consumes much water and generates many wastewaters (Singkran, 2017). Bangkok Metropolitan area, located in the lower Chao Phraya River Basin, faces significant challenges in sourcing freshwater. Excessive groundwater extraction in Bangkok causes a groundwater drawdown (Saowiang & Giao, 2021). Simultaneously, the surface water reservoirs within the Bangkok Metropolitan region house numerous counts of fecal coliform bacteria (FCB) and total coliform bacteria (TCB) (Sompong et al. 2021), and microplastics (Ounjai et al. 2022) above the water quality threshold. After the freshwater is used, the domestic wastewater will be discharged.

Due to rapid urbanization, domestic wastewater pollution discharge into surface water resources in Bangkok is under pressure (PCD, 2016). To remove contaminant and pollutants before discharging into the environment, Bangkok Metropolitan Administration (BMA) operates (Singkran, 2017) and plan the construction of the Wastewater Treatment Plant (WWTP) (PCD, 2020). Along with various stages and treatment system technologies, wastewater treatment plants can separate contaminants and pollutants from domestic wastewater. The wastewater treatment plant can also be integrated with the water reclamation system for sustainable reuse. This system integration promotes the circular economy principle and has already been implemented in the Bang Sue wastewater treatment plant. However, operating a wastewater treatment plant requires significant energy (M. Lee et al. 2017). The energy these plants consume has become a significant concern due to its environmental impact. Accurate measurement and assessment of the environmental impact of energy use in WWTPs are crucial to investigating their environmental footprint. In 2010, the Department of Drainage and Sewerage Bangkok and Japan International Cooperation Agency (JICA) drafted the master plan to address the Global Warming footprint of the WWTP (Department of Drainage and Sewerage, 2020). Furthermore, the strategy aimed at mitigating the energy utilization impact on WWTPs aligns with the energy-saving recommendations of the Ministry of Natural Resources and Environment of Thailand (PCD, 2020).

Identification of energy use in WWTPs has become a cornerstone of environmental concern activity. Research by M. Lee et al. (2017) observes the water-energy nexus in urban water cycle from water supply to WWTP. The research study provides a relationship and detailed analysis of greenhouse gas emissions impact from energy used. A review study conducted by Pesqueira et al. (2020) on urban wastewater technologies also provides insights about the environmental impacts generated mainly from the energy consumption. Each one underscores the significance of Life Cycle Assessment (LCA) frameworks in assessing the environmental impact of WWTPs throughout their life cycle.

LCA is extensively employed for quantifying the environmental ramifications of WWTPs in the Bangkok area. Limphitakphong et al. (2016) compare the environmental and economic performance of five activated sludge WWTPs in Bangkok. The research investigates comprehensive environmental impacts and mitigation strategies. At the same time, LCA research on different scales and WWTPs treatment system technology has been conducted by Polruang et al. (2018). The research compares seven activated sludge WWTPs in Bangkok using three energy generation scenarios. By considering the entire life cycle, LCA captures the indirect impacts of energy generation to ensure an accurate assessment.

Moreover, LCA allows the comparison of products, processes, or systems to identify the highest environmental burdens and highlight areas for optimization. Further research has also been done using LCA to compare centralized WWTP in Bangkok with different nutrient removal processes by Prateep Na Talang et al. (2020) and decentralized WWTPs by Prateep Na Talang et al. (2022). LCA provides a holistic approach to assessing the energy use phase and impact categories.

The state-of-the-art research conducted to identify the environmental impact of WWTPs in Bangkok that compares the wider scope of the life cycle of WWTPs and different treatment system technologies has been carried out by some researchers.

However, in depth study on evaluating midpoint and endpoint impacts from energy consumption of WWTP and water reclamation from the wastewater to provide sustainable water reuse, is still not carried out. Thus, this study focuses on the Bang Sue WWTP gap and identifies the impact at the operational stage based on current energy consumption and future energy mix scenarios in Thailand.

## 1.2 Research objectives

a. To calculate the environmental impact of a wastewater treatment plant with water reclamation in Bangkok based on energy, chemical consumption, transportation, direct air emissions, and water pollution.
b. To identify the hotspot at present and propose strategies for lowering the environmental impact of the energy use in future.

## 1.3 Scope of the study

This research mainly examines the energy use phase of Bang Sue WWTPs using the LCA framework from gate-to-gate. Gate-to-gate enables comparisons between different process configurations, allowing energy reduction and transition opportunities. Focusing on the specific product system makes it crucial to consider the implications for the scope of the system boundary. The system boundary neglects the construction phase, maintenance phase, and demolition phase of the plant. In comparison, the operational phase covers wastewater influent until reused water production.

The result aims to provide insight for the BMA about the environmental impact of water reclamation from the WWTP in Bangkok. At the country level, insight is provided for the Ministry of Energy related to the energy transition impact on the WWTP. In this research, the impact assessment is carried out using the ReciPe 2016. The input output inventory data was examined through midpoint and endpoint impact assessments using Open LCA software. Results of the study will be beneficial for the government stakeholder to make a decision. The data collection procedure was conducted through a questionnaire, and the data verification process was conducted during the onsite audit. We also use the secondary data representing Thailand's energy mix dataset to fulfill the missing dataset.

## 1.4 Limitation

a. Thailand divides its energy mix based on regions that can support each other when needed. This study assumes that the energy mix represents the entire country. The energy mix fraction includes only Thailand EGAT's energy generation and excludes electricity from third parties.

b. The data for natural gas energy generation, hydro reservoirs, deep geothermal, and photovoltaic (PV) modules retrieved from the ecoinvent database represent the grid-connected data in Thailand for the year 2012. Meanwhile, municipal solid waste incineration uses the Malaysia dataset as a neighboring country. Some data that does not reflect Thailand, such as diesel oil, biomethane, and biomass waste energy generation, uses data from Global (GLO) and the Rest of the world (RoW).

c. The integration of floating photovoltaic, buoy, and hydropower is calculated using proportions from Ecoinvent, which describes a database of real conditions in Thailand in 2023.

d. Due to equipment limitations, the odor produced from the bioreactor was not measured. The methane and nitrous oxide emission rate produced from the bioreactor was calculated using modeling.

e. This study relies on current energy data to model the future environmental impact of Scenario 2. During the future energy mix impact assessment, it assumes other contributing factors, such as chemical consumption, transportation, direct air emissions, and water pollution, remain constant.

# CHAPTER 2
# REVIEW OF LITERATURE

## 2.1 Urban water cycle

The urban water cycle consists of interconnected operations between the water resources and applications. At the cycle's starting point, raw water is sourced from pure water bodies (Apipattanavis et al. 2018), including rainwater, groundwater, and surface water. Thailand's water sourcing and consumption rely on various factors, including economic and climate conditions (Tangworachai et al. 2023). The water sourcing in Thailand will increase rapidly, as shown in Figure 2.1.

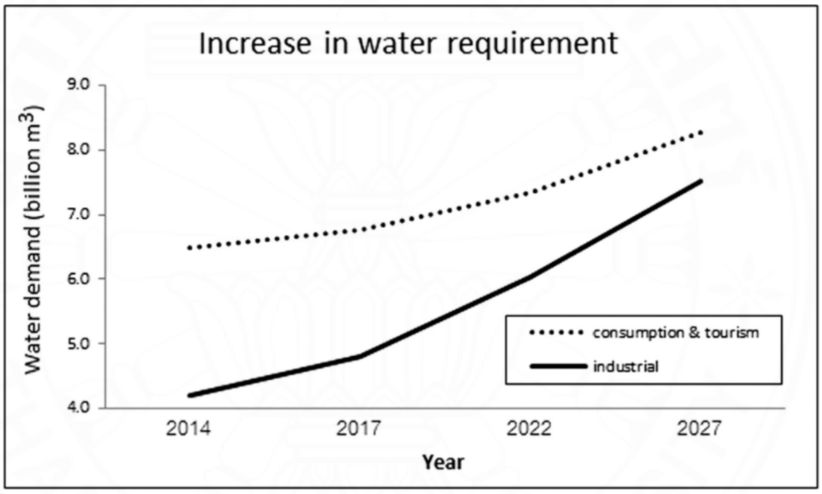


**Figure 2.1** Water Demand Projection in Thailand.

After the raw water is used inside the metropolitan area, wastewater will be discharged. The wastewater in Bangkok is classified into grey wastewater and black wastewater. The image in Figure 2.1 is quoted from Apipattanavis et al. (2018) research. Grey wastewater comes from the sinks, and showers have varying levels of contaminants. The black wastewater, primarily derived from sanitation, necessitates a higher organic load and pathogens typically directed to septic tanks, as shown in Figure 2.2.

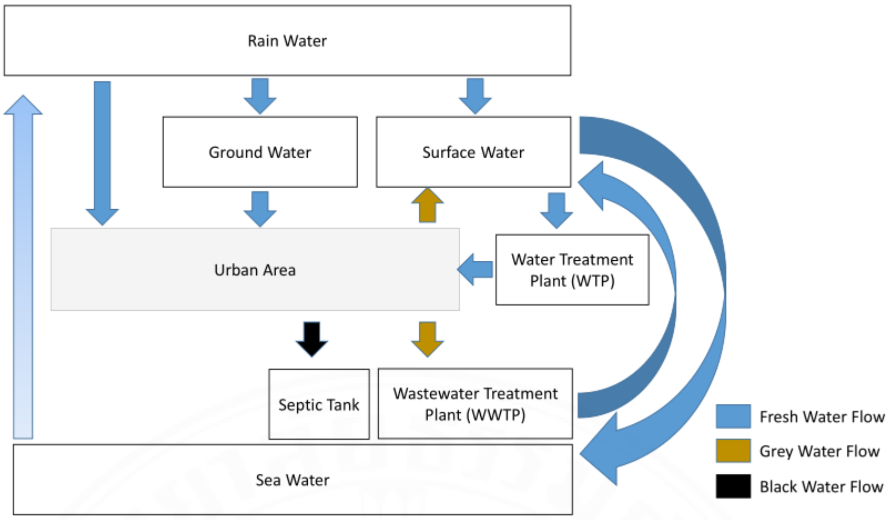


**Figure 2.2** Urban Water Cycle.

A higher proportion of grey wastewater is discharged directly into the environment. A fraction of the grey sewage is treated in WWTPs before release into the atmosphere. Only 10 years ago, the grey wastewater discharged in Bangkok jumped from 2.76 million $m^3$ per day into 3.68 million $m^3$ per day in 2019 (Department of Drainage and Sewerage, 2020). While the existing WWTP capacity in 2022 only reached 1.136 million $m^3$ per day (Kanchanapiya & Tantisattayakul, 2022). Bangkok Metropolitan Administration (BMA) authorities aim to plan significant expansion of WWTPs to reduce the direct discharge into the environment.

The primary goal of wastewater treatment is to remove the pollutant from water. The selection process of specific treatment system technologies depends on influent characteristics, effluent standards, land availability, and budget constraints of every region.

### 2.2. Wastewater treatment plant in bangkok

Bangkok, a densely populated urban center in Thailand, faces significant challenges in managing the water source (Kittigul & Pombubpa, 2021). The challenge consists of water withdrawal from the upstream (Gheewala et al. 2018), climate change, energy-intensive supply system (Babel et al. 2021), and large domestic wastewater generated from the high population density.

Bangkok manages the wastewater discharge through the underground drainage system distribution pipes. The water distribution in the trunk main network in Bangkok was handled by the Bangkok Metropolitan Waterworks Authority (MWA) (Lapprasert et al. 2018). District flowmeters (DMs) already monitor each flow in the trunk main network. The total volume of domestic wastewater in Bangkok was estimated to be discharged annually at around 434 million cubic meters yearly. The capacity of municipal wastewater flow into sewage treatment plants in Bangkok was only 283 million cubic meters per year (Okadera et al. 2020). WWTP employs the economics of scale. According to Limphitakphong et al. (2016) research shows that an incoming raw wastewater flow rate above 70 % of capacity can increase the efficiency of the plant.

The pollutant characteristics of domestic wastewater in Bangkok contain a range of substances, including nutrients Buathong et al. (2013), pharmaceuticals Tewari et al. (2013), human antibiotics (Sinthuchai et al. 2015), personal care (Jindal, 2017) and pathogens (Kittigul & Pombubpa, 2021). To address these pollutant characteristics, Bangkok Metropolitan Authorities employ centralized and decentralized WWTPs (Suriyachan et al. 2012). By 2022, Bangkok's combined wastewater treatment capacity will account for 1,136,800 $m^3$/day (Kanchanapiya & Tantisattayakul, 2022). Centralized municipal WWTPs in Bangkok have a ranging treatment capacity from 10 - 350 × $10^3$ $m^3$/day (Limphitakphong et al. 2016). The Centralized municipal WWTPs are shown in the Table 2.1. The table shown in Table 2.1 is compiled from Suriyachan et al. (2012) research and the Pollution Control Department.

**Table 2.1** Bangkok Large Capacity Wastewater Treatment Plant.

| No | Wastewater Treatment Plant | Treatment System | Area | Construction Year |
|---|---|---|---|---|
| 1 | Si Phraya Water Quality Control Plant | Contact Stabilization Activated Sludge | N/A | 1994 |
| 2 | Chong Nongsi | Cyclic Activated Sludge System | 28.5 | 1999 |

| No | Wastewater Treatment Plant | Treatment System | Area | Construction Year |
|---|---|---|---|---|
| 3 | Rattanakosin Water Quality Control Plant | Two-stage Activated Sludge | N/A | 2000 |
| 4 | Thung Kru | Vertical Loop Reactor Activated Sludge System | 42 | 2002 |
| 5 | Nong Khaem | Vertical Loop Reactor Activated Sludge | 44 | 2002 |
| 6 | Din Daeng | Activated Sludge with Nutrients Removal | 37 | 2004 |
| 7 | Chatuchak | Cyclic Activated Sludge | 33.4 | 2005 |
| 8 | Bang Sue Environmental Education and Conservation Center | Activated Sludge with pilot scale Ultrafiltration | 21 | 2013 |

Various studies have been conducted to compare the nutrient removal performance (Noophan et al. 2009), metal content detection (Chanpiwat et al. 2010), nitrogen discharge (Buathong et al. 2013), life cycle costing (Prateep Na Talang et al. 2022), and environment impact of large-scale WWTPs in Bangkok (Prateep Na Talang et al. 2020).

Large-scale or centralized WWTP aims to serve a large population. However, to tackle the land constraint, Bangkok also serves a small population by employing decentralized WWTPs. Decentralized WWTPs, as shown in Table 2.2 have a lower capacity and use modular subsystems around the household to minimize the sewer piping complexity (Prateep Na Talang et al. 2022).

**Table 2.2** Bangkok Small Capacity Wastewater Treatment Plant.

| No | Wastewater Treatment Plant | Treatment System | Covered Area (km) | Construction Year |
|---|---|---|---|---|
| 1 | Bangkok (Khlong Toei) | Activated Sludge System | N/A | N/A |
| 2 | Bangkok (Thonburi) | Activated Sludge System | N/A | N/A |
| 3 | Bangkok (Min Buri) | Activated Sludge System | 2.85 | N/A |
| 4 | Bangkok (Huai Khwang) | Activated Sludge System | 0.13 | 1990 |
| 5 | Bangkok (Bangna) | Oxidation Ditch | 0.08 | 1990 |
| 6 | Bangkok (Thung Song Hong 1) | Aerated Lagoon | 0.36 | 1993 |
| 7 | Bangkok (Thung Song Hong 2) | Activated Sludge System | 0.05 | 1993 |
| 8 | Bangkok (Ramintra) | Activated Sludge System | 0.08 | 1993 |
| 9 | Bangkok (Khlong Chan) | Activated Sludge System | 0.49 | 1993 |
| 10 | Bangkok (Bang Bua) | Oxidation Ditch | 0.13 | 1997 |
| 11 | Bangkok (Tha Sai) | Activated Sludge System | 0.37 | 1997 |
| 12 | Bangkok (Bonkai) | Activated Sludge System | 0.01 | 1997 |
| 13 | Bangkok (Khlong Toei) | Activated Sludge System | 0.05 | 1997 |
| 14 | Bangkok (Huamark) | Stabilization Pond System | 0.15 | 1997 |
| 15 | Bangkok (Romklao) | Activated Sludge System | 1.28 | 1997 |

Suriyachan et al. (2012) have studied decentralized wastewater management potential in Bangkok. The research found that treated water produced by a decentralized WWTP demonstrates high TSS removal and lower BOD than the Centralized WWTP. However, a centralized WWTP is better in terms of energy efficiency.

WWTP aims to protect the environment. Chemical doses and energy use are needed to maintain WWTP performance. However, the chemical amounts and energy used can harm the atmosphere. Thus, the next section studies the recent literature on environmental impact assessment related to energy, chemical dosing, and WWTP operation.

## 2.3 Thailand electricity condition

The energy situation in Thailand is analyzed and disseminated by the Department of Alternative Energy Development and Efficiency (DEDE) under the Ministry of Energy, Thailand. The Minister of Energy has established a policy guideline for the country's energy development, emphasizing sustainable development. Sustainable energy must have a fair and acceptable cost, be accessible to the population, and promote economic development through mechanisms that enable community participation in energy initiatives, thereby creating jobs and generating income at the grassroots level (Energy for All). This policy aims to develop energy infrastructure that focuses on producing electricity within communities based on the potential of clean energy fuels.

To align with the policy of community power plants for the grassroots economy, the Ministry of Energy, in collaboration with the Electricity Generating Authority of Thailand and related agencies, has developed Thailand's Power Development Plan 2018-2037 (PDP2018). This plan serves as the main framework for providing sufficient electricity to meet the nation's needs. The PDP2018 focuses on three main areas: energy security (Security), economic conditions, and environmental aspects (Ecology).

The Office of the Economic Development Council and the National Society of Thailand has prepared an estimate of the country's electricity demand. The forecast is based on the trend of long-term economic expansion (GDP), projected to grow at an average rate of 3.8 percent per year from 2017 to 2037, and an average population growth rate of -0.02 percent per year. The energy demand forecast for Thailand is illustrated in Figure 2.3. The figure shown in Figure 2.3 is compiled from the Energy Policy and Planning Office (EPPO), (2018) report.

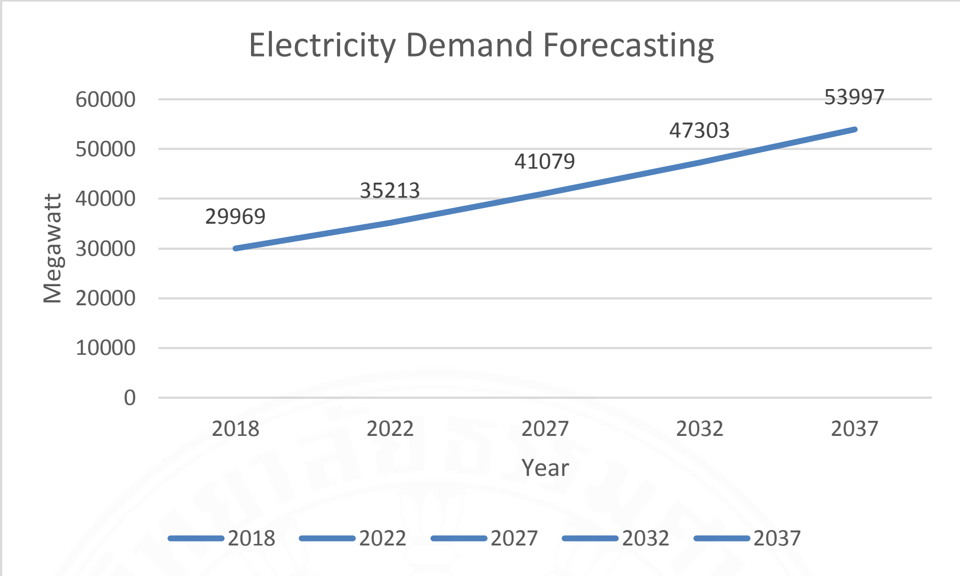


**Figure 2.3** Electric Power Demand Forecast Net Peak In Thailand.

At the end of 2017, total electricity production capacity in Thailand reached 46,090 megawatts. Between 2018 and 2037, an additional 56,431 megawatts of new energy capacity will be installed. However, during this period, approximately 25,310 megawatts of existing capacity will be phased out. Based on current planning, the total electricity production capacity is projected to reach 77,211 megawatts by the end of 2037. Compared to the net peak electric power projection, this represents a safety margin of approximately 30% above the maximum capacity.

In Southeast Asia, cross-border power purchase agreements are becoming increasingly popular as a solution to energy security issues and insufficient resources for power generation. Thailand and Laos have signed a memorandum of understanding related to electricity trading. Additionally, Laos has recently made significant investments in hydroelectric projects as part of its initiative to engage in cross-border power trade through grid interconnections. Thailand's total contract electricity in 2037 is illustrated in Table 2.3. The Table shown in Table 2.3, 2.4, 2.5, 2.6 and 2.7 is compiled from the Energy Policy and Planning Office (EPPO), (2018) report.

**Table 2.3** Thailand Total Contract Electricity in 2037.

| No | Region | Total Contracted Capacity (MW) |
|---|---|---|
| 1 | Northern | 9,379 |
| 2 | Northeastern | 16,302 |
| 3 | Eastern | 14,653 |
| 4 | Western | 7,581 |
| 5 | Central | 9,451 |
| 6 | Southern | 8,662 |
| 7 | Metropolitan area | 11,183 |
| | **Total** | **77,211** |

By the end of 2037, the northeastern region will have a total contracted power generation capacity of 16,302 megawatts, divided by type of power producer as follows: EGAT's power plants will contribute 2,043 megawatts (12%), new power plants 1,400 megawatts (8%), small private power plants 1,500 megawatts (9%), very small private power plants 3,659 megawatts (26%), community power plants 225 megawatts (1%), electricity purchased from abroad 6,888 megawatts (42%), and energy conservation measures 587 megawatts (4%).

In the upper central region, the total contracted power generation capacity will reach 9,451 megawatts by the end of 2037. This capacity will be divided as follows: EGAT's power plants will provide 768 megawatts (8%), major private power plants 3,200 megawatts (34%), new natural gas power plants 1,400 megawatts (15%), small private power plants 1,795 megawatts (19%), very small private power plants 1,417 megawatts (15%), community power plants 455 megawatts (5%), and energy conservation measures 416 megawatts (4%).

By the end of 2037, the eastern region will have a total contracted power generation capacity of 14,653 megawatts, distributed as follows: EGAT's power plants will supply 1,386 megawatts (9%), major private power plants 5,540 megawatts (38%), new power plants 1,700 megawatts (12%), small private power plants 2,913 megawatts (20%), very small private power plants 2,190 megawatts (15%), community power plants 216 megawatts (1%), and energy conservation measures 706 megawatts (5%).

The western region will have a total contracted power generation capacity of 7,581 megawatts by the end of 2037. This capacity will be divided by type of power producer as follows: EGAT's power plants will provide 2,135 megawatts (28%), major private power plants 1,400 megawatts (18%), small private power plants 660 megawatts (9%), very small private power plants 2,436 megawatts (32%), community power plants 513 megawatts (7%), and energy conservation measures 437 megawatts (6%).

In the southern region, the total contracted power generation capacity will be 8,662 megawatts by the end of 2037. This capacity will be divided as follows: EGAT's power plants will contribute 2,838 megawatts (33%), major private power plants 930 megawatts (11%), new power plants 1,700 megawatts (20%), small private power plants 285 megawatts (3%), very small private power plants 1,965 megawatts (23%), community power plants 274 megawatts (3%), electricity purchased from abroad 300 megawatts (3%), and energy conservation measures 371 megawatts (4%).

Finally, by the end of 2037, the metropolitan area will have a total contracted power generation capacity of 11,183 megawatts. This capacity will be divided as follows: EGAT's power plants will supply 5,548 megawatts (48%), new power plants 700 megawatts (6%), small private power plants 943 megawatts (8%), very small private power plants 2,917 megawatts (28%), community power plants 17 megawatts, and energy conservation measures 1,058 megawatts (10%). Thailand's detailed new electricity contract for 2037 is shown in Table 2.4.

**Table 2.4** Thailand Detailed New Electricity Contract in 2037.

| No | Type | Capacity (MW) |
|---|---|---|
| 1 | Renewable energy power plant | 18,833 (Updated to 18,696) |
| 2 | Community power plant | 1,933 |
| 3 | Pumped hydroelectric power plant | 500 |

| No | Type | Capacity (MW) |
|---|---|---|
| 4 | Cogeneration power plant | 2,112 |
| 5 | Combined cycle power plant | 15,096 |
| 6 | Coal/lignite power plant | 1,200 |
| 7 | Purchase of foreign electricity | 5,857 |
| 8 | New/replacement power plant | 6,900 |
| 9 | Energy conservation measures | 4,000 |
| | **Total** | **56,431** |

The preparation of PDP2018 Revision 1 has placed significant importance on the stability of the electricity system in each region, encompassing the electricity generation system, electricity transmission system, and electricity distribution system.

### 2.3.1 Non-renewable energy source in thailand

In accordance with the PDP2018 plan, electricity distribution in Thailand is organized to maintain regional security across all seven regions: the northern region, northeastern region, eastern region, western region, central region, southern region, and the metropolitan area. The Thailand non-renewable power plant construction plan is shown in Table 2.5.

**Table 2.5** Thailand Non-Renewable Power Plant Construction Plan.

| No | Region | Year | Power Plant | New Capacity (MW) |
|---|---|---|---|---|
| 1 | Northern | 2026 | Mae Moh Unit 8 & 9 (Lignite) | 600 sub total **(600)** |
| 2 | Northeastern | 2025, 2030 & 2033 | Nam Phong; NPP, NPP 2, (Combined Cycle Natural Gas) | 650, 700 and 700 sub total **(2050)** |
| 3 | Eastern | 2020,2021, 2022, 2023, 2024, 2027, 2033 & 2037 | Bang Pakong Machine 1&2 (Natural Gas); Gulf SRC (Natural Gas) Set 1, Set 2; Gulf PD Set 1, Set 2; Burapha Power | 1386, 1250, 1250, 1250, 1250, 540, 1000 and |

| No | Region | Year | Power Plant | New Capacity (MW) |
|---|---|---|---|---|
| | | | (Natural Gas); NPP (Bitumen Coal); NPP (Natural Gas) | 700 sub total **(8626)** |
| 4 | Western | 2024 & 2025 | Hin Kong Power Set 1 and Set 2 (Natural Gas) | 700 and 700 sub total **(1400)** |
| 5 | Central | 2032 | NPP Upper (NG) | 1400 |
| 6 | Southern | 2027, 2029, 2034 & 2035 | Surat Thani (Natural Gas) Set 1, Set 2; NPP (Bitumen Coal); NPP (Natural Gas) | 700, 700, 1000 and 700 sub total **(3100)** |
| 7 | Metropolitan area | 2019, 2026, 2027, 2035 & 2036 | South Bangkok (Combined Cycle Natural Gas), Addition 1, Addition 2;( North Bangkok (Natural Gas) Set 1, Addition; NPP Metro (Natural Gas) | 1220, 700, 1400, 700, 700 and 700 sub total **(5420)** |
| **Total** | | | | 22,596 |

Most of the electricity generating capacity in the western region comes from a major private power plant. The contracted power production capacity includes 700 megawatts from Hin Kong Power Company Limited, using natural gas as the main fuel, scheduled for 2024 and 2025.

The main electricity generating capacity of the metropolitan area has been provided by the South Bangkok Combined Cycle Power Plant (Blocks 1-3), with a total contracted power production capacity of 1,588 megawatts, and the North Bangkok Power Plant (Blocks 1-2), with a total contracted power production capacity of 1,498 megawatts. According to the plan, the South Bangkok Power Plant and the North Bangkok Power Plant will begin to be phased out from the system between 2020 and 2036. The total contracted power production capacity being phased out is 2,258 megawatts.

The South Bangkok Power Plant Extension Project aims to maintain the stability of the metropolitan electricity system. It involves an additional contracted power production capacity of 2,100 megawatts, using natural gas as the main fuel, to replace the capacity that will be removed from the system in 2026 and 2027. Additionally, the North Bangkok Power Plant will provide an extra contracted power production capacity of 1,400 megawatts, also using natural gas as the main fuel, with a scheduled start date in 2028 and 2035, respectively. The Thailand non-renewable power plant phase-out plan is shown in Table 2.6.

**Table 2.6** Thailand Non-Renewable Power Plant Phase-Out Plan.

| No | Region | Year | Power Plant | Removed Capacity (MW) |
|---|---|---|---|---|
| 1 | Northern | 2018<br>2022, 2025, & 2026 | Mae Moh machine 4 & 7, Unit 8, Unit 9, Unit 10, Unit 11, Unit 12, Unit 13 (Lignite) | 560, 270, 270, 540, 540 sub total **(2180)** |
| 2 | Northeastern | 2025 | Nam Phong Block 1 & 2 (Natural Gas) | Sub total **(650)** and 1000 (Pumping Storage) |
| 3 | Eastern | 2018, 2027, 2028 & 2035 | Bang Pakong (Natural Gas) Block 4, Unit 3, Unit4, Block 5; Eastern Power (Natural Gas), BLCP Rayong (Lignite),Gecho one (Lignite) | 314, 576, 350, 576, 710, 1347 and 660 sub total **(4533)** |
| 4 | Western | 2025 & 2033 | Ratchaburi (Natural Gas), Unit 1-3 & Sets 1-2 | 1440, 2041 and 1400 sub total **(4881)** |
| 5 | Central | 2032 & 2033 | Wang Noi (Natural Gas) Block 1&2; and Gulf Power Generation | 1224, 734 and 1468 sub total **(3426)** |

| No | Region | Year | Power Plant | Removed Capacity (MW) |
|---|---|---|---|---|
| 6 | Southern | 2034 | Chana Power Plant (Natural Gas) Block 1 and Krabi Power Plant (Thermal Power Plant Fuel Oil) | 710 and 315 sub total **(1025)** |
| 7 | Metropolitan area | 2019 - 2035 | South Bangkok (Natural Gas) Blocks 1, Block 2, Block 3, Set 3 and North Bangkok (Natural Gas) Block 1-2 | 316, 562, 686, 710 and 670 sub total **(2944)** |
| 8 | All (Private) | 2020, 2025, 2028 and 2032 | Try Energy (Natural Gas), Global Power Sinergy (Natural Gas), Glow IPP (Natural Gas) | 700, 700 and 713 sub total **(2113)** |
| **Total** | | | | 21,752 |

According to the plan, the Mae Moh Power Plant will begin to be gradually decommissioned from the system in 2022, 2025, and 2026, with production capacities of 270 megawatts, 540 megawatts, and 540 megawatts, respectively. In the Eastern region, the main power plants include the Global Power Synergy Power Plant, Bang Pakong Power Plant, Glow IPP Power Plant, BLCP Power Plant, and Gheco-One Power Plant. These plants will be gradually decommissioned from the system between 2025 and 2037, with a total contracted power production capacity of 5,282 megawatts.

In the central region, the main power plants include the Wang Noi Power Plant and the Gulf Power Generation Power Plant, which will begin to be gradually decommissioned from the system between 2019 and 2033, with a total contracted power production capacity of 3,378 megawatts.

The primary electrical generating capacity of the southern region comes from the Ruamchana Thermal Power Plant, Blocks 1-2, with a contracted electricity production capacity of 1,476 megawatts, and the Khanom Combined Cycle Power

Plant, which will replace the contracted electricity production capacity of 930 megawatts according to the plan. The Chana Power Plant Set 1 and Krabi Power Plant were decommissioned from the system in 2018. By 2034, the total contracted electricity production capacity to be decommissioned is 1,025 megawatts.

In the metropolitan area, there will be a replacement of the decommissioned electricity production capacity, with 700 megawatts scheduled for 2036. A total of approximately 25,231 megawatts will be phased out, of which 15,571 megawatts are managed by EGAT.

### 2.3.2 Renewable energy source in thailand

The development of renewable and alternative energy relies on the availability of raw materials for energy production and the application of appropriate technology. The goal is to have renewable and alternative energy contribute 30% to final energy consumption by 2037. Renewable energy sources in Thailand, including wind, solar, and hydro energy, depend on the natural potentials influenced by the terrain and climate characteristics (EPPO, 2018). The renewable energy potential of Thailand in 2037 is shown in Table 2.7.

**Table 2.7** Thailand Renewable Energy Potential in 2037.

| Renewable Energy and Alternative | | Potential Energy Generated (MW) |
|---|---|---|
| 1 | Solar Energy | 9,290 |
| 2 | Solar energy, floating buoys, combined with hydroelectric power plants. | 2,725 |
| 3 | Hydropower | 3,380 |
| 4 | Biomass | 120 |
| 5 | Wind energy | 1,485 |
| 6 | Biogas (Wastewater/waste/energy plants) | 1,183 |
| 7 | Waste to Energy | 400 |
| 8 | Industrial waste energy generation | 44 |

| Renewable Energy and Alternative | | Potential Energy Generated (MW) |
|---|---|---|
| 9 | Small hydropower | 69 |
| **Total** | | **18,696** |

**2.3.2.1 Solar energy**

The Department of Alternative Energy Development, under the Ministry of Energy, mapped the solar energy potential for Thailand using satellite images and a mathematical model to calculate intensity values. Data were collected over a 15-year period, from 2001 to 2015, covering areas throughout the country. The average solar radiation intensity throughout the year was 17.6 $MJ/m^2$ per day. However, the value of atmospheric aerosols continues to increase due to human activities and rising temperatures, which cause an increase in the amount of water vapor in the atmosphere (EPPO, 2018).

**2.3.2.2 Wind Energy**

The southern region has relatively higher wind speeds compared to other regions, particularly in the mountainous areas. The southwest monsoon winds originate from the Andaman Sea, while the northeast monsoon winds flow from the Gulf of Thailand. The average annual wind speed in the southern region ranges from 6 to 7 meters per second. In the northern region, the influence of the monsoon is relatively minor, resulting in wind speeds of approximately 5 meters per second in the mountainous and valley areas (EPPO, 2018).

**2.3.2.3 Hydropower energy**

The strategy involves increasing the production capacity of existing power plants through the integration of floating solar energy systems. Additionally, there are plans to develop small and very small hydroelectric power plants between 2018 and 2037, with a total capacity of 371 megawatts. Approximately 2,725.25 megawatts of floating solar energy systems will be installed on Bang Lan Dam, Chulabhorn Dam, Ratchaprapa Dam, Sirikit Dam, Sirindhorn Dam, Srinakarin Dam, Ubonrat Dam, and

Vajiralongkorn Dam from 2018 to 2037 (EPPO, 2018). Thailand's new hydropower energy potential in 2037 is shown in Table 2.8.

**Table 2.8** Thailand's New Hydropower Energy Potential in 2037.

| Project | | Energy Generation (MW) |
|---|---|---|
| 1 | Production improvement by solar energy and floating buoys | 336 |
| 2 | Small hydropower projects | 29 |
| 3 | Micro hydropower projects | 6 |
| **Total** | | **371** |

### 2.3.2.4 Geothermal energy

More than 90 percent of the country's potential is distributed in the northern region, including Chiang Mai Province with 24,173 kilowatts, Mae Hong Son Province with 9,951 kilowatts, Chiang Rai Province with 4,123 kilowatts, and Lampang Province with 2,018 kilowatts. The current energy source in the region is fang hot springs in Chiang Mai Province, which has an installed capacity of 300 kilowatts and is operated by the Electricity Generating Authority of Thailand (EGAT).

### 2.3.2.5 Biomass energy

Biomass derived from forestry and agricultural waste can be beneficial for energy generation (Sasongko et al. 2023). Thailand boasts high potential in biomass derived from agricultural waste, such as bagasse from the sugar industry, rice husk from rice mills, palm fiber, and empty palm bunches obtained from the palm oil extraction industry. However, other biomass waste materials such as cassava rhizomes, rice straw, sugarcane shoots and leaves, tree stumps and roots, and rubber trees cannot be efficiently utilized for energy production due to the high costs associated with their collection and transportation (EPPO, 2018).

### 2.3.2.6 Waste to energy

The Pollution Control Department has provided data on the amount of solid waste generated throughout Thailand in 2018, indicating that approximately 27.93 million tons of solid waste were produced, averaging approximately 76,529 tons per day. This marks an increase from the previous year, attributed to population growth, urban community expansion, tourism promotion, and increased consumption. Consequently, solid waste volumes have risen in many areas.

Refuse Derived Fuel (RDF) is utilized to partially substitute coal-based fuel in the production process. The demand for RDF is contingent upon the price of coal; a higher coal price typically leads to increased consumption of RDF (EPPO, 2018).

### 2.3.2.7 Biogas energy

The primary sources of biogas production are wastewater from industrial factories and livestock farms. These sources predominantly contain organic substances, which, when decomposed through biological processes in the absence of oxygen, generate methane gas (EPPO, 2018). In addition to biochar and organic fertilizer, other viable feedstocks for biogas energy generation include rice straw and paunch manure (Arianti et al. 2024).

### 2.3.3 Energy conservation plan in thailand

Future challenges for Thailand include ensuring energy supply security, addressing steadily rising energy prices, reducing reliance on energy imports, mitigating pollution emissions, and curbing rising carbon dioxide ($CO_2$) emissions. Therefore, energy conservation emerges as a crucial strategy to tackle these issues. Thailand has already established energy conservation targets as part of a 20-year plan spanning from 2010 to 2030 (Ministry of Energy Thailand, 2011). This strategy encompasses five strategic approaches, further subdivided into sixteen discrete measures. These approaches include implementing mandatory requirements through rules, regulations, and standards, fostering encouragement and support for energy conservation, raising public awareness and promoting behavioral change, advancing technology and innovation, and enhancing institutional and human resources development. Energy conservation practices are integrated into Thailand's energy mix percentage as a means to achieve total energy savings in the future. The energy conservation strategy for Thailand is depicted in Figure 2.4.

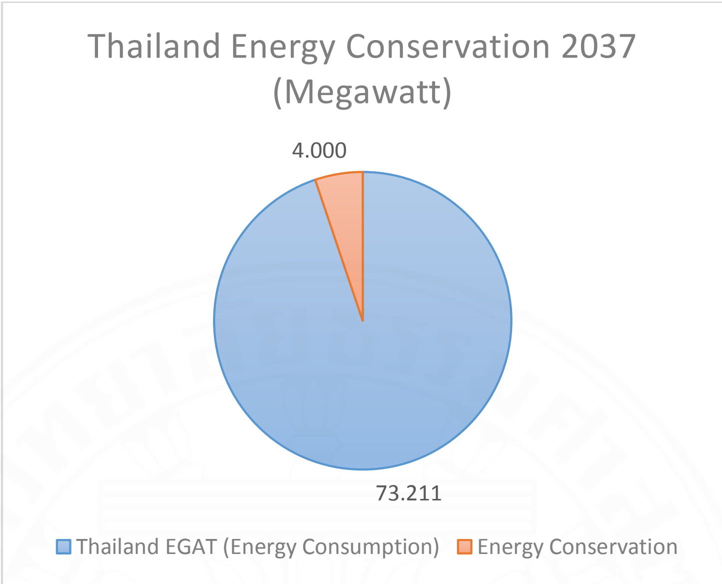


**Figure 2.4** Energy Conservation in 2037.

## 2.4 Environmental impact assessment

The environmental system consists of an interconnected biosphere that creates a balance essential for living organisms on earth (H. Tian et al. 2016). However, fossil fuel combustion (Panggabean et al. 2021), excessive conditioning chemicals (Pohl, 2020) and WWTP operation (Polruang et al. 2018) can lead to environmental impact. According into ILCD, (2010), The environmental impact encompass acidification, climate change, ecotoxicity, eutrophication in both aquatic and terrestrial ecosystems, human toxicity, ionizing radiation, land use, ozone depletion, ozone formation, resource consumption, and respiratory inorganics.

### 2.4.1 Acidification

Acidification is a process that involves the decrease in pH levels of freshwater, soil (Zeng et al. 2017), or ocean, leading to an increase in acidity. The primary cause of acidification is the release of acidic substances into the environment from anthropogenic activities, including nutrient release, burning fossil fuels (Rice & Herman, 2012), and mining (Qingguang et al. 2022). Nutrient oxidation generates strong acid $HNO_3$, through fossil fuel. Sulfur oxidation results in the production of concentrated sulfuric acid, $H_2SO_4$, while the smelting process releases hydrogen ions ($H^+$) through iron oxidation (Rice & Herman, 2012).

Numerous studies, including hydrochemical sampling and modeling approaches, have been conducted to assess the impact of acidification. In freshwater, pH levels are directly measured using a water quality analyzer (Qingguang et al. 2022). In soil, research measures the pH using a combined glass electrode (Yan et al. 2018). However, studies conducted by Zeng et al. (2017) were able to model soil acidification by daily meteorological data and nutrient discharge. The study aims to get quick and broad regional data. Ocean acidification is predominantly driven by atmospheric carbon dioxide, leading to the formation of carbonic acid (Rheuban et al. 2019). The concentration of carbonate ions in seawater can also be analyzed to understand the impact of acidification on marine ecosystems.

However, the measurement of acidification impact also faces certain limitations. Study reveals that pH measurement from acidification can vary depending on the chemical element and ecosystem. The part oxidized can affect regional or global (Rice & Herman, 2012). Forest soils are less sensitive to acidification compared to grassland soils (D. Tian & Niu, 2015). Moreover, assessing the acidic compounds remains a complex and time-consuming task. Several studies simplify the acidification environmental impact by certain VSD model-based analyses on fertilizer (Zeng et al. 2017) and Life Cycle Impact Assessment of electricity used in WWTPs (Polruang et al. 2018).

### 2.4.2 Climate change

The main driver of global warming stems from the emission of greenhouse gases (GHGs), including carbon dioxide ($CO_2$), methane ($CH_4$), and nitrous oxide ($N_2O$), into the Earth's atmosphere (Lamb et al. 2021). Studies by Anderson et al., (2016) review the calculation methodology of Earth System Models (ESM) implemented by (Intergovernmental Panel on Climate Change) IPCC. The IPCC converted the various greenhouse gas emissions into $CO_2$eq characterization (De Schryver et al. 2009). The review concludes that the GHG distribution modeling through ESMs is trustworthy. Despite this situation, the ongoing efforts of researchers measuring the impact by combining top-down (atmospheric inversions) and bottom-up approaches (Statistical extrapolation and inventory process modeling) (H. Tian et al. 2016). The 2019 refinement of The IPPC inventory model is based on the latest science measurement. The 2019 refinement of the IPPC inventory model is based on the latest scientific measurement. The 2019 IPCC impact assessment method has already been compared with research on WWTPs. Prateep Na Talang et al. (2020) model the GHG emission rate produced from the WWTP in Thailand. The calculation is based on the US Environmental Protection Agency model.

Moreover, the green house gas produced during WWTP operation can measured through the onsite measurement. Pascale et al. (2017) conducted research that characterized and measured the $N_2O$ and $CO_2$ concentrations in WWTPs using gas chromatography with the barrier discharge detector system. The methods were able to identify the environmental impact of water utilities for further improvement. Another method employed by IPCC characterization. As a result, IPCC 2019 has an excessive estimation of direct emissions ($N_2O$ and $CH_4$) compared to IPCC 2006 (Xi et al. 2021).

**2.4.3 Ecotoxicity**

Ecotoxicity refers to the harmful effects of substances on living organisms. The impact assessment measures toxicity or hazard magnitude on the exposed population's biological responses (death, enzyme inhibition, DNA damage, and behavioral changes) (Viegas, 2021). Compared to traditional ecotoxicity assessments, microbial-based bioassays offer economic advantages. However, microbial assay for risk assessment only detects 11 microbial strains simultaneously (Fai et al. 2015). Broader microbial strains for ecotoxicity impact offered by modeling tools. The modeling study conducted by Rashid & Liu, (2021) measured pharmaceutical pollutant release from the WWTP from an ecotoxicity perspective. Researchers conduct a comparative analysis of impact assessment methods such as Recipe, CML-IA, EDIP 2003, IMPACT 2002+, and USEtox. The study focused on direct emission (EDC, Metal, and PPCP) from WWTP and found that USEtox and EDIP 2003 offer more consistent results than CML-IA, IMPACT 2002+, and Recipe.

### 2.4.4 Eutrophication

Eutrophication is portrayed by the high nitrogen (N) and or phosphorus (P) concentrations both in aquatic and terrestrial environments (Burkholder & Glibert, 2013). Nutrient is not only contained from the fertilizer but also in the domestic wastewater effluent (Prateep Na Talang et al. 2020). Eutrophication was also a strong reason for ocean acidification (Rheuban et al. 2019). The study used carbonate and nutrient chemistry measurements to capture aragonite saturation state (Ω) seasonal variations in the ocean. The research found a correlation between the eutrophication from water discharge and ocean acidification. However, the carbonate chemistry measurement has many drivers that lead to higher complexity. Another direct measurement has been conducted to assess the environmental impact of eutrophication. Researchers use monitoring stations to obtain continuous data on nutrient concentrations, amount of phytoplankton, and Dissolved Oxygen (DO) shortfall in water bodies. These studies encompass laboratory experiments (Yan et al. 2018), field monitoring, and remote sensing approaches  to capture eutrophication existence. Satellite-based remote sensing provides a broader image recognition by monitoring large water bodies, enabling the identification of algal blooms over vast areas (Sayers et al. 2015). However, some limitations exist in measuring the environmental impact of eutrophication on huge lake water areas. The density of the image only concentrates on the center of the lake water. Nutrient concentrations are also measured in soil samples before flowing into water. The concentrations in soil can be determined using the Vario Max CN Analyzer and inductively coupled plasma atomic emission spectroscopy (Yan et al. 2018). Previous studies also characterized the COD as an eutrophication potential; however, the impact is not potential compared to the release of nitrogen or phosphorus (Bai et al. 2017). Impact assessment modeling through CML-IA and Recipe methods offers quick and However, CML-IA provides more detailed quantification of nitrogen or phosphorus in product system.

### 2.4.5 Human toxicity

Chemical pollutants present in water can be inhaled by humans through the consumption of drinking water or indirectly through the ingestion of substances that accumulate within the human body (Jolliet & Fantke, 2015). Because of the limited effectiveness in removing metals and pharmaceuticals/personal care products/endocrine-disrupting compounds (PPCPs/EDCs) in wastewater treatment facilities, the discharge of these pollutants can contribute to terrestrial, freshwater, and human toxicity risks (Rashid & Liu, 2021). Once ingested by humans, chemicals spread throughout the body and may harm certain organs and cause the start of different diseases. The characterized chemical substance that can lead to human toxicity was already identified by Rosenbaum, (2015), retrieved from American Chemical Society (CAS) database. Between 180 and 1,250 chemical substances have already been characterized using the USEtox model. Moreover, the USEtox model also includes the key driving uncertainties, including (a) bioaccumulation and bioconcentration, (b) chemical partitioning, (c) compartment and place of emission, (d) degradation processes, (e) dietary habits of the population (Jolliet & Fantke, 2015).

### 2.4.6 Ionising radiation

Growing evidence about emitting ionizing radiation during energy generation over the life cycle has been published by United Nations, (2021) report. Ionizing radiation poses a danger of causing mutagenic and carcinogenic on cell organs (Jones et al. 2010). The cell's organ can be affected by ionizing radiation depending on the timing and amount of the radiation exposure (Evans, 2020). The environmental impact characterization of LC-IMPACT limits the collective dose assumption that declares the global population is to be uniformly distributed and stable at 10 billion people for 100,000 years (Steinmann & Huijbregts, 2014). Following the further Study by Huijbregts et al. (2017), ReciPe 2016 impact methods characterized the ionising radiation potential (IRP) into midpoint factor in Cobalt-60eq to air. The result is that ReciPe 2016 offers benefits for regional-specific characterization.

### 2.4.7 Land use

Land is a crucial terrestrial ecosystem for human and ecological balance. This land conversion can lead to severe environmental problems (Abebe et al. 2021), negatively impacting soil and hydrological properties (Hasan et al. 2020). Nguyen et al. (2020) includes land inventory data during WWTP construction. ReciPe 2016 was taken into account for measuring the environmental impact. The inventory data aims to characterize terrestrial biodiversity impacts of Land use/Land cover (LULC). Dorber et al. (2018) calculated the net land occupation of plant construction for the life cycle inventory. However, conducting a LCA limits data transparency when the research boundary is determined (Nguyen et al. 2020). Ground observations and stratified estimation become accurate information sources but have a cost-prohibitive constraint for collecting complete LULC data (McRoberts et al. 2018).

### 2.4.8 Ozone layer depletion

The ozone layer shields the living organisms on Earth from damaging solar ultraviolet radiation that enters the atmosphere. During 1980-2000, the stratospheric ozone layer was depleted by releasing ozone-depleting substances (ODS) (Fang et al. 2019). The observation was conducted through atmospheric measurement data to provide longer observational records. Atmospheric measurement is crucial in simulating the ozone layer depletion and projecting future scenarios. However, the Ozone Monitoring Instrument is only available in limited regions (Levelt et al. 2018). The identified ozone depletion potentials also can be retrieved from CFC-11 equivalents by impact assessment method. Moreover, the ozone-depleting substance nitrous oxide production can be emitted during WWTP operation (Duan et al. 2017). The ozone-depleting substance also can be characterized by the ReciPe 2016 on midpoint factor kg CFC-11 equivalents (Huijbregts, Steinmann, Elshout, Stam, Verones, Vieira, Zijp, et al. 2017). The assessment methods also characterized the midpoint to the endpoint of ozone depletion consequences on UVB increase and human skin disease. The ReciPe 2016 is widely used because it covers broadens the scope of the global region.

### 2.4.9 Ozone formation

van Zelm et al. (2016) identified the risk factors for respiratory death due to Tropospheric ozone formation. Tropospheric ozone results from the interaction between emissions of volatile organic compounds, both anthropogenic and natural, in the presence of heat and sunlight. This is distinct from stratospheric ozone, which naturally develops in the upper atmosphere. The Tropospheric ozone formation hurts human and terrestrial ecosystems based on midpoint characterization. Non-methane volatile organic compounds (NMVOC), especially nitrogen oxides (NOx) emitted from wastewater treatment, became the main precursor (Liu et al. 2021). The ReciPe 2016 impact assessment method characterized the ozone formation potential (HOFP) in kg NOx eq (Huijbregts, Steinmann, Elshout, Stam, Verones, Vieira, Zijp, et al. 2017). However, the existing impact assessment characterization factor has certain limitations on area-weighted and population-weighted relations (van Zelm et al. 2016). Some regions have a higher population density compared to others.

### 2.4.10 Resource consumption

Resource consumption in WWTPs refers to using water (Huijbregts, Steinmann, Elshout, Stam, Verones, Vieira, Zijp, et al. 2017), natural and minerals resources (Nguyen et al. 2020) to fullfill human needs. Resource consumption depletion has been adapted as an environmental impact category in WWTPs. The ReciPe 2016 characterized the water use midpoint factor as $m^3$ of water consumed per $m^3$ of water extracted (Huijbregts, Steinmann, Elshout, Stam, Verones, Vieira, Zijp, et al. 2017). ReciPe 2016 identifies the associated carbon footprint environmental impact and water reuse production to reduce the water footprint consumption (Santana et al. 2019). Meena et al. (2019) recap resource recovery trends to tackle the resource depletion issues. The impact assessment method can identify the association between the resources recovered and the increase in energy usage and cost.

### 2.4.11 Respiratory inorganics

Respiratory inorganics are expressed as consequences of primary and secondary particulate matter (PM) exposure to human health (Fantke et al. 2015). The high concentration of PM levels can lead to respiratory inorganics illnesses (Dahari et al. 2021). Recent research characterized the massive air pollutants of respiratory inorganics are produced by industry (Dahari et al. 2021), fossil fuel-based transportation (Phuang et al. 2022), and fossil fuel-based energy generation (Panggabean et al. 2021). However, odorous emission generated by odorant compounds from wastewater also harms the respiratory (Piccardo et al. 2022). Zhou et al. (2016) identified and quantify the odorous emission from wastewater by using Gas

Chromatography-Mass Spectrometry. After identifying the pollutant, the emission can be characterized to measure respiratory inorganics impact.

Panggabean et al. (2021) and Phuang et al. (2021) mentioned the characterization method aims to quantify the environmental impact. Phuang et al. (2021) combined Eco-Indicator 99 and ReCiPe 2016 impact assessment method for endpoint characterization. They found that respiratory inorganics mostly account for chemical doses and fossil fuel-based transportation. The research suggests the organic substitution of chemical doses and Diesel Particulate Filter (DPF) installation on diesel vehicles.While Panggabean et al. (2021) research implemented IMPACT 2002+ for respiratory inorganics potential detection on kiln systems mostly generated by coal-based electricity and diesel-powered transport. Tabesh et al. (2019) research on WWTPs revealed that PM from energy generation relates to the respiratory inorganics impact. The Study suggests the combination of renewable energy and the use of Biogas for reducing respiratory inorganics impact potential. However, the anaerobic digestion of Biogas can enhance the odorant compound. A literature review of environmental impact assessment is shown in Table 2.9.

**Table 2.9** Literature Review of Environmental Impact Assessment.

| No | Environmental Impact | Assessment Method | Unit | Finding | Limitation |
|---|---|---|---|---|---|
| 1 | Acidification | A)Real Study:<br>• Combined glass electrode (Soil)<br>• Carbonic acid (Ocean)<br>B)Modeling:<br>• VSD model- | Kg mol H+ & kg $SO_2$eq | | Direct measurements result varies depend on the ecosystem, complex and time-consuming task (D. Tian & Niu, 2015) |

| No | Environmental Impact | Assessment Method | Unit | Finding | Limitation |
|---|---|---|---|---|---|
| | | based analysis | | | |
| 2 | Climate Change | A)Real Study:<br>• GC-BDD (Barrier Discharge Detector System).<br>B)Modeling:<br>• IPCC based System Models | kg $CO_2$-eq | Based on the latest science measurement (Xi et al. 2021) | The system model leads to data gaps in some regions (H. Tian et al. 2016) |
| 3 | Ecotoxicity | A)Real Study:<br>• Microbial-based bioassays<br>B)Impact Assessment Method:<br>• USEtox and EDIP 2003 | CTUe | USEtox and EDIP 2003 have consistent result on (EDC, Metal and PPCP) emission (Rashid & Liu, 2021) | Microbial Assay for Risk Assessment (MARA) only detect 11 microbial strains simultaneously (Fai et al. 2015) |
| 4 | Eutrophication | A)Real Study: | Kg N-eq (eutrophic | Impact assessment | The image captured by |

| No | Environmental Impact | Assessment Method | Unit | Finding | Limitation |
|---|---|---|---|---|---|
| | | • Nutrient concentrations, amount of phytoplankton and Dissolved Oxygen (DO)<br>B)Impact Assessment Method:<br>• Satellite-based remote sensing<br>• Impact Assessment Method (CML-IA and Recipe) | ation – marine), mol n-eq (eutrophication – terrestrial) | modeling offers quick and quality decision support on eutrophication (Bach & Finkbeiner, 2017) | Satellite-based remote sensing only concentrates on the centre of the lake water areas (Sayers et al. 2015) |
| 5 | Human Toxicity | USEtox impact assessment methods | CTUh | USEtox include key driving | The USEtox didn't cover region-specific |

| No | Environmental Impact | Assessment Method | Unit | Finding | Limitation |
|---|---|---|---|---|---|
| | | | | uncertainties on Human Toxicity impact assessment (Jolliet & Fantke, 2015) | spatialisation (Rashid & Liu, 2021) |
| 6 | Ionising radiation | LC-IMPACT and ReciPe 2016 impact assessment methods | kBq U-235, Cobalt-60eq | | LC-IMPACT population distribution characteriztion use too confident assumption (Steinmann & Huijbregts, 2014) |
| 7 | Land use | A)Real Study:<br>• Ground observations and stratified estimation<br>B)Impact Assessment Method: | Dimensionless | Ground observations and stratified estimation become the accurate source collecting complete LULC data | Lack of data transparancy on impact assessment methods (Nguyen et al. 2020) |

| No | Environmental Impact | Assessment Method | Unit | Finding | Limitation |
|---|---|---|---|---|---|
| | | • ReciPe 2016 impact assessment methods | | (McRoberts et al. 2018) | |
| 8 | Ozone depletion | A)Real Study:<br>• Atmospheric measurement<br>B)Impact Assessment Method:<br>• ReciPe 2016 impact assessment methods | kg CFC-11-eq | Atmospheric measurement provide longer observational records (Levelt et al. 2018). The ReciPe 2016 method able to characterized the UVB increase and human skin disease (Huijbregts, Steinmann, Elshout, Stam, Verones, | Ozone Monitoring Instrument for Atmospheric measurement only available in limited region (Levelt et al. 2018) |

| No | Environmental Impact | Assessment Method | Unit | Finding | Limitation |
|---|---|---|---|---|---|
| | | | | Vieira, Zijp, et al. 2017) | |
| 9 | Photochemical Ozone formation | ReciPe 2016 impact assessment method | kg NMVOC-eq, kg NOx eq | Volatile organic compounds (NMVOC) and nitrogen oxides (NOx) characterization | Area-weighted and population-weighted relation (van Zelm et al. 2016) |
| 10 | Resource Consumption | ReciPe 2016 impact assessment method | $m^3$ eq (Water use), kg Sb-eq (Mineral & metal), MJ (Fossil Fuel) | ReciPe 2016 able to identify the association between the resources recovered with the energy and cost (Meena et al. 2019) | Need contextual understanding for analysis of potential ecological interactions |
| 11 | Respiratory inorganics | A)Real Study: <br>• Gas Chromatography-Mass Spectrometry | Human Health Issue | Impact assessment methods offers detailed quantification for | The accuracy and reliability of impact quantification depend on the quality of the |

| No | Environmental Impact | Assessment Method | Unit | Finding | Limitation |
|---|---|---|---|---|---|
| | | (Zhou et al. 2016)<br>B)Impact Assessment Method:<br>• Eco-Indicator 99, IMPACT 2002+ and ReCiPe 2016 impact assessment method | | system improvement | data characterized |

The terrestrial biodiversity impacts can occur during the WWTP lifetime and affect the use/Land cover (LULC). Throughout their operation, WWTPs release greenhouse gases (GHGs) such as carbon dioxide ($CO_2$), methane ($CH_4$), and nitrous oxide ($N_2O$) through the process of anaerobic digestion. The emitted gas can be quantified by gas chromatography and IPCC model calculation. Nutrient is not only contained from the fertilizer but also in the domestic wastewater effluent. If the nutrient removal process is not optimal, it can lead to eutrophication environmental impact. The excess nutrient discharge into the environment can lead to oxidation, generating strong acid $HNO_3$. The amount of $HNO_3$ in the water can lead to acidification. Due to the low removal efficiency of metals and PPCPs/EDCs in WWTPs, the pollutant release can cause human toxicity.

Furthermore, the generation of ozone-depleting nitrous oxide can occur as a byproduct during the operation of WWTPs, potentially impacting ozone layer depletion. Non-methane volatile organic compounds (NMVOC), with a particular emphasis on nitrogen oxides (NOx) emitted from wastewater treatment processes, serve as the primary contributors to ozone formation. At the same time, the $m^3$ of water extracted water reuse production to reduce the water footprint consumption on resource consumption environmental impact.

WWTPs also use the energy. The energy has an indirect environmental impact depending on the energy mix. If the energy use comes from fossil fuel, Sulfur oxidation generates strong acid $H_2SO_4$ and lead acidification. If the fuel is collected from the crop, the biomass crop affects the land use change. Moreover, coal-based electricity affects the respiratory inorganics and produce green house gas. Defining the environmental impact needs to be careful. Growing evidence about emitting ionizing radiation during energy generation over the life cycle has been published by United Nations, (2021) report. However, Thailand does not have nuclear energy. Thus, the ionizing radiation is not included.

Based on the literature review, the environmental impact assessment consists of real study, calculation, and modeling. Real studies study involving laboratory experiments (Yan et al. 2018), stratified estimation (McRoberts et al. 2018), and field monitoring are the primary methods for quantifying direct environmental impacts (Sayers et al. 2015). Real study provides accurate data but can be time-consuming, resource-intensive, and costly (D. Tian & Niu, 2015). Calculation and modeling are normally derived through the characterization of real study results. This step also transforms qualitative observations into quantitative values, enabling researchers to model and assess environmental impacts more efficiently. This characterization involves organizing raw data into manageable categories, datasets, measuring units, and impact assessment. Researchers utilize the quantified impact indicators to measure the potential environmental impact normally based on the database, impact assessment method, and simulation models. For specific impact assessment, several impact assessment method has their strength and weaknesses. In the eutrophication case, CML-IA methods offer more completed flows and combined compartments than ReCiPe. While the ecotoxicity and human toxicity (EDC, Metal, and PPCP) from WWTP, USEtox and EDIP 2003 have consistent results compared to CML-IA. While ReciPe 2016 offers benefits on regional-specific characterisation.

## 2.5 Environmental impact of wastewater treatment plant

Assessing the environmental impact on the region-specific area depends on limited geographical factors (Sacchi et al. 2022). Thus, the environmental impact of WWTPs in this section will focus on gathering the recent research conducted in South East Asia regional.

### 2.5.1 Research conducted in malaysia

Rashid et al. (2020) identified the trade-off between chemical dose and environmental performance by magnifying the current phosphorus and nutrient removal technology. A WWTP located in Penang Malaysia with 148,950 $m^3$/day daily capacity is selected as a case study for LCA. The system boundary covers cradle to grave, so data curation includes construction, operational, and demolition stages. Magnesium chloride, magnesium hydroxide, sodium hydroxide, and polymer that are commonly used for chemical doses are also considered as life cycle inventory. The study uses the Intergovernmental Panel on Climate Change (IPCC) methodology for calculating the air emission impact. The use of chemicals is assessed in terms of abiotic (fossil fuel) depletion potential (ADFP), acidification potential (AP), freshwater ecotoxicity potential (FEP), and the impact on the human toxicity potential (HTP) category. During the wastewater operational stage, a chemical substance was used to enhance sludge dewatering, denitrification, and phosphorus removal. Rashid & Liu, (2021) doing an improvement to reduce the eutrophication impacts of sludge. Sharvini et al. (2022) suggest the acclimatized sludge procedure to transform the nitrate into nitrite using bacteria.

### 2.5.2 Research conducted in philipines

Domestic wastewater resource recovery can harness the value to create a more resilient and resource-efficient nutrient. Pausta et al. (2018) integrated the nutrient recovery from WWTPs into fertilizer production and extended on Pausta et al. (2020) next research by using multi-criteria decision analysis. The system boundaries cover the fertilizer manufacturing and wastewater treatment operation. The research employs the IMPACT 2002+ baseline method, which encompasses impact categories related to climate change, ecosystem quality, human health, and resource depletion. The introduction of a nutrient recovery system into the existing context may result in an elevation of the global warming potential while concurrently offering the potential to mitigate eutrophication. The research found human health is the most significant environmental effect indicator that should be taken into account when evaluating the scores for overall environmental performance, followed by ecosystem quality, resources,aquatic eutrophication, climate change, and aquatic acidification.

### 2.5.3 Research conducted in singapore

WWTPs can recover the water during operation. The water management system in Singapore has already integrated the WWTP with the water reclamation process (Hsien et al. 2019). Integrating the water reclamation and WWTP aligns with circular economy principles. The reuse water is being used as raw water for Industries.While in Thailand, the integration of a WWTP with water reclamation has been carried out on a Bang Sue WWTP. The reuse water is being used as raw water for buildings operations. Hsien et al. (2019) implemented a LCA approach to compare the water production from wastewater reclamation and desalination plants in Singapore. The system boundaries are grouped into water reclamation and pot-water desalination. The water reclamation system boundary covers the collection, treatment (both wastewater and water reclamation), and water distribution. While pot-water desalination system boundary covers water abstraction, water treatment (Desalination and Another Treatment), and water distribution. The study uses the Recipe baseline method occupied with the climate change, fossil depletion, human toxicity, ozone layer depletion, particulate matter, photochemical oxidation, terrestrial acidification, and water depletion impact categories. The research found that water reclamation has a higher impact on all eight impact categories, however, the water reclamation itself can reduce the water depletion potential. This holistic approach aligns with sustainable development goals and underscores the intrinsic value of water reclamation in creating a harmonious coexistence between urban development and ecological preservation.

Ramachandran et al. (2017) assess the environmental implications of a decentralized sewage sludge and woody biomass co-gasification system in Singapore. Through a rigorous life cycle assessment (LCA), the study aims to quantify the environmental impact. The existing system relies on centralized sewage sludge incineration and woody biomass combustion, and the proposed decentralized co-gasification system. The study reveals substantial environmental benefits (GHG emission reduction and biochar production) associated with the proposed decentralized co-gasification system. Moreover, Hsien et al. (2019) highlight that $CO_2$ produced from from wastewater treatment is considered biogenic as noted by IPCC 2006. Furthermore, $CO_2$ produced is not required to be included in the inventory.

### 2.5.4 Research conducted in thailand

Furthermore, LCA is widely used to quantify the environmental impact of wastewater treatment systems in Thailand. Limphitakphong et al. (2016) compare seven WWTPs with five different types of activated sludge (AS) technology. The study was clustering the wastewater into different flow rate capacities. The system boundaries cover the operating phase and neglect the demolition and construction stage. The study uses the LIME endpoint method and JEMAI-Pro Software that widely used in Japan and Asian Countries. The research declares that environmental impact is not only present in the treated wastewater and chemical use but also in the electricity consumption during the operational stage. The research endowed global warming potential and acidification as an electricity impact category.

LCA research that highlights the energy usage in WWTPs was also conducted by Polruang, Sirivithayapakorn, and Prateep Na Talang in 2018. Polruang et al. (2018)compare seven conventional WWTPs in Bangkok using three power (electricity) scheme scenarios combined with the effluent management scenarios. The reason behind the choice of various energy scenarios in Thailand is based on a literature study that stated energy use at the operational stage contributes 80% to the overall environmental impact. The system boundaries cover the operational stage and neglect the maintenance, construction, and demolition phases due to data availability. The sludge output was analyzed using sensitivity analysis by calculating biogas energy recovery by converting the sludge into electricity. The study uses the CML-IA baseline method with the midpoint environmental impact categories including abiotic depletion (fossil fuels), acidification, eutrophication, global warming (GWP100a), and photochemical oxidation. Global warming (GWP100a) measurement based on the electricity and methane emissions during the operational stage. While photochemical oxidations impact appears from the biofuel energy scenarios. However, considering the energy use scenario on the regional scope is needed due to the uniqueness of the country's energy mix. During the analysis, the research suggests that it is also necessary to pay attention to the contribution of the amount of methane emission from the unit operation.

The eutrophication impact occurred by the nutrients released from the WWTP (Polruang et al. 2018). Since the nutrient discharge led to eutrophication, research to find out the most effective nutrient removal and eco-efficiency technology was carried out by Prateep Na Talang, Sirivithayapakorn, and Polruang in 2020. Prateep Na Talang et al. (2020) compare and assess eight different centralized WWTP in Bangkok. The system boundaries cover the operation stage, sludge management, and system maintenance. However, the study omits the wastewater distribution through the pipes, plant construction, and plant demolition. The research equipped with the Stepwise 2006 method with acidification, aquatic eutrophication, global warming (fossil), mineral extraction, natural occupation, respiratory (organics and inorganics) and terrestrial eutrophication as defined impact categories. The research found that eutrophication impact is dependent on treated effluent. The research declares certain limitations about the construction phase that have already been done in Prateep Na Talang et al. (2022) recent research. For future research, they suggest further relation analysis between aerator age and energy consumption. Related to energy consumption, Polruang et al., (2018) identify the abiotic depletion of WWTPs occur through fossil fuel consumption on the electricity production and sludge transportation. Recent life cycle assessment research in Southeast Asia is shown in Table 2.10.

**Table 2.10** Recent Life Cycle Assessment Research in South East Asia Regional.

| No | Reference | Location | Product System | Methods | Impact Category |
|---|---|---|---|---|---|
| 1 | (Rashid et al., 2020) | Malaysia | Cradle-to-grave | IPCC 100 years and CML-IA | Abiotic depletion (fossil fuel) potential (ADFP), acidification |

| No | Reference | Location | Product System | Methods | Impact Category |
|---|---|---|---|---|---|
| | | | | | potential (AP), eutrophication potential (EP), freshwater ecotoxicity potential (FEP), global warming potential (GWP) and human toxicity potential (HTP) |
| 2 | (Rashid & Liu, 2021) | Malaysia | Gate-to-gate | CML-IA, EDIP 2003, IMPACT 2002+, Recipe and USEtox | Abiotic depletion (fossil fuel) potential (ADFP), acidification potential (AP), eutrophication potential (EP), freshwater eutrophication, global warming potential, human toxicity potential, ozone layer depletion potential (OLDP), terrestrial eutrophication |
| 3 | (Sharvini et al., 2022) | Malaysia | Gate-to-gate | ReCiPe midpoint method | Climate change, freshwater eutrophication potential and marine eutrophication potential |
| 4 | (Pausta et al., 2018) | Philippines | Cradle-to-grave | IMPACT2002+ | Climate change, ecosystem quality, human health and resource depletion |
| 5 | (Pausta et al., 2020) | Philippines | Cradle-to-grave | IMPACT2002+ | Aquatic acidification, aquatic eutrophication, climate change, ecosystem quality, |

| No | Reference | Location | Product System | Methods | Impact Category |
|---|---|---|---|---|---|
| | | | | | human health and resource depletion |
| 6 | (Ramachandran et al., 2017) | Singapore | Gate to grave occupied with system expansion | GHG Calculation (Carbon Footprint) without LCA Methods | Global warming potential |
| 7 | (Hsien et al., 2019) | Singapore | Gate to gate | ReCiPe Midpoint | Climate change, fossil depletion, human toxicity, ozone layer depletion, particulate matter, photochemical oxidation, terrestrial acidification and water depletion |
| 8 | (Limphitakphong et al., 2016) | Thailand | Gate to gate | LIME Endpoint | Acidification, eutrophication and global warming |
| 9 | (Polruang et al., 2018) | Thailand | Gate to gate | CML-IA | Abiotic depletion, acidification, eutrophication, global warming (gwp100a), and photochemical oxidation |
| 10 | (Prateep Na Talang et al., 2020) | Thailand | Gate to gate | Global-scale Stepwise midpoint and endpoint weighting factor | Acidification, eutrophication (aquatic), eutrophication (terrestrial), global warming (fossil), mineral extraction, nature occupation, respiratory organics and respiratory inorganics |
| 11 | (Prateep Na Talang et al., 2022) | Thailand | Cradle-to-grave | Stepwise 2006 midpoint-endpoint | 14 Environmental Impacts categorized into ecosystem |

| No | Reference | Location | Product System | Methods | Impact Category |
|---|---|---|---|---|---|
| | | | | weighting factor | (atmospheric; lithospheric; hydrospheric), human well-being and resource depletion |

*) Country name based on alphabetic order

Based on the literature review, the characteristics of domestic wastewater in the South East Asia region contain nutrients. In recent years, a LCA of WWTP study formulated the goal and scope of comparing nutrient removal technology in Malaysia (Rashid et al. 2020), Philipines (Pausta et al. 2018) & Thailand (Prateep Na Talang et al. 2020). Nutrient removal from wastewater is necessary to minimize the nutrient discharge into the environment.

Moreover, the operation of a WWTP is dominated by the use of fossil-based energy sources. This condition causes an indirect environmental impact. The research in Thailand has simulated several scenarios related to the energy mix through the LCA (Polruang et al. 2018). As a result, the transition process towards environmentally friendly energy can lower the environmental impact.

Countries facing water scarcity problems, such as Singapore integrate the sourcing of fresh water with WWTPs (Hsien et al. 2019). To overcome the problem of water scarcity, water reclamation can also reduce groundwater extraction. Through LCA, Hsien et al. (2019) aims to develop the future possible scenario related to water supply in Singapore. Besides Singapore, Thailand also has a water reclamation from WWTPs. However, currently, LCA research related to water reclamation has not been carried out in Thailand.

During the treatment operation, WWTPs can produce direct air emissions through the unit operation. The global warming potential is categorized as biogenic activity, thus the calculation could be neglected. Furthermore, to enhance the flocculation process of sludge dewatering and phosphorus removal, chemical doses were used in WWTPs.

Conducting an environmental impact assessment on WWTPs is crucial to identifying potential risks and finding improvement opportunities. By incorporating environmental considerations into the operation phases, WWTPs can be operated in an environmentally responsible. From the state of the art, This study will fulfill the research gap by conducting LCA research related to water reclamation from wastewater in Thailand.

## 2.6 LCA methodology adopted for wastewater treatment plants case studies

Based on previous literature reviews, the environmental impact assessment of WWTPs in Southeast Asia uses the LCA methodology. LCA is an iterative process. Thus, the process will iterate until get the reliable result. This section will review the previous case study's LCA step methodology.

### 2.6.1 Goal and scope

The Goal and Scope of the LCA study on WWTP vary between South East Asia regions. Researchers aimed to comprehensively evaluate the environmental impacts considering a wide range of factors, such as technology comparison combined with multiple scenarios. During the Goal formulation, Rashid et al. (2020) research can identify the burdens and benefits from the study regarding technological improvement. While Hsien et al. (2019) addresses the actor informed to benefit from the study when determining the Goal.

Since the Gate-to-Gate became the dominant Scope, most research neglected the maintenance phase due to complexity and data variability. However, only Prateep Na Talang et al. (2022) study covers a wider scope of Cradle-to-Grave, including the construction phase, operation, system maintenance, and demolition. The functional unit is normally determined as one cubic meter of treated domestic wastewater. Only Hsien et al. (2019) uniquely specified the functional unit as one cubic meter of water delivered to the customer due to the system expansion. Through a well-defined Goal and Scope, researchers were able to comprehensively assess the entire life cycle of both technology types and scenarios. Setting clear goals and Scope for an LCA study is a pivotal initial step, as it defines the boundaries of assessing the specific environmental issues to be addressed.

### 2.6.2 Inventory analysis

The variety of data inventory collected depends on the Scope in the previous stages. The Cradle-to-Grave scope includes the material procurement for construction, chemical, transportation distance, influent characteristics from wastewater, energy consumption, emissions, and demolition (Prateep Na Talang et al. 2022). The researcher gathered the data both through primary and secondary data collection. Rashid et al. (2020) selected four points, collected the data through sampling on glass bottles, and then stored it in the iceboxes before further laboratory analysis. Polruang et al. (2018) gather wastewater treatment operation data in Thailand from the Government Agency.

Moreover, secondary data collection mostly includes the published work, dataset, mathematical calculation, and simulation. Ramachandran et al. (2017) obtain the experimental energy generation data through the published work and calculate the transportation distance through the Geographic Information System (GIS) software dataset. Rashid et al. (2020) research implements the mass balance principle to calculate the flow rate modeling. At the same time, energy balance is implemented to find a certain amount of energy needed for every unit operation. The gaseous emission that consists of $CO_2$, $CH_4$ and $N_2O$ data was calculated by Prateep Na Talang et al. (2020) and Rashid & Liu, (2021) based on the IPCC modeling. While Hsien et al. (2019) studies put the $CH_4$ emission from the sludge. By quantifying these inputs and outputs, the study revealed the environmental hotspots within the WWTP operation and the opportunities for process optimization.

In LCA (LCA), there are a variety of uncertainties in inventory dataset, and scenarios (Sheikholeslami et al. 2023). Evaluating the uncertainty of LCA output findings (LCIA) while accounting for uncertain input parameters (LCI) is the goal of uncertainty analysis. Uncertainty analysis and sensitivity analysis (SA) can be combined to investigate their sensitivity from uncertain inventory data (Wei et al. 2015).

A wide range of uncertainty analysis technique both statistical method and expert judgement method have been implemented on LCA Study in WWTP. Pintilie et al. (2016) research on Urban Wastewater in Spain, implement the Monte Carlo Simulation for dealing with the parametic uncertainties (inventory data variability and measurement error). Maeseele & Roux, (2021) research conducted in India on Wastewater Reuse Impact Assessment also use the Monte Carlo Simulation for uncertainty analysis. A more precise estimate of uncertainty is provided by Monte Carlo analysis, which also determines the system impacts sensitivity (Thibodeau et al. 2014).

Monte Carlo Simulation work by randomly sampling input parameters from probability distributions. Monte Carlo simulation allows for the exploration of how variations in these parameters affect LCA outcomes, thus enhancing the credibility of the assessment. However, there are also limitations associated with Monte Carlo simulation in LCA. One notable drawback is the computational complexity and resource-intensive nature of the method, as it requires running a large number of simulations to achieve accurate results. This can pose challenges in terms of computational time and resources, particularly for complex LCA models with numerous input parameters.

Most of Software for LCA also occupied with the Monte Carlo simulation (Heijungs & Lenzen, 2014). With Open LCA, uncertainty also can be calculated by Monte Carlo simulation after defining the uncertainty distribution.

### 2.6.3 Impact assessment

One crucial step in LCA is the Impact Assessment, where the collected data from the Inventory Analysis phase is evaluated and interpreted to understand the significance of various environmental indicators. This stage is crucial as it empowers decision-makers to prioritize and gain insights into the possible implications across various impact categories. The indicators situated in the middle of the impact pathway for each impact category are referred to as "midpoints" These midpoint impact categories represent the translation of the actual phenomenon. The midpoint is more difficult to interpret than the endpoint, but the endpoint has a higher level of uncertainty (Tabesh et al. 2019).

Impact Assessment considers several aspects, including Normalization and Weighting. Normalization helps place the impact indicators into a meaningful context by comparing them to reference values. At the same time, Weighting assigns relative importance to different environmental impacts based on societal or stakeholder preferences. Pausta et al. (2018) normalization converts the ecological effects into percentages for easy comparison. Rashid et al. (2020) normalized the midpoint based on per person per year calculation. Polruang et al. (2018) use the SI standard on the normalized result by the ecoinvent database and provide a clear perspective on the significance of each impact category. The normalization procedure implemented in the research aims to reduce the complexity during result comparison. Subsequently, weighting was applied by Prateep Na Talang et al. (2020) and Prateep Na Talang et al. (2022) research using monetary weighting factors to prioritize the life cycle cost and environmental impact in Thailand. The result allowed decision-makers to focus on mitigating the most critical implications while considering other factors.

Normalization, which is comparable to weighting based on ISO 14044 (ISO 2006), is an optional stage in the Life Cycle Impact Assessment process. If the system measured involve Global Supply Chain. Sala et al. (2018) recommends to use the Global Normalization. Nevertheless, the outcomes cannot be guaranteed to accurately represent Thailand's context. Lecksiwilai & Gheewala, (2019) propossed the Thai Eco Factors (TEFs) method based on the environmental policy-derived aggregation. The normalization factor is retrieved from the Thailand Environmental Reduction Target in 2011.

### 2.6.4 Interpretation

Interpretation is the last step that provides meaningful insights about LCA Studies. The goal of LCA step interpretation is to enable appropriate communication of the study's results to target audience about the conclusion and recomendation (Laurent et al. 2020).

Rashid & Liu, (2021) found the secondary treatment to be a major contributor to toxicity impact. Then, the researcher also identifies opportunities for improvement and sustainable alternatives. Thus, Rashid & Liu, (2021) highlight the correlation between energy consumption and impact reduction in secondary treatment. During the Interpretation step, the researcher not only interprets the environmental and technological outcomes but also considers economic Prateep Na Talang et al. (2020) and sustainability (Hsien et al., 2019). The result helped policymakers make informed decisions about the most environmentally and socially responsible approach, demonstrating the essential role of the Interpretation step in LCA methodology in shaping sustainable water management practices.

# CHAPTER 3
# METHODOLOGY

## 3.1 Bang sue wastewater treatment plant study site

Bangkok Metropolitan Administration (BMA) intends to undergo significant extension and advancement to accommodate the increasing quantity of domestic wastewater (PCD, 2020). To reinforce the plan, BMA has been wandering innovative ways to boost wastewater treatment technology sustainability and performance by establishing the Bang Sue WWTP project (Honda et al. 2010).

The Bang Sue WWTP's raw domestic wastewater originates from Bang Sue District, Chatuchak Districts, Dusit, parts of Phaya Thai, and Lak Si, which have an area of around 23.97 square kilometers. Supported by the 213 sewer overflows and 470 manholes, the number of people served reached 275,160 customers in 2023. Bang Sue WWTP integrated with the membrane ultrafiltration to optimize the circular economy principle. The treated wastewater is then reused for sustainable water sources. This practice represents the concept of closing the urban water loop. The Bang Sue WWTP unit operation is shown in Figure 3.1. Reusing the treated wastewater satisfies The Thailand Water Management Plan (Kanchanapiya & Tantisattayakul, 2022).

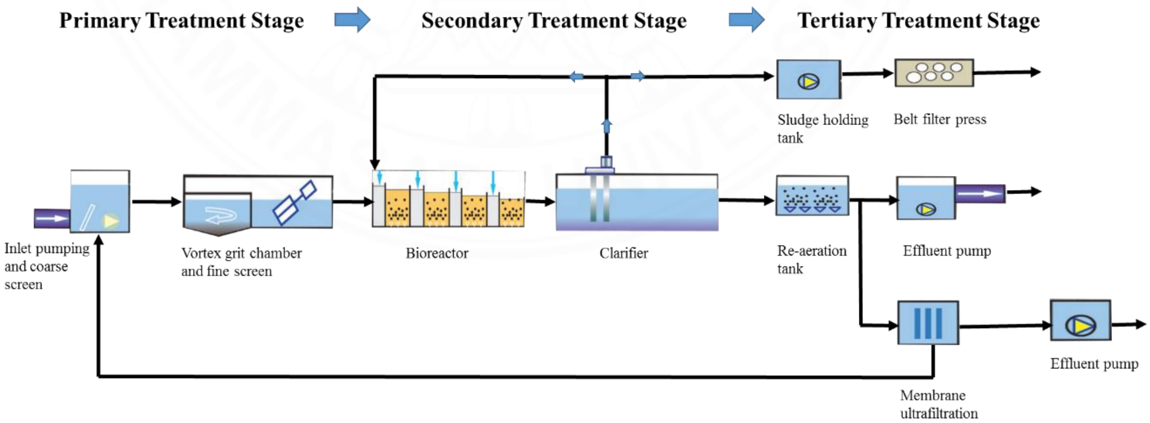


**Figure 3.1** Bang Sue Wastewater Treatment Unit Operation.

The Bang Sue wastewater treatment system technology consists of a sequential process including preliminary, primary, secondary, and tertiary treatment.

### 3.1.1 Preliminary and primary treatment

Preliminary treatment consists of equipment for the screening and filtering process. Some equipment used for the screening process include a coarse screen, grit chamber, and fine screen. The coarse screen is used for screening a large slug of debris at the influent of a sewage treatment facility (Ali et al. 2019). Numerous coarse or bar screening options consist of trash racks, bar screens that require manual cleaning, and Bar Screens that are cleaned mechanically (Asthana et al. 2017). Mechanical Bar Screen equipped with a hoisting motor offers an advantage compared to other types of bar screens in terms of productivity. The preliminary treatment in Bang Sue implements the gravitational force to flow the wastewater from the coarse screen to the vortex grit chamber. The grit chamber aims to reduce grit accumulation to prevent pump damage and pipe clogging (Plana et al. 2018). Numerous variations of grit chambers are available, such as hydro cyclones, horizontal flow grit chambers, vortex grit removal systems, and aerated grit chambers. After passing through the bar screen and grit chamber, the wastewater is filtered through a fine screen. The Bang Sue WWTP in Bangkok operates vortex grit equipped with a fine screen.

The wastewater can employ Chemically Enhanced Primary Treatment (CEPT) during Treatment. CET aims to achieve flocculation, coagulation, and sedimentation of the wastewater effluent (Shewa & Dagnew, 2020). Compared to other chemicals, the research found that ferric chloride is an effective coagulant dose (Taboada-Santos et al. 2020). However, ferric chloride released into the environment can affect toxicity in aquatic animals (Sayadi et al. 2020). In recent conditions, the Bang Sue WWTP stopped the chemical-enhanced primary treatment.

### 3.1.2 Secondary treatment

Activated sludge is a common treatment system technology used for centralized WWTPs in Bangkok. However, according to Limphitakphong et al. (2016) review, activated sludge has a different configuration. Bang Sue WWTP employs a sequential bioreactor, rectangular clarifier, and re-aeration tank. The Bioreactor consists of the oxic and anoxic zones, the integral components of the Bang Sue WWTP's secondary treatment process. The fundamental function of the bioreactos is to remove the pollutant from the wastewater through the controlled environment. The controlled environment aims to shore up the growth of microorganisms. Oxygen is supplied into the oxic zone to foster the aerobic bacteria. The aerobic bacteria break down the organic matter and produce carbon dioxides. The anoxic zone contains the denitrifying bacteria that aims to remove the nitrogen compound from the wastewater. The bioreactor is energy-efficient and cost-effective. However, the bioreactor can be sensitive to influent quality fluctuations.

After the bioreactor, the wastewater will flow into the rectangular clarifier. Rectangular clarifier is intended to remove the suspended solid particles from wastewater by gravity and create thick sludge. However, some particle has buoyancy, making them flow with the wastewater to the re-aeration tank. The suspended sludge in the bottom will be transferred into the sludge holding tank. Simultaneously, a portion of the sludge will be returned to the bioreactor via the reverse-activated sludge pump.

### 3.1.3 Tertiary treatment

Tertiary treatment is a crucial stage in the process that ensures the highest quality of effluent before it is discharged into the environment. Bang Sue WWTP employs belt filter press and membrane ultrafiltration in tertiary treatment. A few amounts of treated wastewater from secondary treatment were delivered to membrane ultrafiltration to conform to the standards before reusing (Theepharaksapan et al. 2021). Membrane ultrafiltration functions as a highly effective physical barrier that aims to remove suspended solids, bacteria, viruses, and even some dissolved contaminants from wastewater. This method employs a porous membrane to achieve filtration, which leads to exceptional water quality improvement. One of its prominent benefits is producing exceptionally clear and clean water, making it suitable for various reuse applications. The fouling control aims to ensure the long-term usage of membrane filtration (Liu et al. 2021). Stable cleaning procedures on a fouling control mechanism are usually performed (Kumar & Ismail, 2015). Chemical cleaning frequency is becoming common (Shin et al. 2021). Chlorine dioxide, hydrogen peroxide, or sodium hypochlorite dosing are viable options for enhancing the backwash mechanism. The backwash mechanism in membrane ultrafiltration is a crucial operational step that ensures the efficient and sustained performance of the filtration system. Sodium hypochlorite, commonly known as bleach, plays a significant role in this process. The chemical doses became a dosing agent during backwashing. This disinfection stage is crucial to preserve the long-term effectiveness of the membranes and guarantee the production of high-quality treated water.

The belt filter press plays a vital role in dewatering the wastewater sludge generated during treatment. Its primary function involves the mechanical pressing of sludge to extract water. The Bang Sue WWTP uses the cationic polymer to enhance flocculation. The flocculation and dewatering mechanism of the belt filter press in the Bang Sue WWTP represents a pivotal stage of sludge handling. Polyacrylamide, a commonly used polymer, is crucial in this operation. The flocculation process is essential for efficient water separation from the sludge. Polyacrylamide forms molecular chains that attach themselves to individual sludge particles when added to the sludge. As these chains grow, sludge particles are drawn together, creating larger and denser flocs. These flocs are more effectively trapped and removed by the belt filter press, facilitating water separation from the sludge solids.

## 3.2 Methodology of life cycle assessment

In line with the ISO 14040:2006 standard, LCA comprises four distinct stages: (i) the goal and scope step, (ii) the inventory analysis step, (iii) the impact assessment step, and (iv) the interpretation step:

### 3.2.1 Goal and scope

Water-energy resilience in Thailand consists of managing water reclamation from wastewater with a robust energy transition strategy. This research primarily pertains to the interconnection with the Sustainable Development Goals (SDGs), encompassing SDG 3, which focuses on promoting good health and well-being; SDG 6, which targets clean water and sanitation; SDG 11, concerning sustainable cities and communities; SDG 13, addressing climate action; SDG 14, directed towards life below water; and SDG 17, emphasizing partnerships for achieving the goals.

### 3.2.2 Inventory analysis

The inventory analysis entails the compilation of data pertaining to the inputs and outputs of the treatment system. After reviewing the recent studies conducting the preliminary survey, possible environmental impacts in the Bang Sue WWTP are grouped into the Figure 3.3.

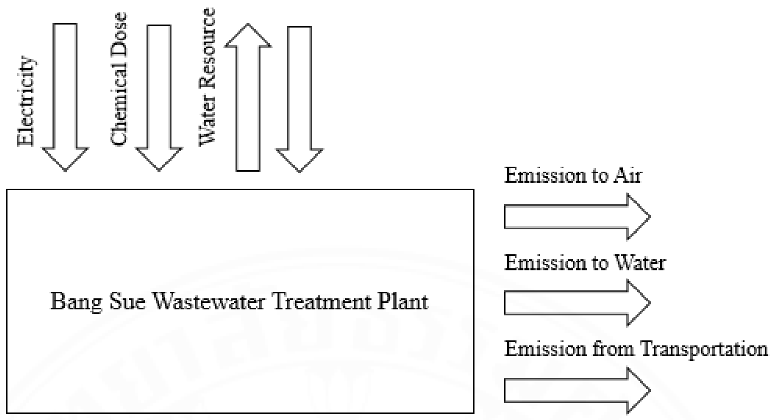


**Figure 3.2** Possible Environmental Impact.

During treatment, the Bang Sue WWTP uses energy, intakes the chemical dosing, and produce the direct air emission from the anaerobic treatment system. The effluent discharged was the reused water that contained nutrients. Thus, water resources, energy, chemical dose, air emission, and nutrient discharge data inventory are parameters to quantify the associated environmental impact in the Bang Sue WWTP. Primary and secondary data were employed in this study.

### 3.2.2.1 Primary data collection

The primary data collection involves direct measurements, retrieval of historical data, conducting questionnaire surveys, and utilizing calculation models. Bang Sue WWTP collected the historical data collection timeline for system performance during 2021-2023. The raw wastewater influent fluctuations adorn the major source of uncertainty. Data variability from the historical data is examined to address uncertainties in flow modeling. This study considers the standard deviation and uncertainties for data volatility in equations (3.1) and (3.2). The standard deviation equation and uncertainties are adopted from Brenner & Subrahmanyan, (1988).

Standard deviation (SD):

$$\sigma = \sqrt{\frac{\sum_{i=1}^{n}(y_i - \overline{y})^2}{n-1}} \tag{3.1}$$

where $\overline{y}$ is the mean and $\sigma$ is the standard deviation.

Uncertainties $(\sigma_M)$:

$$(\sigma_M) = \frac{\sigma}{\sqrt{n}} \tag{3.2}$$

where $\sigma_M$ is the uncertainties and $n$ represents the quantity of data.

The Bang Sue WWTP has a SCADA automated system with sensors. The automated system in the WWTP aims to make data acquisition easier (Moldovan & Nuca, 2019). While the effluent quality parameters only align six-month historical data for portraying the cyclic conditions.

a. Water Quality Inventory Data

The parameter intake and effluent discharge of wastewater in the Bang Sue WWTP were monitored daily through collector shown in Figure 3.3. After collection, the wastewater sample was analyzed in the internal Bang Sue WWTP laboratory to get specific information for further operation adjustment.

**Figure 3.3** Automatic Wastewater Sample Collector.

The laboratory analyst analyzed the wastewater quality parameters and recapt using Microsoft Excel. The wastewater quality parameters include DO, VSS, TSS, TKN, BOD, COD, Total Nitrogen, Total Phosphorus, $NO_2^-$ and $NO_3^-$.

b. Emission to Air Inventory Data

The air emission produce from the sewage treatment consists of greenhouse gases (Xi et al. 2021) and the odorous compounds (González et al. 2020). Bang Sue WWTPs uses biofilter media made from eucalyptus to filter odors. Helen et al. (2018) found that a combination of biochar, water, and nitrogen in lava rock is an effective medium for methylobacter and ethylomicrobium to filter methane. However, there is a lack of data on biofilter performance for treating the odorous emissions in the Bang Sue WWTP. Thus, the emission after the biofilter cannot be modeled.

Several studies recommend that the filtered gas on the biofilter is collected through the tedlar bag and characterized using gas chromatography. Odor characterization is important in LCA studies for odor footprint (Peters et al. 2014). A wide range of odor gas can be characterized using gas chromatography coupled with a quadruple mass spectrometer clarus 500 detector (Anet et al. 2013). At the same time, Zhou et al. (2016) characterized the specific odor gas from a WWTP using gas chromatography-mass spectrometry olfactometry, then determined by an expert panel. For measuring filtered greenhouse gas, including $N_2O$ and $CO_2$ concentrations from biofilters, gas chromatography with the barrier discharge detector system offers high-precision measurement (Pascale et al. 2017). However, due to the equipment limitation, the odor gas is not measured.

c. Water Flow Inventory Data

The water flow inventory data is important for mapping every unit operation's flow on energy calculation.

**Figure 3.4** Flow Meter Monitoring Instrument.

The wastewater flow inventory data was collected through a flow monitoring instrument. The generated data was then recaptured through Microsoft Excel.

d. Chemical Inventory Data

The precise amount of sodium hypochlorite is required for effective membrane ultrafiltration backwash based on equation 3.3 to calculate the amount of the amount of water needed for backwash. The Bang Sue WWTP provided the data through a questionnaire survey to determine the appropriate chemical dosages.

$$Q_{backwash} = B_{freq} \times t \times 60 \times Q_{pump} \tag{3.3}$$

where $Q_{backwash}$ is the water needed for backwash per day, $B_{freq}$ is the backwash frequency, $Q_{pump}$ is the backwash pump flow rate per second and $t$ is the backwash time in minutes.

The Bang Sue WWTP implements a chemically enhanced backwash for membrane cleaning. The membrane's cleaning chemical resistance when using sodium hypochlorite is 250,000 ppm hours cumulatively. The typical concentration of chemical used is 200 ppm or 0.1997718 kg/m$^3$ backwash water.

The average backwash frequency is two times per day. The backwash pump can discharge around 0.013 m$^3$ per hour. The backwash time varies from 4 to 8 minutes, depending on the polluter. In this study, we assume 6 minutes of average backwash time.

Moreover, The number of polymer doses in the sludge treatment process was also provided historically by the staff.

e. Energy Inventory Data

The electricity demand of the Bang Sue WWTP was determined as kilowatt-hours of electricity. The electricity data is collected through SCADA systems. This data is collected in real time and can be used to identify trends and patterns in power consumption. The energy needs equation is based on SCADA control panel calculation methods and is shown in equations 3.4.

Energy needs for treating 1 $m^3$ of wastewater:

$$\frac{E}{Q} \qquad (3.4)$$

Where E (kWh) account for the energy needed, while Q ($m^3$) is the flow rate.

The data collected by SCADA systems is validated using electricity equipment specification data and flow effluent parameters.

The energy inventory data can be assessed by capturing the full spectrum of energy flows, including direct and indirect energy consumption. In this study, a mathematical approach is adopted to calculate energy datasets by leveraging unit operation power by multiplying it with the corresponding energy mix ratio. This technique enables us to precisely quantify the energy consumption associated with various operations or processes within the system. The energy mix inventory data calculation is adopted from Polruang et al. (2018) and shown in equations 3.5.

The mathematical calculation of the specific energy mix inventory data ($E_D$).

$$E_D = P_{unit} \times E_{ratio} \qquad (3.5)$$

Where $P_{unit}$ is the unit operation power in watt. While $E_{ratio}$ is the Energy mix ratio. By integrating unit power measurements with the proportions of different energy sources used in the energy mix, we obtain a comprehensive understanding of the overall energy requirements and contributions of each unit operation.

**3.2.2.2`Secondary data collection**

The secondary data is retrieved from the mathematical calculation, mass balance simulation, published work, transportation modeling, and ecoinvent database.

a. Air Emission from Unit Operation

During operation, the wastewater treatment plan produced air emissions from anaerobic and aerobic treatment units (U.S. Environmental Protection Agency, 2010). The emissions consist of carbon dioxide ($CO_2$) emissions, methane ($CH_4$) emissions, and nitrous oxide ($N_2O$) emissions. Since the carbon dioxide ($CO_2$) emissions come from biogenic origin, the emission is not included (IPCC, 2006). The mathematical calculation is adopted from the LCA study by Prateep Na Talang et al. (2020).

The carbon dioxide emission rate ($MgCO_2$/hour) can be calculated as follows:

$$CO_2\left(\frac{MgCO_2}{hour}\right) = \left[\left(1 - MCF_{ww} \times BG_{CH_4}\right)(1-\lambda)\right] \times 10^{-6} \times Q_{Dw} \times OD \times Eff_{OD} \times CF_{CO_2} \quad (3.6)$$

To determine the methane emission rate ($MgCH_4$/hour), you can use the following equation:

$$CH_4\left(\frac{MgCH_4}{hour}\right) = \left[\left(MCF_{ww} \times BG_{CH_4}\right)(1-\lambda)\right] \times 10^{-6} \times Q_{Dw} \times OD \times Eff_{OD} \times CF_{CH_4} \quad (3.7)$$

The nitrous oxide emission rate ($MgN_2O$/hr) is computed as:

$$N_2O\left(\frac{MgN_2O}{hour}\right) = Q_{Dw} \times 10^{-6} \times TKN_i \times EF_{N_2O} \times \frac{44}{28} \quad (3.8)$$

For calculating the emissions in carbon dioxide equivalents ($kgCO_2$ eq), use the formula:

$$CO_{2e}(kgCO_2eq) = \sum_{i=1}^{n}(GHG_i \times GWP_i) \quad (3.9)$$

where

| | | |
|---|---|---|
| $CO_2$ | = | Carbon dioxide emission rate ($MgCO_2$/hr) |
| $N_2O$ | = | Nitrous oxide emission rate ($MgN_2O$/hr) |
| $CH_4$ | = | Methane emission rate ($MgCH_4$/hr) |
| $10^{-6}$ | = | Conversion factor (Mg/g) |
| $Q_{ww}$ | = | Domestic Wastewater flow rate ($m^3$/hr) |
| OD | = | Oxygen demand of influent wastewater to the Bioreactor unit operation determined as either BOD5 or COD (mg/L = g/$m^3$) |
| $Eff_{OD}$ | = | Oxygen demand removal efficiency of the Bioreactor unit operation |

$CF_{CO2}$ = Conversion factor for maximum $CO_2$ generation per unit of oxygen demand
= 44/32 = 1.375 g $CO_2$/g oxygen demand

$CF_{CH4}$ = Conversion factor for maximum $CH_4$ generation per unit of oxygen demand
= 16/32 = 0.5 g $CO_2$/g oxygen demand

$MCF_{WW}$ = Methane correction factor for wastewater treatment unit, indicating the fraction of influent oxygen demand that is converted anaerobically in the wastewater treatment unit (see Table 3.1)

$BG_{CH4}$ = Fraction of carbon as CH4 in generated biogas (the default value is 0.65)

Λ = Biomass yield (g C converted to biomass/g C consumed in the wastewater treatment process)

$TKN_i$ = Amount of TKN in the influent (mg/L=g/m$^3$)

$EF_{N2O}$ = $N_2O$ emission factor (g N emitted as $N_2O$ per g TKN in influent), where 0.005 g N emitted as $N_2O$/g TKN (Chandran, 2010)

44/28 = Molecular weight conversion (g $N_2O$/g N emitted as $N_2O$)

$CO_2e$ = Emissions in carbon dioxide equivalents (kg$CO_2$ eq)

$GHG_i$ = Emissions of GHG pollutant "i" (tpy) (kg)

$GWP_i$ = GWP of GHG pollutant "i" (from Table SI-2)

N = Number of GHG emitted from the source

The yield of biomass calculation for equation 3.6 is adopted from Polruang et al. (2018) and shown in equation 3.9.

$$\lambda = \frac{Q_{sludge} \times CF_S \times MLVSS_S}{Q_{Dw} \times CF_S \times OD \times Eff_{OD}} \tag{3.10}$$

where

Λ = Represents the yield of biomass (g C converted to biomass/g C consumed in the WWTPs)

$Q_{Sludge}$ = Wastewater sludge stream flow rate (m$^3$/hr)

$MLVSS_S$ = Mixed liquor volatile suspended solids concentration on the wastewater sludge (mg/L=g/m$^3$)

$CF_S$ = Correction factor for the carbon content of the biomass (i.e., $MLVSS_S$) where 0.53 g C/g MLVSS (default)

$CF_C$ = Stands for the conversion factor for maximum C consumption per unit of oxygen demand where 12/32 = 0.375 g C/g oxygen demand

The methane correction factor for equation 3.9 is adopted from Polruang et al. (2018) and shown in Table 3.1. The methane correction factor in Table 3.1 is retrieved from (IPCC, 2006) **and** (Prateep Na Talang et al. 2020) research.

**Table 3.1** Default Values for Methane Correction Factor (MCF) and Biomass Yield (Λ)

| Unit Operation | MCF[a] | λ[b] |
|---|---|---|
| A well-managed aerated treatment process in the activated sludge system | 0 | 0.65 |
| An overloaded condition in the aerated treatment process, specifically in anoxic areas | 0.3 | 0.45 |
| Anaerobic Bioreactor | 0.8 | 0.1 |

b. Reuse Water Fraction

The Bang Sue WWTP can produce water reuse through water reclamation. This study implements the mass balance principle shown in Figure 3.5.

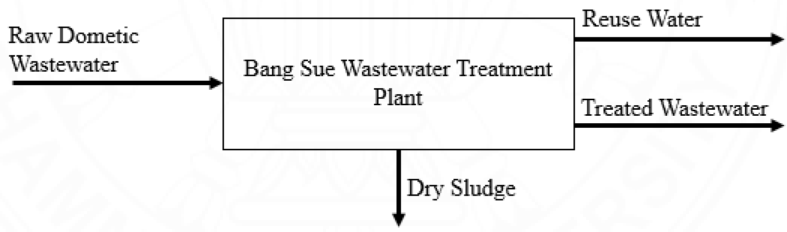


**Figure 3.5** System Allocation.

The mathematical calculation of the effluent ratio on treated wastewater (TW) and reused water (RW) uses fraction calculations on equations 3.11, 3.12, 3.13, and 3.14.

$$Q_{InfTW} = \frac{Q_{InfTot} \times TW_{ratio}}{Q_{EffTot}} \quad (3.11)$$

Where $Q_{InfTW}$ is the hourly influent flow fraction for the treated wastewater.

$$Q_{InfRW} = \frac{Q_{InfTot} \times TW_{ratio}}{Q_{EffTot}} \quad (3.12)$$

Where $Q_{InfRW}$ is the hourly influent flow fraction for the reuse water.

$$DS_{InfTW} = \frac{DS_{Tot} \times TW_{ratio}}{Q_{EffTot}} \tag{3.13}$$

Where $DS_{InfTW}$ is the hourly dry sludge by-product from treated wastewater processing.

$$DS_{InfRW} = \frac{DS_{Tot} \times RW_{ratio}}{Q_{EffTot}} \tag{3.14}$$

Where $DS_{InfRW}$ is the hourly dry sludge by-product from reuse water processing.

c. Transportation System

In this study, the dry sludge was not characterized as a pollutant discharge because it was transported outside the system boundary in the Nongkhaem WWTP. At the same time, The chemical and polymer suppliers were not purchased directly from the factory. In this study, the factory production is located in Pathum Thani. The tonne-kilometer (TKM) is modeled through Google Maps.

d. Chemical Production and Electricity Generation

The Ecoinvent Database offers life cycle inventory data for various products and processes. This study retrieved chemical production, electricity generation, and transportation from the database. The Ecoinvent Database covers many stages and includes the input-output dataset. The Ecoinvent Database is regularly updated based on regional to ensure accuracy.

However, some weaknesses need to be considered when using the Ecoinvent Database. Several data from the rest of the world (RoW) and global (GLO) may not represent Thailand. The global representation can lead to inaccurate analysis. Additionally, uncertainty is associated with the data due to variations in measurement techniques and assumptions made during data collection.

### 3.2.2.3 Ecoinvent database

Chemical dosing for backwash on membrane ultrafiltration and sodium hypochlorite production were retrieved from the manufacture of basic chemicals within the regional boundary of the rest of the world (RoW). While cationic polymer dosing, polyacrylamide is manufactured from the basic chemical within the regional boundary.

Even though the energy data is already collected through the primary data collection within the system, the background data of the energy generation in Thailand was collected through secondary data based on the Thailand Energy Mix based on EPPO Thailand.

In Thailand, the freight indicates emission per tkm (tonne-kilometres) (ASEAN - German Technical Cooperation, 2016). The freight transportation by road for chemical and polymer doses retrieved from lorry 3.5-7.5 metric ton EURO 4 standard with the regional boundary rest of the world (RoW). The freight transportation by road for sludge, retrieved from lorry 7.5-16 metric ton EURO4 standard with the regional boundary rest of the world (RoW).

### 3.2.2.4 Inventory data uncertainty

Monte carlo analysis generates a sample model from many random samples. These random sample generators are then used to run multiple iterations of the LCA model, with each iteration producing a set of results representing different combinations of input parameter values. The random number generator depicted in Figure 3.6 uses the binary number system. The results from the monte carlo simulations are analyzed to assess the sensitivity of LCA outcomes based on the mean and the standard deviation as an indication of the dispersion of the results (Steinbach, 2019).

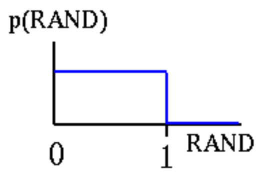


**Figure 3.6** Monte Carlo Random Generator.

In LCA, probability distributions for data, normalization, weighting, allocation, and characterization factors will generate a model as an inventory vector. The inventory vector, g, which we will denote as $g^1$, $g^2$ etc, will be obtained as $\{g^1, g^2, \ldots, g^N\}$ for analysis. Equations 3.15, 3.16, 3.17, 3.18, and 3.19, informed by Steinbach, (2019), offer a more nuanced representation of monte carlo mathematical calculation. The number of runs or iterations (N) of the Monte Carlo Simulation is 1000.

The mean value $\bar{g}k$ :

$$\bar{g}k = \frac{1}{N} \sum_{i=1}^{N} (g^i)_k \tag{3.15}$$

Denote environmental intervention k in Monte Carlo trial number i

The variance :

$$s^2\,(g_k) = \frac{1}{N-1} \sum_{i=1}^{N} ((g^i)_k - \bar{g}k\,)^2 \tag{3.16}$$

The standard deviation:

$$s(g_k) = \sqrt{s^2\,(g_k)} \tag{3.17}$$

Max value:

$$g_k^+ = \max_{i=1}^{N}\,(g^i)_k \tag{3.18}$$

Min value:

$$g_k^- = \min_{i=1}^{N}\,(g^i)_k \tag{3.19}$$

Numerous sampling techniques exist, including latin hypercube, stratified, random, and quasi-random sampling. Even though the latin hypercube sampling and quasi-monte carlo sampling have more accuracy compared to the monte carlo simulation (Groen et al. 2014). This research uses the monte carlo simulation since it is embedded in Open LCA Software.

### 3.2.3 Impact assessment

Impact assessment aims to identify different impact categories. This study's impact assessment is based on ReCipe, adapted from Huijbregts, Steinmann, Elshout, Stam, Verones, Vieira, Hollander, et al. (2017), as shown in Figure 3.7.

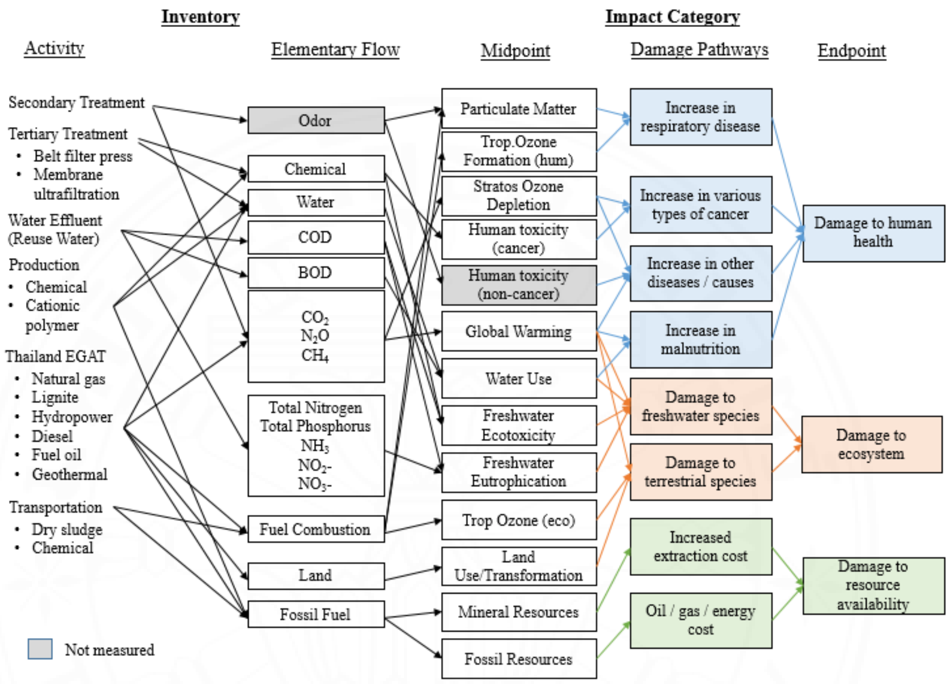


**Figure 3.7** Impact Category Flow.

The relevant pathway of the midpoint and endpoint is based on the elementary flow and existing literature. The normalization aims to convert the environmental impact into a percentage for easy comparison, While the weighting uses the SI standard on normalized results for the standardized result.

a. Recipe 2016 Midpoint to Endpoint

Endpoint characterization factors (CFe) shown in equation 3.19 are obtained from midpoint characterization factors (CFm), with a constant mid-to-endpoint factor for each effect category based on Huijbregts, Steinmann, Elshout, Stam, Verones, Vieira, Hollander, et al. (2017).

$$CFe_{x,a} = CFm_x \times Fm \rightarrow, E, a \quad (3.20)$$

The given equation number 3.20, is represents the protected area: human health, freshwater, marine or terrestrial ecosystems, or resource scarcity. The stressor of concern is denoted by x, and FM→E, a is the midpoint-to-endpoint conversion factor for the protected region. Because environmental mechanisms are considered to be the same for every stressor after the midway impact location on the cause-effect pathway, these mid-to-endpoint parameters are constant per impact category.

b. Contribution Analysis

Contribution analysis in LCA (LCA) identifies the share of impacts from the overall environmental effects of a product or system (Laurent et al. 2020). The origins and causes of the largest impact from hotspot analysis can be identified through contribution analysis. Research on contribution analysis conducted by Hernández-Padilla et al. (2017) revealed that electricity production is the primary source of carbon emissions and health hazards to humans. Extended aeration is the worst-case scenario for a country where fossil fuels dominate the electricity mix. After knowing the areas of significant contribution, the area can be intervented for further improvement.

Despite its numerous advantages, contribution analysis also presents certain drawbacks and challenges. Contribution analysis overlooks the cumulative effects that arise from complex interactions within the life cycle. If quantitative methods cannot perform contribution analysis, Laurent et al. (2020) research suggests a qualitative approach to analyzing the data source critically.

c. Sensitivity Analysis

The sensitivity analysis is useful for error detection in the computations of the LCA System (Heijungs, n.d.). The sensitivity analysis consists of local and global sensitivity analysis. Local sensitivity analysis examines how the system behaves locally in the combined phase space of the parameters and state variables centered around a selected point or trajectory. At the same time, global sensitivity analysis aims to find the critical point in the system (bifurcations, turning points, response extrema) formed by the parameters (Cacuci, 2003). However, most LCA studies use local sensitivity analysis (Wei et al. 2015). The basic approach of local sensitivity analysis is one-at-a-time (OAT) or perturbation analysis by applying input variation (Igos et al. 2019). Tosti et al. (2020) research on LCA uses local sensitivity analysis to calculate the sensitive inputs from the scenario-made assumption. The study implements the perturbation analysis to identify the sensitive parameters retrieved from the contribution analysis. Around 33 parameters from the scenario and 73 parameters for the reference scenario were investigated. The sensitivity index (SI) was then computed for each parameter to determine which was the most sensitive after each parameter was increased/decreased by 5% or 10% of its default value. Sensitivity indices characterize how variable factors affect a model's output result (Wei et al. 2015). The outcome was compared with the default scenario (i.e., all parameters set to their default value) to find the most sensitive one.

Applying different activities, normalization, and weighting scales to LCA will perform differently in terms of life cycle impact—in a non-linear way. Variance-based techniques are the most appropriate sensitivity analysis for non-linear models (Saisana et al. 2005). Thus, this study applies the Saltelli et al. (2000) variance-based model to calculate the parameter sensitivity.

Sensitivity analysis can be employed as an integral part of dealing with the source of uncertainty in the monte carlo simulation. Ideally, one random selection from each distribution should be made in each monte carlo iteration. A random selection is taken from the log-normal distribution during the random number generator. The z score shows the standard deviations of a value that deviates from the mean, as shown in equation 3.21 and adapted from Schauer & Eckman, (2014).

Z score,

$$Z\ score\ = \frac{x - \bar{g}k}{s(g_k)} \tag{3.21}$$

### 3.2.4 Interpretation

This study aims to elucidate the outcomes of the environmental impact calculation related to water reclamation from the WWTP. The interpretation step identifies the system's significant environmental impacts (hotspot). Then, the result is modeled by varying energy parameters and analyzed using sensitivity analysis. The sensitivity analysis helps to identify the key drivers for lowering the environmental impact, especially on the specific impact category.

# CHAPTER 4
# RESULTS AND DISCUSSION

## 4.1 Research goal and scope

This study compare the environmental impact of water reclamation from the wastewater based on Thailand's energy transition scenario." The functional unit of this study is one cubic meter of the reused water produced.

The result aims to provide insight for Bangkok Metropolitan Authorities (BMA) about the environmental impact of Bang Sue WWTP technology. At the country level, it provides insight into the impact of the energy transition on water security. Considering the research results for government stakeholders, the research characterized the endpoint interpretation. The energy scenario chosen in this study mostly occurred during the operational stage (Gate-to-Gate). Gate-to-gate enables the comparisons between different process configurations, allowing energy reduction and transition opportunities. By focusing on the specific gate-to-gate product system, it is crucial to consider the system boundary, as shown in Figure 4.1.

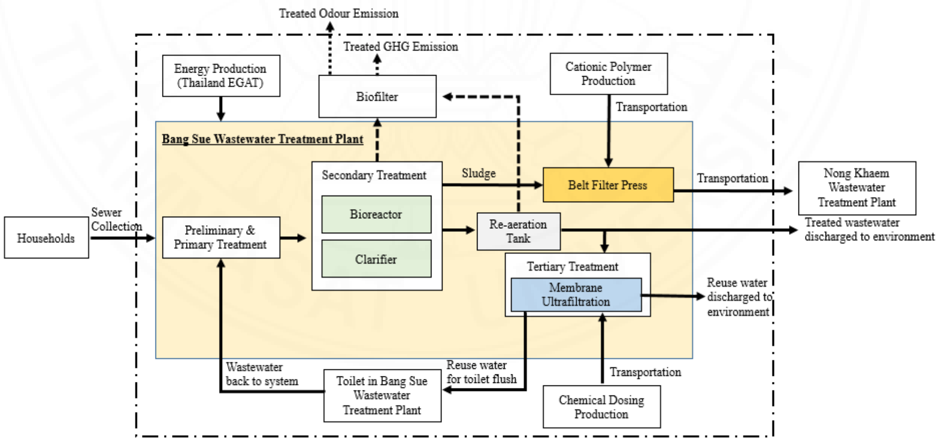


**Figure 4.1** System Boundary.

The system boundary includes the operational phase and neglects the plant's construction, maintenance, and demolition phases. This study includes the production of the cationic polymer and chemical dosing to maintain the system performance. Moreover, the Bang Sue WWTP produces reused water as a co-product of the wastewater treatment process. Around 30% of the water product is used internally, and

70% will go into watering for the nearby pond. After the wastewater is generated for internal use, it returns to the system. The nearby pond watering process belongs to discharged into the environment. Thus, the calculation will be considered by the system allocation. Since the sludge was not discharged directly into the environment, it is not characterized as an emission. However, the sludge transferred into Nong Khaem WWTPs, and the transportation calculation is included.

## 4.2 Energy transition scenario

Formulating scenarios that encapsulate the current energy landscape and future trajectories becomes imperative to assess the sustainability implications of energy planning. In this study, we delve into the scenario formulation process of the existing energy plan with a visionary projection for the year 2037. The formulated scenario comprises the current energy plan (September 2023) and the 2037 energy plan scenario.

### 4.2.1 Existing energy mix (scenario 1)

The energy plan was retrieved from the energy authorities. Thailand's energy situation is analyzed and disseminated by The Department of Alternative Energy Development and Efficiency (DEDE), Ministry of Energy Thailand. Thailand energy mix on september 2023 is shown in Figure 4.2.

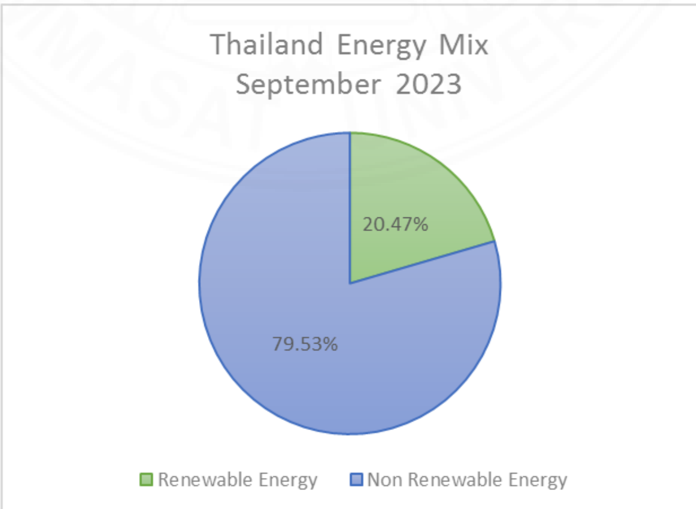


**Figure 4.2** Thailand Energy Mix on September 2023.

The total energy generated in the current situation is 50,800.79 megawatts. Thailand's energy consumption consists of 20.47 % from renewable energy and 79.53% from Non-renewable Energy. The detailed percentage of Thailand's EGAT power generation capacity as of September 2023 is shown in Figure 4.3.

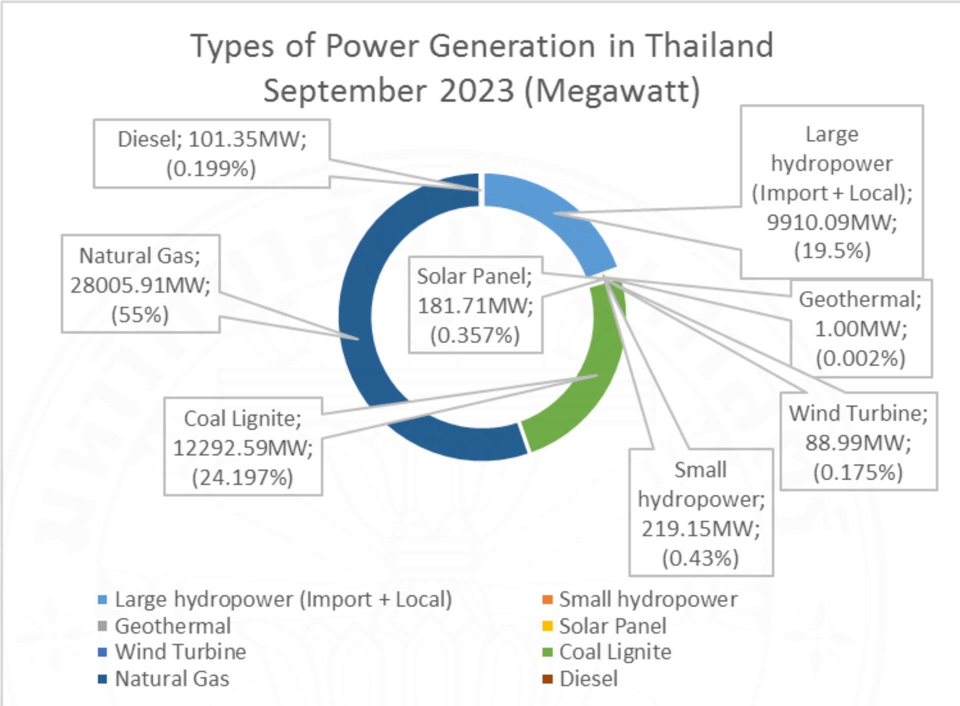


**Figure 4.3** Types of Current Power Generation Capacity in Megawatts and Percentage in September 2023.

Around 26.6% of natural gas is imported from Myanmar (EPPO, 2023). 61.1 % of crude oil is imported from the Middle East, 14.9 % from the Far East, and 24 % from other countries. Table 4.1 shows a detailed Thailand renewable energy scenario adapted from EGAT, (2023).

**Table 4.1** Renewable Energy Mix September 2023.

| Renewable Energy and Alternative | | Capacity (MW) | Percentages |
|---|---|---|---|
| 1 | Large hydropower (import and local) | 9910.09 | 19.5% |
| 2 | Small hydropower | 219.15 | 0.43% |
| 3 | Geothermal | 1.00 | 0.0019% |
| 4 | Solar Panel | 181.71 | 0.357% |
| 5 | Wind Turbine | 88.99 | 0.175% |

| Renewable Energy and Alternative | Capacity (MW) | Percentages |
|---|---|---|
| **Total** | **10,400.93** | **20.47%** |

### 4.2.2 Energy mix scenario in 2037 (scenario 2)

The energy scenario is based on Thailand's future energy plan, provided by the Energy Policy and Planning Office (EPPO), Ministry of Energy Thailand. EPPO published the AEDP2018, covering a 20-year national strategy timeframe (2018 – 2037). Thailand energy mix on 2037 is shown in Figure 4.4.

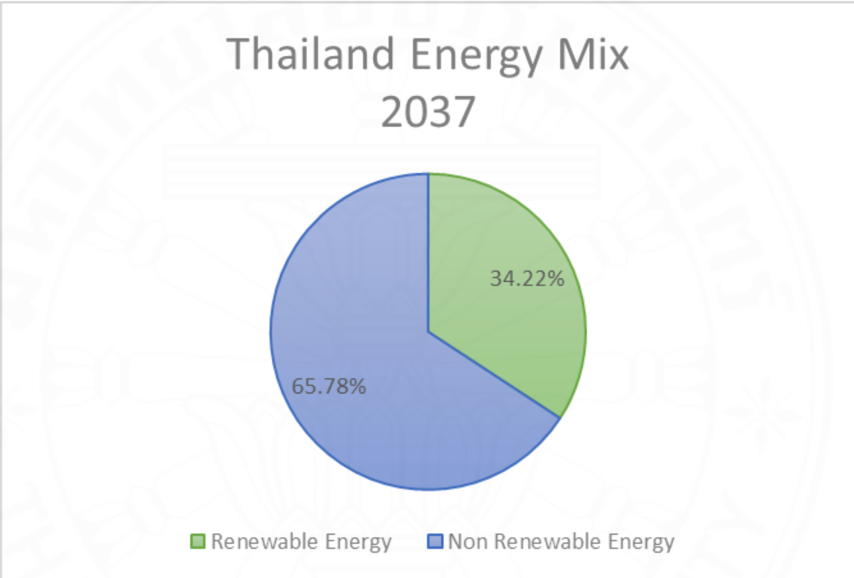


**Figure 4.4** Thailand Energy Mix on 2037.

Thailand's energy mix in 2037 will consist of 34.22 % demand from renewable energy and 65.78% from non-renewable energy. Thailand's EGAT non-renewable energy mix in 2037 plans to phase out diesel fuel oil and reduce the lignite percentage to 12.69% and 53.4% natural gas. The detailed percentage of Thailand's EGAT power generation capacity as of 2037 is shown in Figure 4.5.

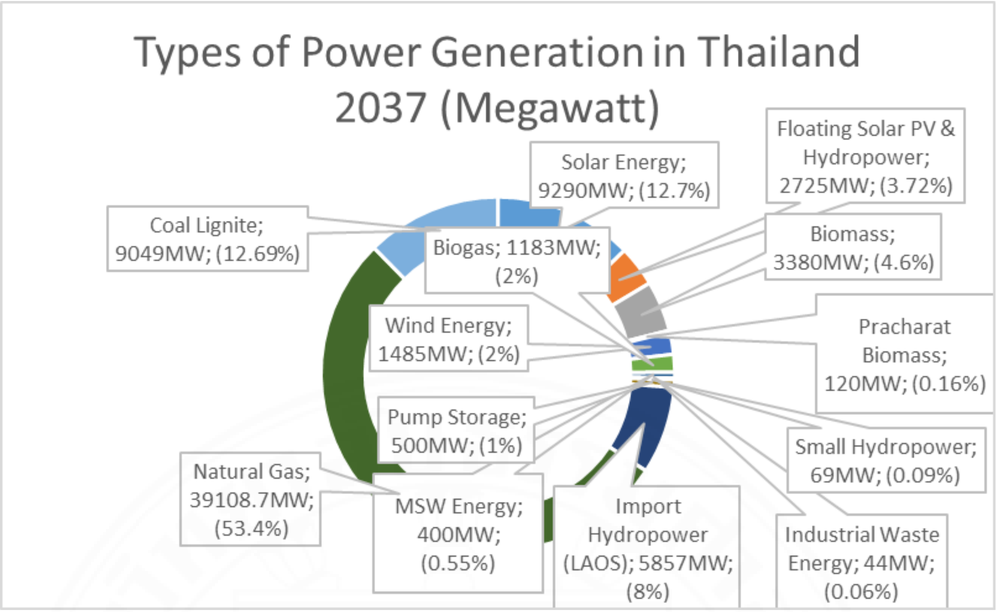


**Figure 4.5** Types of Power Generation Capacity in Megawatts and Percentage in 2037.

The total energy generated in 2037 is 73,211 megawatts. Overview of Thailand's Power Development Plan 2018 - 2037, 1st revised edition (PDP2018 Rev.1) has set new production capacity targets for power plants from renewable energy. Alternative energy includes community power plants for the grassroots economy. A total of 18,696 megawatts of renewable energy are generated from various fuel types, as shown in Table 4.2 is adapted from EPPO, (2018).

**Table 4.2** Renewable Energy Mix 2037.

| Renewable Energy and Alternative | | Contract Production Capacity (MW) | Percentages |
|---|---|---|---|
| 1 | Solar energy | 9,290 | 12.69% |
| 2 | Solar energy, floating buoys, combined with hydroelectric power plants. | 2,725 | 3.72% |
| 3 | Biomass (Rubber trees, Woodchip and Palm Empty Fruit Bunch (EFB)) | 3,380 | 4.61% |
| 4 | Pracharat Biomass Power Plant in the 3 southern border provinces | 120 | 0.16% |

| Renewable Energy and Alternative | | Contract Production Capacity (MW) | Percentages |
|---|---|---|---|
| 5 | Wind energy | 1,485 | 2.02% |
| 6 | Biogas (Wastewater/waste/energy plants) | 1,183 | 1.6% |
| 7 | MSW energy generation | 400 | 0.55% |
| 8 | Industrial waste energy generation | 44 | 0.06% |
| 9 | Small hydropower | 69 | 0.09% |
| **Total** | | **18,696** | **34.22%** |

The Target value of electricity production from renewable energy, shown in Table 4.2, is defined as the contract capacity with the government commitments purchase agreement. The planned hydro-floating energy is shown in Table 4.3.

**Table 4.3** Planned Hydro-Solar Floating in Thailand.

| Renewable Energy and Alternative | | Planned Hydro-Floating Operation | Existing Turbin Capacity (MW) | Solar-Floating With Buoy Generation Capacity Construction (MW) |
|---|---|---|---|---|
| 1 | Sirindhorn Dam | 2021 | 36 | 45 verified to 45.25 |
| 2 | Ubol Ratana Dam | 2023 | 25.2 | 24 |
| 3 | Bhumibol Dam *) | 2026 | 608.2 + 171 (Pumped Storage) | 156 verified to 158 |
| 4 | Srinagarind Dam **) | 2026 | 120 + 180 (Pumped Storage) | 140 |
| 5 | Vajiralongkorn Dam ***) | 2027 | 300 | 50 |
| 6 | Srinagarind Dam (Extension) | 2029 | **) | 280 |

| Renewable Energy and Alternative | | Planned Hydro-Floating Operation | Existing Turbin Capacity (MW) | Solar-Floating With Buoy Generation Capacity Construction (MW) |
|---|---|---|---|---|
| 7 | Bhumibol Dam (Extension) | 2030 | *) | 300 |
| 8 | Vajiralongkorn Dam (Extension) | 2031 | ***) | 250 |
| 9 | Srinagarind Dam (Extension 2) | 2032 | **) | 300 |
| 10 | Chulaborn Dam | 2033 | 40 | 40 |
| 11 | Bang Lang Dam | 2033 | 84 | 78 |
| 12 | Bhumibol Dam (Extension 2) | 2033 | *) | 320 |
| 13 | Rajjaphraba Dam ****) | 2034 | 240 | 140 |
| 14 | Sirikit Dam *****) | 2035 | 500 | 325 |
| 15 | Rajjaphraba Dam (Extension) | 2036 | ****) | 100 |
| 16 | Sirikit Dam (Extension) | 2037 | *****) | 175 |
| **Total** | | | **2,304.4 (1953.4 + 351 pumped storage)** | **2,725** verified to **2,728.25** |

Source

Table 4.3 is compiled from EGAT, (2005) and verified with the EPPO, (2018) document. The table above shows that the fraction consists of Hydro power plants at 71.68%, pumped hydro storage at 12.88, and floating photovoltaic at 15.44%. Since the solar floating database was not available in ecoinvent, the fraction will be considered a parameter to determine the Life Cycle Inventory Data.

## 4.3 Inventory data collection

Inventory data is an essential part of LCA studies. When conducting a comprehensive LCA for a wastewater treatment system, meticulous attention is given to the inventory data collection phase. This crucial step involves gathering detailed information that forms the foundation for the subsequent analysis. The inventory data is categorized into primary and secondary data sources. The following paragraphs will delve into the methodologies and importance of primary and secondary data collection in the context of the LCA for wastewater treatment systems.

### 4.3.1 Primary data

The primary data encompasses system allocation in the wastewater flow process, electricity consumption, emissions, chemical demand, and transportation.

a. System Allocation

The mass balance principle helps to model the hourly rate of influent. It is based on the law of conservation of mass, which states that the mass of any system must remain constant over time. The existing system flow condition is shown in Figure 4.6.

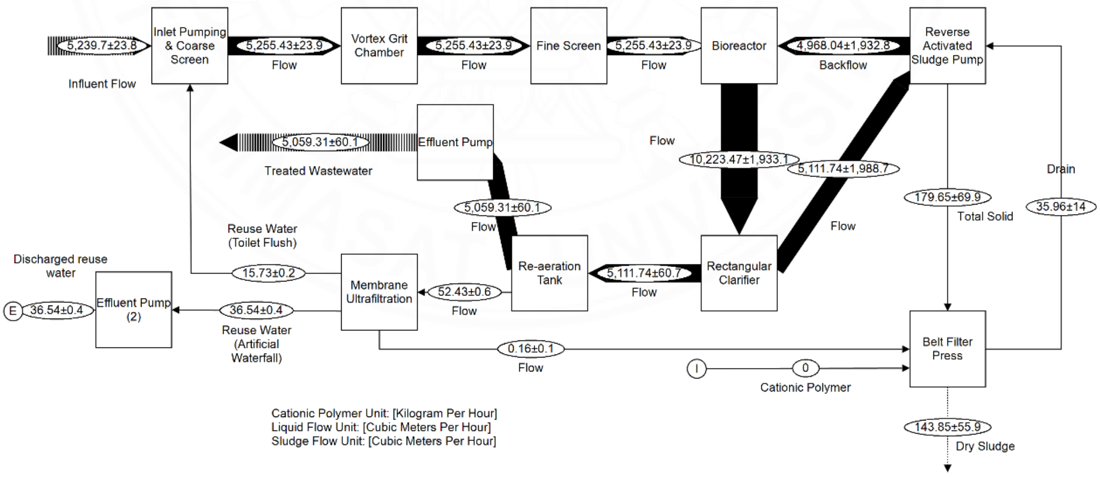


**Figure 4.6** System Flow Condition.

In the Bang Sue WWTP, the mass balance principle helps to model the influent hourly rate to achieve a 1 $m^3$ per hour reuse water product. The normalized system flow condition is shown in Figure 4.7.

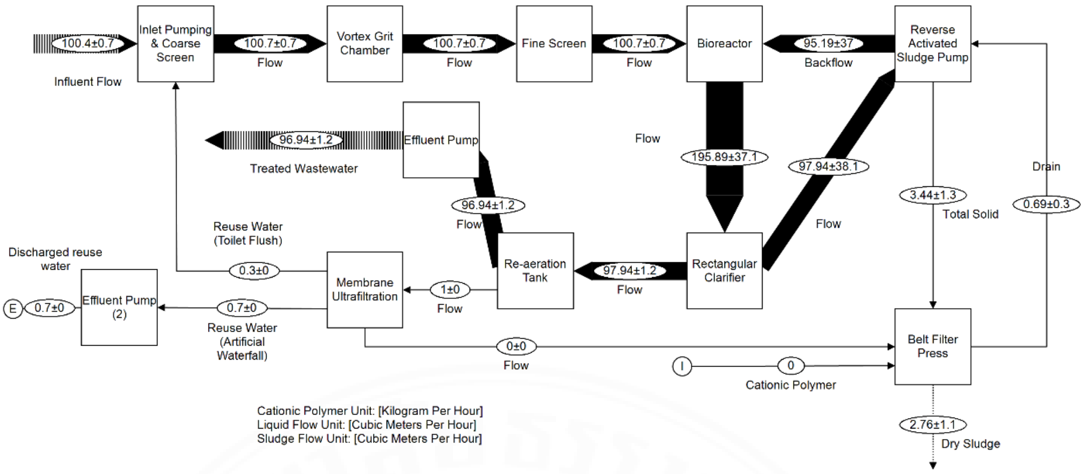


**Figure 4.7** Normalized System Flow Condition.

One cubic meter of reclaimed water is needed to achieve the functional unit. The average hourly flow from the Bioreactor to the rectangular clarifier is 195.98±37.1 $m^3$ per hour. The average hourly backflow pumped by reverse-activated sludge is 95.28±37.1 $m^3$ per hour.

Based on the solid composition, the cationic polymer is diluted to a 0.5%–0.05% concentration. The concentration and turbidity of the water determine the dosage. The jar test determines the most cost-effective dosage. With an estimated total solid around 3.44±1.3 $m^3$ will need 6 gram of Poly(diallyl dimethyl ammonium chloride) in Solid Sate. The cationic polymer density is 1.09 grams/mL. So, the cationic polymer demand is 0.0065 Liter or 6 X $10^{-6}$ $m^3$ in the solution phase. To allocate the estimated solid at around 0.04±0.013 $m^3$, we will need a 0.0000755 Liter or 6 X $10^{-8}$ $m^3$ in solution phase.

This study applies system allocation to narrow the water reclamation system at the Bang Sue WWTP. However, in Figure 4.8, only reused water is taken into account.

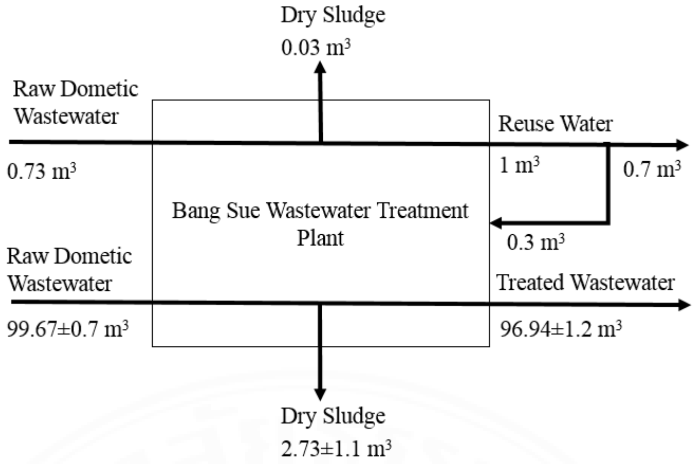


**Figure 4.8** System Flow Fraction.

Equation (3.11) calculates that the hourly influent flow fraction for the treated wastewater is 99.67±0.7 m$^3$ per hour. Equation (31.2) calculates that the hourly influent flow fraction for the reuse wastewater is 1.03 m$^3$ per hour. Equation (31.3) calculates that the hourly dry sludge by-product from treated wastewater processing is 2.73±1.1 m$^3$ per hour. Equation (3.14) calculates that the hourly dry sludge by-product from reuse water processing is 0.03 m$^3$ per hour. The dry sludge density is 1.2-1.4 g/cm$^3$ or 1200-1400 kg/m$^3$. Thus, the average of dry sludge is around 39 kg. After modeling, the reuse water production flow is shown in Figure 4.9.

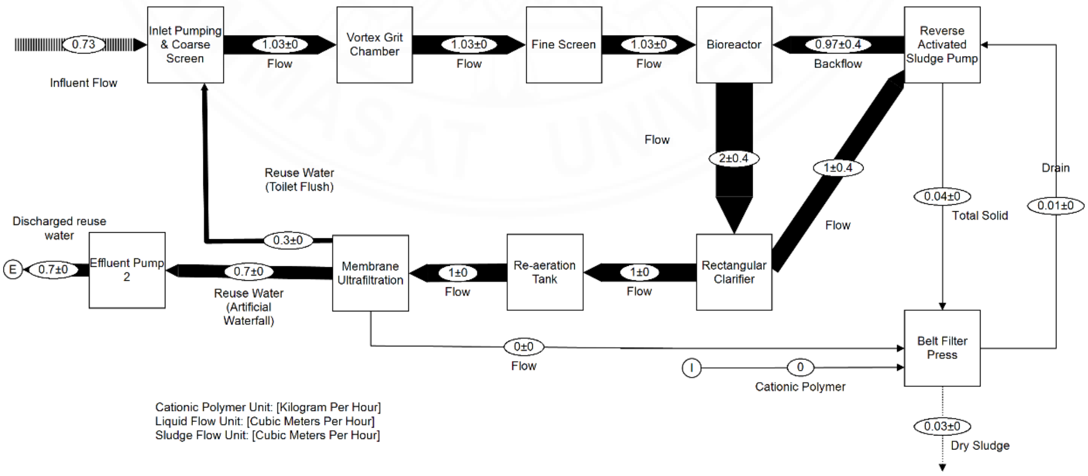


**Figure 4.9** Reuse Water Production Flow.

b. Water pollution

The following Table 4.4 presents water pollution data collected over a six-month historical period, focusing on key pollutants, including Total Phosphorus (TP), Total Nitrogen (TN), Ammonia ($NH_3$), Nitrate ($NO_3^-$), and Nitrite ($NO_2^-$). This data, measured in milligrams per cubic meter ($mg/m^3$), provides a comprehensive overview of the pollutant levels in the water, enabling an assessment of the water quality and its potential impacts on the environment and public health. The subsequent sections will detail the concentration levels of these pollutants and discuss the implications of the findings. However, this study limits the allocation of reuse water discharge. Thus, the wastewater flow effluent will neglected.

**Table 4.4** Water Quality of Discharged Reuse Water.

| | TP ($mg/m^3$) | TN ($mg/m^3$) | $NH_3$ ($mg/m^3$) | $NO_{3-}$ ($mg/m^3$) | $NO_2$ ($mg/m^3$) |
|---|---|---|---|---|---|
| Jan | 11.97 | 68.24 | 28.9 | 23.09 | 0.34 |
| Feb | 15.4 | 61.82 | 29.2 | 19.57 | 0.25 |
| Mar | 15.24 | 55.32 | 24.57 | 13.09 | 0.67 |
| Apr | 13.17 | 67.27 | 29.49 | 20.6 | 0.38 |
| May | 12.14 | 60.37 | 31.07 | 8.45 | 0.62 |
| June | 13.41 | 63.37 | 30.6 | 10.53 | 1.32 |
| AVG | 13.55 | 62.73 | 28.97 | 15.89 | 0.59 |
| SD (Uncertainty) | 0.603 | 1.939 | 0.946 | 2.446 | 0.159 |

After normalizing the proportion, the TP was 9.49± 0.42 mg, the TN was 43.9±1.36 mg, the ammonia was 20.28±0.66 mg, the nitrate was 11.12±1.7 mg, and the nitrite was 0.42±0.11 mg.

c. Unit Operation Energy Distribution

The energy usage of a WWTP depends on various factors, such as the type of treatment process, the influent characteristics, efficiency, and the size of the plant. The energy usage of the Bang Sue WWTP unit operation is shown in Figure 4.10.

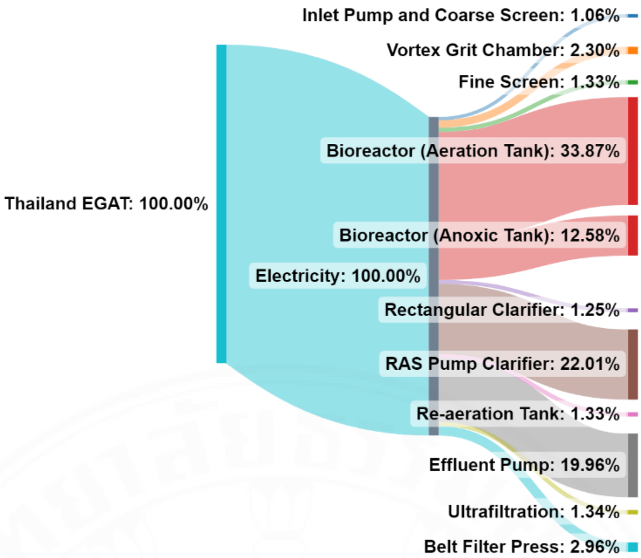


**Figure 4.10** Energy Usage (in %) for Each Unit Process.

Bioreactor unit operation at Bang Sue WWTPs applies four-step biological nutrient removal technology. The Bang Sue WWTP uses the most energy to aerate the air and circulate the water. The aeration process supplies the air needed to degrade the organic matter inside the bioreactor. The secondary treatment operating setup includes a bioreactor based on influent samples from jar tests taken every 6 hours. Meanwhile, wastewater influent quality parameters varies hourly. Research conducted by I. Lee et al. (2015) in Korea found that adding a buffer tank and implementing a control system can reuce energy usage by 28% in the aeration process.

The WWTP's unit operation power consumption can be measured in kilowatt-hours per cubic meter of wastewater treated, which measures the energy required to treat one cubic meter of wastewater. The Bang Sue WWTP's kilowatt-hours per cubic meter (kWh/m$^3$) data is shown in Table 4.5 below.

**Table 4.5** Unit Operation Power Consumption.

| No | Unit Operation | Power Consumption (kWh/cubic meter) | Uncertainties (kWh/cubic meter) |
|---|---|---|---|
| 1 | Inlet Pumping and Coarse Screen | 1.72x10$^{-3}$ | 0.45% |

| No | Unit Operation | Power Consumption (kWh/cubic meter) | Uncertainties (kWh/cubic meter) |
|---|---|---|---|
| 2 | Vortex Grit Chamber | $3.7 \times 10^{-3}$ | 0.45% |
| 3 | Fine Screen | $2.2 \times 10^{-3}$ | 0.45% |
| 4 | Bioreactor | $7.5 \times 10^{-2}$ | 19.02% |
| 5 | Rectangular Clarifier | $1.01 \times 10^{-3}$ | 1.02% |
| 6 | RAS Pump | $3.4 \times 10^{-2}$ | 40.55% |
| 7 | Reaeration | $2.15 \times 10^{-3}$ | 2.17% |
| 8 | Belt Filter Press | $4.07 \times 10^{-3}$ | 61% |
| 9 | Ultrafiltration Membrane | $2.12 \times 10^{-1}$ | 2.13% |

Every power consumption of the unit operation is multiplied by the flow generated in Table 4.5 to determine the amount of energy needed to produce one cubic meter of reused water product. The total energy needed to produce one cubic meter of reused water product is 0.3586 kWh. The energy dataset in Table 4.6 was calculated using equation (3.5).

**Table 4.6** Energy Dataset of Scenario 1.

| No | Energy Mix | Inlet pumping and coarse screen (kWh) | Vortex grit chamber (kWh) | Fine screen (kWh) | Bioreactor (kWh) | Rectangular clarifier (kWh) | Ras pump (kWh) | Reaeration energy (kWh) | Belt filter press (kWh) | Membrane ultrafiltration (kWh) |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | Large hydro power | 3.27E-04 | 7.05E-04 | 4.08E-04 | 1.43E-02 | 3.85E-04 | 6.76E-03 | 4.07E-04 | 7.94E-04 | 4.00E-02 |
| 2 | Small hydro power | 7.20E-06 | 1.55E-05 | 9.00E-06 | 3.15E-04 | 8.50E-06 | 1.49E-04 | 8.98E-06 | 1.75E-05 | 8.82E-04 |

| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| 3 | Geothermal | 3.18E-08 | 6.87E-08 | 3.98E-08 | 1.39E-06 | 3.75E-08 | 6.58E-07 | 3.97E-08 | 7.73E-08 | 3.90E-06 |
| 4 | Solar Panel | 5.98E-06 | 1.29E-05 | 7.47E-06 | 2.61E-04 | 7.05E-06 | 1.24E-04 | 7.45E-06 | 1.45E-05 | 7.33E-04 |
| 5 | Wind Turbine | 2.93E-06 | 6.33E-06 | 3.66E-06 | 1.28E-04 | 3.46E-06 | 6.06E-05 | 3.65E-06 | 7.12E-06 | 3.59E-04 |
| 6 | Lignite | 4.05E-04 | 8.75E-04 | 5.07E-04 | 1.77E-02 | 4.78E-04 | 8.39E-03 | 5.05E-04 | 9.85E-04 | 4.97E-02 |
| 7 | Natural Gas | 9.23E-04 | 1.99E-03 | 1.15E-03 | 4.04E-02 | 1.09E-03 | 1.91E-02 | 1.15E-03 | 2.24E-03 | 1.13E-01 |
| 8 | Diesel Fuel Oil | 3.33E-06 | 7.19E-06 | 4.17E-06 | 1.46E-04 | 3.93E-06 | 6.89E-05 | 4.15E-06 | 8.10E-06 | 4.08E-04 |

The energy dataset in Table 4.7 was calculated using equation (3.5).

**Table 4.7** Energy Dataset of Scenario 2.

| No | Energy Mix | Inlet pumping and coarse screen (kWh) | Vortex grit chamber (kWh) | Fine screen (kWh) | Bioreactor (kWh) | Rectangular clarifier (kWh) | Ras pump (kWh) | Reaeration energy (kWh) | Belt filter press (kWh) | Membrane ultrafiltration (kWh) |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | Solar energy | 2.1E-02 | 4.6E-02 | 2.7E-02 | 9.3E-01 | 1.3E-02 | 4.3E-01 | 2.7E-02 | 5.1E-02 | 2.7E-02 |
| 2 | Solar energy, | 9.7E-04 | 2.1E-03 | 1.2E-03 | 4.2E-02 | 5.7E-04 | 1.9E-02 | 1.2E-03 | 2.3E-03 | 1.2E-03 |

| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | floating buoys, combined with hydroelectric power plants (PV) | 4.5E-03 | 9.7E-03 | 5.6E-03 | 2.0E-01 | 2.6E-03 | 9.0E-02 | 5.6E-03 | 1.1E-02 | 5.6E-03 |
| | | 8.1E-04 | 1.7E-03 | 1.0E-03 | 3.5E-02 | 4.8E-04 | 1.6E-02 | 1.0E-03 | 1.9E-03 | 1.0E-03 |
| 3 | Biomass | 7.8E-03 | 1.7E-02 | 9.7E-03 | 3.4E-01 | 4.6E-03 | 1.6E-01 | 9.7E-03 | 1.8E-02 | 9.8E-03 |
| 4 | Pracharat Biomass Power Plant in the 3 southern border provinces | 2.8E-04 | 6.0E-04 | 3.5E-04 | 1.2E-02 | 1.6E-04 | 5.5E-03 | 3.5E-04 | 6.6E-04 | 3.5E-04 |
| 5 | Wind energy | 3.4E-03 | 7.4E-03 | 4.3E-03 | 1.5E-01 | 2.0E-03 | 6.8E-02 | 4.3E-03 | 8.1E-03 | 4.3E-03 |
| 6 | Biogas (Wast | 2.7E-03 | 5.9E-03 | 3.4E-03 | 1.2E-01 | 1.6E-03 | 5.4E-02 | 3.4E-03 | 6.5E-03 | 3.4E-03 |

| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | ewater/waste/energy plants) | | | | | | | | | |
| 7 | MSW energy generation | 9.2E-04 | 2.0E-03 | 1.2E-03 | 4.0E-02 | 5.4E-04 | 1.8E-02 | 1.2E-03 | 2.2E-03 | 1.2E-03 |
| 8 | Industrial waste energy generation | 1.0E-04 | 2.2E-04 | 1.3E-04 | 4.4E-03 | 6.0E-05 | 2.0E-03 | 1.3E-04 | 2.4E-04 | 1.3E-04 |
| 9 | Small hydropower | 1.6E-04 | 3.4E-04 | 2.0E-04 | 6.9E-03 | 9.4E-05 | 3.2E-03 | 2.0E-04 | 3.8E-04 | 2.0E-04 |
| 10 | Lignite | 2.1E-02 | 4.5E-02 | 2.6E-02 | 9.1E-01 | 1.2E-02 | 4.2E-01 | 2.6E-02 | 4.9E-02 | 2.6E-02 |
| 11 | Natural Gas | 9.0E-02 | 1.9E-01 | 1.1E-01 | 3.9E+00 | 5.3E-02 | 1.8E+00 | 1.1E-01 | 2.1E-01 | 1.1E-01 |
| 12 | Pump Storage | 1.2E-03 | 2.5E-03 | 1.4E-03 | 5.0E-02 | 6.8E-04 | 2.3E-02 | 1.4E-03 | 2.7E-03 | 1.4E-03 |
| 13 | Import Hydr | 1.3E-02 | 2.9E-02 | 1.7E-02 | 5.9E-01 | 7.9E-03 | 2.7E-01 | 1.7E-02 | 3.2E-02 | 1.7E-02 |

| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | opow er (LAO S) | | | | | | | | | |

d. Air Emission

WWTPs are designed to remove pollutants from wastewater before it is discharged into the environment. However, the treatment process itself can generate greenhouse gases (GHGs). The greenhouse gases (GHGs) are carbon dioxide, methane, and nitrous oxide. However, the carbon dioxides are from the biogenic emission. thus, only methane and nitrous oxide are taken into account. In the current situation, biofilter media made from eucalyptus is used by Bang Sue WWTP to filter odors. Bang Sue WWTP can improve methane removal by implementing biofilter media made from a combination of biochar, water, nitrogen, and lava rock. Helen et al., (2018) found that biochar, water, nitrogen, and lava rock are effective mediums for methanotrophic growth which can utilize methane.

The wastewater influent is as presented referred on the Figure 4.9 and the value is 0.73±0.0046 $m^3$. The oxygen demand of influent wastewater to the bioreactor unit operation is determined as either BOD5 or COD, which accounts for 0.67 mg. The bioreactor unit operation's average oxygen demand removal efficiency is 95.32%. The conversion factor for maximum $CH_4$ generation per unit of oxygen demand is 0.5. The methane correction factor for the anaerobic wastewater treatment unit is 0.8. The fraction of carbon as $CH_4$ in generated biogas is 0.65. Meanwhile, the biomass yield in anaerobic environments is 0.1. Around $7.12x10^{-4}±3.18x10^{-6}$ mg of methane is produced, and the methane calculation is based on equation 3.7.

Aeration is an essential process in wastewater treatment that provides oxygen to bacteria for treating and stabilizing the wastewater. However, it can also generate nitrous oxide. The amount of TKN in the effluent is around 13.75 mg. Around 1.11 $x10^{-7}$ mg of nitrous oxide is produced, and the nitrous oxide calculation is based on equation 3.8.

e. Chemical Demand

Following the 3.3 equation, the water needed for backwash per day is around 9.6 $m^3$/d. The existing system produces reuse water around 36.54±0.4 $m^3$ per hour or 876.96±9.6 $m^3$/d. So, the freshwater needed for backwashing to produce one cubic meter of reuse water is 1.07 $x10^{-2}$ $m^3$ , and the chemical need is 2132.2 mg.

f. Sludge and Chemical Transportation

To allocate the estimated solid at around 0.04±0.013 $m^3$, need a 0.0000755 Liter or 6 X $10^{-8}$ $m^3$ in solution phase. The cationic polymer is 0.082 mg of Poly(diallyl dimethyl ammonium chloride) in solid state. The average dry sludge weight is around 39 kg. The sludge and chemical transportation are shown in Table 4.8.

**Table 4.8** Sludge and Chemical Transportation.

| No | Commodity | Mode of transport | D (km) | W (Tonne) | TKM |
|---|---|---|---|---|---|
| 1 | Sodium hypochlorite | lorry 3.5-7.5 metric ton EURO 4 standard | 30.8 | $2.132x10^{-6}$ | $6.56x10^{-5}$ |
| 2 | Polyacrylamide | lorry 3.5-7.5 metric ton EURO 4 standard | 49 | $8.2x10^{-11}$ | $4.018x10^{-9}$ |
| 3 | Dry Sludge | lorry 7.5-16 metric ton EURO 4 standard | 38 | $3.9x10^{-2}$ | 1.482 |

g. Inventory Input and Output

In this study, the inventory data collection was recapped into input inventory data Table 4.9 and output inventory data Table 4.10. The input inventory data includes electricity, freshwater resources, sodium hypochlorite, and polyacrylamide.

**Table 4.9** Input Inventory Data.

| No | Parameter | Unit | Value |
|---|---|---|---|
| | **Input** | | |
| 1 | Electricity | kWh | 0.3586 |
| 2 | Freshwater resource (Backwash) | $m^3$ | 1.07 $x10^{-2}$ |
| 3 | Sodium hypochlorite | mg | 2132.2 |
| 4 | Polyacrylamide | mg | 0.082 |

The output inventory data consist of methane, dinitrogen oxide, BOD, COD, total nitrogen, total phosphorus, $NH_3$, $NO_2^-$, $NO_3^-$, water reuse resource, sodium hypochlorite transportation, polyacrylamide transportation, and dry sludge transportation.

**Table 4.10** Output Inventory Data.

| No | Parameter | Unit | Value |
|---|---|---|---|
| | **Output** | | |
| 1 | Methane | mg | $7.12 \times 10^{-4} \pm 3.18 \times 10^{-6}$ |
| 2 | Dinitrogen monoxide | mg | $1.11 \times 10^{-7}$ |
| 3 | Nitrogen, total | mg | 43.9±1.36 |
| 4 | Phosphorus, total | mg | 9.49± 0.42 |
| 5 | $NH_3$ | mg | 20.28±0.66 |
| 6 | $NO_2$- | mg | 11.12±1.7 |
| 7 | $NO_3$- | mg | 0.42±0.11 |
| 8 | Water reuse resource | $m^3$ | 0.7 |
| 9 | Sodium hypochlorite transportation | tkm | $6.56 \times 10^{-5}$ |
| 10 | Polyacrylamide transportation | tkm | $4.018 \times 10^{-9}$ |
| 11 | Dry sludge transportation | tkm | 1.482 |

### 4.3.2 Secondary Data from the Ecoinvent Dataset

In contrast with the primary data, the secondary data consists of life cycle inventory data sourced from established databases and literature.

a. Electricity Dataset

The non-renewable energy data are available for Thailand (TH) and forsome Global data are used (GLO). These sources include natural gas, lithium, diesel, and oil. The inventory data collection for non-renewable energy sources is shown in Table 4.11.

**Table 4.11** Non-Renewable Energy Retrieved from Ecoinvent Database.

| No | Electricity Generation Type | Location |
|---|---|---|
| 1 | Electricity production (Combined cycle power plant) from natural gas | Thailand (TH) |
| 2 | Electricity production (High voltage) from lignite | Thailand (TH) |
| 3 | Diesel (Burned in diesel-electric generating set, 18.5kW) | Global (GLO) |
| 4 | Electricity production (High voltage) from oil | Thailand (TH) |

Renewable energy generation is available for Thailand (TH) and the Rest of the world (RoW) locations. However, to get data representing Thailand, we changed the Global (GLO) to neighboring Malaysia (MY). Renewable energy generation consists of solar panels, wind energy, hydro power generation, biomass, geothermal, biogas, and waste energy generation. The inventory data collection for chemical dosing is shown in Table 4.12.

**Table 4.12** Renewable Energy Retrieved from Ecoinvent Database.

| No | Electricity Generation Type | Location |
|---|---|---|
| 1 | Electricity production, photovoltaic, 3kWp slanted-roof installation, single-Si, panel, mounted | Thailand (TH) |
| 2 | Electricity production, photovoltaic, 3kWp facade installation, single-Si, panel, mounted | Rest of the world (RoW) |
| 3 | Electricity production, wind, <1MW turbine, onshore | Rest of the world (RoW) |
| 4 | Electricity production (High voltage) from hydro reservoir in tropical region | Thailand (TH) |
| 5 | Heat and power co-generation, wood chips, 6667 kW \| electricity, high voltage | Rest of the world (RoW) |
| 6 | Electricity production (High voltage) from deep geothermal | Thailand (TH) |
| 7 | Electricity, from municipal waste incineration to generic market for electricity, medium voltage | Malaysia (MY) |
| 8 | Biomethane, low pressure burned in micro gas turbine 100kWe | Rest of the world (RoW) |

| No | Electricity Generation Type | Location |
|---|---|---|
| 9 | Treatment of bagasse, from sugarcane, in heat and power co-generation unit, 6400kW thermal \| electricity, high voltage | Rest of the world (RoW) |

b. Chemical Dataset

Chemical dosing for backwash on membrane ultrafiltration: sodium hypochlorite production retrieved from the manufacture of basic chemicals with the regional boundary of the rest of the world (RoW). Cationic polymer dosing: Polyacrylamide is manufactured from the basic chemicals with the regional boundary of the Global (GLO). The inventory data collection for chemical dosing is shown in Table 4.13.

**Table 4.13** Chemical Production Retrieved from Ecoinvent Database.

| No | Chemical | Location |
|---|---|---|
| 1 | Sodium hypochlorite production, product in 15% solution state | Rest of the world (RoW) |
| 2 | Polyacrylamide production | Global (GLO) |

c.Transportation Dataset

The freight transportation by road for chemical and polymer doses retrieved from lorry 3.5-7.5 metric ton EURO 4 standard with the regional boundary rest of the world (RoW). The freight transportation by road for sludge, retrieved from lorry 7.5-16 metric ton EURO 4 standard with the regional boundary rest of the world (RoW). The inventory data collection for chemical dosing is shown in Table 4.14.

**Table 4.14** Transportation Retrieved from Ecoinvent Database.

| No | Mode of transport | Location |
|---|---|---|
| 1 | Lorry 3.5-7.5 metric ton EURO 4 standard | Rest of the world (RoW) |
| 2 | Lorry 7.5-16 metric ton EURO 4 standard | Rest of the world (RoW) |

### 4.3.3 Model Graph

The following section presents a system model graph designed to illustrate the relationship between each unit operation within the wastewater treatment process and its corresponding environmental impacts. This visual representation aims to provide a clear understanding of how each operational component contributes to overall environmental performance. The subsequent discussion will analyze the key different and implications of the system model to each scenario.

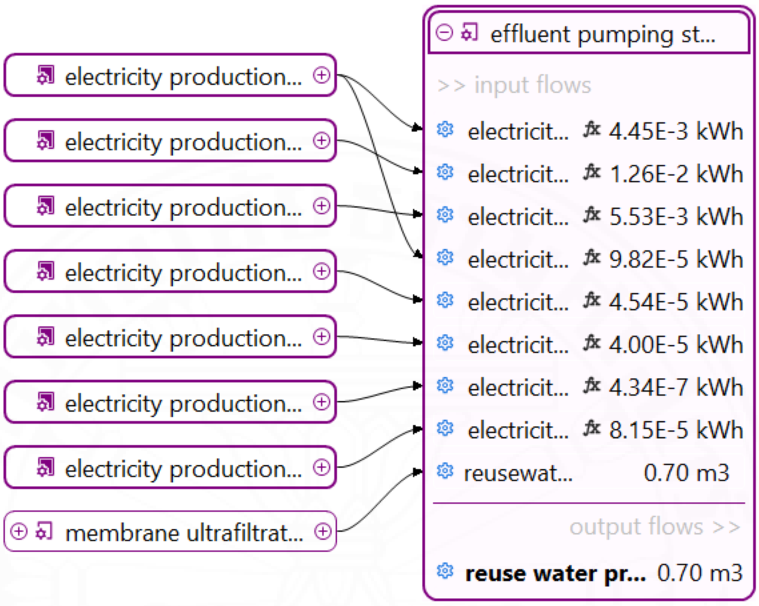


**Figure 4.11** Model Graph (scenario 1).

Model graph in Scenario 1 features a simpler connection compared to Scenario 2, primarily due to the minimal association of the energy mix. This streamlined configuration in Scenario 1 reduces the interdependencies and simplifies the overall system dynamics. In contrast, Scenario 2 incorporates a more intricate network of interactions, driven by a diverse and complex energy mix.

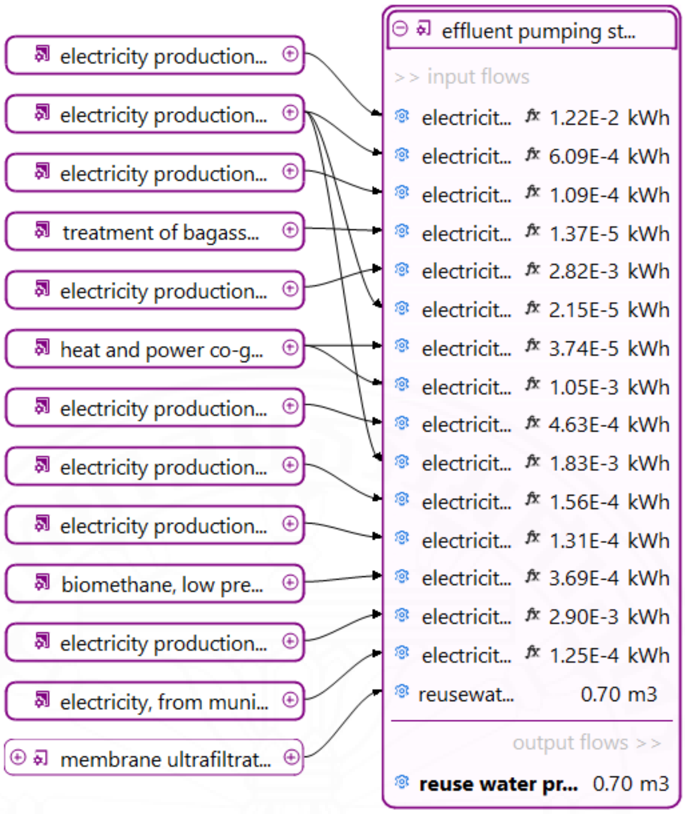


**Figure 4.12** Model Graph (scenario 2).

## 4.4 Environmental impact assessment

This study evaluates the environmental impacts associated with different energy sources to provide insights into the sustainability of wastewater treatment processes. Scenario 1 represents the current energy mix used in the plant, while Scenario 2 represents the energy mix in 2037.

The study can generate a comparative LCA of the relative scenario indicator in Open LCA. For each indicator, the maximum result is set to 100%, and the results of the other variants are displayed as this result. The relative indicators of comparative mindpoint impact are displayed in Figure 4.13.

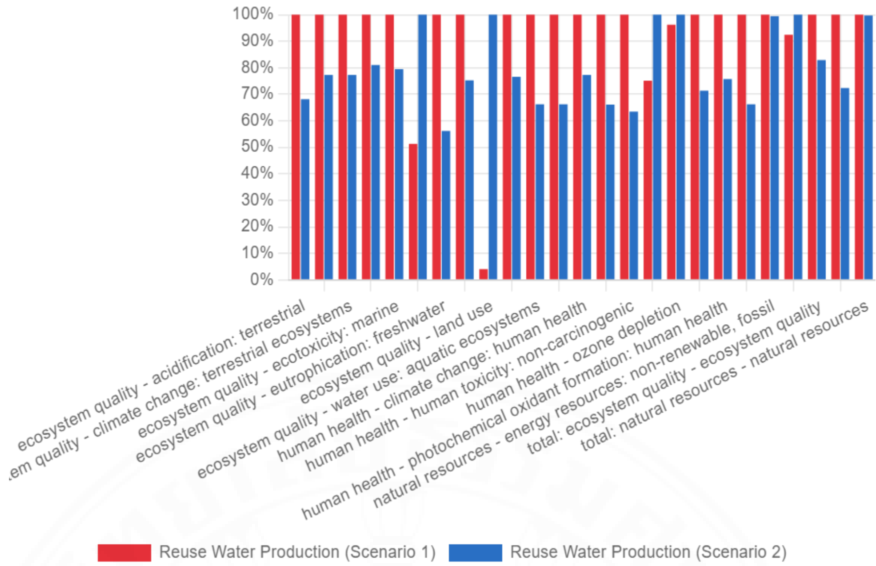


**Figure 4.13** Comparative Impact of Reuse Water Production.

### 4.4.1 Midpoint impact assessment

By interpreting these comparative results, we gain a nuanced understanding of how different energy scenarios influence the WWTP's overall environmental performance. In general, scenario 2 reduces overall ecosystem quality and environmental impacts, especially freshwater eutrophication and water use in aquatic and terrestrial ecosystems. Only land use and terrestrial ecotoxicity showed a decline in midpoint impact performance. Table 4.15 shows the detailed environmental quantification difference for the midpoint impact of ecosystem quality.

**Table 4.15** Midpoint Impact of Ecosystem Quality.

| No | Impact categories | Unit | Base Scenario / Scenario 1 | Scenario 2 | % Difference |
|---|---|---|---|---|---|
| 1 | ecosystem quality - acidification: terrestrial | Species.year /kg $SO_2$ eq. | 1.47E-10 | 1.00E-10 | 31.87% |
| 2 | ecosystem quality - climate change: freshwater ecosystems | Species.year /kg $CO_2$ eq. | 2.09E-14 | 1.61E-14 | 22.72% |

| No | Impact categories | Unit | Base Scenario / Scenario 1 | Scenario 2 | % Difference |
|---|---|---|---|---|---|
| 3 | ecosystem quality - climate change: terrestrial ecosystems | Species.year /kg $CO_2$ eq. | 7.65E-10 | 5.91E-10 | 22.72% |
| 4 | ecosystem quality - ecotoxicity: freshwater | Species.year /kg 1,4-DBC emitted to freshwater eq. | 5.99E-12 | 4.85E-12 | 18.98% |
| 5 | ecosystem quality - ecotoxicity: marine | Species.year /kg 1,4-DBC emitted to sea water eq. | 1.25E-12 | 9.92E-13 | 20.54% |
| 6 | ecosystem quality - ecotoxicity: terrestrial | Species.year /kg 1,4-DBC emitted to industrial soil eq. | 1.68E-12 | 3.27E-12 | -94.95% |
| 7 | ecosystem quality - eutrophication: freshwater | Species.year /kg P to freshwater eq. | 2.15E-10 | 1.21E-10 | 43.83% |
| 8 | ecosystem quality - eutrophication: marine | Species.year /kg N to marine water eq. | 5.76E-14 | 4.34E-14 | 24.75% |
| 9 | ecosystem quality - land use | Species.year /($m^2$ annual crop eq) | 5.25E-12 | 1.29E-10 | -2354.46% |
| 10 | ecosystem quality - photochemical oxidant formation: terrestrial ecosystems | Species.year/kg NOx eq. | 6.94E-11 | 5.31E-11 | 23.43% |

| No | Impact categories | Unit | Base Scenario / Scenario 1 | Scenario 2 | % Difference |
|---|---|---|---|---|---|
| 11 | ecosystem quality - water use: aquatic ecosystems | Species.year /$m^3$ consumed | 1.93E-15 | 1.28E-15 | 33.78% |
| 12 | ecosystem quality - water use: terrestrial ecosystems | Species.year /$m^3$ consumed | 4.31E-11 | 2.85E-11 | 33.78% |

Freshwater eutrophication adds nutrients, particularly nitrogen and phosphorus compounds, to water, which accelerates the development of algae and other higher plants and disturbs the natural balance of organisms and the water's quality (Farley, 2012). Eutrophication in freshwater significantly increased its environmental performance by around 43.83% by implementing scenario 2. Our result shows that lignite energy generation releases approximately 0.83 grams of phosphate. The reduction in lignite energy mix proportion from 24.197% in scenario 1 to 12.36% in scenario 2 has the potential to reduce phosphate emissions to around 0.42 grams. This decrease led to a reduction in eutrophication's severity.

Moreover, water use in aquatic and terrestrial ecosystems also shows the increase of performance. Based on the results, the use of aquatic and terrestrial water is dominated by hydropower. The reduction in the large hydropower energy mix proportion from 19.5% in scenario 1 to 8% in scenario 2 correlates with the decrease in water use for energy purposes. Dorber et al., (2019) review that hydroelectric reservoir operation can lower the average annual discharge downstream by reducing the frequency and amplitude of the flow. This condition affects the aquatic and terrestrial ecosystems water use. Figures 4.14 (scenario 1) and 4.15 (scenario 2) show a comparison of water use in terrestrial ecosystems. While in Figures 4.16 (scenario 1) and 4.17 (scenario 2), the water use in aquatic ecosystems is compared.

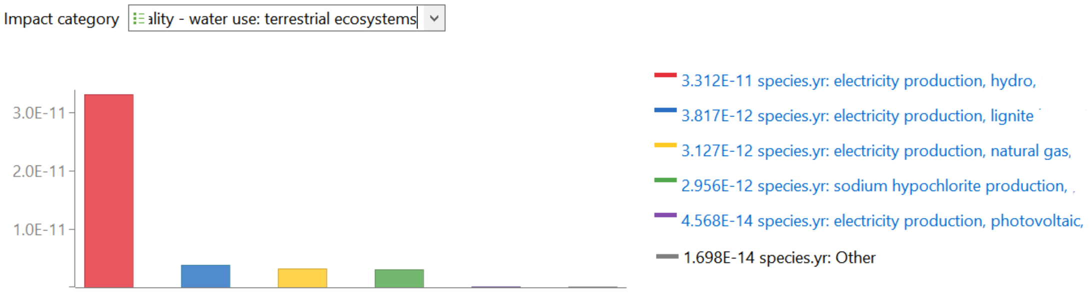


**Figure 4.14** Water Use in Terrestrial Ecosystem (scenario 1).

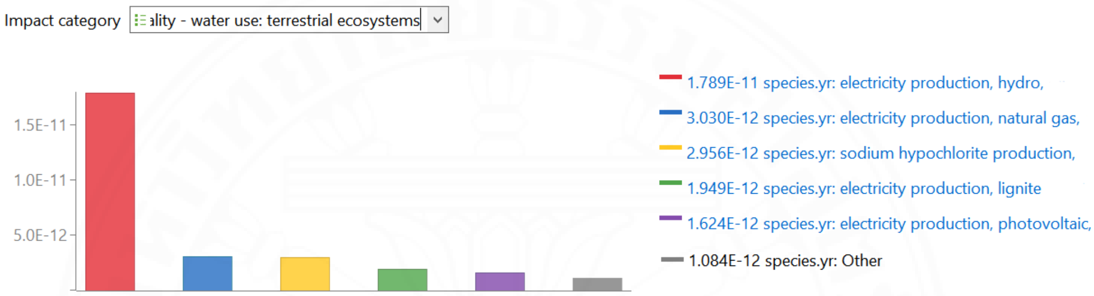


**Figure 4.15** Water Use in Terrestrial Ecosystem (scenario 2).

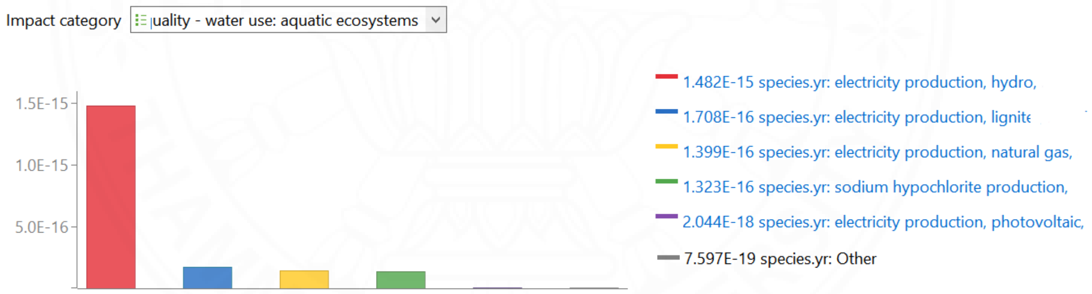


**Figure 4.16** Water Use in Aquatic Ecosystem (scenario 1).

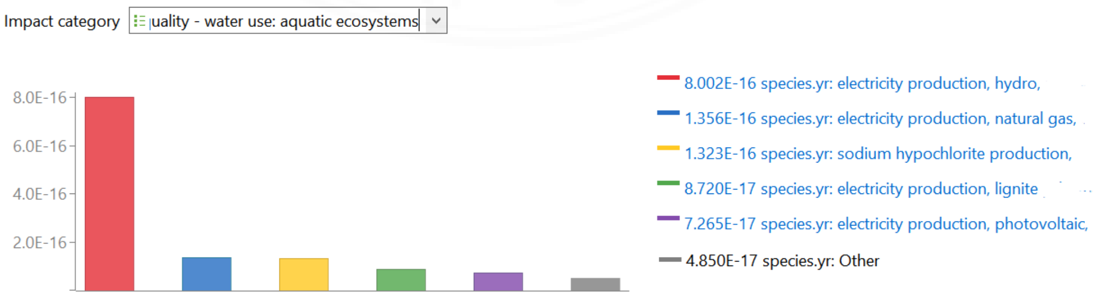


**Figure 4.17** Water Use in Aquatic Ecosystem (scenario 2).

Land use (annual crops, permanent crops, mosaic agriculture, forestry, urban land, pasture) refers to the relative loss of species caused by a particular land use type

(Huijbregts, Steinmann, Elshout, Stam, Verones, Vieira, Hollander, et al. 2017). The biomass power plant is planned to be built in southern Thailand (EPPO, 2018). There is a potential supply of rubber and woodchip in southern Thailand (Wongsapai et al. 2020). Around 4.16% of the biomass energy mix proportion in scenario 2, as shown in Figure 4.19, contributes to the 2,354.46% increase in land use midpoint impact compared to scenario 1, as shown in Figure 4.18. Apart from that, the government is also considering the possibility of increasing the use of biomass waste energy generation from bagasse as a viable option.

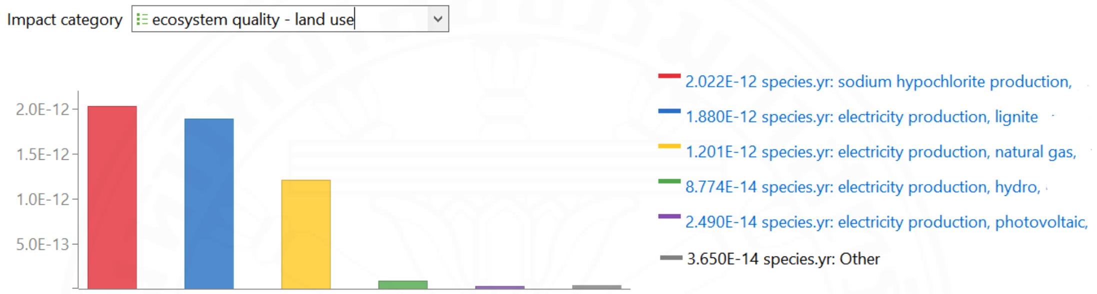


**Figure 4.18** Ecosystem Land Use (scenario 1).

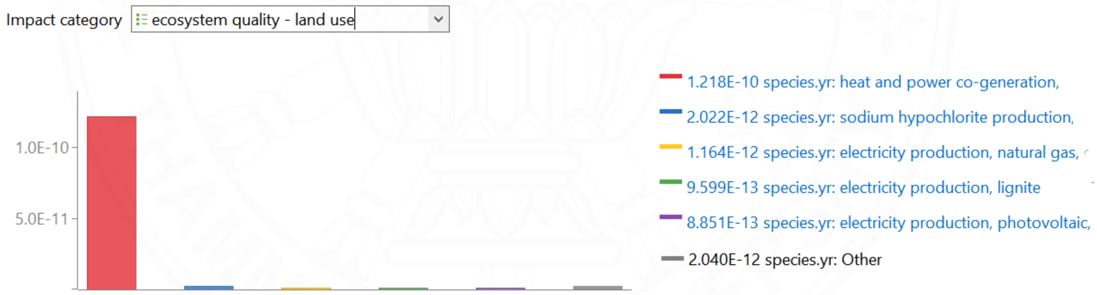


**Figure 4.19** Ecosystem Land Use (scenario 2).

Installing photovoltaics from Thai EGAT in scenario 2 significantly increases the impact of terrestrial ecotoxicity by 94.95%. Based on the process contribution analysis, terrestrial ecotoxicity is characterized by the 1,4-dichlorobenzene and nickel emitted in urban air, freshwater, seawater, and industrial soil (Huijbregts, Steinmann, Elshout, Stam, Verones, Vieira, Zijp, et al. 2017). In scenario 2, as shown in Figure 4.21, photovoltaic became the major contributor to ecotoxicity in terrestrial environments by releasing copper ions, showing a significant increase compared to scenario 1, as shown in Figure 4.20.

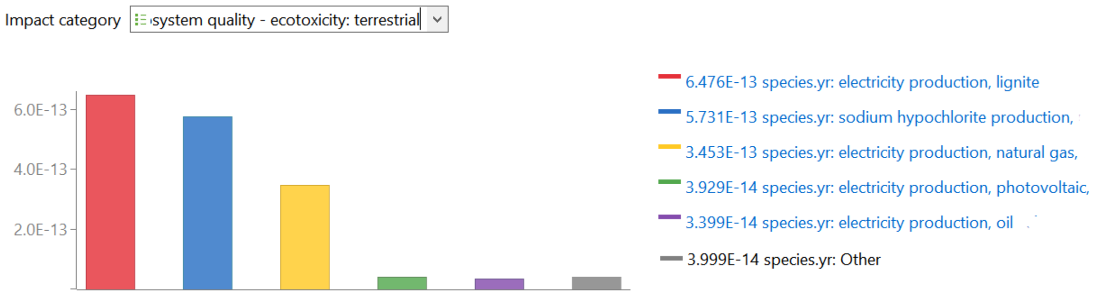


**Figure 4.20** Ecosystem Terrestrial Eco-Toxicity (scenario 1).

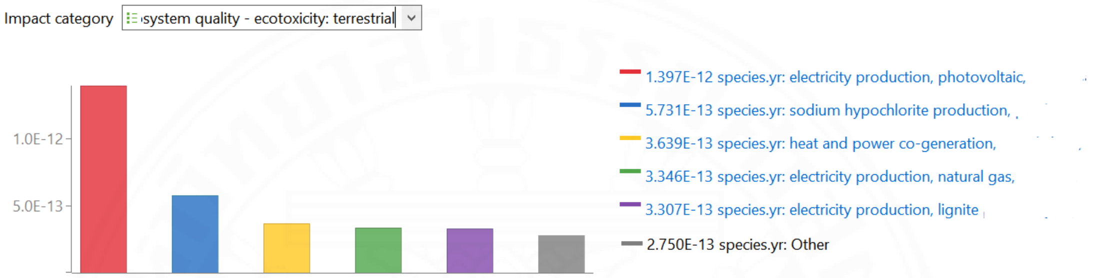


**Figure 4.21** Ecosystem Terrestrial Eco-Toxicity (scenario 2).

In general, scenario 2 increase overall human health midpoint environmental performance, especially human health impact on non-carcinogenic toxicity, carcinogenic toxicity and water use. Only ionising radiation and ozone depletion showed a decline in midpoint impact performance. Table 4.16 shows the detailed environmental quantification difference for the midpoint impact of human health.

**Table 4.16** Midpoint Impact of Human Health.

| No | Impact categories | Unit | Base Scenario / Scenario 1 | Scenario 2 | % Difference |
|---|---|---|---|---|---|
| 1 | human health - climate change: human health | DALY/kg $CO_2$ eq. | 2.53E-07 | 1.96E-07 | 22.72% |
| 2 | human health - human toxicity: carcinogenic | DALY/kg 1,4-DCB emitted to urban air eq. | 5.88E-08 | 3.89E-08 | 33.89% |

| No | Impact categories | Unit | Base Scenario / Scenario 1 | Scenario 2 | % Difference |
|---|---|---|---|---|---|
| 3 | human health - human toxicity: non-carcinogenic | DALY/kg 1,4-DCB emitted to urban air eq. | 7.40E-08 | 4.69E-08 | 36.55% |
| 4 | human health - ionising radiation | DALY/kBq Co-60 emitted to air eq. | 1.24E-11 | 1.65E-11 | -33.14% |
| 5 | human health - ozone depletion | DALY/kg CFC11 eq. | 2.94E-11 | 3.06E-11 | -3.94% |
| 6 | human health - particulate matter formation | DALY/kg PM2.5 eq. | 1.84E-07 | 1.31E-07 | 28.66% |
| 7 | human health - photochemical oxidant formation: human health | DALY/kg NOx eq. | 4.74E-10 | 3.59E-10 | 24.28% |
| 8 | human health - water use: human health | DALY/$m^3$ consumed | 7.09E-09 | 4.69E-09 | 33.78% |

Insofar as they are connected to non-cancer consequences, human toxicity non-carcinogenic describes the harmful health effects on humans brought on by the hazardous chemicals by ingestion of food or drink, skin penetration, or air inhalation. Human toxicity non-carcinogenic environmental performance in scenario 2 is improved by 36.55% compared to scenario 1. In scenario 2, as shown in Figure 4.23, lignite became the major contributor to non-carcinogenic human toxicity by releasing zinc II and arsenic ions, showing a significant increase compared to scenario 1, as shown in Figure 4.22.

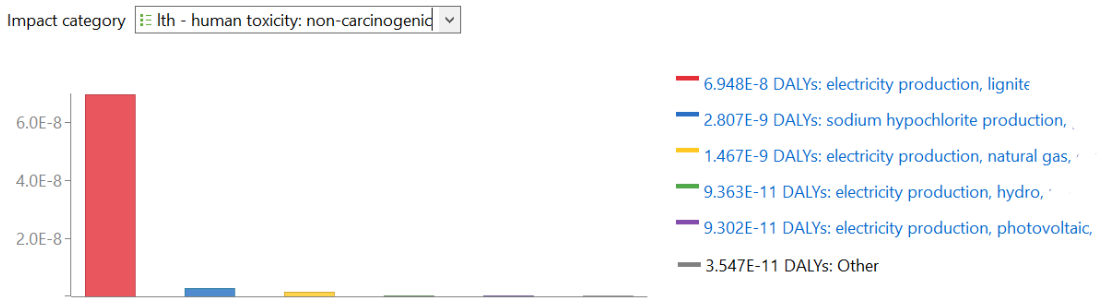


**Figure 4.22** Human Toxicity Non-carcinogenic (scenario 1).

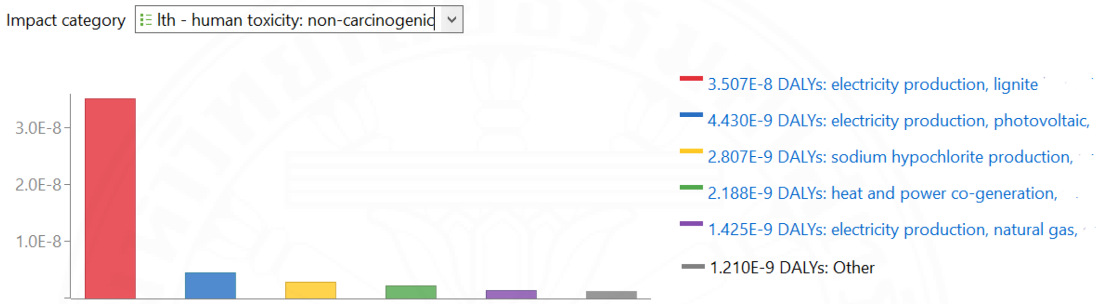


**Figure 4.23** Human Toxicity Non-carcinogenic (scenario 2).

According into modeling scheme of characterization factors for the effects of water consumption on human health use a water stress index (WSI) (Huijbregts, Steinmann, Elshout, Stam, Verones, Vieira, Hollander, et al. 2017), insufficient irrigation will result in lower crop yields, leading to increased malnutrition among the local population. Implementing Scenario 2 as shown in Figure 4.25, reduces overall human health and environmental impacts compared to scenario 1 as shown in Figure 4.24. In particular, increasing the reservoir area contributes to a 33.78% reduction in the human health impact of water use due to increased irrigation.

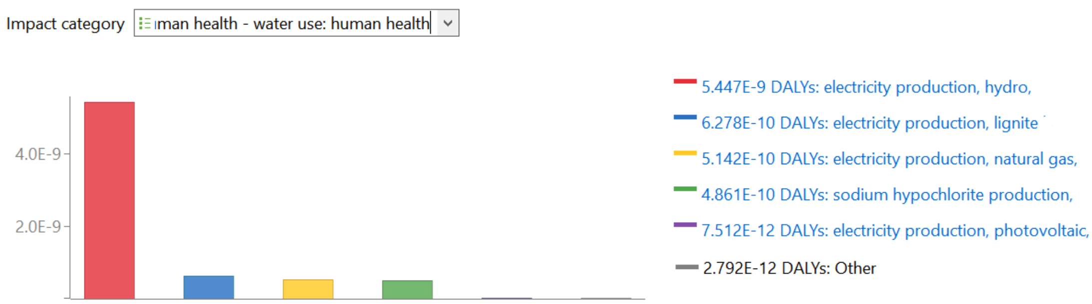


**Figure 4.24** Water Use in Human Health (scenario 1).

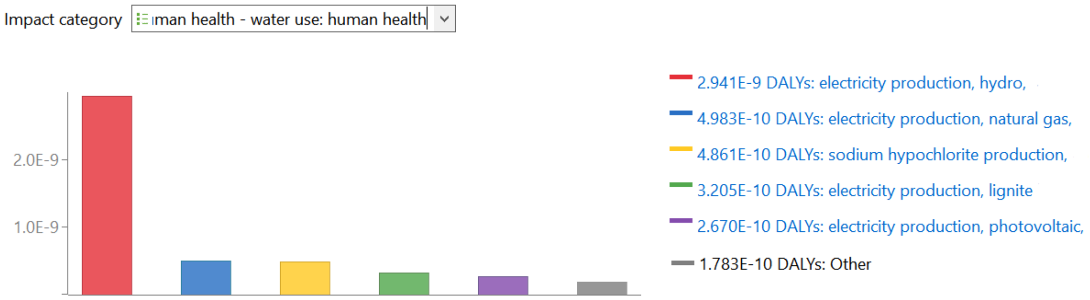


**Figure 4.25** Water Use in Human Health (scenario 2).

Human toxicity is carcinogenic, which means it has the potential to cause cancer. Lignite is a major contributor to human toxicity by releasing chromium VI. Human toxicity non-carcinogenic accounts for the adverse health effects on human beings caused by the intake of toxic substances through inhalation of air, food/water ingestion, and penetration through the skin insofar as they are related to non-cancer effects. Human toxicity carcinogenic environmental performance in scenario 2 is improved by 33.89% compared to scenario 1. In scenario 2, as shown in Figure 4.27, lignite became the major contributor to carcinogenic human toxicity by releasing zinc II and arsenic ions, showing a significant increase compared to scenario 1, as shown in Figure 4.26.

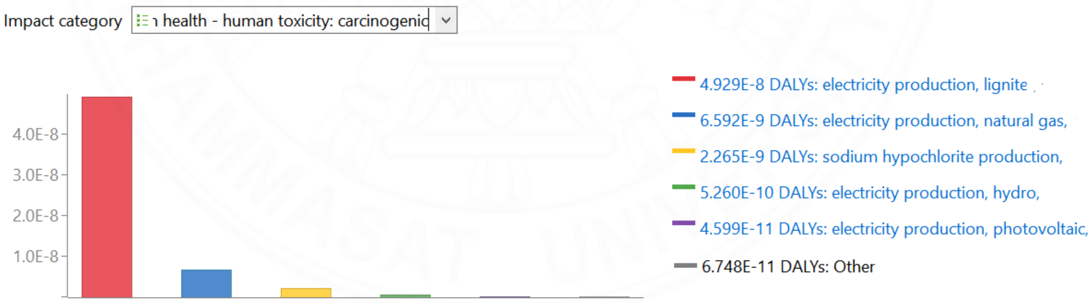


**Figure 4.26** Human Toxicity Carcinogenic (scenario 1).

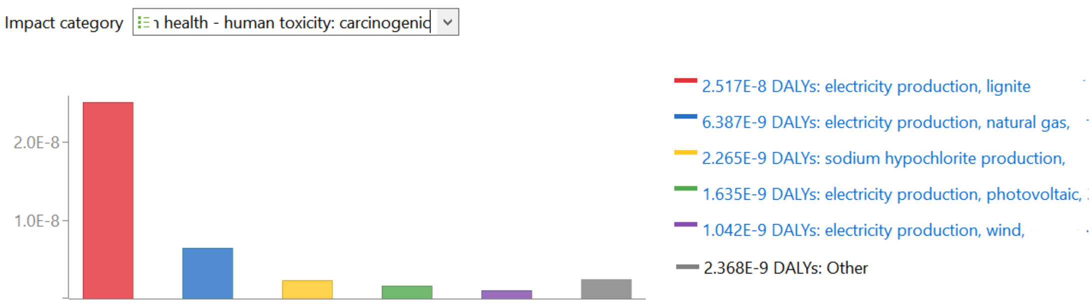


**Figure 4.27** Human Toxicity Carcinogenic (scenario 2).

The cumulative dosage of cancer incidence plus the disability weight per cancer type determines how ionizing radiation affects human health (Huijbregts, Steinmann, Elshout, Stam, Verones, Vieira, Zijp, et al. 2017). Damage to DNA molecules can result from exposure to the ionizing radiation produced by these radionuclides. Other human activities that can produce anthropogenic radionuclide emissions include burning coal and extracting phosphate rock (Huijbregts, Steinmann, Elshout, Stam, Verones, Vieira, Hollander, et al. 2017). Both in scenario 1 and 2, as shown in Figure 4.28 and Figure 4.29, sodium hypochlorite production became the major contributor to ionizing radiation on human health by 33.14% by releasing copper ions emitting Radon-222 and Carbon-14.


**Figure 4.28** Ionizing Radiation in Human Health (scenario 1).

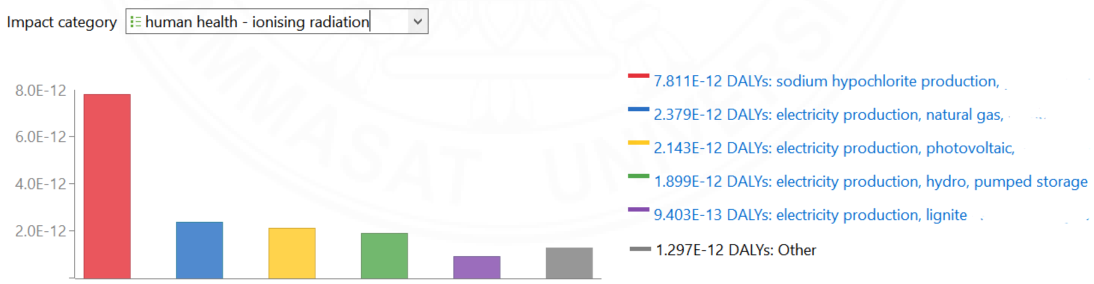


**Figure 4.29** Ionizing Radiation in Human Health (scenario 2).

The human health effect of a decrease in stratospheric ozone concentration is increased by an increase in UVB radiation and the burden of disease (skin cancer and cataracts) (Huijbregts, Steinmann, Elshout, Stam, Verones, Vieira, Hollander, et al., 2017). Even though natural gas became a major contributor in both scenario 1 and scenario 2 by emitting dinitrogen monoxides, as shown in Figure 4.30 and Figure 4.31, the decline in coal power generation can reduce the contribution to ozone depletion.

However, at the same time, heat and power generation in scenario 2 make a significant contribution to ozone depletion, as shown in Figure 4.31.

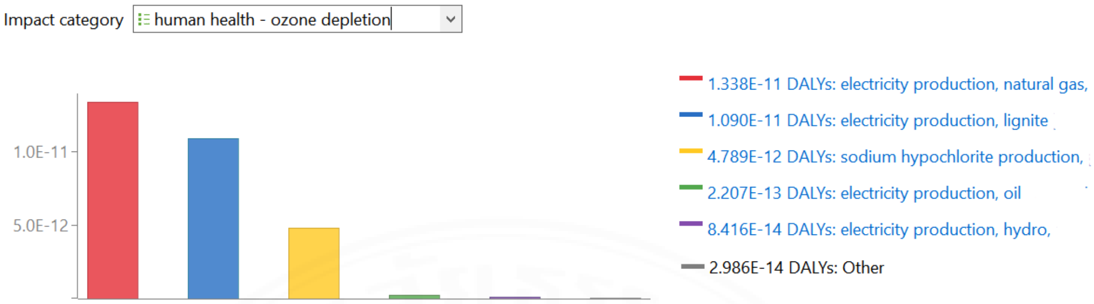


**Figure 4.30** Ozone Depletion in Human Health (scenario 1).

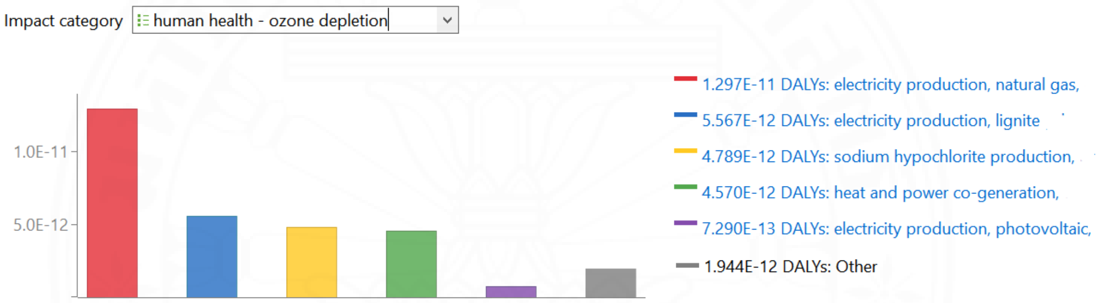


**Figure 4.31** Ozone Depletion in Human Health (scenario 2).

The natural resource impact of non-renewable fossils showed an increase in midpoint impact performance of 0.55%. While the natural resource impact of metals and minerals showed a significant decline in midpoint impact performance by -8.33%. Table 4.17 shows the detailed environmental quantification difference for the midpoint impact of natural resources.

**Table 4.17** Midpoint Impact of Natural Resources.

| No | Impact categories | Unit | Base Scenario / Scenario 1 | Scenario 2 | % Difference |
|---|---|---|---|---|---|
| 1 | natural resources - energy resources: non-renewable, fossil | USD2013 /kg | 0.01649 | 0.0164 | 0.55% |
| 2 | natural resources - material resources: metals/minerals | USD2013 /kg Cu | 0.00048 | 0.00052 | -8.33% |

Regarding the use of natural resources (natural gas), which has significantly decreased, there is only a small reduction in natural gas costs, from 0.016 USD in 2013 on scenario 1 (as shown in Figure 4.32) to 0.015 USD in 2013 on scenario 2 (as shown in Figure 4.33).

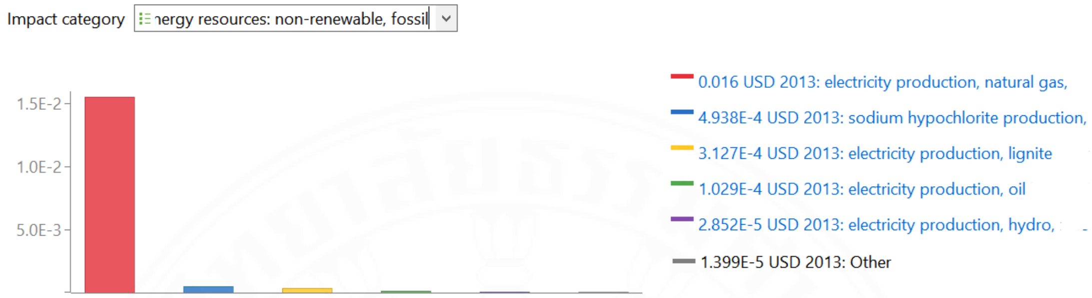


**Figure 4.32** Non-Renewable Fossil in Natural Resources (scenario 1).

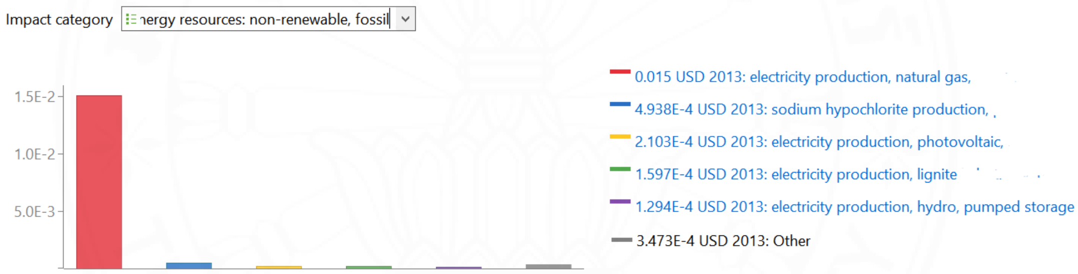


**Figure 4.33** Non-Renewable Fossil in Natural Resources (scenario 2).

The overuse of natural resources and minerals can have detrimental effects on the ecosystem. Unsustainable mineral and metal extraction affects resource depletion (Xiong et al. 2023). This section compares fossil fuels using the energy content perspective instead of the scarcity perspective to quantify the true pricing technique (Galgani et al. 2021). Sodium hypochlorite became a major contributor by consuming cerium. While a significant increase in the total environmental impact of natural resources comes from photovoltaics. Furthermore, installing photovoltaics in scenario 2, as shown in Figure 4.35, compared to scenario 1, as shown in Figure 4.34, significantly increases the impact of metal and mineral usage from natural resources by 8.3%.

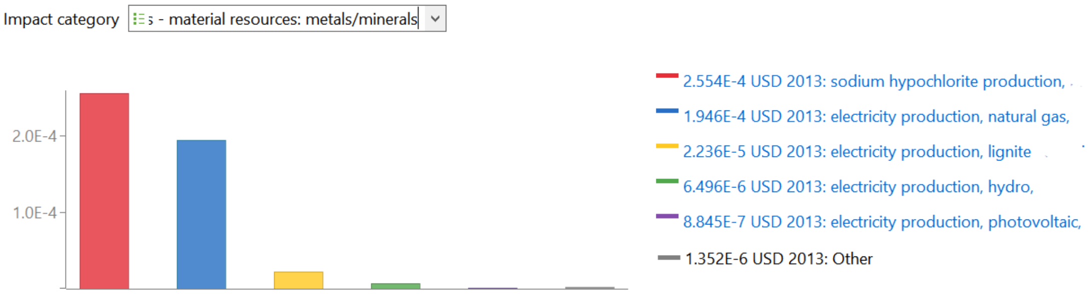


**Figure 4.34** Metal/mineral in Natural Resources (scenario 1).

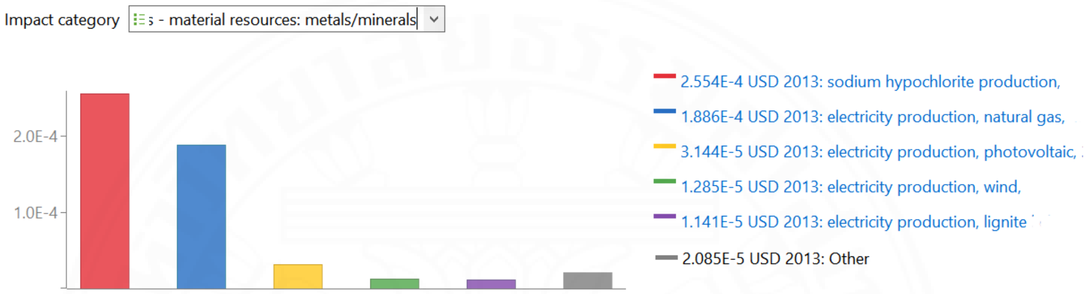


**Figure 4.35** Metal/mineral on Natural Resources (scenario 2).

### 4.4.2 Comparative endpoint impact assessment

The life cycle inventory results were characterized into a midpoint impact category, then transformed again to the endpoint impact. Based on a hierarchical (H) perspective, a weighting of 100 years was selected to convert the midpoint to the endpoint. The increase or decrease rates in impact assessment are intricately linked to the characterization factors assigned to each midpoint impact.

#### 4.4.2.1 Total ecosystem quality

The Total Ecosystem Quality (TEQ) impact category serves as a comprehensive indicator for various environmental stressors on ecosystem. Damage to ecosystem quality in ReCiPe2016 refers to the aggregated local loss of species over space and time (Huijbregts, Steinmann, Elshout, Stam, Verones, Vieira, Hollander, et al. 2017). Global species extinction can also be considered an indicator of ecosystem quality and local species loss. In general, total ecosystem quality in scenario 2 shows a significant increase in good performance compared to scenario 1. The comparative total ecosystem quality endpoint impact is shown in Figure 4.36.

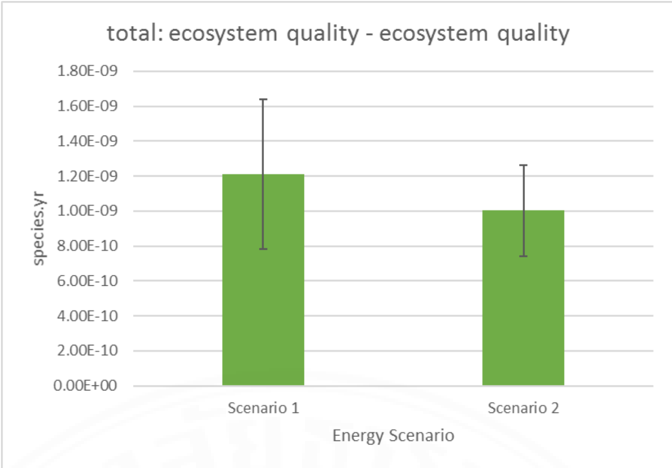


**Figure 4.36** Total Ecosystem Quality Endpoint Impact.

As illustrated in Figure 4.37, a major contributor to total ecosystem quality in scenario 1, the energy sector emerges as the dominant factor influencing ecosystem quality, contributing a substantial 96% to the overall risk. The remaining contributors, though less significant, still warrant attention. Chemical production occupies the second position by contributing, 4%, followed by direct emissions from unit operations, chemical transportation, and other miscellaneous sources.

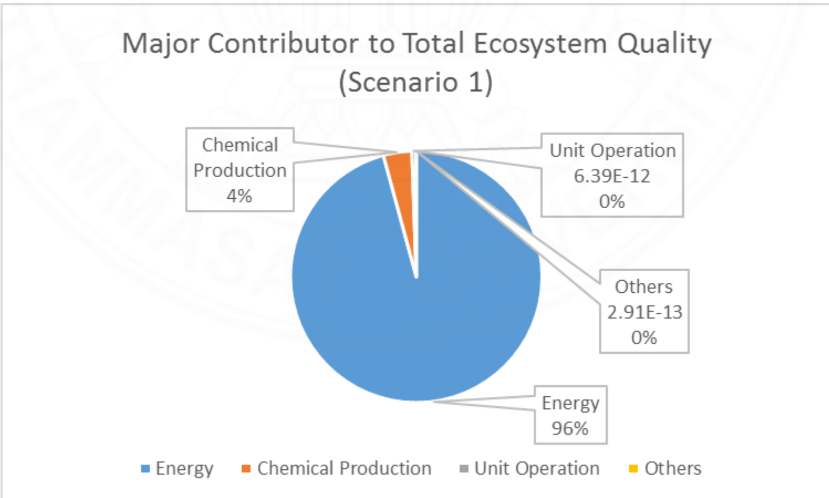


**Figure 4.37** Major Contributor to Total Ecosystem Quality (scenario 1).

As illustrated in Figure 4.38, a major contributor to total ecosystem quality in scenario 2, the energy sector emerges as the dominant factor influencing ecosystem quality, contributing a substantial 95% to the overall risk. The remaining contributors, though less significant, still warrant attention. Chemical production occupies the second position by contributing, 4%, followed by other miscellaneous sources.

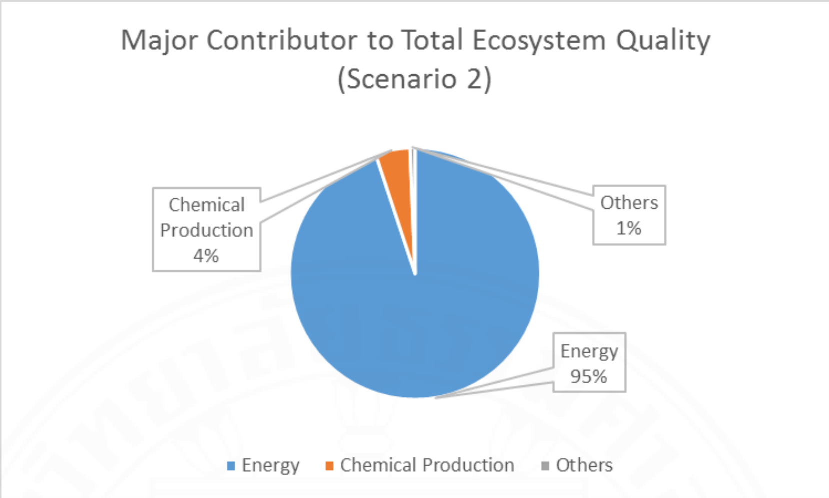


**Figure 4.38** Major Contributor to Total Ecosystem Quality (scenario 2).

As illustrated in Figure 4.39, around 63% of electricity production comes from lignite, and 30% comes from natural gas, the highest contributor to the total ecosystem quality (TEQ) impact of scenario 1. Then, in scenario 2, decreasing the percentage of lignite reduces the contribution by 50%.

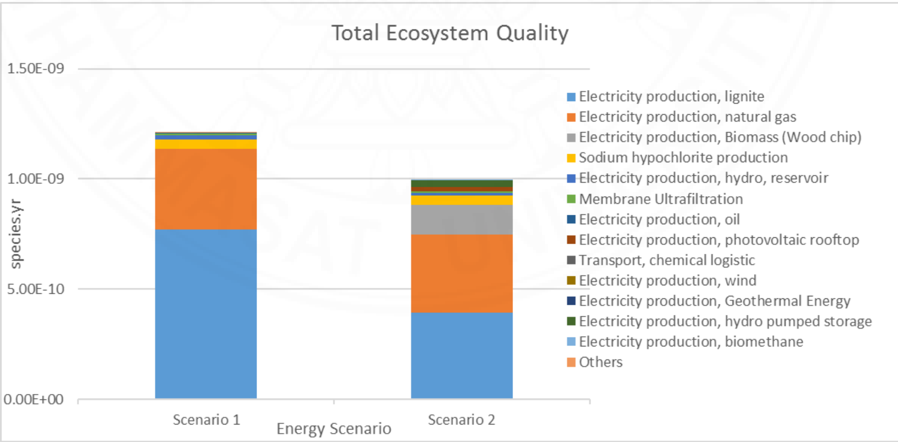


**Figure 4.39** Contribution Analysis of Total Ecosystem Quality.

However, biomass energy generation contributes a significant increase in the overall endpoint impact of scenario 2, even though the increase in proportion in the energy mix is not significant. Biomass in mixed energy is divided into wood pellet biomass and waste biomass. Wood pellet biomass makes a significant contribution because it affects land use, as mentioned in the midpoint impact assessment in the previous sub-chapter.

#### 4.4.2.2 Total Human Health

The Total Human Health (THH) impact category is a comprehensive metric that integrates various health endpoints, including, but not limited to, respiratory illnesses, carcinogenic risks, and neurological disorders arising from exposure to pollutants and other environmental hazards. Total human health is quantified as DALYs (disability-adjusted life years), which representing the years lost or disabled due to a disease or accident. In general, total human health in scenario 2 shows a significant increase in good performance compared to scenario 1. The comparative total human health endpoint impact is shown in Figure 4.40.

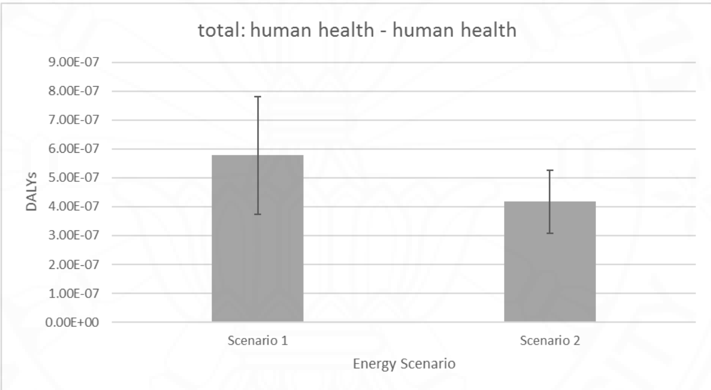


**Figure 4.40** Total Human Health Endpoint Impact.

As illustrated in Figure 4.41, a major contributor to total human health in scenario 1, the energy sector emerges as the dominant factor influencing human health, contributing a substantial 95% to the overall risk. The remaining contributors, though less significant, still warrant attention. Chemical production occupies the second position, followed by direct emissions from unit operations, chemical transportation, and other miscellaneous sources.

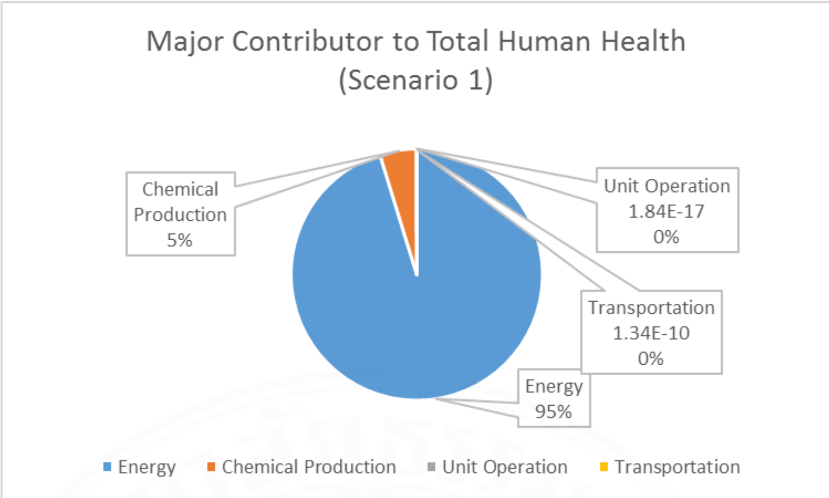


**Figure 4.41** Major Contributor to Total Human Health (scenario 1).

As illustrated in Figure 4.42, a major contributor to total human health in scenario 2, the energy sector emerges as the dominant factor influencing human health, contributing a substantial 93% to the overall risk. The remaining contributors, though less significant, still warrant attention. Chemical production occupies the second position by contributing, 7%, followed by other miscellaneous sources.

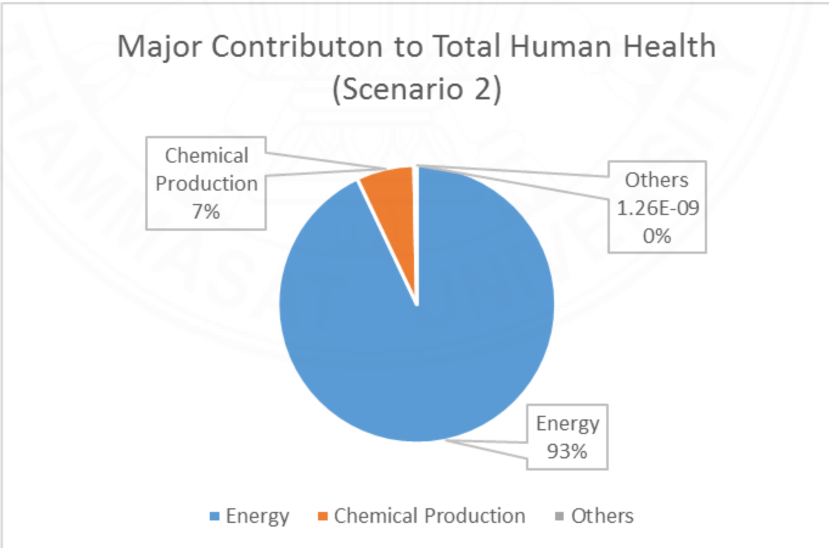


**Figure 4.42** Major Contributor to Total Human Health (scenario 2).

In this context, contribution analysis emerges as a pivotal analytical approach, aiming to dissect and quantify the relative influences of different stressors and activities on overall human health outcomes. As illustrated in Figure 4.43, electricity production from lignite and electricity production from natural gas become the highest contributors to the total human health impact category of scenario 1. Apart from fossil energy and sodium hypochlorite production, the implementation of solar photovoltaic also shows an increase in the impact contribution to the total human health impact.

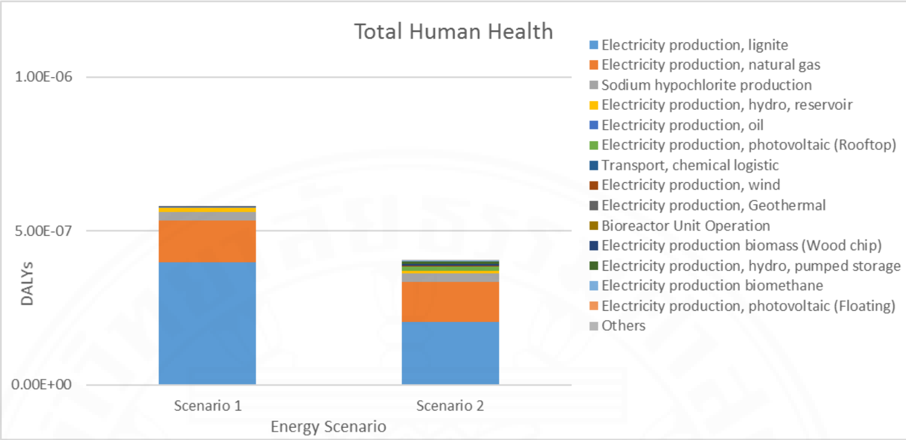


**Figure 4.43** Contribution Analysis of Total Human Health.

### 4.4.2.3 Total natural resources

The Total Natural Resources (TNR) impact category holds particular significance, serving as a comprehensive measure of the utilization and depletion of natural resources within a given system. TNR encompasses a broad spectrum of resources, including water, soil, minerals, energy sources, and biodiversity, reflecting the interconnectedness of ecological, economic, and social dimensions inherent in resource management. Total natural resources are quantified in USD, representing resource scarcity due to the conversion from surplus ore to surplus costs. In general, total natural resources in scenario 2 show a little increase in good performance compared to scenario 1. The comparative total natural resource endpoint impact is shown in Figure 4.44.

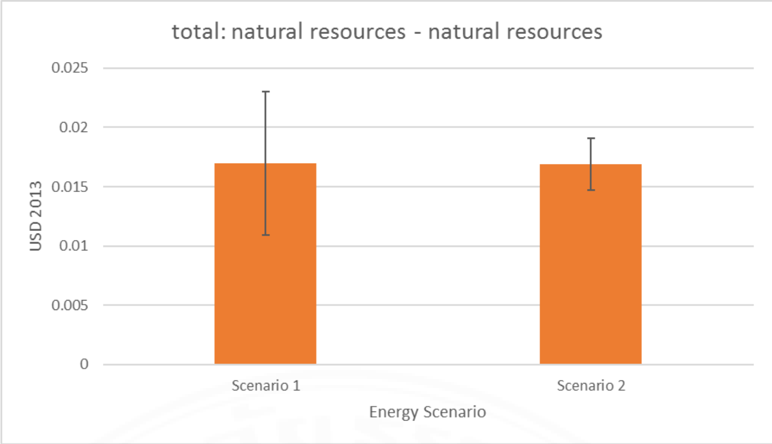


**Figure 4.44** Total Natural Resources Endpoint Impact.

As illustrated in Figure 4.45, a major contributor to total natural resources in scenario 1, the energy sector emerges as the dominant factor influencing natural resources, contributing a substantial 96% to the overall risk. The remaining contributors, though less significant, still warrant attention. Chemical production occupies the second position by contributing, 4%, followed by other miscellaneous sources.

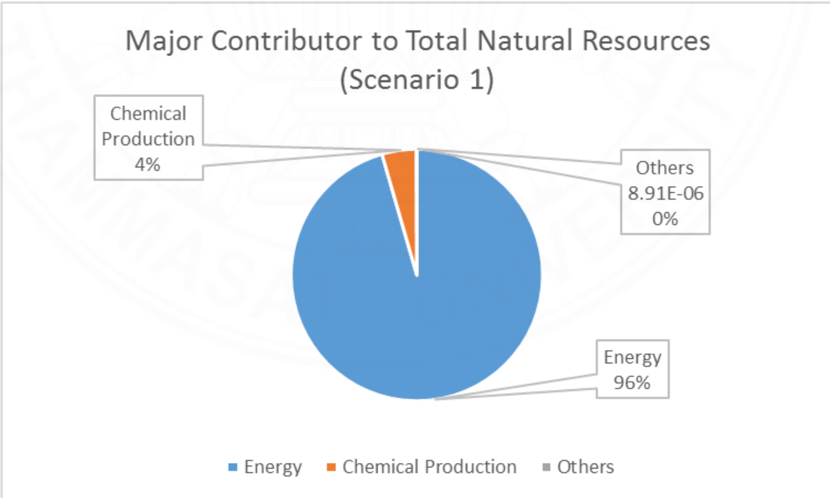


**Figure 4.45** Major Contributor to Total Natural Resources (scenario 1).

As illustrated in Figure 4.46, a major contributor to total natural resources in scenario 2, the energy sector emerges as the dominant factor influencing natural resources, contributing a substantial 96% to the overall risk. The remaining contributors, though less significant, still warrant attention. Chemical production occupies the second position by contributing, 4%, followed by other miscellaneous sources.

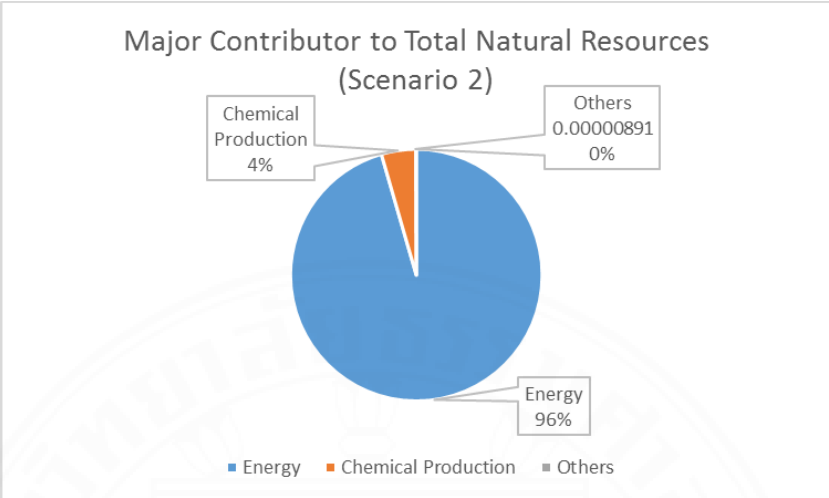


**Figure 4.46** Major Contributor to Total Natural Resources (scenario 2).

As illustrated in Figure 4.47, natural gas, followed by sodium hypochlorite production, is the main contributor to the total natural resource endpoint impact. In scenario 2, although the proportion of solar photovoltaic is below lignite, solar photovoltaic beats lignite energy generation in terms of impact contribution.

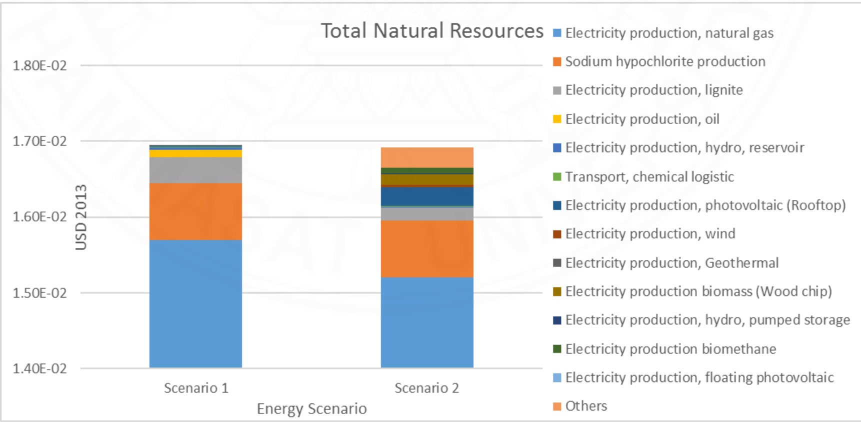


**Figure 4.47** Contribution Analysis of Total Natural Resources.

At the total ecosystem quality impact endpoint, environmental performance increased by 17.11% as illustrated in Table 4.18. Based on contribution analysis, the increase in performance is due to a reduction in the percentage of electricity generation from coal in the 2037 energy mix scenario.

Meanwhile, on the total human health impact endpoint, there was a significant increase in environmental performance of 27.65%. Based on the contribution analysis, the increase in performance is also due to a reduction in the percentage of electricity generation from coal in the 2037 energy mix scenario. Then, although not significant, the increase in solar PV contribution is quite high in the 2037 energy mix. Furthermore, the total natural resource environmental performance also increased by 0.29%. This condition is due to the increase in solar PV contribution.

**Table 4.18** Endpoint Impact.

| No | Impact categories | Unit | Base Scenario / Scenario 1 | Scenario 2 | % Difference |
|---|---|---|---|---|---|
| 1 | total: ecosystem quality - ecosystem quality | species.yr | 1.21E-09 | 1.00E-09 | 17.11% |
| 2 | total: human health - human health | DALYs | 5.77E-07 | 4.18E-07 | 27.65% |
| 3 | total: natural resources - natural resources | USD 2013 | 0.01697 | 0.01692 | 0.29% |

### 4.5 Uncertainty analysis of input parameter

The sensitivity analysis method using Monte Carlo simulation was applied to this work. In this study, we model 200 times iterations with a 95% confidence interval for each inventory data based on the scenario. The Monte Carlo simulation run using Open LCA with input and output inventory data then linked to impact characterization factors. Thus, the result will sum up the emission on the specific impact category. The study focused on the midpoint-endpoint impact category.

The output of the Monte Carlo Simulation is a histogram with the x-axis representing the different outcomes while the y-axis represents the number of outcomes. The uncertainty data were traced through the statistical parameters, including standard deviation and data range. If the standard deviation is large compared to the mean, the data is more spread out, indicating higher uncertainty. This study estimates the uncertainty analysis for existing scenario 1 and the future energy projection scenario in 2037.

### 4.5.1 Inventory data of scenario 1

In the following analysis, a random number generator is employed to facilitate Monte Carlo simulations, enabling a robust examination of the variability and uncertainty within the system. This statistical approach leverages random sampling to generate a wide range of possible outcomes, thereby providing a comprehensive understanding of potential system behaviors under different scenarios. In scenario 1, the Thailand energy mix shows that 20.47% of energy consumption is from Renewable Energy and 79.53% from Non-renewable Energy. The Monte Carlo simulation of scenario 1 is shown in Figures 4.48, 4.49, and 4.50. The subsequent figures present the output of these simulations, with outliers systematically removed to ensure a clearer and more accurate representation of the data trends and patterns.

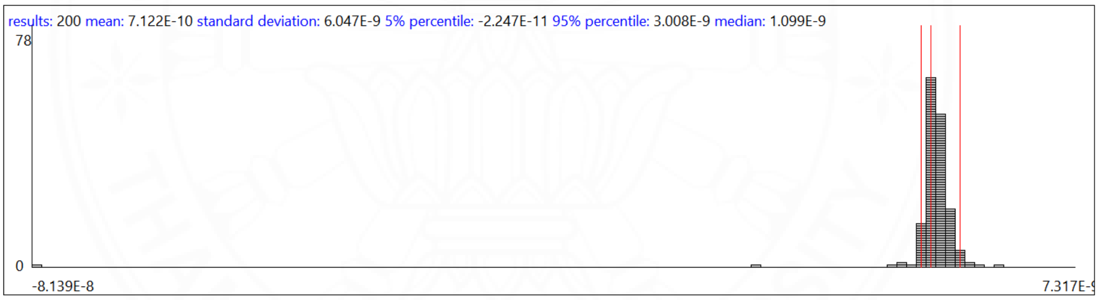


**Figure 4.48** Random Number Generated of Total Ecosystem Quality Inventory Data (scenario 1).

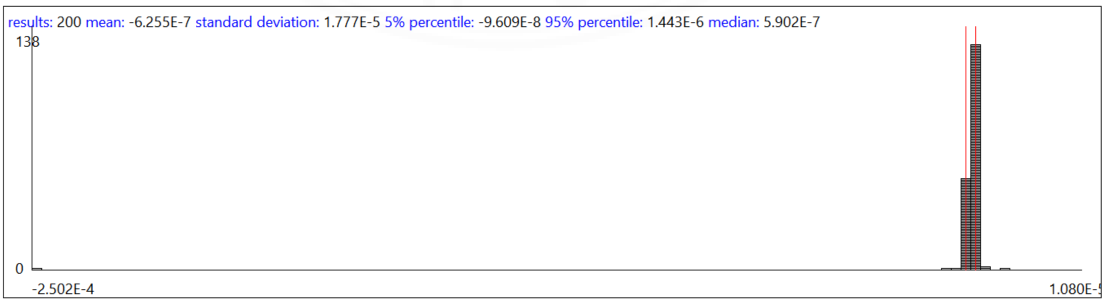


**Figure 4.49** Random Number Generated of Total Human Health Inventory Data (scenario 1).

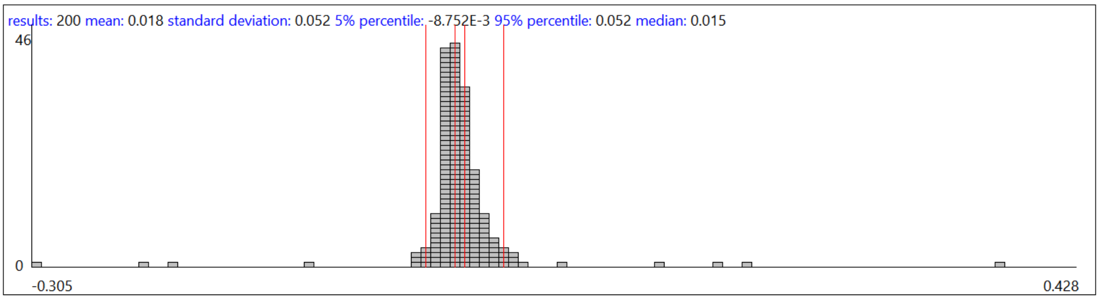


**Figure 4.50** Random Number Generated of Total Natural Resources Inventory Data (scenario 1).

Based on the simulation results, total human health in Figure 4.49 shows that the results generated by the random generator are highly likely to fall near the mean compared to total ecosystem quality and total natural resources.

In Scenario 1, the direct emissions from the WWTP constitute a significant source of uncertainty, influencing the total ecosystem quality uncertainty. These emissions include various pollutants such as nitrogen compounds, phosphorus, and greenhouse gases. However, the areas of improvement are outside of the study boundary because they involve the performance of unit operations. So, in this study, the uncertainty in each impact is depicted in the results without a further reduction process. Then transportation sludge and non-renewable energy also contribute uncertainty overall endpoint impact. The impact of these parameters will be further measured in a sensitivity analysis. The detailed Monte Carlo simulation scenario 1 inventory data is shown in Table 4.19.

**Table 4.19** Monte Carlo Simulation of Scenario 1.

| No | Impact category | Reference unit | Mean | Standard deviation |
|---|---|---|---|---|
| 1 | ecosystem quality - acidification: terrestrial | Species.year /kg $SO_2$ eq. | 8.62216E-11 | 7.37186E-10 |
| 2 | ecosystem quality - climate change: freshwater ecosystems | Species.year /kg $CO_2$ eq. | 1.22484E-14 | 1.04961E-13 |

| No | Impact category | Reference unit | Mean | Standard deviation |
|---|---|---|---|---|
| 3 | ecosystem quality - climate change: terrestrial ecosystems | Species.year /kg $CO_2$ eq. | 4.48403E-10 | 3.84253E-09 |
| 4 | ecosystem quality - ecotoxicity: freshwater | Species.year /kg 1,4-DBC emitted to freshwater eq. | 3.52253E-12 | 3.00542E-11 |
| 5 | ecosystem quality - ecotoxicity: marine | Species.year /kg 1,4-DBC emitted to sea water eq. | 4.40228E-14 | 1.66689E-13 |
| 6 | ecosystem quality - ecotoxicity: terrestrial | Species.year /kg 1,4-DBC emitted to industrial soil eq. | 1.00913E-12 | 8.29183E-12 |
| 7 | ecosystem quality - eutrophication: freshwater | Species.year /kg P to freshwater eq. | 1.28322E-10 | 1.04813E-09 |
| 8 | ecosystem quality - eutrophication: marine | Species.year /kg N to marine water eq. | 4.40228E-14 | 1.66689E-13 |
| 9 | ecosystem quality - land use | Species/($m^2$·annual crop eq) | 3.16631E-12 | 2.58753E-11 |
| 10 | ecosystem quality - photochemical oxidant formation: terrestrial ecosystems | Species.year /kg NOx eq. | 4.07321E-11 | 3.48449E-10 |
| 11 | ecosystem quality - water use: aquatic ecosystems | Species.year /$m^3$ consumed | 1.13335E-15 | 9.66874E-15 |
| 12 | ecosystem quality - water use: terrestrial ecosystems | Species.year /$m^3$ consumed | 2.53315E-11 | 2.16106E-10 |
| 13 | human health - climate change: human health | DALY/kg $CO_2$ eq. | 1.48598E-07 | 1.27339E-06 |

| No | Impact category | Reference unit | Mean | Standard deviation |
|---|---|---|---|---|
| 14 | human health - human toxicity: carcinogenic | DALY/kg 1,4-DCB emitted to urban air eq. | 3.44824E-08 | 2.95382E-07 |
| 15 | human health - human toxicity: non-carcinogenic | DALY/kg 1,4-DCB emitted to urban air eq. | 4.3391E-08 | 3.71727E-07 |
| 16 | human health - ionising radiation | DALY/kBq Co-60 emitted to air eq. | 7.59816E-12 | 6.01409E-11 |
| 17 | human health - ozone depletion | DALY/kg CFC11 eq. | 1.74196E-11 | 1.46702E-10 |
| 18 | human health - particulate matter formation | DALY/kg PM2.5 eq. | 1.07894E-07 | 9.20403E-07 |
| 19 | human health - photochemical oxidant formation: human health | DALY/kg NOx eq. | 2.78419E-10 | 2.38163E-09 |
| 20 | human health - water use: human health | DALY/$m^3$ consumed | 4.16563E-09 | 3.55374E-08 |
| 21 | natural resources - energy resources: non-renewable, fossil | USD2013 /kg | 0.009664662 | 0.082887817 |
| 22 | natural resources - material resources: metals/minerals | USD2013 /kg Cu | 0.000293298 | 0.002351747 |
| 23 | total: ecosystem quality - ecosystem quality | species.yr | 7.12167E-10 | 6.04703E-09 |
| 24 | total: human health - human health | DALYs | 3.38834E-07 | 2.89902E-06 |
| 25 | total: natural resources - natural resources | USD 2013 | 0.00995796 | 0.08523616 |

### 4.5.2 Inventory data of scenario 2

In Scenario 2, the Monte Carlo simulation utilizes a random number generator similar to the approach in Scenario 1, but with increased complexity due to incorporating a more diverse energy mix. The Monte Carlo simulation of scenario 2 is shown in Figures 4.51, 4.52, and 4.53.

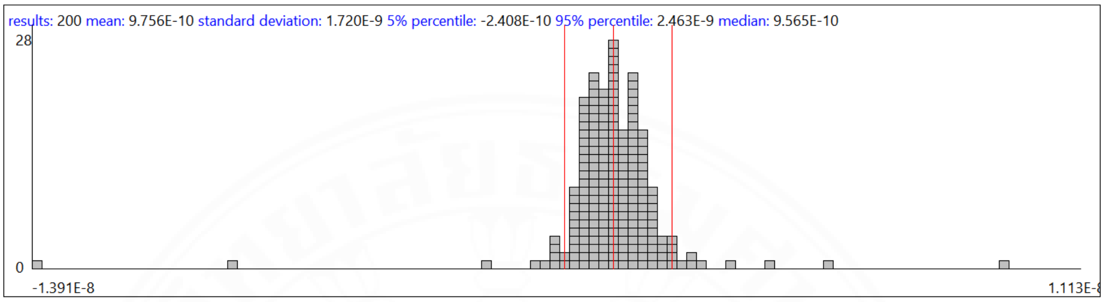


**Figure 4.51** Random Number Generated of Total Ecosystem Quality Inventory Data (scenario 2).

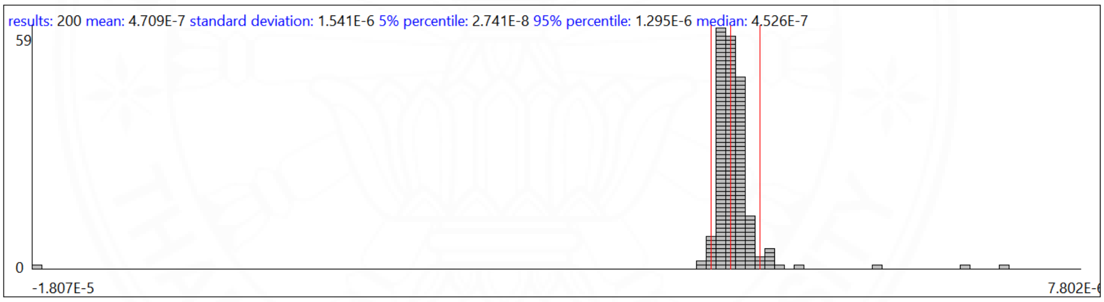


**Figure 4.52** Random Number Generated of Total Human Health Inventory Data (scenario 2).

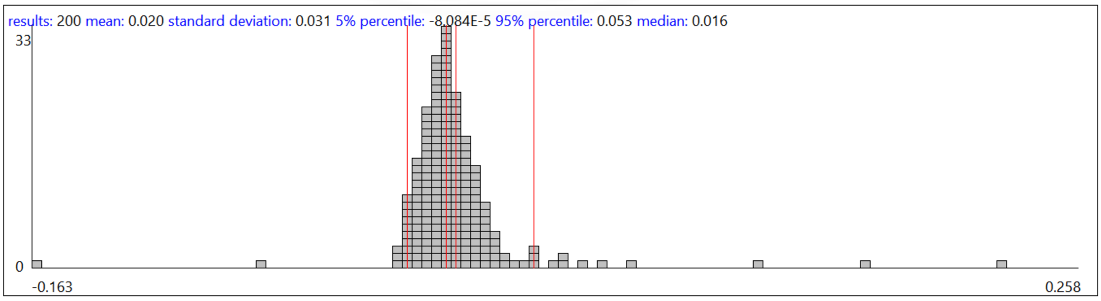


**Figure 4.53** Random Number Generated of Total Natural Resources Inventory Data (scenario 2).

In general, the inventory data in scenario 2 has a wider level of uncertainty compared to the inventory data in scenario 1. Characterization factors related to natural resources, particularly the increased use of metals, are a primary source of uncertainty in assessing the environmental impacts of resource extraction. Predicting future material demand for PV production is particularly challenging, as the anticipated rise in PV deployment will significantly escalate metal usage. One potential solution is the application of circular economy principles, such as incorporating recycled materials from other products into PV manufacturing, which warrants further investigation.

Apart from that, the machine's uncertainty flow and electrical requirements in Scenario 2 are greater, making the range even wider. To mitigate this uncertainty, optimizing machinery performance and implementing energy conservation can be effective strategies. These approaches not only enhance efficiency but also contribute to reducing the system's environmental footprint. The detailed Monte Carlo simulation scenario 2 inventory data is shown in Table 4.20.

**Table 4.20** Monte Carlo Simulation of Scenario 2.

| No | Impact category | Reference unit | Mean | Standard deviation |
|---|---|---|---|---|
| 1 | ecosystem quality - acidification: terrestrial | Species.year /kg $SO_2$ eq. | 1.12562E-10 | 3.69148E-10 |
| 2 | ecosystem quality - climate change: freshwater ecosystems | Species.year /kg $CO_2$ eq. | 1.81756E-14 | 5.95247E-14 |
| 3 | ecosystem quality - climate change: terrestrial ecosystems | Species.year /kg $CO_2$ eq. | 6.6543E-10 | 2.17927E-09 |
| 4 | ecosystem quality - ecotoxicity: freshwater | Species.year /kg 1,4-DBC emitted to freshwater eq. | 5.50276E-12 | 1.78352E-11 |
| 5 | ecosystem quality - ecotoxicity: marine | Species.year /kg 1,4-DBC emitted to sea water eq. | 1.12307E-12 | 3.64351E-12 |

| No | Impact category | Reference unit | Mean | Standard deviation |
|---|---|---|---|---|
| 6 | ecosystem quality - ecotoxicity: terrestrial | Species.year /kg 1,4-DBC emitted to industrial soil eq. | 3.68653E-12 | 1.2044E-11 |
| 7 | ecosystem quality - eutrophication: freshwater | Species.year /kg P to freshwater eq. | 1.35153E-10 | 4.2143E-10 |
| 8 | ecosystem quality - eutrophication: marine | Species.year /kg N to marine water eq. | 4.58518E-14 | 6.97724E-14 |
| 9 | ecosystem quality - land use | Species/($m^2$annual crop eq) | 1.45873E-10 | 4.7667E-10 |
| 10 | ecosystem quality - photochemical oxidant formation: terrestrial ecosystems | Species.year/kg NOx eq. | 5.99505E-11 | 1.96511E-10 |
| 11 | ecosystem quality - water use: aquatic ecosystems | Species.year /$m^3$ consumed | 1.43261E-15 | 4.70909E-15 |
| 12 | ecosystem quality - water use: terrestrial ecosystems | Species.year / $m^3$ consumed | 3.20204E-11 | 1.05253E-10 |
| 13 | human health - climate change: human health | DALY/kg $CO_2$ eq. | 2.20512E-07 | 7.22171E-07 |
| 14 | human health - human toxicity: carcinogenic | DALY/kg 1,4-DCB emitted to urban air eq. | 4.41618E-08 | 1.42791E-07 |
| 15 | human health - human toxicity: non-carcinogenic | DALY/kg 1,4-DCB emitted to urban air eq. | 5.29302E-08 | 1.73253E-07 |

| No | Impact category | Reference unit | Mean | Standard deviation |
|---|---|---|---|---|
| 16 | human health - ionising radiation | DALY/kBq Co-60 emitted to air eq.bin | 1.78603E-11 | 6.00848E-11 |
| 17 | human health - ozone depletion | DALY/kg CFC11 eq. | 3.43402E-11 | 1.13298E-10 |
| 18 | human health - particulate matter formation | DALY/kg PM2.5 eq. | 1.47586E-07 | 4.84492E-07 |
| 19 | human health - photochemical oxidant formation: human health | DALY/kg NOx eq. | 4.05219E-10 | 1.3284E-09 |
| 20 | human health - water use: human health | DALY/$m^3$ consumed | 5.26557E-09 | 1.73083E-08 |
| 21 | natural resources - energy resources: non-renewable, fossil | USD2013 /kg | 0.018483985 | 0.06048996 |
| 22 | natural resources - material resources: metals/minerals | USD2013 /kg Cu | 0.000567916 | 0.001893217 |
| 23 | total: ecosystem quality - ecosystem quality | species.yr | 1.12934E-09 | 3.67666E-09 |
| 24 | total: human health - human health | DALYs | 4.7091E-07 | 1.54149E-06 |
| 25 | total: natural resources - natural resources | USD 2013 | 0.0190519 | 0.062381263 |

**4.6 Sensitivity analysis**

Sensitivity analysis determines which input uncertainties are causing the output uncertainty. This study uses local sensitivity analysis to see how the system responds to parameter changes and state variables around a specific point or path.

### 4.6.1 Energy conservation sensitivity

Energy has the largest proportion of environmental impacts. To reduce the overall impact, this study implemented what-if energy conservation practices. Energy conservation in a WWTP refers to the implementation of strategies and technologies designed to reduce energy consumption during the treatment process. We modeled the energy conservation process to measure the impact reduction from the modified parameters (reduce 5% and 10%).

Figure 4.54 presents a sensitivity analysis of the total ecosystem quality response to energy conservation. The scenario 2 energy mix shown as a normal value exhibits a baseline ecosystem quality of 1.00E-09 species per year. Reducing this scenario 2 energy need value by 5% and 10% by implementing energy conservation results in corresponding decreases in total ecosystem quality impact of 4.74% species per year and 9.48% species per year, respectively. This trend provides a positive correlation between implementing energy conservation and reducing the total ecosystem quality endpoint impact.

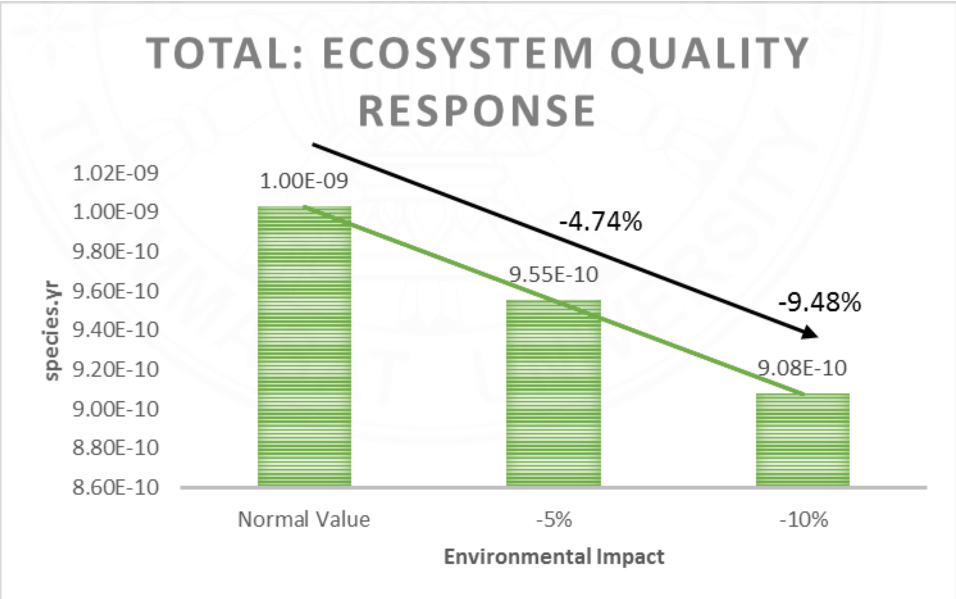


**Figure 4.54** Total Ecosystem Quality Response After Implementing Energy Conservation by 5% and 10%.

Figure 4.55 presents a sensitivity analysis of the total human health response to energy conservation. The scenario 2 energy mix shown as a normal value exhibits a baseline ecosystem quality of 4.18E-07 DALYs. Reducing this scenario 2 energy need value by 5% and 10% by implementing energy conservation results in corresponding decreases in total human health impact of 4.65% DALYs and 9.31% DALYs, respectively. This trend provides a positive correlation between implementing energy conservation and reducing the total human health endpoint impact.

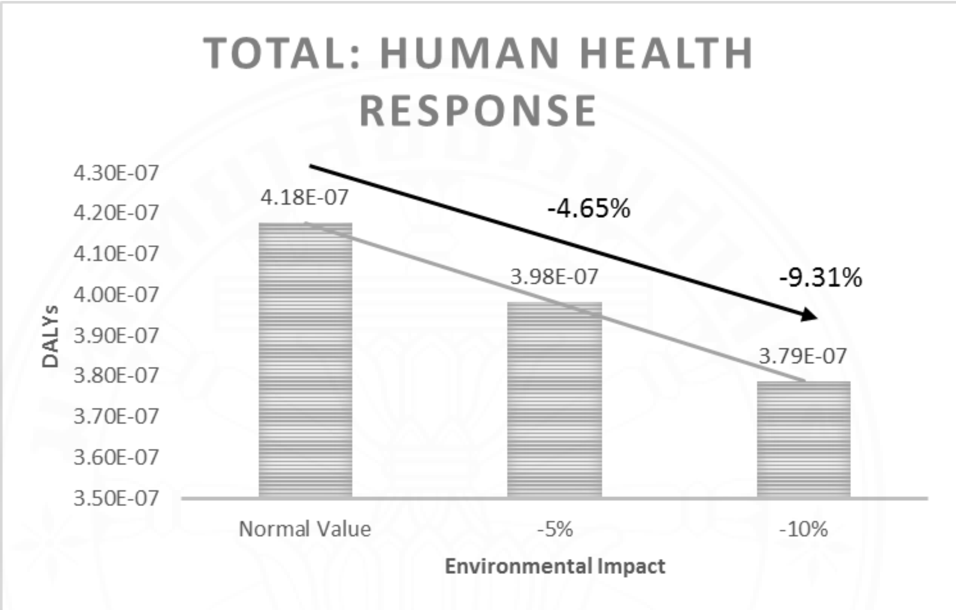


**Figure 4.55** Total Human Health Response After Implementing Energy Conservation by 5% and 10%.

Figure 4.56 presents a sensitivity analysis of the total natural resource response to energy conservation. The scenario 2 energy mix shown as a normal value exhibits a baseline natural resource of 1.69E-02 USD in 2013. Reducing this scenario 2 energy need value by 5% and 10% by implementing energy conservation results in corresponding decreases in total natural resource impact of 4.79% USD 2013 and 9.57% USD 2013, respectively. This trend provides a positive correlation between implementing energy conservation and reducing the total natural resource endpoint impact.

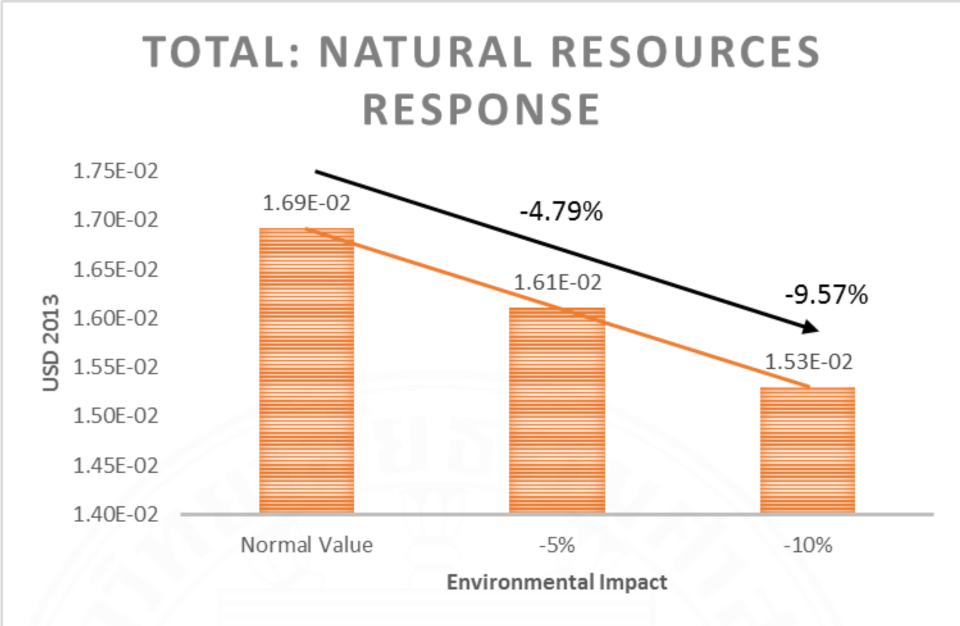


**Figure 4.56** Total Ecosystem Quality Response After Implementing Energy Conservation by 5% and 10%.

Based on the modeling of each endpoint impact, the results approach the reduction of energy conservation parameters. However, there are some limitation on energy conservation practice including financial challenge and technological obstacle that need to be analyzed in future study.

### 4.6.2 Energy variation sensitivity

Energy indirectly impacts uncertainty because it multiplies with the electricity needs of each unit operation, which has energy consumption variability. Since the total amount of energy mix is constant, when making variations, a decrease in one fossil fuel must be balanced by an increase in other energy mixes. The variation in fossil fuel input is to determine how much the environmental impact will decrease if the proportion of fossil fuel is reduced.

At this stage, this study varied the values when lignite energy generation was reduced by 5% and 10%, then balanced by an increase in renewable energy (solar photovoltaic, biomass wood chip, and biomass waste) by 5% and 10% in Table 4.21.

**Table 4.21** Total Endpoint Impact Response After Varying Lignite Energy to Renewable Energy by 5% and 10%.

| | | Total Ecosystem Quality | | Total Human Health | | Total Natural Resource | |
|---|---|---|---|---|---|---|---|
| | | Lignite | | | | | |
| | | -5% | -10% | -5% | -10% | -5% | -10% |
| Photovoltaic | +5% | 0.82% | | 1.00% | | 0.00% | |
| | +10% | | 1.68% | | 2.07% | | 0.06% |
| Biomass Waste (Bagasse) | +5% | 0.74% | | 0.75% | | 0.06% | |
| | +10% | | 1.48% | | 1.51% | | 0.06% |
| Wood Chip | +5% | 0.10% | | 0.96% | | 0.00% | |
| | +10% | | 0.19% | | 1.92% | | 0.00% |

The results show that the modification of lignite to renewable energy fraction shows a positive contribution for reducing environmental impacts. In general, changes to Solar Photovoltaic Energy show the greatest results, followed by changes to Biomass Waste (Bagasse) and Biomass (Wood chip) energy generation.

Research shows that reducing the proportion of lignite by 5% and increasing the proportion of photovoltaic by 5% contributes to the greatest increase in environmental impact performance (0.82%), higher than other renewable energy sources such as biomass bagasse waste (0.74%) and woodchip (0.10%).

### 4.6.3 Sludge transportation sensitivity

In the previous uncertainty analysis step, sludge transportation became the primary uncertainty contributor to endpoint impact. Converting sludge volume into mass uses density range calculation assumptions. At this stage, we measured how much transporting sludge contributes to the response endpoint impact by varying the input by adding up 5% (1.5561 tkm) and 10% (1.6302 tkm) from normal value in scenario 2.

Figure 4.57 presents a sensitivity analysis of the total ecosystem quality response to transportation variation. The scenario 2 transportation parameter shown as a normal value exhibits a baseline ecosystem quality of 1.00E-09 species per year. Increasing this scenario 2 transportation variation value by 5% and 10% results in a notable 2.2% shift, with a corresponding increase in total ecosystem quality impact of 7.22% species per year and 11.68% species per year.

The transportation sensitivity analysis revealed notable shifts in the results across various impact categories. Specifically, the total ecosystem quality response exhibited a shift of approximately 2.2%, indicating that minor variations in the system parameters can moderately impact ecosystem quality. Thus, the ecosystem's response is sensitive to changes within the system.

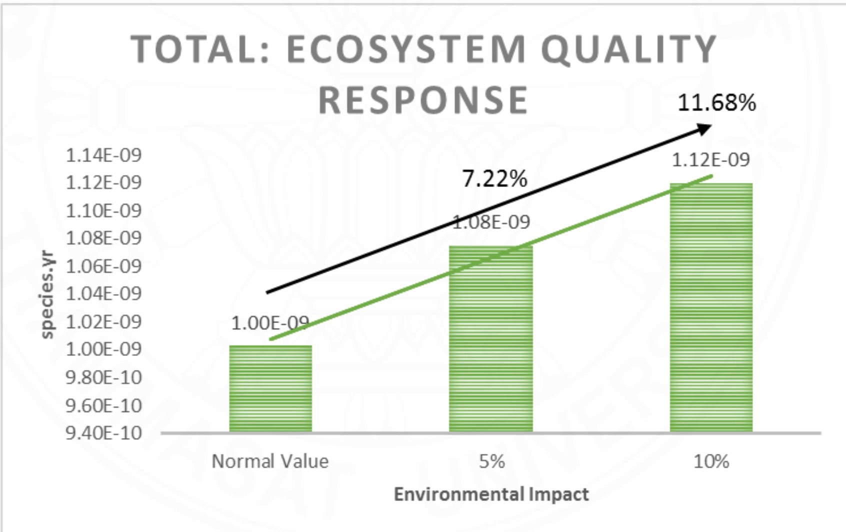


**Figure 4.57** Total Ecosystem Quality Response After Increasing Transportation Unit by 5% and 10%.

Figure 4.58 presents a sensitivity analysis of the total human health response to transportation variation. The scenario 2 transportation parameter shown as a normal value exhibits a baseline human health of 4.18E-07 DALYs. Increasing this scenario 2 transportation variation value by 5% and 10% results in a corresponding increase in total human health impact of 7.65% DALYs and 12.39% DALYs.

The total human health response showed a slightly higher shift of around 2.64%. Furthermore, sludge transportation variation indicates a heightened sensitivity of human health outcomes to parameter variations, highlighting the critical need for precise control and monitoring system parameters to mitigate potential health risks.

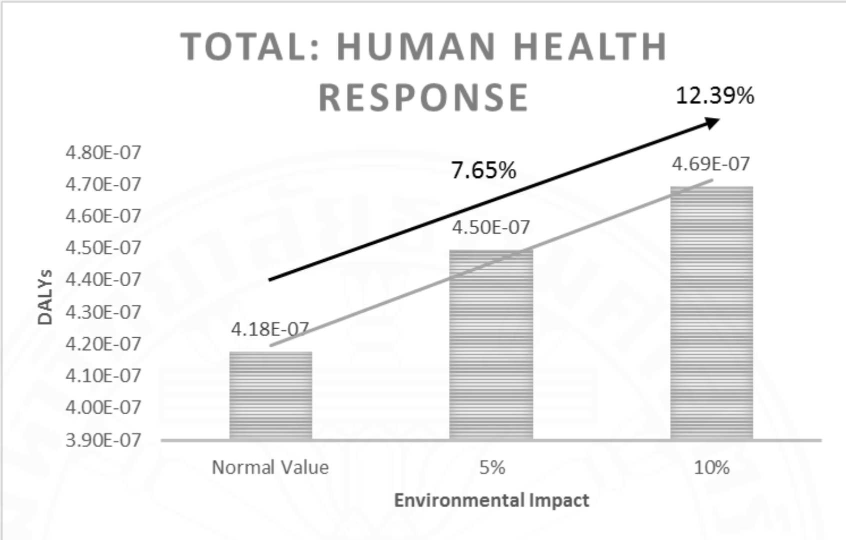


**Figure 4.58** Total Human Health Response After Increasing Transportation Unit by 5% and 10%.

Figure 4.59 presents a sensitivity analysis of the total natural resource response to transportation variation. The scenario 2 transportation parameter shown as a normal value exhibits a baseline natural resource of 1.69E-02 USD in 2013. Increasing this scenario 2 transportation variation value by 5% and 10% results in a corresponding increase in total natural resource impact of 5.77% DALYs and 9.35% DALYs.

On the other hand, the total natural resources response on transportation variation demonstrated a smaller shift of about 0.64%. This smaller shift suggests that the ecosystem quality is relatively more stable and less affected by transportation variations than the other factors analyzed.

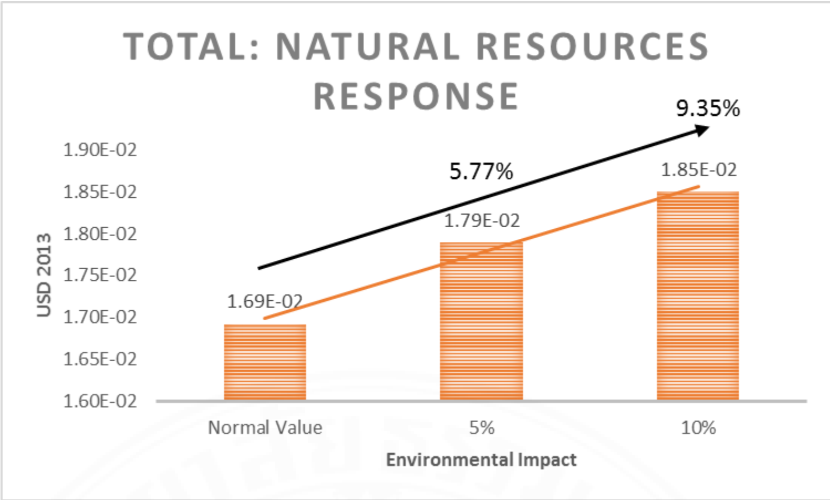


**Figure 4.59** Total Ecosystem Quality Response After Increasing Transportation Unit by 5% and 10%.

# CHAPTER 5
# CONCLUSION AND SUGGESTION

## 5.1 Conclusion

This section aims to conclude the environmental impact assessment, hotspot identification and provide recommendation.

### 5.1.1 Environmental impact assessment

Energy mix in scenario 2 compared to scenario 1 significantly improved freshwater quality (eutrophication) by 43.83%. However, land use had the greatest negative impact increase (2,354.46%) in scenario 2, potentially due to the use of biomass energy. Reducing lignite use in scenario 2 led to a substantial improvement (36.55%) in non-carcinogenic human health impacts, likely due to a decrease in zinc and arsenic emissions. However, ionizing radiation remained unchanged in both scenarios, with sodium hypochlorite production as the major contributor. A significant decrease (-8.33%) in the impact of metals and minerals was observed in scenario 2, likely due to reduced natural gas usage. Despite a small decrease in natural gas cost, photovoltaics significantly increased the overall midpoint impact of metals and minerals (8.3%) in scenario 2.

Based on midpoint impact assessment, scenario 2 offers significant environmental benefits in freshwater quality and human health by reducing reliance on lignite. However, increased use of biomass and photovoltaics in scenario 2 requires further investigation to mitigate potential negative impacts on land use and metal/mineral resource depletion.

From the endpoint impact perspective, results show that after implementing the energy transition process in the 2037 scenario, there is an increase in environmental performance of 17.11% in the total ecosystem quality impact endpoint. Lignite energy generation was the biggest initial contributor to ecosystem quality impact (7.71E-10 species.yr in scenario 1) but significantly decreased in scenario 2 (3.94E-10 species.yr). While biomass energy generation had no impact in scenario 1, it showed a small increase in scenario 2 (1.35E-10 species.yr). Its overall contribution remains minimal compared to others.

The 2037 energy scenario led to a 27.65% improvement in human health, indicating a reduction in years lost or disabled due to disease or accident. Similar to ecosystem quality, lignite energy generation was the biggest initial contributor to human health impact (3.99E-07 DALYs in scenario 1) but significantly decreased in scenario 2 (2.04E-07 DALYs). While sodium hypochlorite production had the lowest impact on human health in both scenarios (2.73E-08 DALYs).

Furthermore, while not significant, the 2037 energy scenario showed a slight increase (0.29%) in natural resource performance. Natural gas was the biggest contributor to natural resource impact in both scenarios (1.57E-02 USD in 2013 in scenario 1 and 1.52E-02 USD in 2013 in scenario 2). However, its impact slightly decreased in scenario 2. While photovoltaics climbed significantly in natural resource impact contribution from (6.80E-06 USD in 2013 in scenario 1 to 2.42E-04 USD in 2013 in scenario 2).

Shifting to the 2037 energy mix significantly improves overall ecosystem quality and human health by reducing reliance on lignite. The impact on natural resources shows a slight improvement, but further investigation might be needed to optimize resource use.

### 5.1.2 Hotspot identification and sensitivity analysis

Identification of environmental impact hotspots aims to identify processes or components with the highest environmental impacts. Energy consumption was identified as the primary contributor to environmental impacts across various categories (ecosystem quality, human health, and natural resources) by contributing more than 90%.

This study identified membrane ultrafiltration as the most energy-intensive unit operation within the wastewater treatment process, consuming 0.212 kWh per cubic meter with an uncertainty of 2.13%. Aeration in the bioreactor unit ranked second in terms of energy consumption, accounting for 0.075 kWh per cubic meter, but with a significantly higher uncertainty of 19.02%. Further investigation into membrane ultrafiltration and aeration tanks, could lead to substantial reductions in overall treatment plant energy consumption.

Implementing energy conservation measures (5% and 10% reduction) resulted in significant reductions in overall environmental impact:

a) Ecosystem quality: 4.74% and 9.48% decrease, respectively.
b) Human health: 4.65% and 9.31% decrease, respectively.
c) Natural resources: 4.79% and 9.57% decrease (USD 2013), respectively.

This analysis indicates a high sensitivity of environmental impacts to energy consumption. Reducing energy consumption by energy conservation directly translates to positive environmental benefits.

Moreover, shifting the energy mix towards renewable sources (solar photovoltaic, biomass) by reducing lignite usage (5% and 10%) showed positive impacts on environmental performance. Photovoltaic energy contributes to the greatest positive impact (0.82% increase), followed by biomass bagasse (0.74%) and wood chip (0.10%). Compared to energy conservation, the impact of varying energy sources appears less pronounced. However, reducing reliance on lignite and incorporating specific renewable sources (photovoltaic) can contribute further to environmental improvement.

## 5.2 Recommendation

Both energy conservation and energy variation sensitivity analyses highlight the importance of managing energy use to minimize environmental impact. Energy conservation demonstrates high sensitivity, offering significant environmental benefits through reduced consumption. This study provides recommendations to the internal of Bang Sue WWTP to implement energy conservation. Based on the results of the analysis, implementing a 5% energy conservation can contribute to reducing the total ecosystem quality impact by 4.74%, total human health impact by 4.65%, and total natural resources impact by 4.79%.

Considering the findings from Lee's research in South Korea, buffer tanks and control systems can help in reducing the energy requirement of the aeration tank. In this study, we recommend the future feasibility study of implementing a control system and buffer tank at Bang Sue WWTPs.

We appreciate Thailand EGAT's steps in the 2037 energy mix transition process, as it shows an improvement in overall endpoint environmental impact performance. Furthermore, this study also recommends that Thailand EGAT for shifting to cleaner options like solar photovoltaic holds additional potential for environmental improvement.

This study focuses on the environmental impacts, while the economic implications of the energy mix scenario are not considered. To gain a more comprehensive comparison with the economic benefit, future research should analyze its economic feasibility. This could involve life-cycle costs and evaluations of potential economic benefits.

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# APPENDICES

# APPENDIX A

# POWER PLANT CONSTRUCTION AND PHASE-OUT PLAN

**Table A.1** The Thailand Energy Project Timeline from 2018 until 2037.

| Year | Power Plant Project | Energy Generating Capacity (MW) | Fuel Type |
|---|---|---|---|
| 2017 | Electricity production capacity until December 2017 | 46,090 | |
| 2018 | Dismissal of small private power producers | -43.1 | - |
| | Decommissioning of Bang Pakong Power Plant, Block 4 | -314 | Natural Gas |
| | Decommissioning of Mae Moh Power Plant, units 4-7 | -560 | Lignite / Coal |
| | Very small private electricity producer | 131.1 | - |
| | Small private electricity producers | 1,542 | - |
| | Pa Sak Chonlasit Dam | 6.7 | Hydro power |
| | Mae Klong Dam | 12 | Hydro power |
| | Bang Lang Dam (improved to increase production capacity) | 8 | Hydro power |
| | Pha Dam Neck | 5.5 | Hydro power |
| | Latakong Power Plant (reverse pump) Units 3-4 | 500 | Hydro power |
| | Solar energy floating buoy, Sirindhorn Dam | 0.25 | Solar Energy |
| | Latakong Wind Power Plant, Phase 2 | 24 | Wind power |
| | Mae Moh Power Plant Replace machines 4-7 | 600 | Lignite / Coal |
| 2019 | Dismissal of small private power producers | -244.5 | - |
| | Discharge of Wang Noi Power Plant, Blocks 1-2 | -1,224 | Natural Gas |

| Year | Power Plant Project | Energy Generating Capacity (MW) | Fuel Type |
|---|---|---|---|
| | Very small private electricity producer | 343.2 | - |
| | Small private electricity producers | 894.1 | - |
| | Hydropower behind Chulabhorn Dam | 1.25 | Hydro power |
| | Renewable power plants South Bangkok Power Plant Phase 1 | 1220 | Natural Gas |
| | Lao PDR (Sepian) | 354 | Hydro power |
| | Lao PDR (Nam Ngiep 1) | 269 | Hydro power |
| | Lao PDR (Xayaburi) | 1,220 | Hydro power |
| 2020 | Dismissal of small private power producers | -248 | - |
| | Decommissioning of South Bangkok Power Plant, Block 1 | -316 | Natural Gas |
| | Release of Tri Energy Co., Ltd. | -700 | Natural Gas |
| | Community power plant | 700 | - |
| | Very small private electricity producer | 103 | - |
| | Small private electricity producers | 135 | - |
| | Khlong Tron Dam | 2.5 | Hydro power |
| | Solar energy floating buoy jointly with a hydroelectric power plant Sirindhorn Dam | 45 | Solar combined with hydro power |
| | Bang Pakong Power Plant Replace the 1-2nd machine | 1386 | Natural Gas |
| 2021 | Dismissal of small private power producers | -241.5 | - |
| | Community power plant | 350 | - |
| | Very small private electricity producer | 67 | - |
| | Small private electricity producers | 584.4 | - |
| | Pha Chuk Dam | 14 | Hydro power |

| Year | Power Plant Project | Energy Generating Capacity (MW) | Fuel Type |
|---|---|---|---|
| | Gulf SRC, Set 1 | 1250 | Natural Gas |
| 2022 | Dismissal of small private power producers | -150 | - |
| | Decommissioning Mae Moh Power Plant Unit 8 | -270 | Lignite / Coal |
| | Dismissal of South Bangkok Power Plant, Set 2 | -562 | Natural Gas |
| | Community power plant | 323 | - |
| | Very small private electricity producer | 140 | - |
| | Small private electricity producers | 60 | - |
| | Pracharat Biomass | 60 | Biomass |
| | Policy waste power plant | 400 | Solid Waste |
| | Gulf SRC, Set 2 | 1250 | Natural Gas |
| | Lao PDR (Nam Theun 1) | 514 | Hydro power |
| 2023 | Dismissal of small private power producers | -41 | - |
| | Decommissioning of Wang Noi Power Plant, Block 3 | -686 | Natural Gas |
| | Discharging Eastern Power and Electric | -350 | Natural Gas |
| | Community power plant | 280 | - |
| | Very small private electricity producer | 140 | - |
| | Small private electricity producers | 30 | - |
| | Pracharat Biomass | 60 | Biomass |
| | Ban Chanday Hydropower | 18 | Hydro power |
| | Solar energy floating buoy water in conjunction with a hydroelectric power plant Ubonrat Dam | 24 | Solar combined with hydro power |
| | Gulf PD Set 1 | 1250 | Natural Gas |

| Year | Power Plant Project | Energy Generating Capacity (MW) | Fuel Type |
|---|---|---|---|
| 2024 | Dismissal of small private power producers | -679.8 | - |
| | Dismiss very small private power producers. | -32.2 | - |
| | Community power plant | 280 | - |
| | Very small private electricity producer | 140 | - |
| | Small private electricity producers | 240 | - |
| | Gulf PD Set 2 | 1250 | Natural Gas |
| | Hin Kong Power Set 1 | 700 | Natural Gas |
| 2025 | Dismiss very small private power producers. | -89 | - |
| | Dismissal of small private power producers | -236 | - |
| | Decommissioning Mae Moh Power Plant Unit 9 | -270 | Lignite / Coal |
| | Decommissioning Mae Moh Power Plant Units 10-11 | -540 | Lignite / Coal |
| | Dismiss Nam Phong Power Plant, Blocks 1-2 | -650 | Natural Gas |
| | Dismissal of Global Power Synergy | -700 | Natural Gas |
| | Disconnect Ratchaburi Electricity Generating Units 1-2 | -1,440 | Natural Gas / Oil |
| | EGAT small hydroelectric power plant, Latakong Dam | 1.5 | Hydro power |
| | Small hydroelectric power plant, EGAT, Nam Pi Dam | 2 | Hydro power |
| | EGAT small hydroelectric power plant, La Pao Dam | 2.5 | Hydro power |
| | Small private electricity producers | 60 | - |
| | Hin Kong Power Set 2 | 700 | Natural Gas |
| | Nam Phong Power Plant Replacement | 650 | Natural Gas |
| 2026 | Dismiss very small private power producers. | -53 | - |

| Year | Power Plant Project | Energy Generating Capacity (MW) | Fuel Type |
|---|---|---|---|
| | Dismissal of small private power producers | -5 | - |
| | Decommissioning Mae Moh Power Plant Units 12-13 | -540 | Lignite / Coal |
| | Solar energy floating buoy together with a hydroelectric power plant Bhumibol Dam | 158 | Solar combined with hydro power |
| | Solar energy floating buoy water in conjunction with a hydroelectric power plant Srinakarin Dam | 140 | Solar combined with hydro power |
| | EGAT small hydroelectric power plant, Huai Mae Tho Dam | 1.3 | Hydro power |
| | Small Hydroelectric Power Plant, EGAT, Phaya Man Dam | 3 | Hydro power |
| | South Bangkok Power Plant (Additional) | 700 | Natural Gas |
| | Mae Moh Power Plant Replacement Units 8-9 | 600 | Lignite / Coal |
| | Buy electricity abroad | 700 | Hydro power |
| 2027 | Dismiss very small private power producers. | -56 | - |
| | Decommissioning of Bang Pakong Power Plant Unit 3 | -576 | Natural Gas / Oil |
| | Discharge of Ratchaburi Electricity Generating Units 1-3 | -2,041 | Natural Gas |
| | Small Hydroelectric Power Plant, EGAT, Pranburi Dam | 1.5 | Hydro power |

| Year | Power Plant Project | Energy Generating Capacity (MW) | Fuel Type |
|---|---|---|---|
| | Small hydroelectric power plant, EGAT, Nam Pad Dam | 2 | Hydro power |
| | Solar energy floating buoy water in conjunction with a hydroelectric power plant Vajiralongkorn Dam | 50 | Solar combined with hydro power |
| | Burapha Power | 540 | Natural Gas |
| | South Bangkok Power Plant (Additional) | 1,400 | Natural Gas |
| | Surat Thani Power Plant, Set 1 | 700 | Natural Gas |
| 2028 | Dismiss very small private power producers. | -93 | - |
| | Dismissal of small private power producers | -103 | - |
| | Decommissioning of Bang Pakong Power Plant Unit 4 | -576 | Natural Gas / Oil |
| | Release Glow IPP | -713 | Natural Gas |
| | Small hydroelectric power plant, EGAT, Nam Kon Dam | 2 | Hydro power |
| | EGAT small hydroelectric power plant, Yasothon-Phanom Phrai Dam | 4 | Hydro power |
| | Very small private electricity producer | 850 | - |
| | North Bangkok Power Plant (Additional) | 700 | Natural Gas |
| | Buy electricity abroad | 700 | Hydro power |
| 2029 | Dismiss very small private power producers. | -179 | - |
| | Release Lao PDR (Huai Ho) | -126 | Hydro power |
| | Very small private electricity producer | 1,650 | - |
| | EGAT small hydroelectric power plant, Nam Ki Dam | 1 | Hydro power |

| Year | Power Plant Project | Energy Generating Capacity (MW) | Fuel Type |
|---|---|---|---|
| | EGAT small hydroelectric power plant, Mae Lamao Dam in the middle | 1.5 | Hydro power |
| | Solar energy floating buoy together with a hydroelectric power plant Srinakarin Dam Extension | 280 | Solar combined with hydro power |
| | Surat Thani Power Plant, Set 2 | 700 | Natural Gas |
| 2030 | Dismiss very small private power producers. | -104 | - |
| | Very small private electricity producer | 1,300 | - |
| | EGAT small hydroelectric power plant, Upper Huai Umphiam Dam | 1.5 | Hydro power |
| | EGAT small hydroelectric power plant, Huai Nam Sai Dam | 2 | Hydro power |
| | Solar energy floating buoy jointly with a hydroelectric power plant Bhumibol Dam Expansion | 300 | Solar combined with hydro power |
| | New Power Plant (Northeast Region) | 700 | Natural Gas |
| 2031 | Dismiss very small private power producers. | -22.8 | - |
| | Dismissal of small private power producers | -40.2 | - |
| | Very small private electricity producer | 2,600 | - |
| | EGAT small hydroelectric power plant, Khlong Luang Dam | 1 | Hydro power |
| | Small hydroelectric power plant, EGAT, rural dam | 1.5 | Hydro power |

| Year | Power Plant Project | Energy Generating Capacity (MW) | Fuel Type |
|---|---|---|---|
| | Solar energy floating buoy water in conjunction with a hydroelectric power plant Navachiralongkorn Dam Extension | 250 | Solar combined with hydro power |
| 2032 | Dismiss very small private power producers. | -74.4 | - |
| | Dismissal of small private power producers | -8.8 | - |
| | Disconnect BLCP Power Units 1-2 | -1,347 | Lignite / Coal |
| | Dismissal of Gulf Power Generation No. 1 | -734 | Natural Gas |
| | Very small private electricity producer | 780 | - |
| | EGAT small hydroelectric power plant, Thap Salao Dam | 1.5 | Hydro power |
| | EGAT small hydroelectric power plant, Krasiao Dam | 1.5 | Hydro power |
| | Solar energy floating buoy together with a hydroelectric power plant Srinakarin Dam Extension 2 | 300 | Solar combined with hydro power |
| | Energy conservation measures | 354 | - |
| | New power plant (upper central region) | 1,400 | Natural Gas |
| | New Power Plant (Northeast Region) | 700 | Natural Gas |
| | Buy electricity abroad | 700 | Hydro power |
| 2033 | Dismiss very small private power producers. | -73 | - |
| | Dismissal of Gulf Power Generation No. 2 | -734 | Natural Gas |
| | Dismissed Ratchaburi Power, Sets 1-2 | -1,400 | Natural Gas |
| | Very small private electricity producer | 2,750 | - |

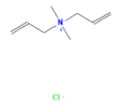
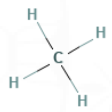
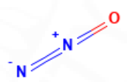
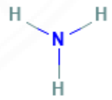
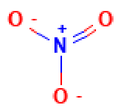
| Year | Power Plant Project | Energy Generating Capacity (MW) | Fuel Type |
|---|---|---|---|
| | Small hydroelectric power plant, EGAT, Mae Kuang Udom Thara Dam | 1 | Hydro power |
| | EGAT small hydroelectric power plant, Mae Suai Dam | 2 | Hydro power |
| | Solar energy floating buoy jointly with a hydroelectric power plant Chulabhorn Dam | 40 | Solar combined with hydro power |
| | Solar energy floating buoy jointly with a hydroelectric power plant Bang Lang Dam | 78 | Solar combined with hydro power |
| | Solar energy floating buoy together with a hydroelectric power plant Bhumibol Dam Expansion 2 | 320 | Solar combined with hydro power |
| | Energy conservation measures | 202 | - |
| | New Power Plant (Eastern Region) | 1,000 | Lignite / Coal |
| | Buy electricity abroad | 700 | Hydro power |
| 2034 | Dismiss very small private power producers. | -3 | - |
| | Dismissal of small private power producers | -20.6 | - |
| | Decommissioning of Krabi Power Plant | -315 | Fuel oil |
| | Dismissal of Chana Power Plant, Set 1 | -710 | Natural Gas |
| | EGAT small hydroelectric power plant, Mae Wong Dam | 12 | Hydro power |

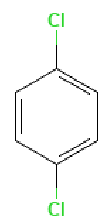
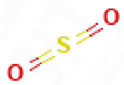
| Year | Power Plant Project | Energy Generating Capacity (MW) | Fuel Type |
|---|---|---|---|
| | Small hydroelectric power plant, EGAT, Mae Khan Dam | 16 | Hydro power |
| | Very small private electricity producer | 206 | - |
| | Solar energy floating buoy together with a hydroelectric power plant Ratchaprapa Dam | 140 | Solar combined with hydro power |
| | Energy conservation measures | 859 | - |
| | New power plant (southern region) | 1,000 | Lignite / Coal |
| 2035 | Dismiss very small private power producers. | -8.2 | - |
| | Dismissal of small private power producers | -90 | - |
| | Dismissal of South Bangkok Power Plant, Set 3 | -710 | Natural Gas |
| | Dismissal of Bang Pakong Power Plant, Block 5 | -710 | Natural Gas |
| | Discharge of Lao PDR (Nam Theun 2) | -948 | Hydro power |
| | Very small private electricity producer | 1,215 | - |
| | EGAT small hydroelectric power plant, Lower Mae Ping Dam | 4.5 | Hydro power |
| | Solar energy floating buoy together with a hydroelectric power plant Sirikit Dam | 325 | Solar combined with hydro power |
| | Energy conservation measures | 1,025 | - |
| | North Bangkok Power Plant (Additional) | 700 | Natural Gas |
| | New power plant (southern region) | 700 | Natural Gas |

| Year | Power Plant Project | Energy Generating Capacity (MW) | Fuel Type |
|---|---|---|---|
| | Buy electricity abroad | 700 | Hydro power |
| 2036 | Dismiss very small private power producers. | -3 | - |
| | Decommissioning of North Bangkok Power Plant, Block 1 | -670 | Natural Gas |
| | Very small private electricity producer | 1,391 | - |
| | EGAT small hydroelectric power plant, Huai Sato Dam | 1.5 | Hydro power |
| | Solar energy floating buoy together with a hydroelectric power plant Ratchaprapha Dam Extension | 100 | Solar combined with hydro power |
| | Energy conservation measures | 860 | - |
| | New power plant (metropolitan area) | 700 | Natural Gas |
| 2037 | Dismiss very small private power producers. | -8 | - |
| | Dismissal of small private power producers | -268 | - |
| | Release Gheko-One | -660 | Lignite / Coal |
| | Very small private electricity producer | 187 | - |
| | EGAT small hydroelectric power plant, La Saphung Dam | 0.8 | Hydro power |
| | Solar energy floating buoy together with a hydroelectric power plant Sirikit Dam Extension | 175 | Solar combined with hydro power |
| | Energy conservation measures | 700 | - |
| | New Power Plant (Eastern Region) | 700 | Natural Gas |

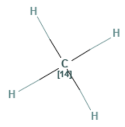
# APPENDIX B
# CHEMICAL DESCRIPTION

**Table B.1** Chemical Compound in This Study.

| No | Compound | Desc | Molecular Weight | Density | Structure | Source |
|---|---|---|---|---|---|---|
| 1 | Poly(Diallyl Dimethyl Ammonium Chloride) $C_8H_{16}ClN$ | A flocculant is made of poly(diallyl dimethyl ammonium chloride) polymer. | 161.67 g/mol | 1.04 g/mL at 25 °C |  | (National Center for Biotechnology Information, 2024j) |
| 2 | Sodium hypochlorite NaClO | Sodium hypochlorite is a disinfectant and bleaching agent. | 74.44 g/mol | 1.097 g/mL at 25 °C |  | (National Center for Biotechnology Information, 2024d) |
| 3 | Methane $CH_4$ | Methane is an odorless, colorless gas that ignites readily. | 16.043 g/mol | 0.716 g/mL at 25 °C (lit.) |  | (National Center for Biotechnology Information, 2024h) |
| 4 | Nitrous oxide $N_2O$ | One type of greenhouse gas is nitrous oxide. | 44.013 g/mol | Vapor density 1.53 (15 °C, vs air) |  | (National Center for Biotechnology Information, 2024o) |
| 5 | Ammonia $NH_3$ | One significant source of nitrogen is ammonia. | 17.031 g/mol | 0.881 g/mL at 25 °C |  | (National Center for Biotechnology Information, 2024c) |
| 6 | Nitrate $NO_3^-$ | Nitrate is a nitrogen oxoanion that is created when nitric acid loses a proton. | 62.005 g/mol | 1.01 g/cm$^3$ |  | (National Center for Biotechnology Information, 2024m) |
| 7 | Nitrite $NO_2^-$ | When consumed, nitrite can be poisonous and irritate the skin and eyes. | 46.006 g/mol | - |  | (National Center for Biotechnology Information, 2024n) |

| No | Compound | Desc | Molecular Weight | Density | Structure | Source |
|---|---|---|---|---|---|---|
| 8 | 1,4-Dichlorobenzene $C_6H_4Cl_2$ | Humans that inhale 1,4-dichlorobenzene experience skin, throat, and eye discomfort during an acute (short-term) exposure. Humans who inhale 1,4-dichlorobenzene over an extended period of time may experience consequences on their liver, skin, and central nervous system (CNS). | 147.00 g/mol | 1.241 g/mL at 25 °C (lit.) |  | (National Center for Biotechnology Information, 2024k) |
| 9 | Sulfur dioxide $SO_2$ | The primary cause of sulfur dioxide in the atmosphere is human activity, such as the burning of coal and oil in power plants. | 64.07 g/mol | - |  | (National Center for Biotechnology Information, 2024b) |
| 10 | Chromium VI $Cr^{+6}$ | Because of its increased redox potential and wider capacity to infiltrate cells, chromium(VI) is more | 51.996 g/mol | - |  | (National Center for Biotechnology Information, 2024g) |

| No | Compound | Desc | Molecular Weight | Density | Structure | Source |
|---|---|---|---|---|---|---|
| | | hazardous than other oxidation states of the chromium atom. | | | | |
| 11 | Zinc II $Zn^{+2}$ | Zinc(2+) functions as a cofactor and a metabolite in humans. | 65.4 g/mol | - | $Zn^{++}$ | (National Center for Biotechnology Information, 2024i) |
| 12 | Arsenic ions $As^{+3}$ | Chronic intake of inorganic arsenic (> 500 mg/L As) in humans has been linked to diabetes mellitus, cancers of the skin, bladder, lung, liver, and prostate, as well as neurological, hepatic, and renal disorders. | 74.92159 g/mol | - | $As^{3+}$ | (National Center for Biotechnology Information, 2024a) |
| 13 | Radon-222 Rn | Odorless and tasteless, radon is a naturally occurring radioactive gas. In the study of atmospheric transport, the prediction of earthquakes, and the search for uranium and petroleum, radon is utilized. | 222.01758 g/mol | - | Rn [222] | (National Center for Biotechnology Information, 2024l) |

| No | Compound | Desc | Molecular Weight | Density | Structure | Source |
|---|---|---|---|---|---|---|
| 14 | Carbon-14 $CH_4$ | When carbon-14 decays and turns back into nitrogen, it releases beta particles. | 18.035 g/mol | - |  | (National Center for Biotechnology Information, 2024f) |
| 15 | Cerium Ce | Skin, eyes, or mucous membranes can be burned by cerium. | 140.116 g/mol | - | Ce | (National Center for Biotechnology Information, 2024e) |

# APPENDIX C
# MIDPOINT IMPACT CATEGORIES

**Table C.1** Midpoint Impact Category in This Study.

| Impact Category | Midpoint Unit | Indicator | CFm |
|---|---|---|---|
| Climate change | kg $CO_2$-eq to air | Infrared radiative forcing increase | Global warming potential (GWP) |
| Ozone depletion | kg CFC-11-eq to air | Stratospheric ozone decrease | Ozone depletion potential (ODP) |
| Ionising radiation | kBq Co-60-eq to air | Absorbed dose increase | Ionising radiation potential (IRP) |
| Fine particulate matter formation | kg PM2.5-eq to air | PM 2.5 population intake increase | Particulate matter formation potential (PMFP) |
| Photochemical oxidant formation: terrestrial ecosystems | kg NOx-eq to air | Tropospheric ozone increase | Photochemical oxidant formation potential: ecosystems (EOFP) |
| Photochemical oxidant formation: human health | kg NOx-eq to air | Tropospheric ozone population intake increase | Photochemical oxidant formation potential: humans (HOFP) |
| Terrestrial acidification | kg $SO_2$-eq to air | Proton increase in natural soils | Terrestrial acidification potential (TAP) |
| Freshwater eutrophication | kg P-eq to freshwater | Phosphorus increase in freshwater | Freshwater eutrophication potential (FEP) |

| Impact Category | Midpoint Unit | Indicator | CFm |
|---|---|---|---|
| Human toxicity: cancer | kg 1,4-DCB-eq to urban air | Risk increase of cancer disease incidence | Human toxicity potential (HTPc) |
| Human toxicity: non-cancer | kg 1,4-DCB-eq to urban air | Risk increase of non-cancer disease incidence | Human toxicity potential (HTPnc) |
| Terrestrial ecotoxicity | kg 1,4-DCB-eq to industrial soil | Hazard-weighted increase in natural soils | Terrestrial ecotoxicity potential (TETP) |
| Freshwater ecotoxicity | kg 1,4-DCB-eq to freshwater | Hazard-weighted increase in freshwaters | Freshwater ecotoxicity potential (FETP) |
| Marine ecotoxicity | kg 1,4-DCB-eq to marine water | Hazard-weighted increase in marine water | Marine ecotoxicity potential (METP) |
| Land use | $m^2 \times$ yr annual cropland-eq | Occupation and time-integrated Land transformation | Agricultural land occupation potential (LOP) |
| Water use | $m^3$ water-eq consumed | Increase of water consumed | Water consumption potential (WCP) |
| Mineral resource scarcity | kg Cu-eq | Increase of ore extracted | Surplus ore potential (SOP) |
| Fossil resource scarcity | kg oil-eq | Upper heating value | Fossil fuel potential (FFP) |

# APPENDIX D
# CONVERSION FACTOR OF HUMAN HEALTH IMPACT

**Table D.1** Human Health Conversion Factor in This Study.

| Conversion Factor | Unit | Individualistic | Hierarchic | Egalitarian |
| --- | --- | --- | --- | --- |
| Global Warming - Human health | DALY/kg $CO_2$ eq. | 8.12E-08 | 9.28E-07 | 1.25E-05 |
| Stratospheric ozone depletion - Human health | DALY/kg CFC11 eq. | 2.37E-04 | 5.31E-04 | 1.34E-03 |
| Ionzing Radiation - Human health | DALY/kBq Co-60 emitted to air eq. | 6.80E-09 | 8.50E-09 | 1.40E-08 |
| Fine particulate matter formation - Human health | DALY/kg PM2.5 eq. | 6.29E-04 | 6.29E-04 | 6.29E-04 |
| Photochemical ozone formation - Human health | DALY/kg NOx eq. | 9.10E-07 | 9.10E-07 | 9.10E-07 |
| Toxicity - Human health (cancer) | DALY/kg 1,4-DCB emitted to urban air eq. | 3.32E-06 | 3.32E-06 | 3.32E-06 |
| Toxicity - Human health (non-cancer) | DALY/kg 1,4-DCB emitted to urban air eq. | 2.28E-07 | 2.28E-07 | 2.28E-07 |

| | | | | |
|---|---|---|---|---|
| Water consumption - human health | Daly/m3 consumed | 3.10E-06 | 2.22E-06 | 2.22E-06 |

Source: (Huijbregts, Steinmann, Elshout, Stam, Verones, Vieira, Hollander, et al., 2017)

# APPENDIX E
# CONVERSION FACTOR OF TERRESTRIAL ECOSYSTEMS IMPACT

**Table E.1** Terrestrial Ecosystems Conversion Factor in This Study.

| Conversion Factor | Unit | Individualistic | Hierarchic | Egalitarian |
|---|---|---|---|---|
| Global Warming - Terrestrial ecosystems | Species.year /kg $CO_2$ eq. | 5.32E-10 | 2.80E-09 | 2.50E-08 |
| Photochemical ozone formation - Terrestrial ecosystems | Species.year /kg NOx eq. | 1.29E-07 | 1.29E-07 | 1.29E-07 |
| Acidification - Terrestrial ecosystems | Species.year /kg $SO_2$ eq. | 2.12E-07 | 2.12E-07 | 2.12E-07 |
| Toxicity - Terrestrial ecosystems | Species.year /kg 1,4-DBC emitted to industrial soil eq. | 1.14E-11 | 1.14E-11 | 1.14E-11 |
| Water consumption - terrestrial ecosystems | Species.year /$m^3$ consumed | 0.00E+00 | 1.35E-08 | 1.35E-08 |
| Land use - occupation and transformation | Species/($m^2$·annual crop eq) | 8.88E-09 | 8.88E-09 | 8.88E-09 |

Source: (Huijbregts, Steinmann, Elshout, Stam, Verones, Vieira, Hollander, et al., 2017)

# APPENDIX F
# CONVERSION FACTOR OF FRESHWATER ECOSYSTEMS IMPACT

**Table F.1** Freshwater Ecosystems Conversion Factor in This Study.

| Conversion Factor | Unit | Individualistic | Hierarchic | Egalitarian |
|---|---|---|---|---|
| Global Warming - Freshwater ecosystems | Species.year/kg $CO_2$ eq. | 1.45E-14 | 7.65E-14 | 6.82E-13 |
| Eutrophication - Freshwater ecosystems | Species.year /kg P to freshwater eq. | 6.71E-07 | 6.71E-07 | 6.71E-07 |
| Toxicity - Freshwater ecosystems | Species.year /kg 1,4-DBC emitted to freshwater eq. | 6.95E-10 | 6.95E-10 | 6.95E-10 |
| Water consumption - aquatic ecosystems | Species.year /$m^3$ consumed | 6.04E-13 | 6.04E-13 | 6.04E-13 |

Source: (Huijbregts, Steinmann, Elshout, Stam, Verones, Vieira, Hollander, et al., 2017)

# APPENDIX G
# CONVERSION FACTOR OF MARINE ECOSYSTEMS IMPACT

**Table G.1** Marine Ecosystems Conversion Factor in This Study.

| Conversion Factor | Unit | Individualistic | Hierarchic | Egalitarian |
|---|---|---|---|---|
| Toxicity - Marine ecosystems | Species.year /kg 1,4-DBC emitted to sea water eq. | 1.05E-10 | 1.05E-10 | 1.05E-10 |
| Eutrophication - Marine ecosystems | Species.year /kg N to marine water eq. | 1.70E-09 | 1.70E-09 | 1.70E-09 |

Source: (Huijbregts, Steinmann, Elshout, Stam, Verones, Vieira, Hollander, et al., 2017)

# APPENDIX H

# CONVERSION FACTOR OF RESOURCES IMPACT

**Table H.1** Resources Conversion Factor in This Study.

| Conversion Factor | Unit | Individualistic | Hierarchic | Egalitarian |
|---|---|---|---|---|
| Mineral resource scarcity | USD2013 /kg Cu | 1.59E-01 | 2.31E-01 | 2.31E-01 |
| Crude oil | USD2013 /kg | 0.46 | 0.46 | 0.46 |
| Hard coal | USD2013 /kg | 0.03 | 0.03 | 0.03 |
| Natural gas | USD2013 /$Nm^3$ | 0.30 | 0.30 | 0.30 |
| Brown coal | USD2013 /kg | - | - | 0.03 |
| Peat | USD2013 /kg | - | - | 0.03 |

Source: (Huijbregts, Steinmann, Elshout, Stam, Verones, Vieira, Hollander, et al., 2017)

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| | |
|---|---|
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| Education | 2016 : Bachelor of Engineering (Industrial Engineering)<br>Faculty of Engineering<br>Universitas Sebelas Maret (UNS), Indonesia |

Publication

Sakti, A. Y. N., Babel, S., Laohhasurayotin, K., & Opaprakasit, P. (2024). Water-Energy Nexus Flow Analysis of a Wastewater Treatment Plant in Thailand. *IOP Conference Series: Earth and Environmental Science, 1368*(1), 12010. https://doi.org/10.1088/1755-1315/1368/1/012010