Biomass Energy Carbon Capture and Sequestration With Nuclear Fusion: A Promising Option for Future Energy Sustainability?

Biomass Energy Carbon Capture and Sequestration with Nuclear Fusion:

A Promising Option for Future Energy Sustainability?

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Abstract

This thesis proposes and analyses an innovative sustainable power plant concept, Nuclear Fusion BECCS. This conceptual plant utilizes nuclear fusion reaction as the heat source for the biomass gasification process. Product synthetic gas will then be used for electricity generation, and the produced carbon dioxide will be removed and sequestrated in the underground reservoir.

The environmental impact of 1 kWh electricity production was assessed through life cycle assessment, and the life cycle GHG emissions of the plant was estimated to be -0.868 kg CO2-eq/kWh. This was the lowest GHG emissions among nine comparable power plants. The economic performance of the plant was also assessed by its levelized cost of electricity. The calculated cost of electricity of Nuclear Fusion BECCS was 0.203 $/kWh, the highest among nine power plants; however, thanks to its large net negative GHG emissions, the economic performance of Nuclear Fusion BECCS improved dramatically as the carbon price increases. It was indicated when the carbon price rises higher than 177 $/t CO2, Nuclear Fusion BECCS would become the most economical plant among nine power plants. Combined with the projected increase in carbon price in the next few decades, it was predicted that Nuclear Fusion BECCS plant would become the most economical plant in the market by 2050.

Is Nuclear Fusion BECCS a promising option for future energy sustainability? I conclude the answer is, "*yes*."

Dedication

To my wife Midori, who has been unconditionally supportive of my career throughout my life.

Acknowledgments

I would like to express my very great appreciation to my thesis director, Dr. Thomas P. Gloria, who has provided invaluable insights and advice on this project. Without him, this study could not have been completed. Also, I would like to offer my special thanks to my research advisor, Dr. Richard Wetzler, for his kind support throughout my research.

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Last but not least, my special thanks are due to my brother Atsuhiro and my mother Harumi, who have been supportive of my unique (by Japanese standards) life choices.

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Acronyms and Definition of Terms

Availability Factor	The percentage of time a power plant produces electricity over a certain period; i.e., the total amount of operational time over the total time.
Balance of Plant (BOP)	A term collectively describes the supporting components of a power plant; e.g., buildings, wirings, parking lot etc.
Bio-Energy with Carbon Capture and Sequestration (BECCS)	A type of power plant that utilizes the chemical energy from biomass while recovering and sequestrating the carbon dioxide emission.
Biomass gasification	A process that converts biomass feedstock into synthetic gas by applying high temperature.
Carbon Capture and Sequestration (CCS)	A process of capturing the carbon dioxide and to depose it to a storage site.
Carbon tax	A charge imposed based on the amount of CO2 emissions.
Decarbonization	Removing carbon dioxide from the atmosphere.
Global Warming Potential (GWP)	An impact assessment index for global warming by the greenhouse effect.
Greenhouse Gas (GHG)	Type of gas that absorbs infrared radiation, including CO2, methane and water vapor.
Integrated Gasification Combined Cycle (IGCC)	A type of power cycle that generates electricity from syngas obtained by gasification of biomass feedstock via gas turbines.

Integrated Gasification Fuel-cell Cycle (IGFC) A type of power cycle that generates electricity from hydrogen obtained by gasification of biomass feedstock via fuel cells.

Intergovernmental Panel on Climate Change (IPCC) A global intergovernmental panel of the United Nations comprised of the scientists and professionals on climate change.

ITER An experimental nuclear fusion reactor currently in construction in France.

Levelized Cost of Electricity (LCOE) An economic metric that represents the estimated cost of unit-cost of electricity over the lifetime of the power plant.

Life Cycle Assessment (LCA) A methodology to assess the impact of a product or a service associated with multiple stages of the product life cycle.

Nuclear fusion A reaction where two or more atomic nuclei overcome the coulombic barrier and, through the quantum tunneling effect, join together to create a heavier nucleus, and to release enormous amounts of energy.

Representative Concentration Pathway (PCR) Trajectories of greenhouse gases concentration adopted by IPCC.

Synthetic gas (syngas) A mixture of hydrogen, carbon monoxide, carbon dioxide, methane and hydrocarbon gas.

Chapter I.

Introduction

Mitigating global warming within this generation is one of humanity's greatest concerns. Under the auspices of the United Nations Framework Convention on Climate Change (UNFCCC), the Paris Agreement was developed with the central aim to strengthen the global response to climate change, through the control of global temperature rises to below 2 degrees Celsius above pre-industrial levels in this century. A further goal is to restrict temperature increases to below 1.5 degrees Celsius, and to strengthen nations' abilities to deal with climate change impacts (UNFCCC, 2018).

However, countries around the world are struggling to come up with clear strategies toward this goal, partly drawing from the lack of technological options to achieve a drastic reduction in the carbon dioxide while providing an abundant amount of energy required for continued economic growth. This study intends to propose an innovative energy option that combines biomass gasification, carbon capture & sequestration and nuclear fusion, which could potentially remove a significant amount of carbon the from the atmosphere while providing substantial amount of energy.

Research Significance and Objectives

According to independent scientific analysis of current climate change policies under the Paris Agreement, the change in temperature by the end of the century is estimated at between 2.5 and 4.4 degrees Celsius. This is an improvement on global warming in the absence of mitigatory policies, estimated at between 4.1 and 4.8 degrees Celsius, however, current efforts are insufficient to meet the 2.0-degree or the more ambitious 1.5-degree targets (Climate Action Tracker, 2018). Intergovernmental Panel on Climate Change (IPCC) adopted its projections of the temperature changes for several trajectories of the future greenhouse gas concentrations in its fifth Assessment Report as Representative Concentration Pathway (RCP) as Figure 1 in 2014. Projections in Figure 1 suggests that to achieve the 2.0-degree goal, humanity has to follow the RCP 2.6 and reduce greenhouse gas emissions rapidly down to zero by around 2050.

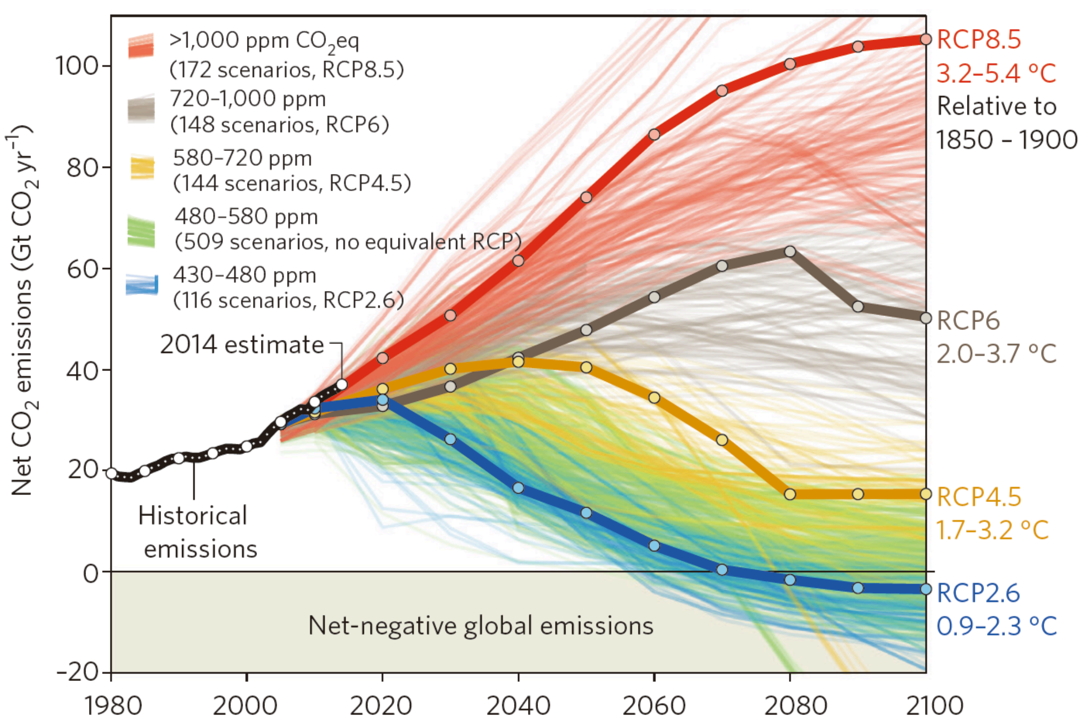


Figure 1. IPCC Representative Concentration Pathway (Fuss et al., 2014).

Decarbonization is the first step toward this pathway. In addition to the decarbonization of industry, transport and building sectors, national energy scenarios provide energy generation options which are carbon neutral (wind, solar, nuclear, biomass) or low carbon (gas, etc.) to achieve deep greenhouse gas (GHG) cuts by 2050 (Mathy, Menanteau, & Criqui, 2018). However, decarbonization alone is insufficient to reach a net zero emissions outcome by mid-century. Climate scenarios meta-analysis study by Fuss et al. (2014) revealed that to achieve net-negative emissions, Bio-Energy with Carbon Capture and Sequestration (BECCS) plant would have to be installed in a large capacity as shown in Figure 2.

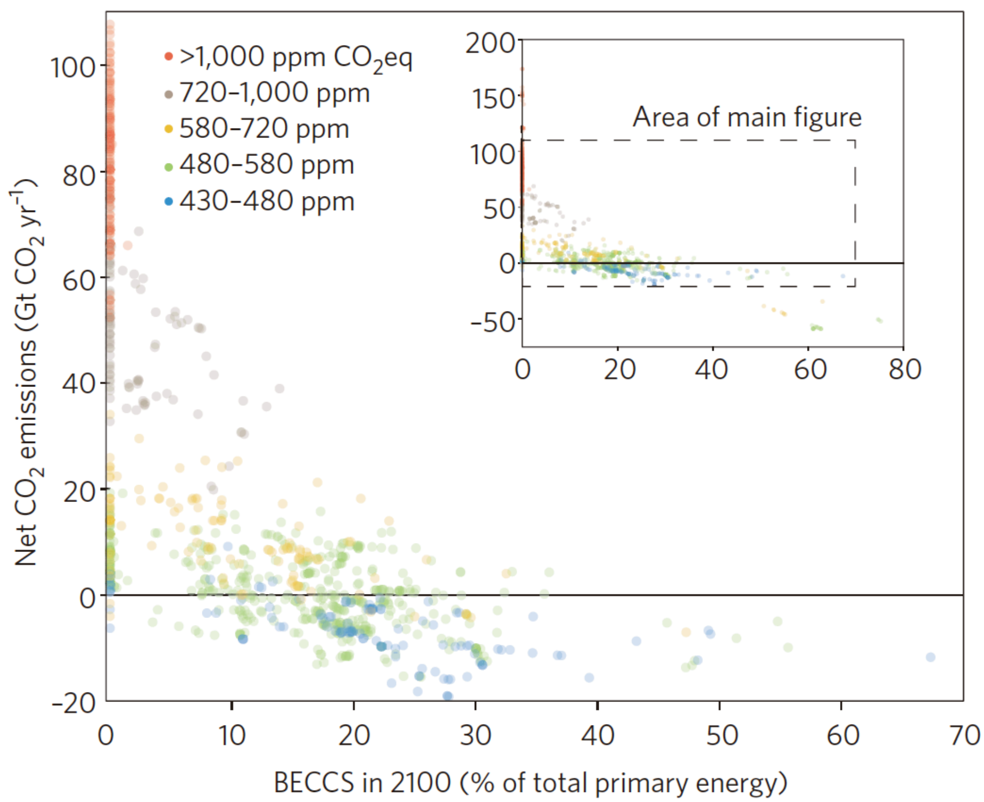


Figure 2. Relation of BECCS Capacities and Carbon Emissions (Fuss et al., 2014).

Theoretically, BECCS plants combined with zero-emission high-temperature heat sources would provide the most sustainable, long-term large-scale carbon sink. However, such concepts have only been explored minimally. In this thesis, I propose nuclear fusion, the same process that powers the sun and the stars, as a candidate for the heat source of future BECCS plants. Nuclear fusion would provide the most sustainable option for future BECCS plants because 1) its primary fuel sources are abundant, 2) it provides high-temperature heat with inherent safety, and 3) it does not produce direct operational GHG emissions. Realization of such a concept would be of great importance not only towards achieving the Paris Agreement targets, but also towards the long-term flourishment of humanity.

Therefore, the objectives of this thesis are:

- to propose an innovative BECCS plant concept with nuclear fusion as a heat source that could provide a 'virtually unlimited' sustainable energy option;
- to evaluate the life-cycle GHG emissions of the proposed Nuclear Fusion BECCS plant concept;
- to assess the economic performance of the plant to gauge if Nuclear Fusion BECCS plant could play a significant role in the future energy market.

Background

There are a number of energy options that could potentially provide large-scale carbon-negative energy sources. In this section, I first clarify the reasonings why I assert the combination of nuclear fusion and BECCS to be one of the most promising options, and then present a plant design of the Nuclear Fusion BECCS concept.

Biomass Energy Conversion

The efficient use of biomass resources is identified as a requirement for a zero-emission future under the least supply cost minimization approach. Great efforts have been made toward the improvement of the efficiency of biomass energy use to this end, and currently, there are several key technologies as summarized in Table 1.

Table 1. Key Technologies of Biomass Energy Conversion (Kumar, Jones, & Hanna, 2009).

Conversion	Process	Product	End-Use
Thermochemical Conversion	Combustion	Heat	Heat, Electricity
	Gasification	Synthetic Gas (H_2 + CO)	Electricity, Chemical Feedstock
		Hydrogen (H_2)	Electricity, Transport Fuel
		Liquid Fuel (Diesel)	Transport Fuel
	Carbonization	Carbon (Solid C)	Fuel, Chemical Feedstock
Biological Conversion	Zymolysis	Methane	Electricity, Transport Fuel
		Alcohol (Ethanol, Butanol)	Electricity, Transport Fuel

Among the key technologies shown in Table 1, the gasification process is regarded as the most promising toward the clean and efficient use of biomass resource due to its potential efficiency. Biomass gasification processes turn biomass into synthetic gas as shown in Eq.1, which can then be converted to either liquid fuel production

(Tijmensen, Faaij, Hamelinck, & van Hardeveld, 2002) or hydrogen production (Turn, Kinoshita, Zhang, Ishimura, & Zhou, 1998).

$(C_6H_{10}O_5)n + nH_2O = 6nH_2 + 6nCO - 814n$ kJ

There are several large-scale demonstration plants already in operation around the world that utilizes biomass gasification process (E4tech, 2009). Notable examples including a gasification plant operated by Holzstrom in Stans, Switzerland (Rüegsegger, 2014) and a woody biomass gasification power generating system designed and operated by Mitsubishi Heavy Industry in Mie, Japan (Yamamoto et al., 2005).

In the case of the hydrogen production process (Table 1: 'Thermochemical Conversion – Gasification – Hydrogen'), the carbon dioxide emitted on site could be recovered to be sequestrated. Such a system can provide clean energy on the one hand and offer options for sequestrating CO2 to achieve a carbon-negative outcome on the other.

<u>Biomass Carbon Capture and Sequestration: BECCS</u>. In their investigation of a zero-emission future scenario, Tokimatsu et al. (2016), identified a series of advanced energy technologies which could be developed and deployed to meet emission targets and achieve global economic growth by adopting a least supply cost minimization model which considered energy, mineral, biomass and food resources across 10 global regions. In their study, it was estimated that negative-emission biomass energy source called *Bio-Energy with Carbon Capture and Sequestration*, or BECCS, would play a significant role alongside with renewable energy technologies (Tokimatsu et al., 2016).

BECCS is a type of power plant that utilizes the chemical energy from biomass while recovering and storing carbon dioxide. Figure 3 illustrates the typical flows of a

BECCS plant. Here, the chemical energy from biomass feedstock is used to generate electricity, while the retrieved carbon dioxide is sequestrated to an underground geological formation.

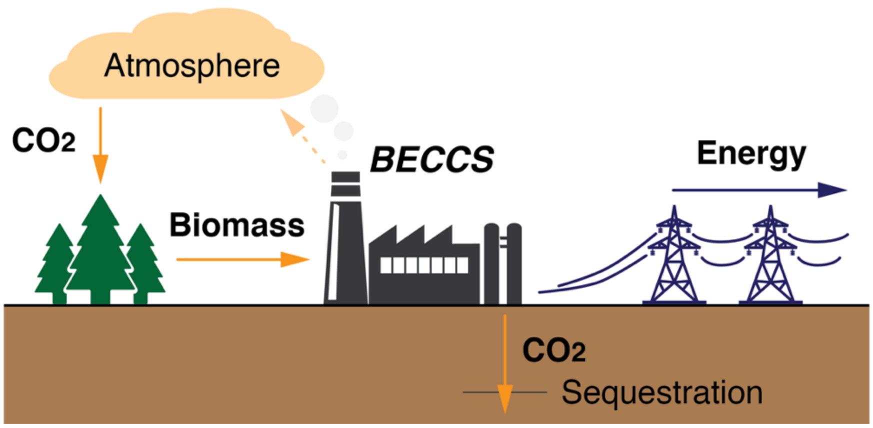


Figure 3. Illustration of BECCS Plant Flows (by author).

Estimated Potential of BECCS Technology. The incorporation of BECCS is found to be essential in keeping temperature increases below 1.5 degrees Celsius (Fuss et al., 2014). In terms of the potential CO2 capability of BECCS when used in collaboration with other carbon removal strategies, Psarras et al. (2017) estimate some 12 giga-tons (Gt) per annum the same amount as offered by direct air capture at about 1/6th the cost. Along with land management (the cheapest method of CO2 removal, with moderate removal capacity), BECCS is likely to play a large role in any future carbon negative technology package. In light of the likelihood of BECCS deployment, a number of national, regional and global case studies have emerged, measuring emission reduction and energy provision capacity, along with policy considerations.

Current Limitations of BECCS Technology. Some planned large-scale BECCS plants including Biorecro/EERC in the U.S. seek to utilize the biomass gasification process (Table 1: 'Thermochemical Conversion – Gasification') for the improved efficiency (Kemper, 2015). However, one of the key requirements for the gasification process is high temperature, as the efficient gasification of biomass requires significant temperatures (1200-1600 degrees Celcius; (Quader & Ahmed, 2017)). In order to generate the required temperature, gasification plants combust either the biomass feedstock or the synthetic gas. Currently, around 30% of the biomass feedstock is consumed for heat generation, which is far from ideal in terms of efficient biomass recourse usage.

A Proposal for the Improvement. For this very reason, in order for BECCS plants to more effectively contribute to the carbon reduction, its heat sources should be replaced with sustainable and zero-emission ones. Table 2 compares zero-emission high-temperature sources from the standpoint of its applicability towards hydrogen production BECCS plant.

Table 2. Comparison of Zero-emission Heat Sources (by Chapman and author).

Technology	**Suitable for Biomass?**		**Notes**
	Temp.	**Resource**	
Concentrated Solar (CSP)	✗ 600-800 °C	✓ Renewable and ubiquitous.	Pros: Solar CSP is readily available. Cons: Lower than ideal temperature means the efficiency will be compromised.
Nuclear Fission	✗ 300-350 °C (Light Water)	✗	Pros: Extraction of heat is relatively simple.

	✓ 600-1000 °C (High-temp. Gas)	✗ Fuel finite and not ubiquitous.	Cons: Only next generation high-temperature reactors could be utilized for gasification. Limited fuel resource. Produces high-level radioactive waste and has a risk of accidents.
Nuclear Fusion	✓ 300-1000 °C	✓ Fuel virtually unlimited and ubiquitous.	Pros: Virtually unlimited fuel resource. Extraction of heat relatively simple, well matched with BECCS requirements. Cons: Nuclear fusion is not yet a mature technology.
Geothermal Heat	✗ ~500 °C	✓ Renewable and ubiquitous.	Pros: Stable heat output. Cons: Requires drilling several km's below ground and has lower than ideal temperature. Currently, this technology is in the pilot phase.
Industrial Waste Heat	✓ 65-1350 °C	✗ Depending on availability and location.	Pros: Some processes yield heat at very high temperature. Cons: May rely on fossil fuels. Quantity available is unclear, intermittency likely to be an issue.

It is known that biomass gasification process occurs most efficiently around 900 degree Celsius. In addition, since my aim is to propose a long-term sustainable energy option, it is critical that the heat source can be sustained for the foreseeable future. Considering BECCS plants are envisioned to be installed in a number of countries, it is also desirable if the heat source is available without locational restrictions.

Based on the analysis in Table 2, in this thesis, I propose that the utilization of nuclear fusion should be considered for future BECCS plants, as it is the only energy source that could satisfy the two key requirements: its temperature and long-term resource abundance.

Nuclear Fusion

Under enormous pressures and temperatures, two or more atomic nuclei are able to overcome the coulombic barrier and, through the quantum tunneling effect, join together to create a heavier nucleus, and to release enormous amounts of energy in the process. This reaction is called *nuclear fusion*. Nuclear fusion has the potential to provide almost limitless energy for mankind (Bradshaw, Hamacher, & Fischer, 2011), and there is no risk of a runaway reaction, and no long-lived high-level radioactive waste or harmful greenhouse emissions are produced (Ueda, Inoue, & Kurihara, 2004).

Figure 4 illustrates the binding energy of atomic nuclei and shows the differences between the easily confused nuclear *fusion* and nuclear *fission* reactions. Nuclear fission involves the splitting of unstable heavy atomic nuclei (the leftward arrow on the right-hand side of the figure), whereas fusion involves the fusing of light atomic nuclei (the upward arrow on the left-hand side of the figure).

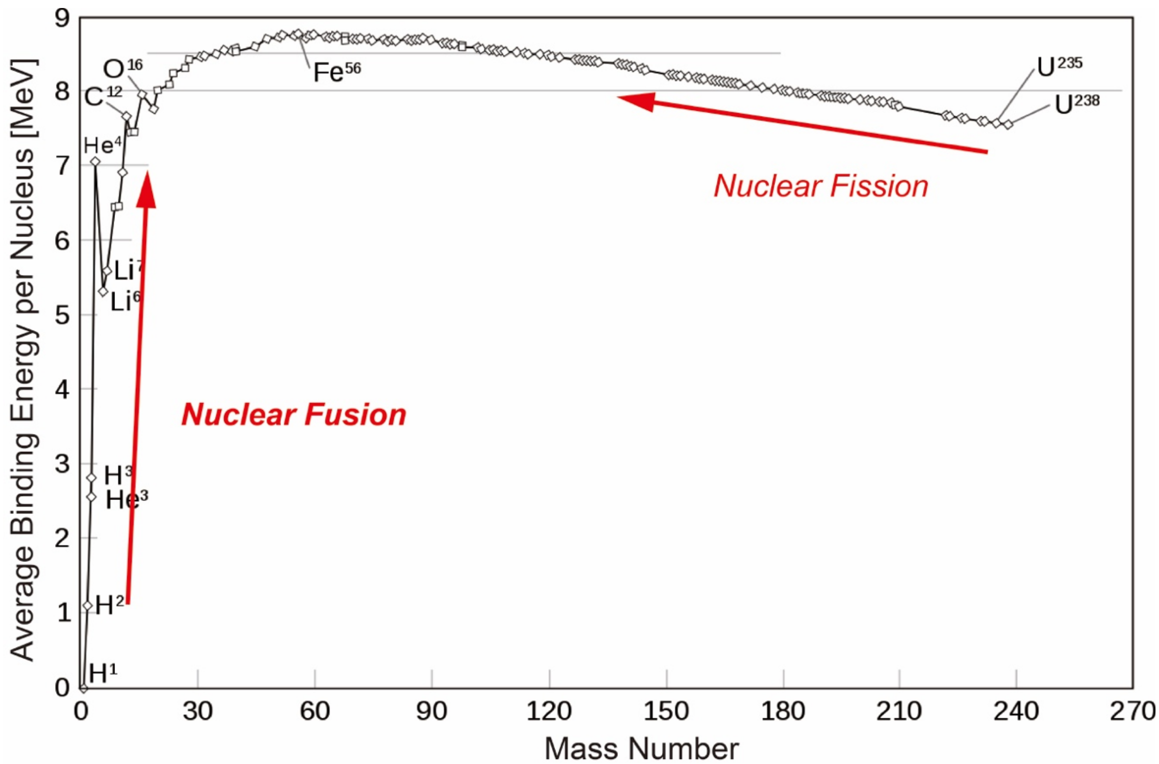


Figure 4. Binding Energies of Atomic Nuclei (from Hydrogen to Uranium) (Browne, Dairiki, & Doebler, 1978).

In case of a nuclear fusion reaction, the surplus binding energy will be released as kinetic energy of particles, as detailed below. Here, the relationship between mass and energy is shown, where E, m and c are the energy released, the mass difference, and the speed of light respectively.

$$E = \Delta mc^2$$

Among other reactions, nuclear fusion between two isotopes of hydrogen, deuterium (^2D) and tritium (^3T) is the best candidates for the fuel cycle in future fusion reactors. (Ueda et al., 2004)

$$^2D + {}^3T \rightarrow \quad {}^4He\ (3.52\ \text{MeV}) \quad + {}^1n\ (14.06\ \text{MeV})$$

Nuclear Fusion Reactors. Although the D-T fusion reaction requires the lowest kinetic temperature for the fusion reaction to occur, extremely high temperatures in the order of tens of keV are still required. Fusion reactors must be designed to provide and contain the conditions needed for nuclear fusion reactions to occur. Although several approaches to controlling and containing a fusion plasma exist, the two primary approaches being explored are based on the concept of magnetic confinement, and inertial confinement.

Magnetic confinement fusion reactors are the more advanced of the two approaches, and they utilize magnetic fields generated by electromagnetic coils to confine a fusion plasma in a donut-shaped (torus) vessel. Together, the European Union, India, Japan, Russia, United States, South Korea and China are involved in the construction of the ITER (formerly known as the International Thermonuclear Experimental Reactor) magnetic confinement tokamak reactor. A diagram showing the cross-section of ITER is shown in Figure 5. Under construction in Saint-Paul-lès-Durance, near Provence, in France, the preliminary operation of ITER is currently scheduled to begin in 2025.

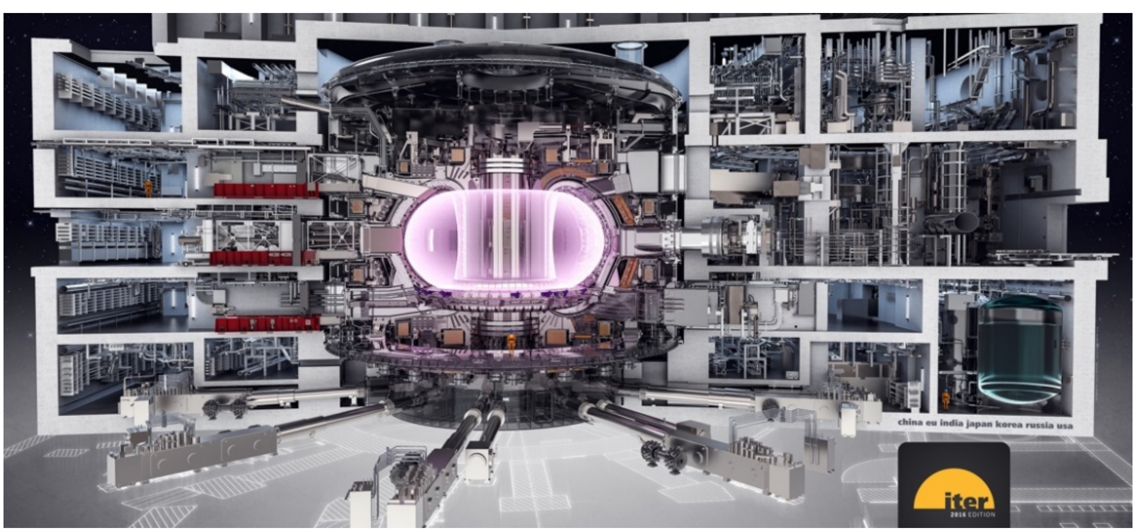


Figure 5. ITER Tokamak and Plant Systems (ITER, 2016).

Safety. Unlike nuclear fission reactors, nuclear fusion reactors do not have any risk of a runaway reaction or meltdown. In the case of any abnormalities in fusion reactor conditions, such as an abnormal plasma pressure or density spike, the plasma will dissociate and collapse, and the fusion reaction will cease. The level of decay heat in a fusion reactor after the termination of the plasma is very low compared with fission reactors, which must be cooled after shutdown to prevent core melt. In addition, nuclear fusion power plants will not produce high level or transuranic radioactive waste like that produced by fission power plants.

Environmental Impacts. Although fusion power plants will release small quantities of tritium to within already defined limits, they will not produce greenhouse gases or other air pollutants (Perrault, 2016). As a result, the environmental impacts associated with nuclear fusion power plants will instead be primarily attributed to construction, operation & maintenance, including fuel supply chains, and waste disposal.

Sustainability. The fuels of nuclear fusion power plants are deuterium and tritium. Deuterium is an isotope of hydrogen with the isotopic ratio of 150 ppm, or 1 part in 6700 atoms of hydrogen. As such, deuterium is abundant in seawater and can be extracted using well-established separation processes. Tritium is a radioactive isotope, decaying with a half-life of 12.3 years, with severely limited supply, as a global stockpile of only around 30 kg is available for commercial use worldwide. For this reason, tritium is expected to be produced by neutron interaction with lithium, specifically the isotope lithium-6, in breeding blankets, under the following reaction:

$$^{6}\text{Li} + \text{n} \rightarrow {}^{4}\text{He}\ (2.05\ \text{MeV}) + {}^{3}\text{T}\ (2.75\ \text{MeV})$$

On lithium and deuterium sources alone, it is estimated nuclear fusion power plants could provide the electricity needs of humanity for tens of millions of years (from 14 million (Bradshaw et al., 2011) to 23 million years (2011)). This leads us to the consideration that the resources for nuclear fusion are '*virtually unlimited*.' Current terrestrial deposits of lithium are estimated at 53 million tons (USGS, 2018). Given that a nuclear fusion power plant with an electrical output of 1 GWe requires between 10 and 35 tons of lithium over its operational lifetime (Bradshaw et al., 2011), 2,500 1 GWe fusion power plants would require up to 90,000 tons, notwithstanding competition for lithium from advanced technologies such as large scale battery storage. However, it is more complex when considering that many fusion breeder concepts rely on the use of lithium-6 rather than natural lithium. Lithium-6 has an isotopic abundance of only 7.5%, and therefore to obtain 90,000 tons of lithium-6, a total of 1.2 million tons of natural lithium would be required. Even so, this is only around 2% of the current known terrestrial deposits, and a backstop also exists in the form of seawater in which the abundance of lithium and some other key minerals is relatively high. Thus, although production cost would likely increase, lithium could be procured from seawater in the future (Nobukawa, 1997; Ooi, 1997).

<u>Global Initiatives Towards Commercialization</u>. In anticipation of the successful demonstration of the technical feasibility of nuclear fusion power plants based on the tokamak approach in ITER, many nations around the world are now proposing Demonstration Nuclear Fusion Power Plants (DEMO) designs. On top of DEMO, alternative fusion energy concepts are also being developed in parallel to the ITER

project and are slowly increasing in technological maturity. And such activities have become the subject of increased international interest over recent years.

Nuclear fusion has received frequent cynicism, with the longstanding quip that it is “always 30 years away,” in reference to the fact that since the 1970s fusion scientists have continually predicted that fusion energy will take 30 years to become commercial (Herrera-Velázquez, 2007). With this in mind, it could appear disingenuous to make the same statement here at the current time, but the realization of a commercial fusion power plant is expected in around 30 years’ time. To conclude this overview study, Figure 6 provides a summary of current efforts, showing key concepts and expected milestones, on the pathway to commercial nuclear fusion energy. This shows that the first commercial operation of nuclear fusion would start around as soon as 2030.

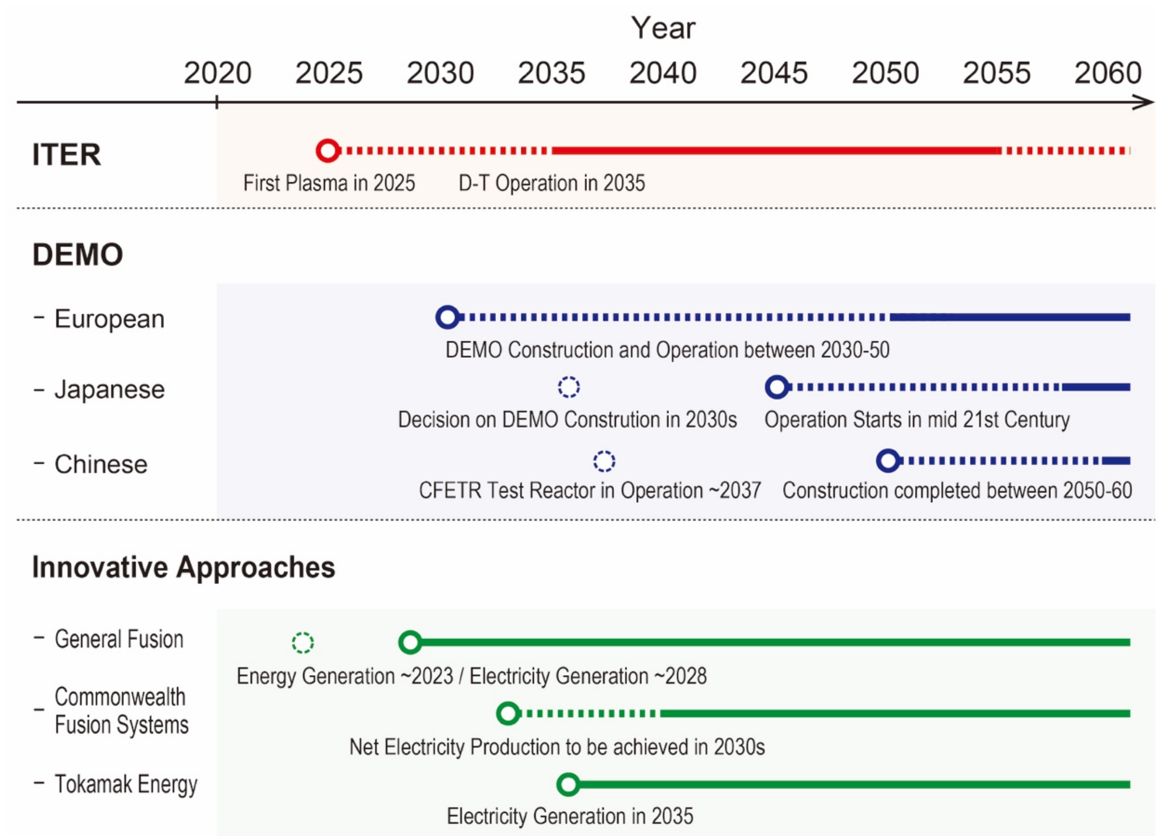


Figure 6. On-going Utility-scale Nuclear Fusion Power Plant Initiatives (Takeda & Pearson, 2019).

Nuclear Fusion BECCS Plant Design

Based on a series of in-depth analyses on the necessary plant components, Nuclear Fusion BECCS plant was designed as Figure 7. Figure 8 and Figure 9 illustrates the plant flow and the energy flow of the plant, respectively. Although the engineering aspect of this plant design is out of the scope of this thesis, an extensive literature review, as well as discussions with qualified professionals in the field were conducted to ensure the engineering feasibility of the plant design.

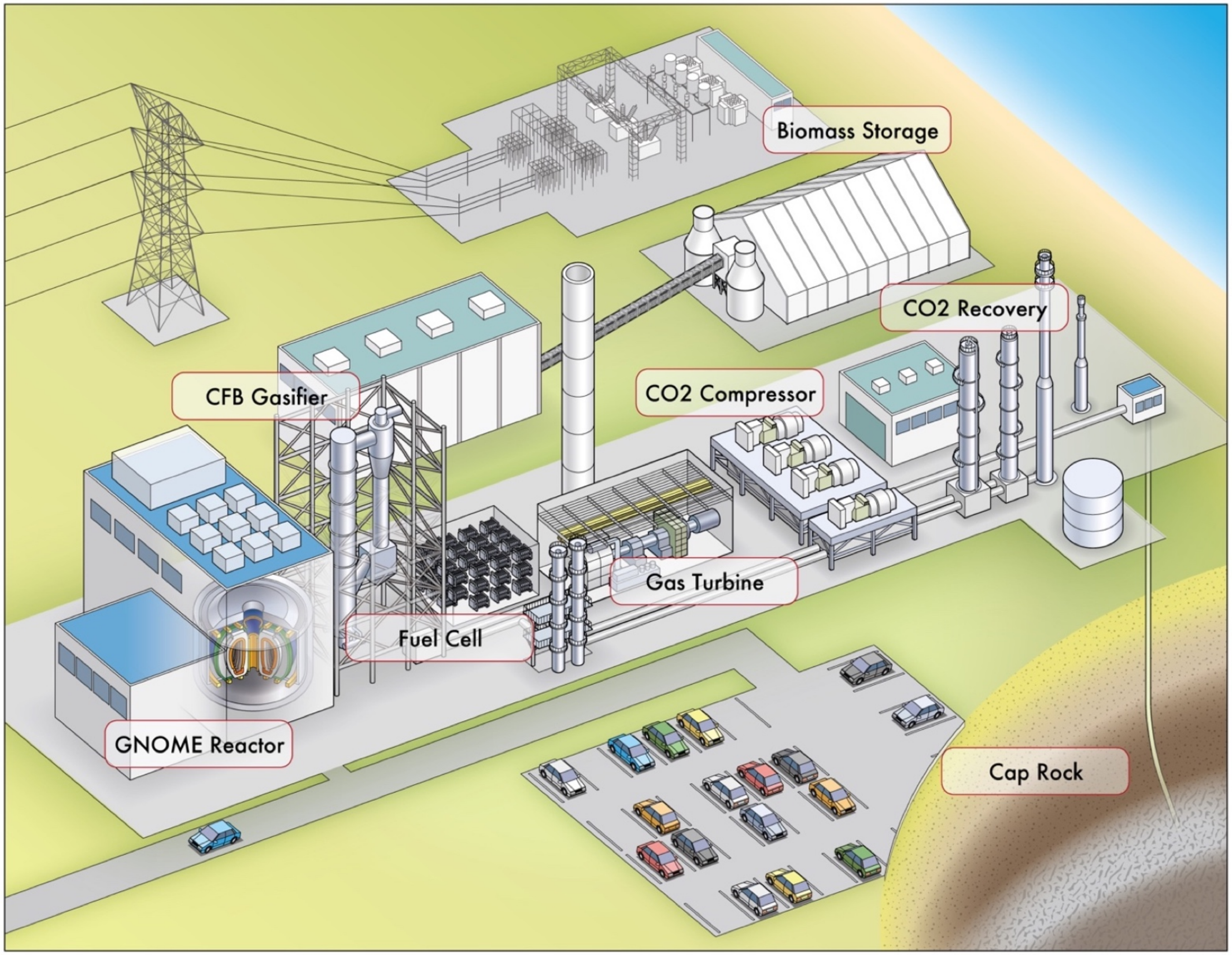


Figure 7. Bird-eye Drawing of the Nuclear Fusion BECCS Plant (by author).

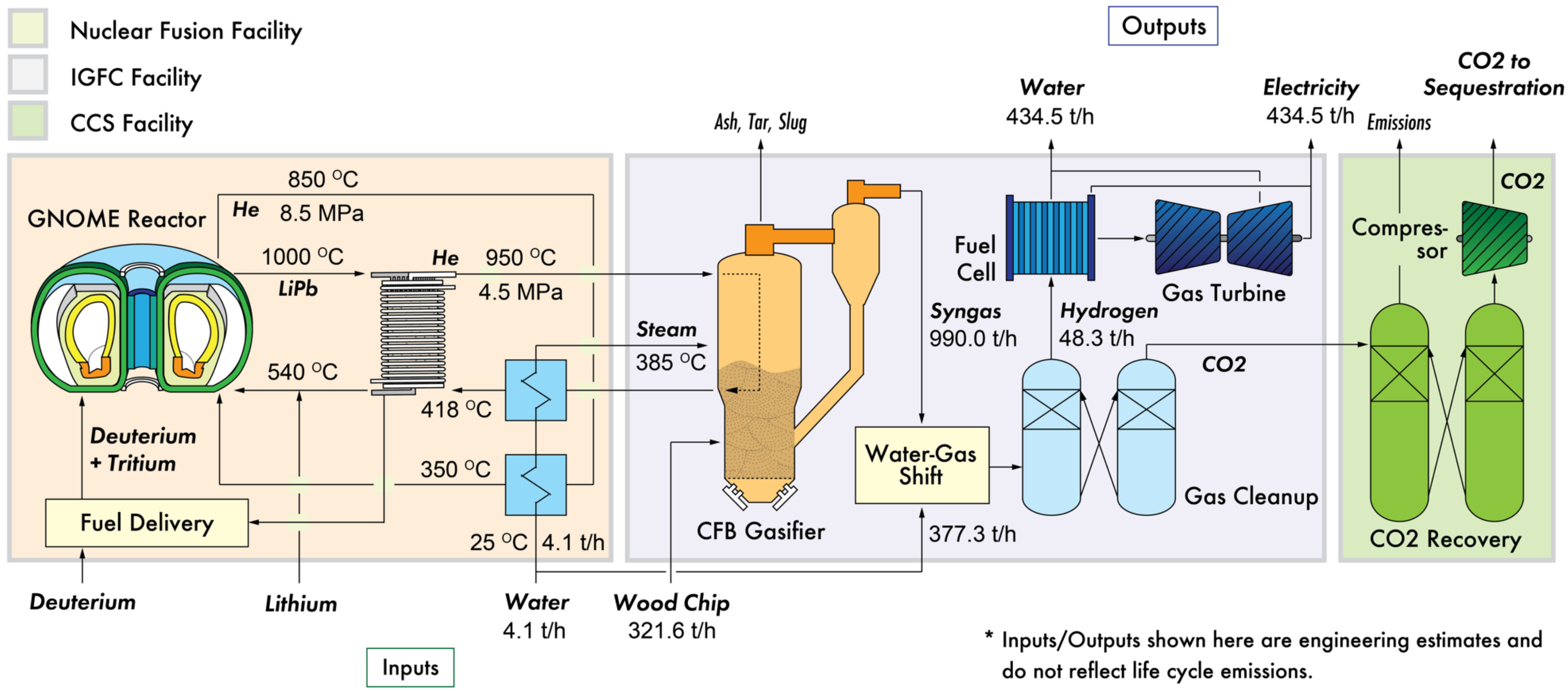


Figure 8. Flow Diagram of the Nuclear Fusion BECCS Plant (by author).

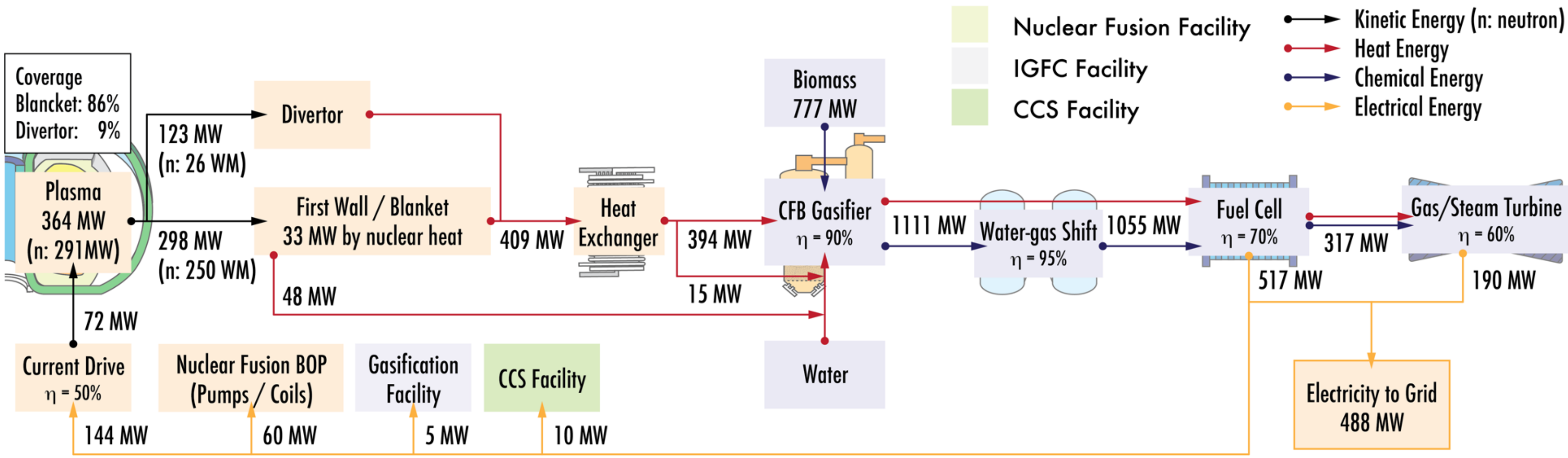


Figure 9. Energy Flow of the Nuclear Fusion BECCS Plant (by author).

Plant Configuration. The designed Nuclear Fusion BECCS plant is comprised of three major facilities: a nuclear fusion facility, an IGFC facility, and a CCS facility. Figure 10 illustrates this configuration.

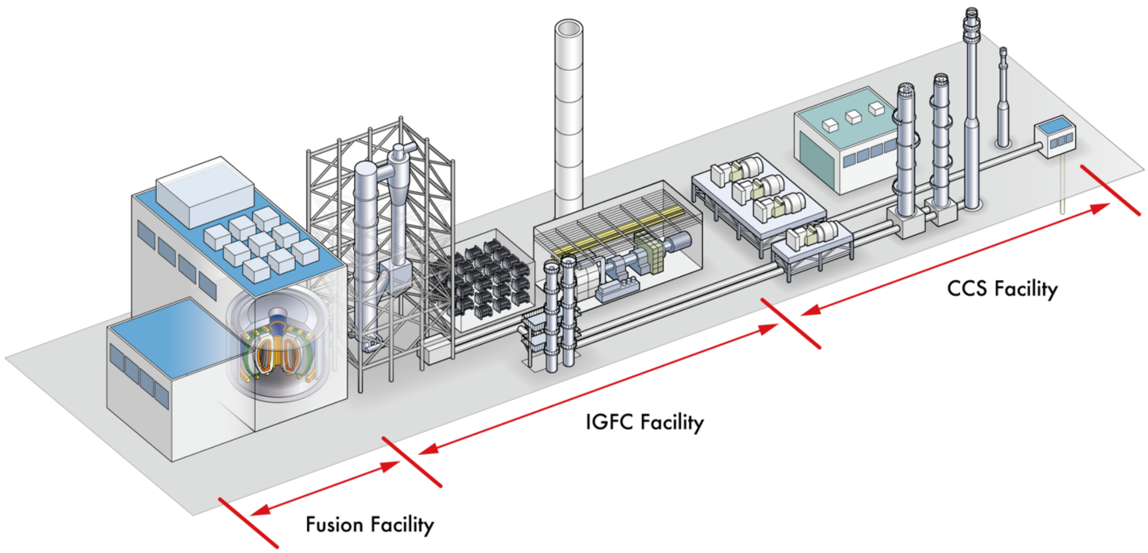


Figure 10. Configuration of the Nuclear Fusion BECCS Plant Concept (by author).

Among the many components of the plant, this section will clarify the design choices behind the following several essential elements.

Nuclear Fusion Reactor. Here, I adopted an existing small-scale nuclear fusion reactor design by (K. Ibano, Utoh, Tobita, Yamamoto, & Konishi, 2011) illustrated in Figure 11. Conceptual Drawing of GNOME Nuclear Fusion Reactor (K. Ibano et al., 2011). This fusion reactor, named GNOME, was designed to extract high-temperature heat from the blanket for process heat application. This reactor was also designed to minimize the technical obstacles on its construction, and it is believed to be one of the most feasible commercial-scale reactor designs.

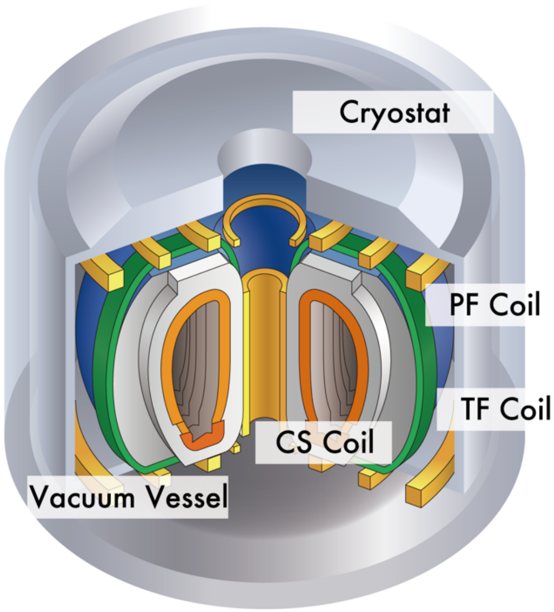


Figure 11. Conceptual Drawing of GNOME Nuclear Fusion Reactor (K. Ibano et al., 2011).

Biomass Gasifier. Dry wood chip was presumed as the biomass feedstock for Nuclear Fusion BECCS plant for its consistency and availability in the market. Based on the operational temperature, the feedstock characteristics (size, composition, and moisture) and the processing capacities of the biomass gasifiers, the Circulating Fluidized Bed (CFB) gasifier was chosen for Nuclear Fusion BECCS plant. A CFB with an external heat supply was designed for this plant concept, which is illustrated in Figure 12.

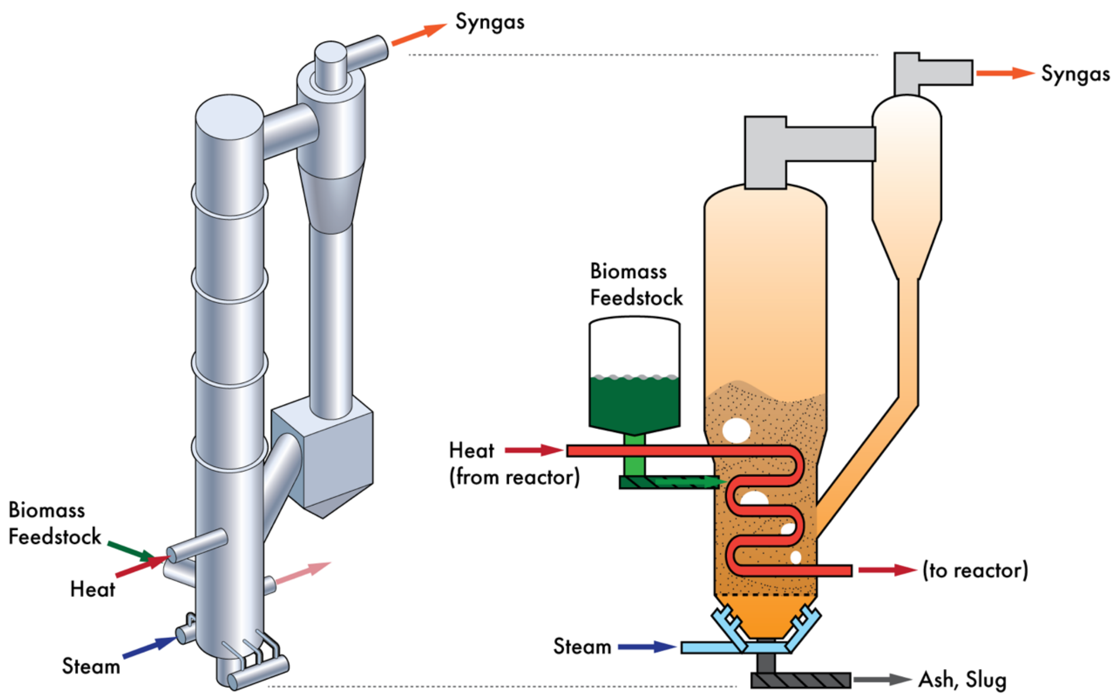


Figure 12. Anaerobic CFB Gasifier Design (by author).

Product Syngas Usage. The usage of product syngas (H_2 + CO) is another essential factor of BECCS plant design. One of the simplest usages is to use syngas as is as feedstock at chemical plants. However, it is known that if a chemical plant would not be located in adjacent to the gasification plant, the transportation cost of syngas would make this usage uneconomic (Watanabe & Naruse, 2012).

The simplest usage of the product syngas is to burn it on site with a gas turbine and generate electricity. This cycle is known as the Integrated Gasification Combined Cycle, or IGCC. A number of IGCC plants are in operation around the globe with coal as the feedstock (Shu-jian, 2009). The efficiency of the IGCC plant is currently around 40% (Guan, 2017). Alternatively, syngas can be converted into liquid fuels on site as summarized in Table 3.

Table 3. Syngas to Fuel Conversion Comparison (E4tech, 2009; Fosgitt, 2010).

	Fischer-Tropsch		**Methanol**	**Water-gas-shift**
Products	Olefins + CO_2	Paraffins + H_2O	Methanol	Hydrogen
Temp. [ºC]	300-350	200-250	200-275	300-500
Pressure [bar]	20-40	10-40	50-100	50-100
H_2/CO rario	0.6-1.7	Slightly >2	Unimportant	Unimportant
Efficiency	~0.6	~0.6	~0.79	(Not stated)

Among these products, the hydrogen produced through the water-gas-shift reaction can be fed to a fuel cell to generate electricity more efficiently as illustrated in Figure 13. This cycle, known as the Integrated Gasification Fuel-cell Cycle (IGFC), is expected to achieve the highest thermal efficiency possible from biomass. Some expect the efficiency of IGFC can even be over 65% (Guan, 2017), a drastic improvement from the efficiency of the current biomass plants, ~20% (Oiwa, 2014). The first large-scale IGFC demonstration plant, the Osaki CoolGen Plant, is expected to start its operation by 2021 (Kenji, 2015).

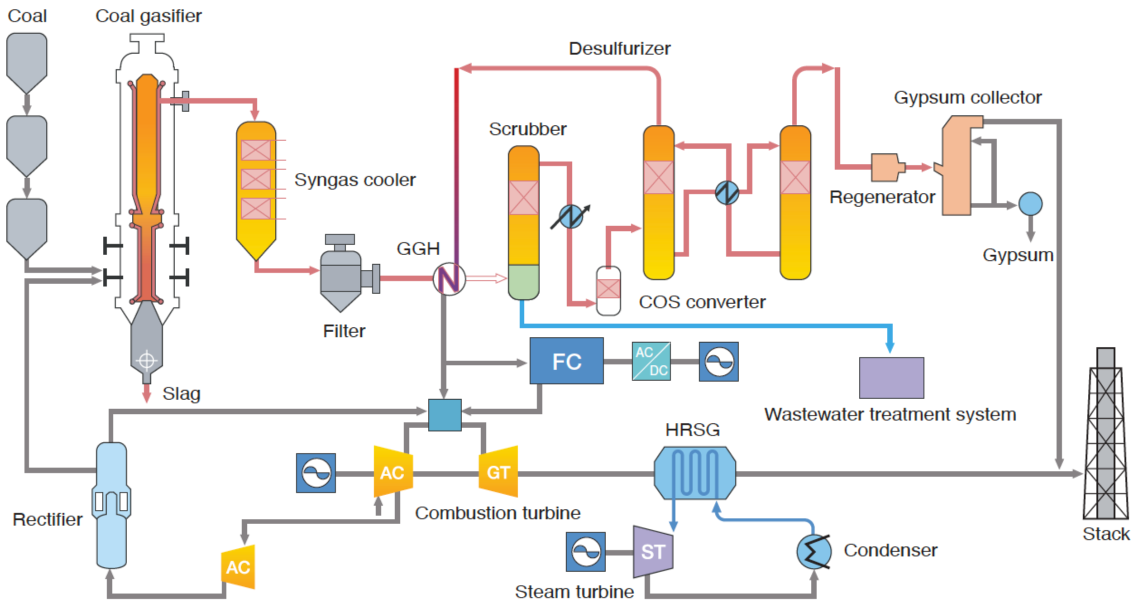


Figure 13. Process Flow of the IGFC Demonstration Plant (Japan Coal Energy Center, 2007).

Both IGCC and IGFC can recover the carbon dioxide emissions to be sequestrated, making them the ideal power cycles for BECCS plants. Among the two, IGFC is technologically more challenging at the moment but can achieve significantly higher efficiency. Considering that the Nuclear Fusion BECCS plants can only be achieved after 2025 at the earliest, I believe the more advanced cycle of IGFC would be the logical choice for Nuclear Fusion BECCS plant toward its aim to achieve carbon removal from the atmosphere while providing the maximum amount of electricity. In particular, I referenced the configuration of the Osaki CoolGen plant when designing the Nuclear Fusion BECCS plant.

Carbon Capture and Sequestration (CCS) Facility. Carbon Capture and Sequestration, or CCS, is a process of capturing the carbon dioxide and to depose it to a storage site, usually an underground geological formation. 22 large-scale CCS facilities are in operation as of 2018, with many more are in the construction or in the planning stage (Gaurina-Medimurec, Novak-Mavar, & Majic, 2018).

Among the large-scale CCS facilities, the Tomakomai CCS Demonstration Project by Japan CCS Co. Ltd. has been particularly successful in its stable continuous operation. Since the capacity of the Tomakomai CCS Demonstration Project is also similar to that of the envisioned Nuclear Fusion BECCS plant, I referenced the design of the Tomakomai plant for the design of CCS facility for this study.

Additional R&D Elements Required for Nuclear Fusion BECCS Plant. Since this conceptual plant is a combination of existing energy facilities plus a nuclear fusion reactor, additional research and development elements for this conceptual plant should be minimal, except for the nuclear fusion reactor. The adopted nuclear fusion reactor, GNOME, was designed with similar parameters of ITER so that it can be constructed with the current technological standards. This leads to some scientist argue that they could start the construction of this reactor today, although scientific and engineering aspect of the reactor is out of the scope of this thesis.

One engineering R&D required for this plant is regarding its gasifier. Conventional gasifiers utilize the partial combustion of biomass feedstock to generate heat, but a CFB gasifier with an external heat supply as illustrated in Figure 12 will be needed for this plant. This is expected to be technologically feasible.

Advantages of Nuclear Fusion BECCS Plant.

Research Questions and Hypotheses

The main research question of this thesis is: Can Nuclear Fusion BECCS plants make a substantial contribution to reducing atmospheric CO_2 and achieving the sustainable energy system of the future defined by the Paris Agreement?

To answer this question, the following three hypotheses will be tested:

- Hypothesis 1: Nuclear Fusion BECCS plant can achieve life cycle GHG emissions of < 0 (life cycle net negative emissions).
    - 1.1: Nuclear Fusion BECCS can achieve larger carbon removal than plain BECCS plant per electricity production.
- Hypothesis 2: The increased cost of Nuclear Fusion BECCS plant over other proposed BECCS plants can be offset by the enhanced carbon removal capacity under a reasonable carbon price (< 200 USD/tCO_2e).

Preceding Studies

An extensive reference search revealed that while there have been discussions on utilizing nuclear fusion for processing heat in the industry in the last decade, no preceding studies have analyzed this particular concept as summarized in Figure 14 (Kobori, Kasada, Hiwatari, & Konishi, 2016; Kwon, Kasada, & Konishi, 2013; Maisonnier et al., 2007; Nam, Kasada, & Konishi, 2017; Robertson, 1956; Schleicher, Raffray, & Wong, 2001; Vesely, Dostal, & Entler, 2017).

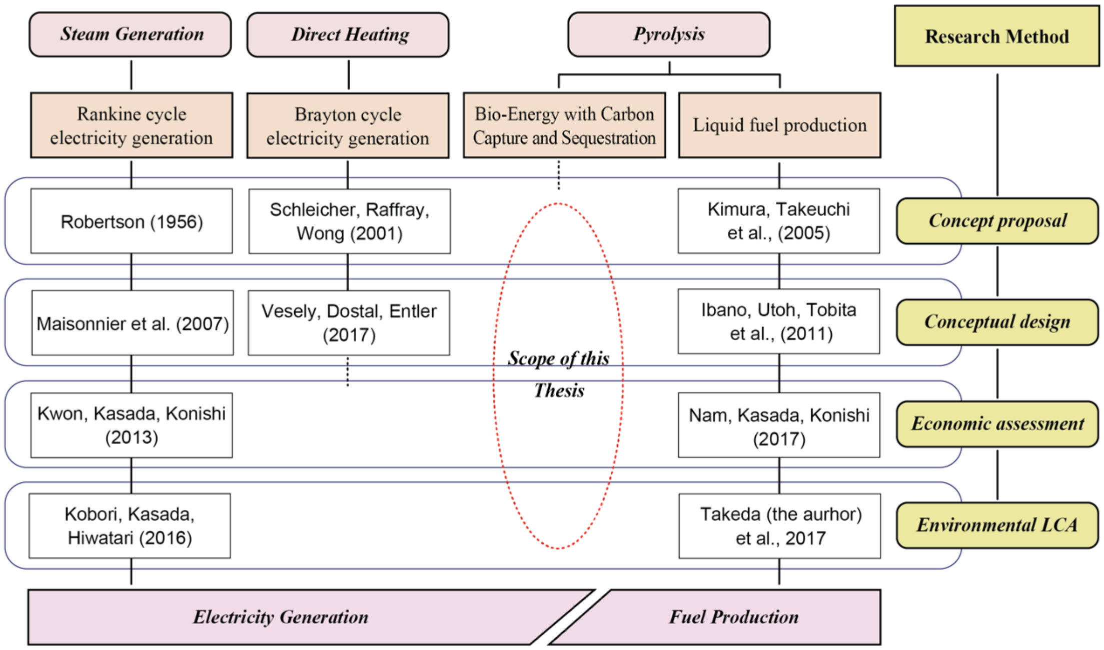


Figure 14. Literature Map of Previously Studied Thermodynamic Cycles for Nuclear Fusion (by author).

Structure of this Thesis

The rest of the thesis is structured as follows. Chapter II presents the research methodology. Chapter III presents the results of the analysis, and Chapter IV presents the discussions and conclusions.

Chapter II.

Methods

As summarized in the Research Questions and Hypotheses section, the research objective of this thesis is two-fold: firstly, to assess the environmental impact of this conceptual plant and secondly, to estimate its economy in the future market. To this end, I will employ two research methodologies: environmental life cycle assessment (LCA) and the calculation of the levelized cost of electricity (LCOE).

Environmental Impact of Nuclear Fusion BECCS Plant

To test the first hypothesis that the designed Nuclear Fusion BECCS plant can achieve life cycle GHG emissions of less than zero, this thesis employs the environmental life cycle assessment (LCA).

Life Cycle Assessment (LCA)

Life cycle assessment (LCA) is a commonly-used analytical framework to quantitatively compare the impacts of a product or a service over its lifetime. LCA has been primarily applied to the assessment of environmental emissions, most notably to compare the GHG emissions of products and services.

LCA is well-suited for energy analyses. The primary advantages of analyzing energy options through LCA are summarized by Skone (2014) that: 1) it draws "*a more complete picture than one focused solely on stack or tailpipe emissions*," 2) it allows a "*direct comparison of dramatically different options*," and 3) it can include "*methods for evaluating a wide variety of burdens*."

The framework for LCA studies is standardized by ISO14040/44 as Figure 15. Goal and scope definition phase include the definition of the goal and scope of the study, and determination of the system boundary and the functional unit. Life cycle inventory analysis phase includes the data collection and modeling of the products, as well as the calculation of the inventory results. Impact assessment is an optional phase in LCA study which includes the analysis of the inventory results using impact assessment methods. Finally, interpretation is a mandatory phase for any LCA studies where the conclusions are drawn, as well as the checks for the integrity of the model including sensibility analysis.

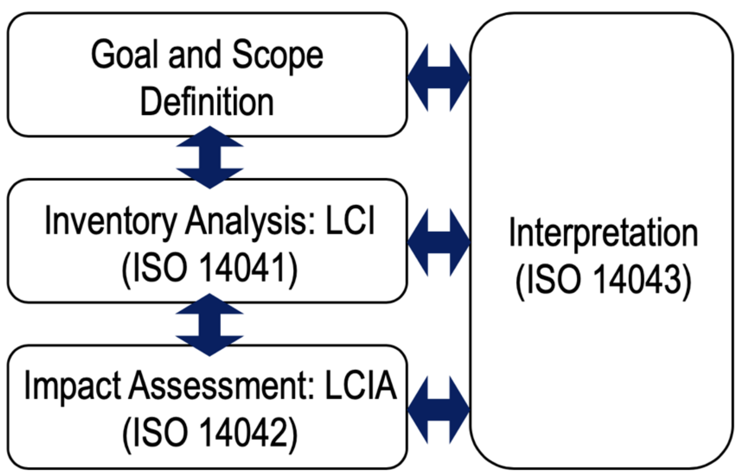


Figure 15. ISO Framework for LCA (ISO14040/44).

Goal and Scope

The goal of the LCA in this thesis is to assess the GHG emissions of electricity generation through Nuclear Fusion BECCS concept and compare it to other environmentally-friendly energy options.

Functional Unit. The product assessed in this assessment is electricity, and the functional unit is 1 kWh.

System Boundary. The system boundary of this analysis is the cradle-to-gate of electricity. Or in other terms, based on the Life Cycle Stage classification by the US DOE illustrated in Figure 16, the system boundary of this LCA is LC Stage #1 to #3.

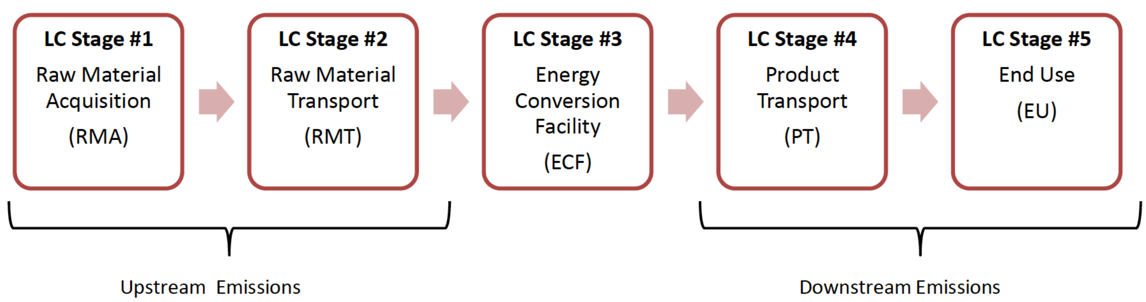


Figure 16. Life Cycle Stages of Energy Plants (Skone, 2014).

The product system of electricity from Nuclear Fusion BECCS plant is illustrated in Figure 17 in accordance with the Life Cycle Stage classification by US DOE, where the red dotted line shows the system boundary of this LCA.

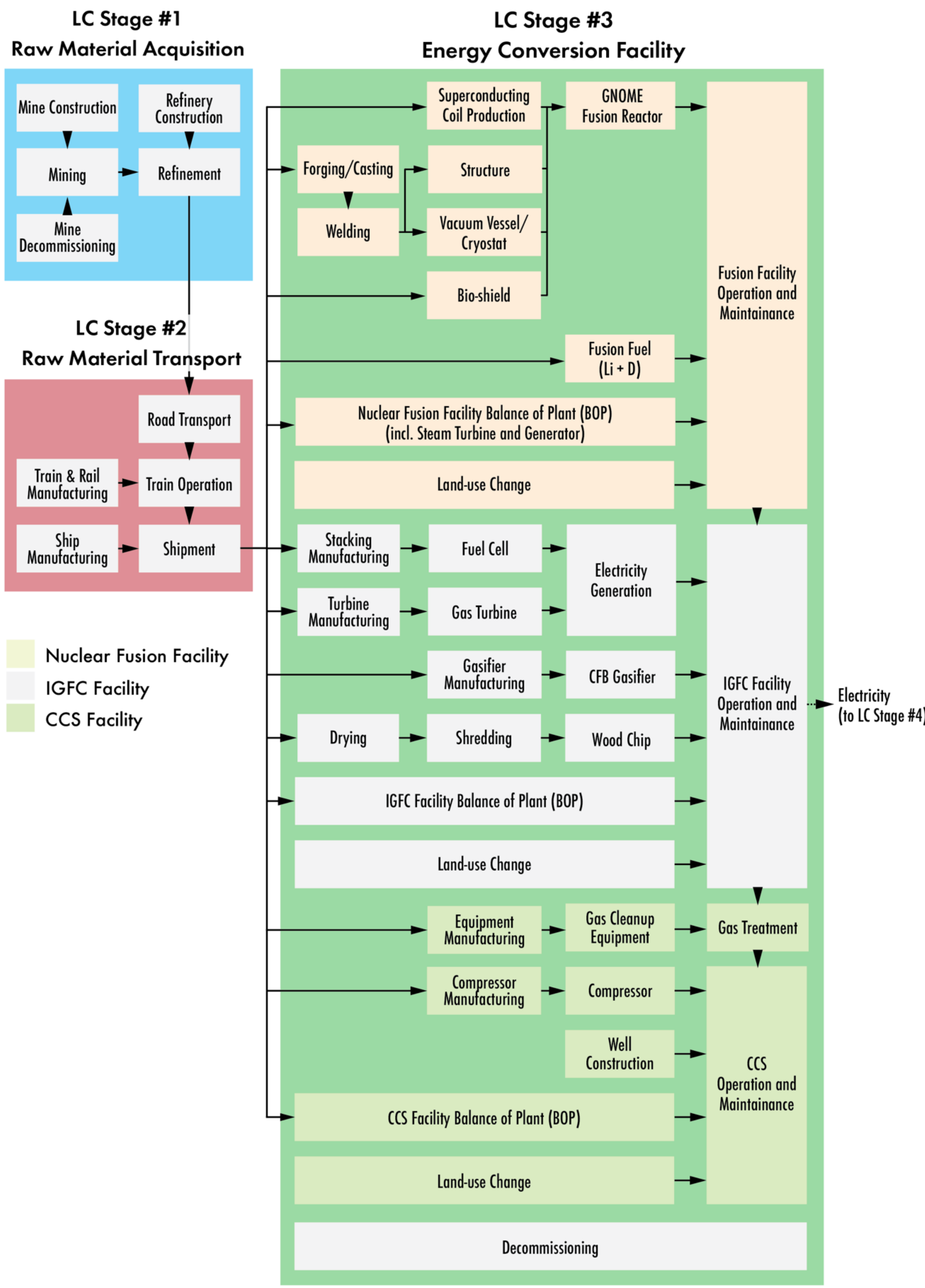


Figure 17. Product System of the Electricity from Nuclear Fusion BECCS (by author).

Software and Database

For this LCA, Ecoinvent 3.5 Cut-off database was used on openLCA version 1.8 software. Ecoinvent is "*the largest transparent unit-process database worldwide*" (Wernet et al., 2016), and its latest version, 3.5, contains LCI data for 16,023 activities. openLCA is a free, open-source software for LCA calculations, which provide a variety of features needed for a detailed LCA study including the uncertainty analysis through Monte-Carlo method (Ciroth, 2007).

Impact Assessment Method

Since the goal of this study is to assess the GHG emissions in the context of the Paris Agreement and the IPCC RCP 2.6 scenario, Global Warming Potential (GWP) values as reported in the page 8SM-39 of the Chapter 8 Supplementary Materials of the IPCC 5th Assessment Report (Stocker, 2014) was used for the impact assessment. The reported weighting metric values are summarized in Table 4. In this thesis, I used the GWP_{100} (Global Warming Potential for 100 years) weighting set as it is one of the most standard methods that is used in the Kyoto Protocol as well as in the IPCC AR4.

Table 4. Global Warming Potential Metric Values Reported in IPCC AR5 (Stocker, 2014).

	Global Warming Potential (GWP)		**Global Temperature Change Potential (GTP)**	
Period	**20 years**	**100 years**	**20 years**	**100 years**
CO_2	1	1	1	1
CH_4	83.9	28.5	67.5	4.3
N_2O	246.6	264.8	276.9	234.2
BC	4349.2	658.6	702.8	90.7

OC	-438.5	-66.4	-70.9	-9.1
SO_2	-253.5	-38.4	-40.9	-5.3
NOx	134.2	-10.8	-86.3	-2.8
CO	8.6	1.9	3.7	0.3

<u>Modification to the Impact Assessment Method</u>. Ecoinvent 3.5 database provides a set of impact assessment methods for IPCC GWP as part of the database. However, these default impact assessment methods do not take the CO2 absorption from the atmosphere into account. In other terms, the input amount of CO2 from the air does not cancel the amount of CO2 emission to the air on ecoinvent 3.5. Ecoinvent 3.5 tries to achieve this by weighing “Carbon dioxide, biogenic” as zero, however, this is a flawed approach. This is because 1) due to the inconsistency in the LCI dataset, some of the biogenic emissions are not labeled as biogenic, and 2) even when all biogenic emissions are correctly weighted as zero towards GWP, carbon removal from the air will not be correctly expressed; i.e., the flow of CO2-eq mass will never be negative.

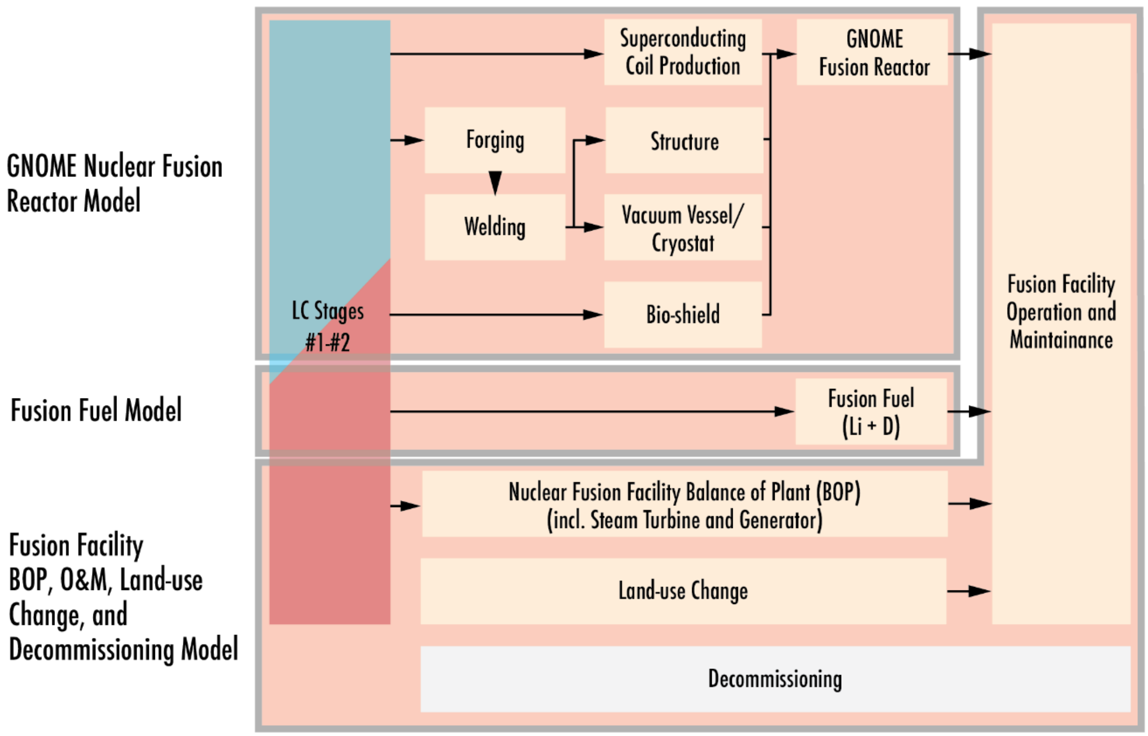
For this reason, I modified the impact assessment methods for IPCC on ecoinvent 3.5 so that 1.0 kg of elementary flow of Carbon Dioxide from air to cancel 1.0 kg of elementary flow of Carbon Dioxide emissions to air. In trade for this, “*carbon dioxide, biogenic*” emissions were modified to be weighted as 1 kg. This is to avoid the double counting of the carbon removal effect.

Data Collection

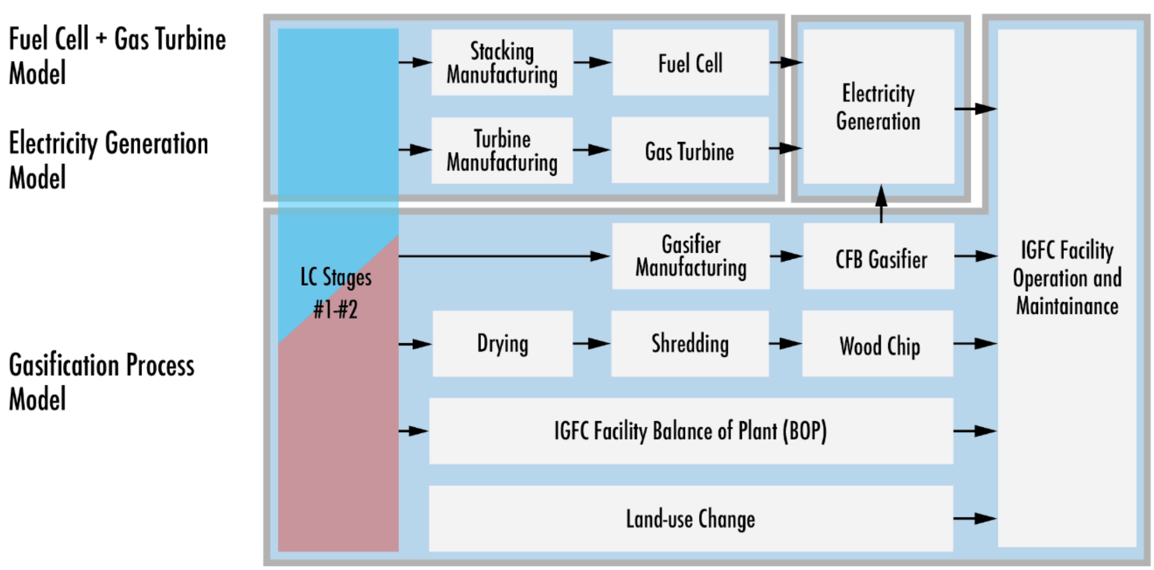
Necessary background data for the plant design and product modeling for Nuclear Fusion BECCS plant were gathered from preceding studies and operational data of existing plants. Specifically, the publications by Ibano et al. (2011; 2012; 2013) were referenced for the product modeling of the nuclear fusion reactor and related facilities. For the IGFC facility, the reported operational data of Osaki CoolGen power plant were referenced (Ishida, 2017; Kenji, 2015). Finally, for CCS facility, the reported operational data of Tomakomak CCS plant (Tanaka et al., 2014) as well as a report published by the U.S. Department of Energy (Skone, Cooney, & Marriott, 2016) were referenced.

Product Modeling

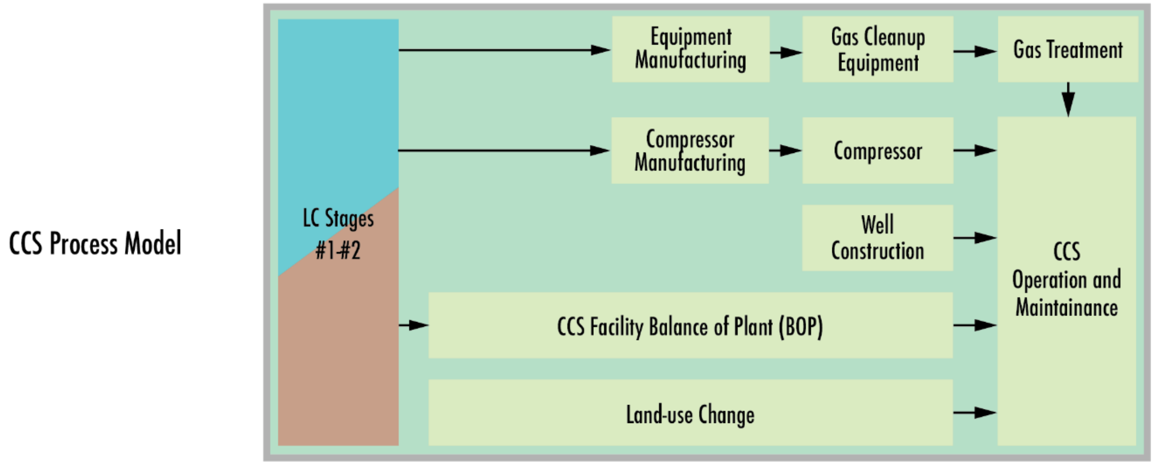
For this LCA, the Nuclear Fusion BECCS plant was modeled as a combination of seven sub-system models as illustrated in Figure 18 (a), (b) and (c) to cover every aspect of the electricity production with this plant from the LC Stages #1-#3.



(a) Product Sub-system Model of the Nuclear Fusion Facility.



(b) Product Sub-system Model of the IGFC Facility.



(c) Product Sub-system Model of the CCS Facility.

Figure 18. Illustration of the LCA Product Modeling (by author): (a) Nuclear Fusion Facility, (b) IGFC Facility and (c) CCS Facility.

The inputs/outputs of 1 kWh electricity production from Nuclear Fusion BECCS process based on the sub-system modeling is shown in Table 5.

Table 5 Inputs/Outputs of 1 kWh electricity production from Nuclear Fusion BECCS.

<u>Basic Assumptions</u>. For the following product modeling, plant lifetime of 40 years and the average availability factor of 85% were assumed for Nuclear Fusion BECCS plant. This equates to the lifetime total electricity generation amount of 1.4549×10^{11} kWh. Although this thesis does not intend to assume a construction site for future Nuclear Fusion BECCS plant, for consistency, data for NPCC region of the U.S. were used throughout in modeling when available.

<u>GNOME Nuclear Fusion Reactor Model</u>. Materials necessary for the construction of GNOME nuclear fusion reactor were estimated based on Ibano et al. (2011, 2012 and 2013) as Table 6. It should be noted that due to the nature of nuclear fusion operation, major components of the reactor have to be replaced every two years. For this reason, the

construction materials were separately estimated both for the initial construction and for the replacements, and then the inputs were summed for the 40 years of total plant lifetime. For each material, default market data on ecoinvent 3.5 were used without modification to describe LC Stages #1-#2 processes. Due to the lack of data, F82H steel was simply modeled as chromium steel 18/8.

Table 6. Construction Materials for the GNOME Nuclear Fusion Reactor (in metric ton) (by author; based on Ibano (2012).

	Superconducting Coils		**Coolant**		**Bio-Shield**	**Structure (incl. Cryostat)**
	Nb3Sn	Cu	LiPb*	He	Concrete	Stainless Steel
Initial	1,012.9	1,092.1	10.0	0.35	4,246	3,512
Replacement	1,012.9	1,092.1	0**	0.2	0	1,756

**Li-6 90% enriched 17Li-83Pb (atomic percent) ** Lithium to be replenished during operation as fusion fuel.*

For the superconducting coil production process, the default "*metal working, average for copper product manufacturing*" product model on ecoinvent 3.5 was used without modifications. For the forging and welding processes, "*forging, steel*" and "*welding, arc, steel*" product models were used without modifications, respectively.

The inputs for GNOME Nuclear Fusion Reactor Model calculated by the assumptions above is shown in Table 7.

Table 7. Inputs for one GNOME Nuclear Fusion Reactor (incl. 40 years of replacements) (by author).

Flow	**Category**	**Flow property**	**Unit**	**Amount**
copper	B:Mining and quarrying	Mass	t	10368

forging, steel	C:Manufacturing	Mass	t	39931.5
helium	C:Manufacturing	Mass	t	4.2
lead	B:Mining and quarrying	Mass	t	45.425
lithium	C:Manufacturing	Mass	t	0.2746
metal working, average for copper product manufacturing	C:Manufacturing	Mass	t	19984
niobium	Elementary flows/Resource/in ground	Mass	t	6743.8
steel, chromium steel 18/8	C:Manufacturing	Mass	t	39931.5
Tin	Elementary flows/Resource/in ground	Mass	t	2872.2
welding, arc, steel	C:Manufacturing	Length	m	400

Fusion Fuel Model. Nuclear fusion fuels needed for 1 kWh of electricity production are 0.00000655 g of Lithium and 0.00000219 g of Deuterium (total of 8.743×10^{-6} g). "*lithium*" product on ecoinvent 3.5 was simply used without modifications as the lithium product model. For deuterium, "*heavy water*" (D_2O) product model was used for the equivalent mass of deuterium (D).

The input for 1 g of fusion fuel calculated by the assumptions above is shown in Table 8.

Table 8. Inputs for 1 kg of fusion fuel production (by author).

Flow	**Category**	**Flow property**	**Unit**	**Amount**
heavy water	C:Manufacturing	Mass	kg	1.2472

lithium	C:Manufacturing	Mass	kg	0.74915

Fusion Facility Balance of Plant (BOP), Plant Operation and Maintenance (O&M), Land-use Change, and Decommissioning Model. Due to the conceptual nature of the Nuclear Fusion BECCS plant, details of the plant design are still undetermined and therefore it is difficult to accurately construct product models for the balance of plant (BOP), operation and maintenance (O&M) and land-use change for Nuclear Fusion BECCS plant. For this reason, in this study, the BOP, O&M, land-use change, and decommissioning model of the plant was constructed based on the existing dataset for an actual pressurized water nuclear fission reactor on ecoinvent 3.5. This is because the envisioned configurations of future nuclear fusion plants are similar to those of current pressurized water nuclear power plants (Tobita et al., 2010).

"*electricity production, nuclear, pressure water reactor – NPCC, US only*" process on ecoinvent 3.5 describes the electricity production activity of a grid-connected pressurized water nuclear power plant; i.e., LC Stages #1-#3. This model includes the plant construction and operation, as well as the fuel reprocessing, low-level radioactive waste streams and decommissioning of the plant. I constructed the BOP, O&M, land-use change, and decommissioning model for Nuclear Fusion BECCS plant with the following modifications. 1) The raw materials for construction of the pressurized water reactor in the original model, 1.0×10^{-4} kg/kWh of Iron from ore and 8.2×10^{-8} kg/kWh of Zirconium, were removed from the model. 2) Quantitative reference output was changed from 1 kWh electricity to 10.29 MJ of heat, assuming 35% of thermal efficiency

(Durmayaz & Sogut, 2006). 3) Nuclear fuel related inputs/outputs, namely radioactive isotopes of Uranium, Plutonium, Carbon-14, Cerium, Cesium, Iodine, Polonium, Protactinium, Radium, Radon, Strontium, Thorium and Xenon as well as the five "*Radioactive species*" were all removed from the model, as nuclear fusion power plants would not emit any of the listed isotopes.

Even after the modifications, however, this process model is still likely to be a significant overestimation. This is because unlike nuclear fission plants, nuclear fusion plants do not require fuel reprocessing facilities nor produce high-level radioactive materials. This point will be considered in the sensitivity analysis.

Fuel Cell + Gas Turbine Model. Fuel cells are one of the well-modeled products in ecoinvent 3.5. This study used "*fuel cell, solid oxide, with micro gas turbine, 180 kW electrical, future*" product model for the combination of fuel cell and gas turbine without modifications. Based on the estimated combined total electrical generation of 707.15 MW, it was calculated 3928.6 units of "*fuel cell, solid oxide, with micro gas turbine, 180 kW electrical, future*" were needed for one Nuclear Fusion BECCS plant.

Gasification Process Model. Syngas production process from woodchip is another well-modeled product set in Ecoinvent 3.5, and the product model of the gasification facility was created based on the existing "*synthetic gas production, from wood, at fluidized bed gasifier -CH*" process model. This model describes the conversion of wood chips into syngas from cradle (LC Stages #1-#3) with necessary feedstock preparation processes. According to the description in the database, composition (% mol.) of the resulting gas is 15.5% H_2, 39.2% CO, 34.9% CO_2, 8.7% CH_4 and 1.7% C_nH_m with the lower heating value of 5.4 MJ/Nm^3.

While this process is well-modeled with an extensive review following the ecoinvent quality guidelines, the default model required a few modifications for use for this study because the default model assumes the heat to be supplied by the syngas combustion. Since the heat for CFB gasifier is designed to be supplied from the nuclear fusion reactor in Nuclear Fusion BECCS plant, 1) the carbon dioxide and monoxide emissions from the partial combustion of the biomass feedstock ("Carbon dioxide, biogenic" and "Carbon monoxide, biogenic") were removed from the output, 2) the input amount of wood chip was reduced from 0.45363 kg per 1kg syngas production to 0.29234 kg per kg-production, assuming the improvement of gasification efficiency from 58% (van der Meijden, Veringa, & Rabou, 2010) to 90%, and 3) the input oxygen of 2.8×10^{-4} kg was replaced with the equivalent water mass of 3.3×10^{-4} kg of H_2O.

Electricity Generation Model. As illustrated in the energy flow of the plant (Figure 9), the efficiency of the fuel cell and the gas + steam combined turbines were assumed to be 70% and 60%, respectively. This equates to be the combined total CO2 emissions to the air and to the downstream (to CCS) of 0.75907 kg/kWh electricity generation.

CCS Process Model. While ecoinvent 3.5 does not provide any product models for CCS, there are ample amount of LCA studies published on the CCS process. For this reason, I referenced a review paper by Corsten, Ramírez, Shen, Koornneef, and Faaij (2013) that covers the LC Stages #1-#3 of CCS process at various power plants with and without CCS. Specifically, I referred to the life cycle GHG reductions through CCS in the GWP_{100} impact category for natural gas combined cycle plant, and assumed the 64.1% reduction of GHG in CO2-eq mass (the reported full life cycle average value of the difference relative to IGCC without CCS). This equates to the life cycle net carbon sequestration rate of 0.9654 kg-CO2eq/kWh-electricity with the addition of CCS.

Uncertainty Analysis. Due to the conceptual nature of this plant, a significant uncertainty lies in product modeling. For this reason, uncertainties the modeling were assumed in compliance the ecoinvent quality guideline as lognormal distribution for the seven product models. The geometric standard deviation values were determined based on the ecoinvent default matrix as shown in Table 9, and the assumed indicator scores are summarized in Table 10. A Monte-Carlo simulation with 10,000 iterations was conducted on the above assumptions to quantify the uncertainty.

Table 9. Ecoinvent Default Uncertainty Factors Based on Reliability Pedigree Matrix (Frischknecht et al., 2005).

Indicator Score	**1**	**2**	**3**	**4**	**5**
Geometric Standard Deviation	1.00	1.05	1.10	1.20	1.50
Reliability	Verified data based on measurements	Verified data partly based on assumptions or non-verified data based on measurements	Non-verified data partly based on qualified estimates	Qualified estimate (e.g. by industrial expert)	Non-qualified estimate

Table 10. Assumed Data Reliability Indicator Score for Nuclear Fusion BECCS Processes (by author).

Process	**Indicator Score in Data Reliability (Geometric Standard Deviation)**
GNOME Nuclear Fusion Reactor	4 (1.20)
Fusion Fuel	3 (1.10)

Fusion Facility BOP, O&M, Land-use Change and Decommissioning	4 (1.20)
Fuel Cell + Gas Turbine	2 (1.05)
Electricity Generation	4 (1.20)
Gasification Process	3 (1.10)
CCS Process	3 (1.10)

Sensitivity Analysis. In addition to the uncertainty analysis, sensitivity analyses were conducted for several selected processes to see their effect on the overall environmental impacts. For visualization, I referenced reports published by National Energy Technology Laboratory of US DOE.

Product Models for Comparing Power Plants. For comparing power plants, the following default process models on ecoinvent 3.5 were adopted without modifications: "*electricity production, wind, >3MW turbine, onshore – NPCC, US only*" for land-based wind; "*electricity production, photovoltaic, 570kWp open ground installation, multi-Si – NPCC, US only*" for utility-scale PV; "*electricity production, hydro, reservoir, alpine region – NPCC, US only*" for hydropower; "electricity production, natural gas, combined cycle power plant – NPCC, US only" for natural gas; "*electricity production, hard coal – NPCC, US only*" for coal; and "*electricity production, nuclear, pressure water reactor – NPCC, US only*" for nuclear.

Since ecoinvent 3.5 does not come with LCI dataset for biomass power plants, they were modeled based on the same assumptions and modeling methods for Nuclear Fusion BECCS plant: Biomass power plant without CCS was modeled as a combination of Gasification Process Model (without modifications for fusion), Fuel Cell + Gas Turbine Model, and Electricity Generation Model; the CCS Process Model was added for biomass power plant with CCS.

Economic Performance of Nuclear Fusion BECCS Plant

According to IEA/NEA (2018), the cost of electricity can be categorized into three different levels; Plant-level costs, Grid-level system costs, and external costs outside the electricity system. Plant-level cost is commonly known as the levelized cost of electricity (LCOE), which represent lifetime costs divided by electricity production. Grid-level system costs concern the costs at the level of the electricity system connected through the transmission and distribution grid. The third category includes items that impact the well-being of individuals and communities outside the electricity sector, including environmental impacts (Matin, Takeda, Tanaka, Sakurai, & Tezuka, 2019).

In this thesis, to assess the economic performance of Nuclear Fusion BECCS Plant in the future market, I calculated the LCOE of the plant and then factored in the carbon pricing to internalize the environmental impacts.

Levelized Cost of Electricity (LCOE)

Levelized Cost of Electricity (LCOE) is a commonly used metric to represent the plant-level cost. One of the advantages of the LCOE methodology is its transparency and straightforward computation. As described in IEA/NEA (2015), the LCOE calculation begins with the following equation expressing the equality between the present value of the sum of discounted revenues and the present value of the sum of discounted costs, including payments to capital providers. The subscript t denotes the year in which the sale of production or the cost disbursement takes place. The summation extends from the start of construction preparation to the end of dismantling, which includes the discounted value at that time of future waste management costs. All variables are real, i.e. net of inflation. On the left-hand side one finds the discounted sum of revenue and on the right-hand side the discounted sum of costs:

$$\Sigma P_{kWh} * kWh_t * (1+r)^{-t} = \Sigma(Capital_t + O\&M_t + Fuel_t + Carbon_t + D_t)(1+r)^{-t}$$

where the different variables indicate:

P_{MWh} = the constant lifetime remuneration to the supplier for electricity;

kWh_t = the amount of electricity produced in year t in kWh;

$(1 + r)^{-t}$ = the discount factor for year t (reflecting payments to capital);

$Capital_t$ = total capital construction costs in year t;

$O\&M_t$ = operation and maintenance costs in year t;

$Fuel_t$ = fuel costs in year t;

$Carbon_t$ = carbon costs in year t;

D_t = decommissioning and waste management costs in year t.

Because P_{kWh} is a constant over time, it can be brought out of the summation, and this equation can be transformed into:

$$LCOE = \Sigma[(Capital_t + O\&M_t + Fuel_t + Carbon_t + D_t)(1+r)^{-t}/MWh_t(1+r)^{t}]$$

,which is the commonly used definition of the LCOE (Matin et al., 2019).

Parameters for Nuclear Fusion BECCS

Parameters for LCOE calculation were assumed in compliance with the methodology adopted by the U.S. Energy Information Administration (EIA) for Annual Energy Outlook 2019. Parameters specific to Nuclear Fusion BECCS plant were estimated based on available literature and system codes (programs to calculate the nuclear fusion power plant configurations).

Discount Rate. The baseline value for the discount rate was adopted from the average discount rate used by EIA (2019) as 7.0%. The year 2018 was used as the base year for calculation.

Amount of Electricity Production. The amount of electricity production in year t, MWh_t, can be simply calculated as

$$kWh_t = 365 \times 24 \times P_e \times f_{avt}$$

where Pe represents the electrical output and f_{avt} represents the availability factor of the plant in year t. The baseline assumptions are summarized in Table 11.

Table 11. Basic Assumptions for Electricity Production (by author).

	Symbol	Unit	Baseline Value
Electrical output	***Pe***	kW	488,000
Availability factor	***fav***	-	0.85
Life Time	***LT***	years	40

Capital Construction and O&M Cost. The construction cost and the O&M costs of Nuclear Fusion Power Plant were estimated separately for the three sub-facilities: nuclear fusion facility, biomass gasification facility, and the CCS facility. For construction cost, the overnight cost, i.e. construction cost without interest during construction, was used for this calculation. O&M cost for electricity production $O\&M_t$ was calculated as a combination of a variable O&M cost [$/kWh] and a fixed O&M cost [$/kW/year] in compliance with EIA (2019).

For the nuclear fusion facility, cost estimations for "advanced nuclear" plant by EIA (2019) was used as the basis of the cost model. Reported costs were adjusted based on the equivalent thermal output of fusion, 364 MW, assuming an efficiency of the advanced nuclear of 40%. On top of the adjustment, the nuclear fusion reactor cost was added. In addition to the initial construction cost for GNOME nuclear fusion reactor, replacement costs were also accounted for. This is to reflect the fact that fusion reactors have to be replaced every two years due to the nature of nuclear fusion operation. For the replacement cost, an estimation by Kenzo Ibano (2012) of 429.3 million USD/replacement, or 214.6 million USD/year was assumed.

For biomass gasification plant and CCS plant costs, "biomass" and "advanced combined cycle with CCS" plants costs were used without modifications.

Table 12 summarizes the cost models adopted from EIA (2019) and Kenzo Ibano (2012).

Table 12. Cost Assumptions for Construction and O&M Costs (by author).

		Adopted from	**Unit**	**Baseline Value**
Overnight Construction Cost	Fusion Facility	Adv nuclear (EIA, 2019)	2018$/kW	1,800
	Gasification Facility	Biomass (EIA, 2019)		3,900

	CCS Facility	Adv CC with CCS (EIA, 2019)		2,205
Replacement Construction Cost	Fusion Reactor Replacement	Kenzo Ibano (2012)	2018M$/year	214.6
Variable O&M	Fusion Facility	Adv nuclear (EIA, 2019)	2018$/kWh	0.707×10^{-3}
	Gasification Facility	Biomass (EIA, 2019)		5.70×10^{-3}
	CCS Facility	Adv CC with CCS (EIA, 2019)		7.34×10^{-3}
Fixed O&M	Fusion Facility	Adv nuclear (EIA, 2019)	2018$/kW/year	30.82
	Gasification Facility	Biomass (EIA, 2019)		114.39
	CCS Facility	Adv CC with CCS (EIA, 2019)		34.43

The costs for three sub-facilities were then simply summed to calculate the total construction and O&M costs. This simple summation of costs for three facilities would overestimate the LCOE, as there would be overlaps in the estimated cost components.

Fuel Cost. There are two types of fuels and feedstocks required for Nuclear Fusion BECCS plant operation: the biomass feedstock (wood chip) and fusion fuel. Although biomass feedstock is technically not fuel, this thesis categorizes biomass feedstock under “fuel” for simplicity.

For the cost of wood chip, the average softwood chips price in the U.S. northeast in 2016 reported by Wood Resources International (2016) was used. For fusion fuel, I referenced the estimation by Kenzo Ibano (2012). The estimated fuel costs are summarized in Table 13.

Table 13. Cost Assumptions for Fuels (by author).

	Adopted from	Unit	Baseline Value
Wood Chips Cost	Wood Resources International (2016)	2018$/t	89
Fusion Fuel Cost	Kenzo Ibano (2012)	2018M$/year	0.22

Uncertainty Analysis. Uncertainty analyses were conducted for the cost modeling assuming the log-normal distribution of each cost component. The geometric standard deviation values were determined based on the ecoinvent default matrix as shown in Table 9, and the assumed indicator scores are summarized in Table 14. A Monte-Carlo simulation with 10,000 iterations was conducted on the above assumptions to quantify the uncertainty.

Table 14. Assumed Data Reliability Indicator Score for the Cost Components (by author).

Costs	**Indicator Score in Data Reliability (Geometric Standard Deviation)**
Construction Cost for Fusion Plant	4 (1.20)
Construction Cost for GNOME Nuclear Fusion Reactor	4 (1.20)
Fusion Fuel	3 (1.10)
O&M Cost for Fusion Plant	4 (1.20)
Availability Factor	4 (1.20)
Costs Associated with the Biomass Gasification Facility	2 (1.05)
Cost Associated with the CCS Facility	2 (1.05)

Sensitivity Analysis. In addition to the uncertainty analysis, sensitivity analyses were conducted for several selected processes to see their effect on the overall environmental impacts. For visualization, I referenced reports published by National Energy Technology Laboratory of the U.S. Department of Energy.

Carbon Pricing

$Carbon_t$ in the LCOE calculation represents the cost of carbon in the respective electricity market. There are multiple initiatives for pricing carbon around the globe in the forms of the carbon tax or the carbon credit. These mechanisms are aimed to help internalize the externality of the environmental impacts of electricity generation.

In this thesis, I collectively call the pricing of carbon as carbon pricing, and simply assume that the cost of carbon will be added to LCOE in proportion to the life cycle GHG emissions amount. This means, if a power source has a negative life cycle GHG emissions, the carbon pricing will yield revenue and reduce the LCOE.

Currently, the implemented prices for carbon vary dramatically around the globe, from <1 USD/kg CO2-eq (Mexico carbon tax) to 139 USD/kg CO2-eq (Sweden carbon tax). In addition, many industry professionals believe that the price of carbon would go up for the next decades globally in order to help achieve the Paris Agreement target. S&P Global (2017) presents a scenario analysis on the carbon pricing to meet the Paris Agreement target as Figure 19.

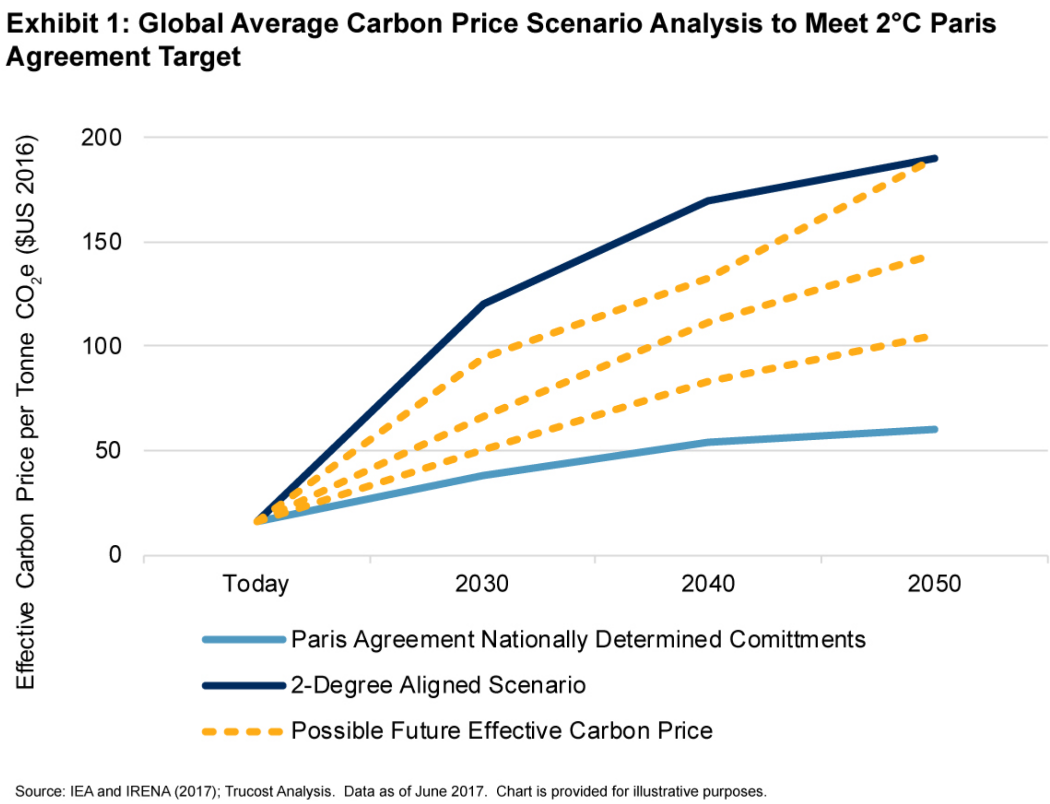


Figure 19. Global Average Carbon Price Scenario to Meet the Paris Agreement Target (S&P Global, 2017).

In this thesis, the carbon price was assumed to be zero for the baseline to be in compliance with the methodology of EIA (2019), with a sensitivity analysis from 0 to 200 USD/kg CO2-eq. For the future carbon prices, the 2-Degree Aligned Scenario presented by S&P Global (2017) was referenced.

LCOE of Comparing Power Plants

For LCOEs of comparing power plants, the Annual Technology Baseline published by the U.S. Department of Energy National Renewable Energy Laboratory (2018) was referenced. Since the methodologies used for Annual Technology Baseline are based on EIA (2019), the LCOEs shown in the Annual Technology Baseline are directly comparable to the LCOE calculated for Nuclear Fusion BECCS in this thesis. For current and future LCOEs, estimations “Land-Based Wind (TRG 4),” “Utility-Scale PV (Kansas City),” “Hydropower (NPD 1),” “Natural Gas (Gas-CC-ConstantCF),” “Coal (Coal-new-ConstantCF),” “Nuclear,” “Biopower (Dedicated)” were used without modifications. For plain BECCS plant, the LOCE was calculated as the summation of biomass and advanced combined cycle with CCS plant costs.

Chapter III.

Results

This chapter reports the results of the analysis on the environmental impact as well as the economic performance of Nuclear Fusion BECCS plant.

Environmental Impact of Nuclear Fusion BECCS

Life cycle inventories of 1 kWh electricity production were calculated for nine power plants. The GWP indicators for each power plant are illustrated in Figure 20.

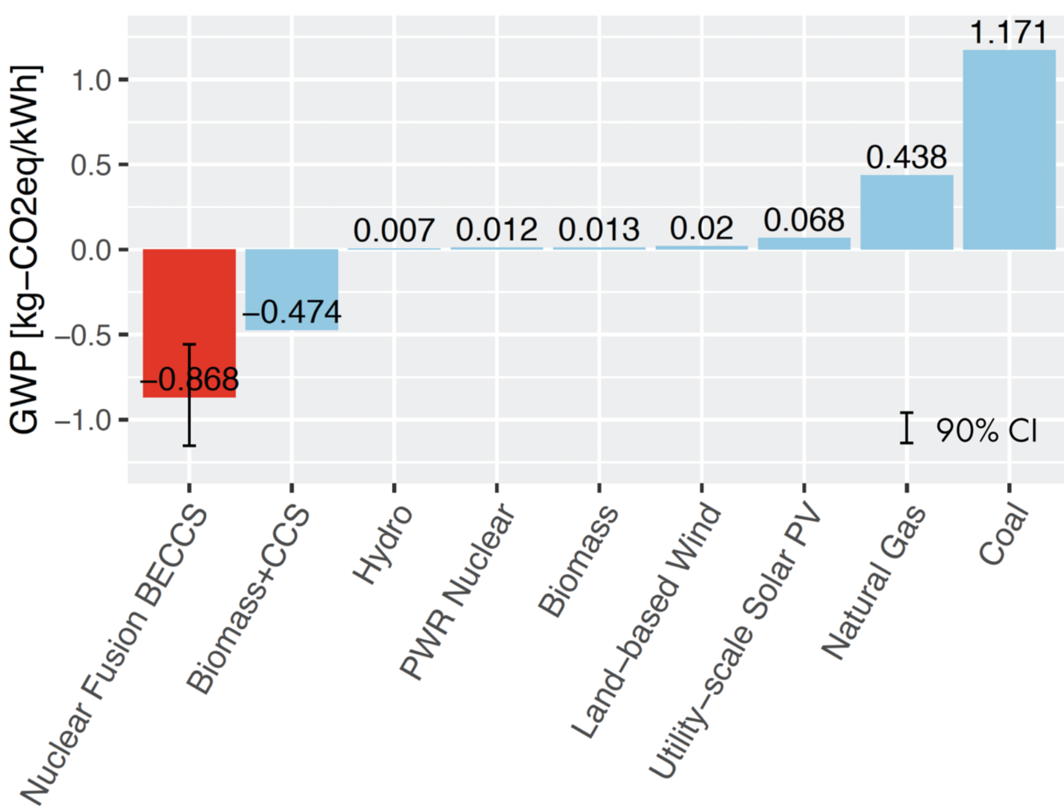


Figure 20. Global Warming Potential for Electricity Production (by author).

The estimated life cycle GHG emissions of the electricity production from Nuclear Fusion BECCS for baseline scenario was -0.86818 kg CO2-eq/kWh electricity production. The breakdown of the emissions factored in by GWP indicator is summarized in Table 15. The entire life cycle inventory for 1 kWh electricity production from Nuclear Fusion BECCS plant is as attached in Appendix as Table A1.

Table 15. Inventory of the GHG Emissions of Electricity Production from Nuclear Fusion BECCS (with the cutoff at impact result = 0.0005 kg) (by author).

Inventory	**Category**	**Inventory Result**	**Impact Factor**	**Impact Result**
Carbon dioxide, fossil	Emission to air / low population density	0.33046 kg	1	0.33046 kg CO2-eq/kWh
Carbon dioxide, biogenic	Emission to air / high population density	0.05170 kg	1	0.05170 kg CO2-eq/kWh
Carbon dioxide, fossil	Emission to air / high population density	0.02474 kg	1	0.02474 kg CO2-eq/kWh
Carbon dioxide, fossil	Emission to air / unspecified	0.01828 kg	1	0.01828 kg CO2-eq/kWh
Methane, fossil	Emission to air / low population density	0.00020 kg	29.7	0.00593 kg CO2-eq/kWh
Carbon monoxide, fossil	Emission to air / low population density	0.00054 kg	4.06	0.00218 kg CO2-eq/kWh
Dinitrogen monoxide	Emission to air / high population density	3.37×10^{-6} kg	264.8	0.00089 kg CO2-eq/kWh
Methane, fossil	Emission to air / unspecified	2.61×10^{-5} kg	29.7	0.00078 kg CO2-eq/kWh
Carbon monoxide, biogenic	Emission to air / high population density	0.00029 kg	2.49	0.00072 kg CO2-eq/kWh
Dinitrogen monoxide	Emission to air / low population density	1.92×10^{-6} kg	264.8	0.00051 kg CO2-eq/kWh
Carbon dioxide, in air	Resource / in air	1.30708 kg	-1	-1.30708 kg CO2-eq/kWh

Interpretation of the LCIA Results

The calculated net GHG reduction amount of 0.86818 kg CO2-eq per 1 kWh electricity production for Nuclear Fusion BECCS is a significant improvement over other comparing power plant. Even compared to the BECCS plant, which is another future power plant, Nuclear Fusion BECCS showed a considerably improved carbon removal capability.

Uncertainty Analysis. A Monte-Carlo simulation with 10,000 iterations was conducted for GWP of Nuclear Fusion BECCS plant. The result is illustrated in Figure 21. The estimated 90% Confidence Interval of the GWP was from -1.154 to -0.555 kg-CO2eq/kWh.

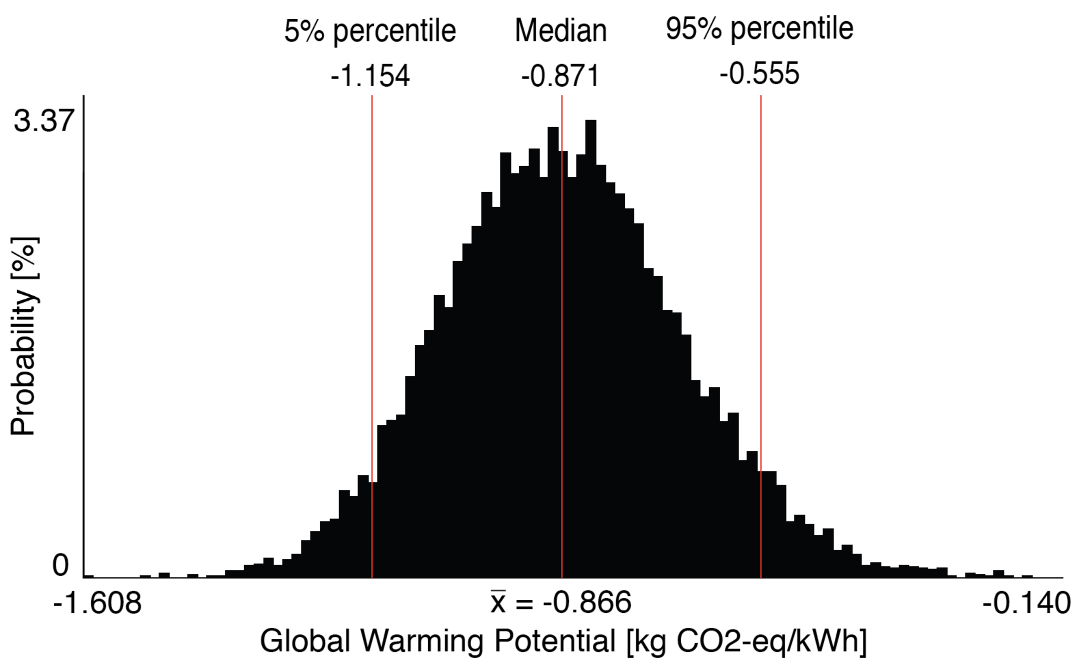


Figure 21. Monte-Carlo Simulation Result for GWP for Nuclear Fusion BECCS (by author).

This result shows that even at the 95% percentile, net GHG emissions from Nuclear Fusion BECCS (-0.555 kg/kWh) is lower than that of a plain BECCS plant (-0.474 kg/kWh). This is an encouraging result for Nuclear Fusion BECCS, as it indicates that even considering the large uncertainty in the plant design, this conceptual plant would outperform plain BECCS plants.

<u>Process Contributions</u>. The contributions of the seven sub-processes of electricity from Nuclear Fusion BECCS plant are illustrated in Figure 22 as a waterfall chart.

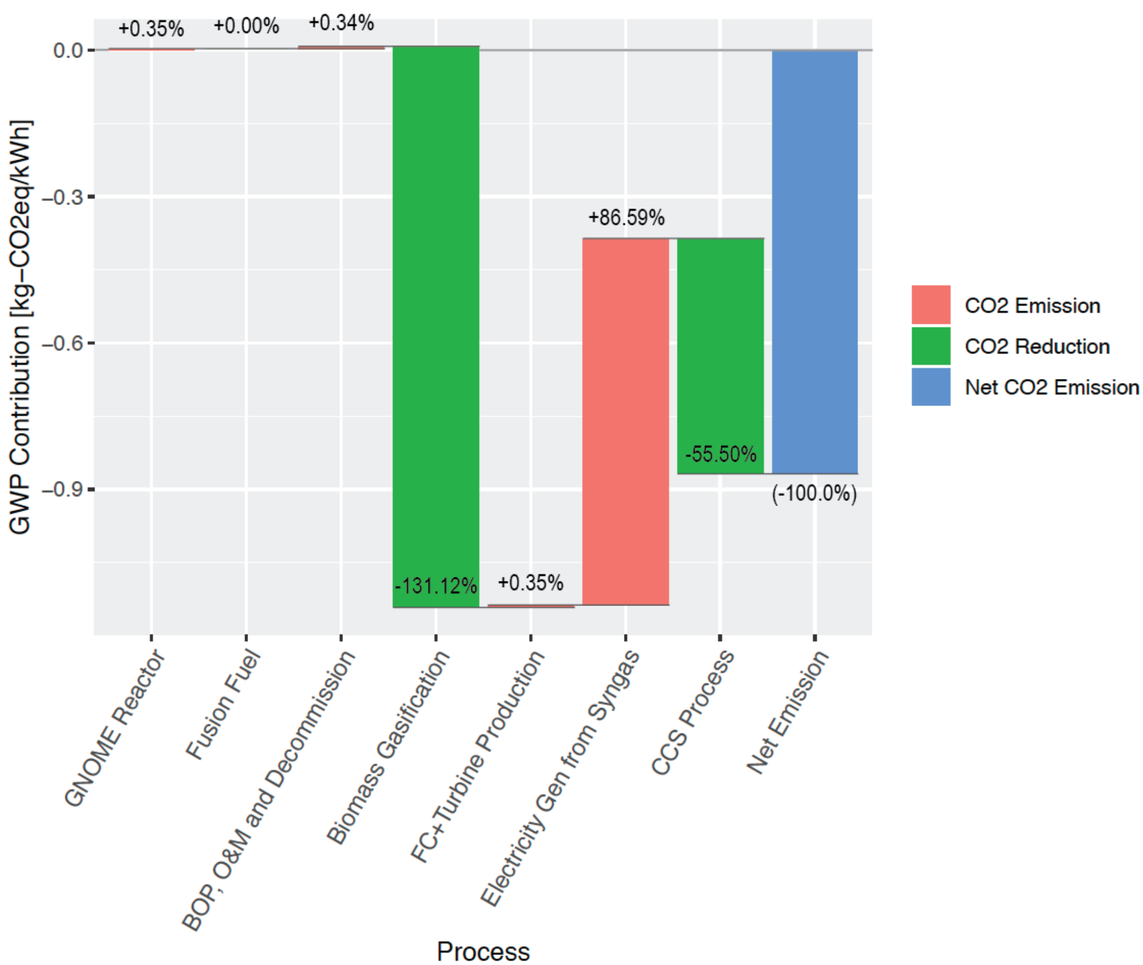


Figure 22. Process Contributions for GWP Indicator (by author).

Figure 22 shows the majority of the GHG emissions/reductions of the electricity production with Nuclear Fusion BECCS plant derive from the Biomass Gasification Process, Electricity Generation Process and the CCS Process. The plant construction processes (GNOME Fusion Reactor, BOP, Fuel Cell and Turbine) amounted for only ~1% of the GHG emissions. Here, the carbon removal through gasification is achieved in the upstream process of wood chip production; i.e., the carbon is removed by the trees.

Sensitivity Analysis. Sensitivity analyses were conducted for selected processes as illustrated in Figure 23.

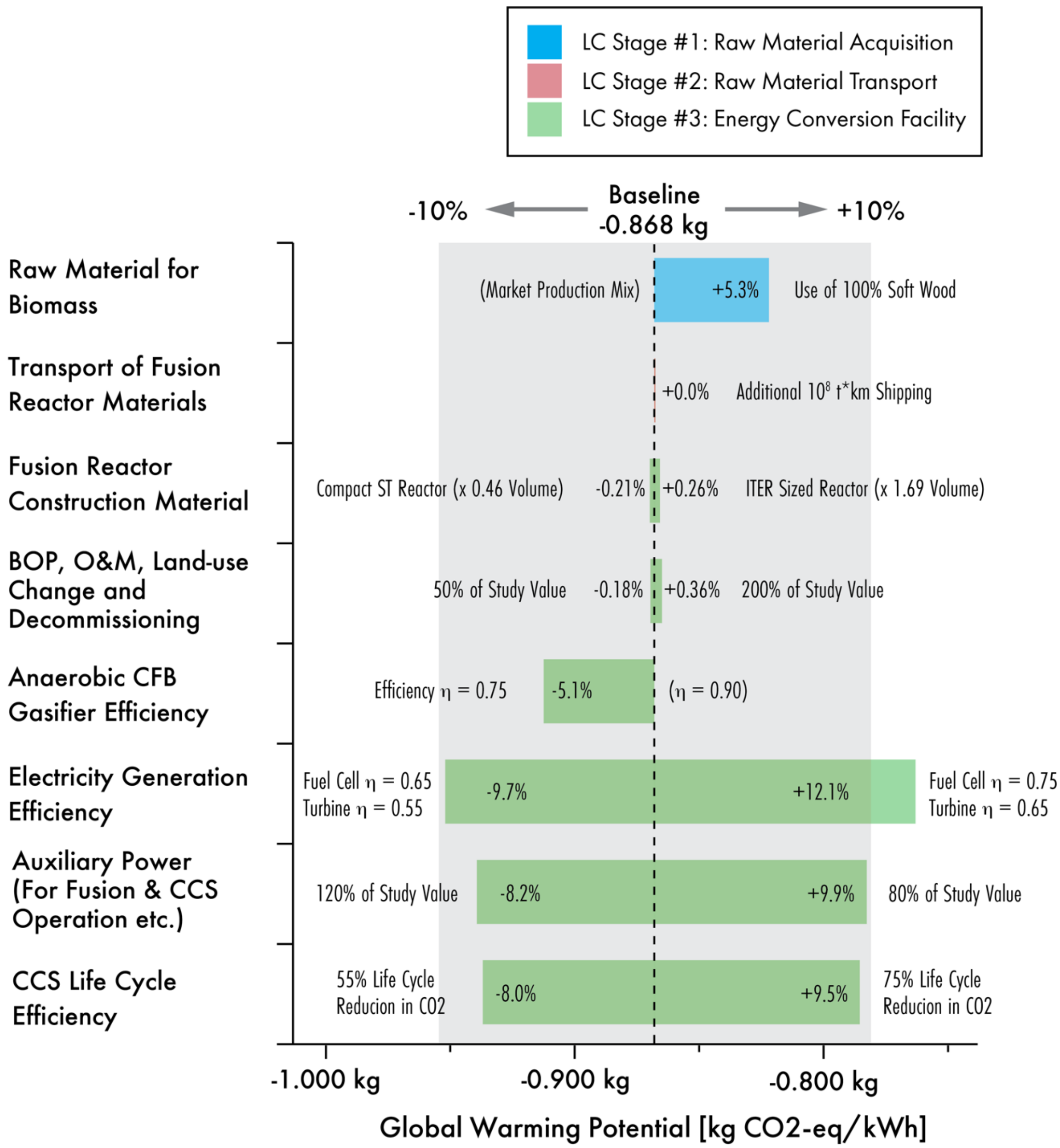


Figure 23. Sensitivity Analysis of GWP Indicator for Electricity Production from Nuclear Fusion BECCS Plant (by author).

As expected from the process contribution, plant construction related process showed very little sensitivities to the result. Even when a 1.67 times necessary construction material was presumed for the fusion reactor the overall GHG emissions saw a 0.26% increase. Likewise, a 100% increase in the inventory for BOP, O&M, Land-use change and Decommissioning had changed the GWP by 0.36%. Furthermore, even then the additional shipping transport of fusion-related materials of 1,000 ton for 20,000 km was taken into account, the contribution was less than 0.0%. For these reasons, it can be concluded that the uncertainties in the Nuclear Fusion BECCS plant would not affect its life cycle GHG emissions.

On the other hand, the raw material choice for the biomass feedstock showed a considerable sensitivity: when the raw material for the wood chip was switched from the default market production mix to 100% softwood, the carbon removal potential was decreased by 5.3%. This implies that while the CFB gasifier can handle a wide variety of biomass feedstocks, the choice for feedstock would be one of the essential factors in the future plant design in terms of life-cycle environmental impact.

As expected, another process that showed significant impacts on the GHG emissions was the efficiencies of facilities. However, even when more conservative efficiencies were assumed for various facilities, the overall GWP indicator stayed advantageous compared to plain BECCS plant. It should be noted that, somewhat counter-intuitively, for Nuclear Fusion BECCS plant, the improved energy conversion efficiency will lead to a decreased amount of carbon removal. This derives from the fact that the majority of the carbon removal takes place in the wood chip production phase. As a result, a lower energy conversion efficiency leads to a larger input amount of wood chop feedstock, which, in turn, leads to a larger carbon removal amount per unit-electricity production. In other terms, a lower energy conversion efficiency compromises the economic performance but improves environmental performance. This is a unique characteristic of this plant, which, again, derives from the fact that the plant construction, O&M and decommissioning contribute so little to the overall GHG emissions.

Overall, the sensitivity analysis results in Figure 23 indicates that even when the uncertainties in the plant design were considered, the Nuclear Fusion BECCS plant can maintain lower GHG emissions than other power plants, including plain BECCS plants.

Economic Performance of Nuclear Fusion BECCS

The estimated LCOE of Nuclear Fusion BECCS plant is shown and compared against other power plants in Figure 24.

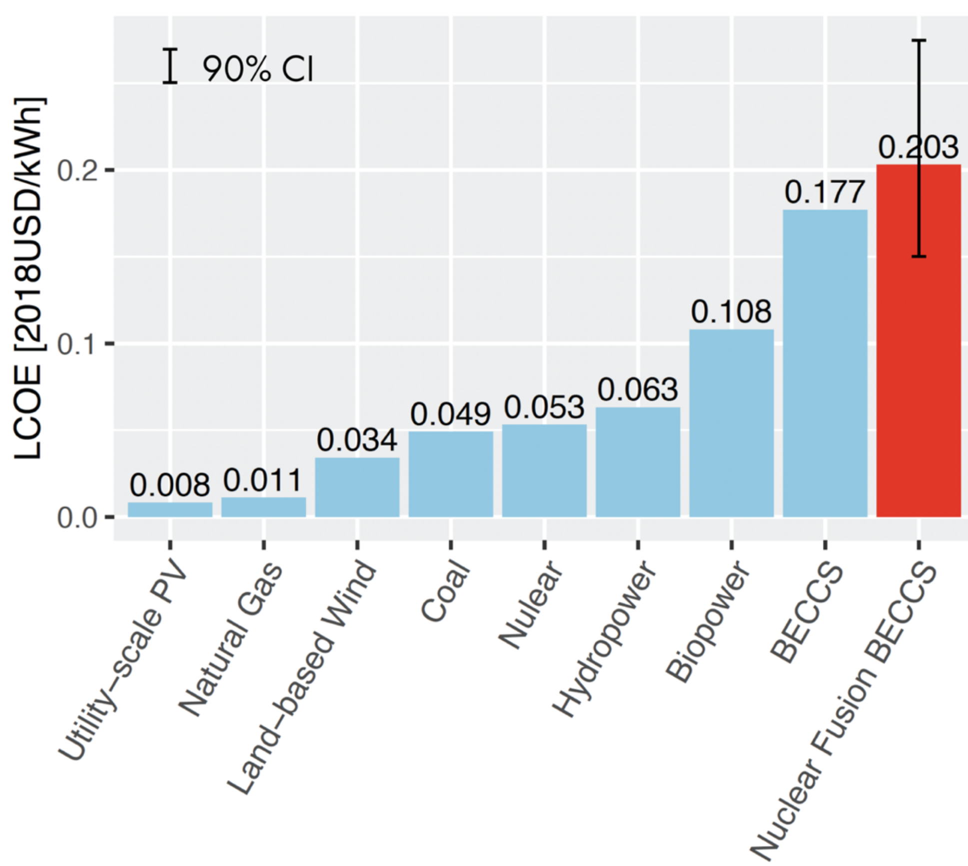


Figure 24. Estimated Levelized Cost of Electricity of Nuclear Fusion BECCS Power Plant (by author).

Levelized Cost of Electricity for Nuclear Fusion BECCS

The estimated increase in LCOE from ordinary biopower plant and plant BECCS to Nuclear Fusion BECCS was +88% and +15%, respectively. This is an expected increase due to the higher construction and O&M costs by the addition of nuclear fusion facility. Figure 25 and Table 16 shows the cost breakdown of the LCOE of Nuclear Fusion BECCS plant.

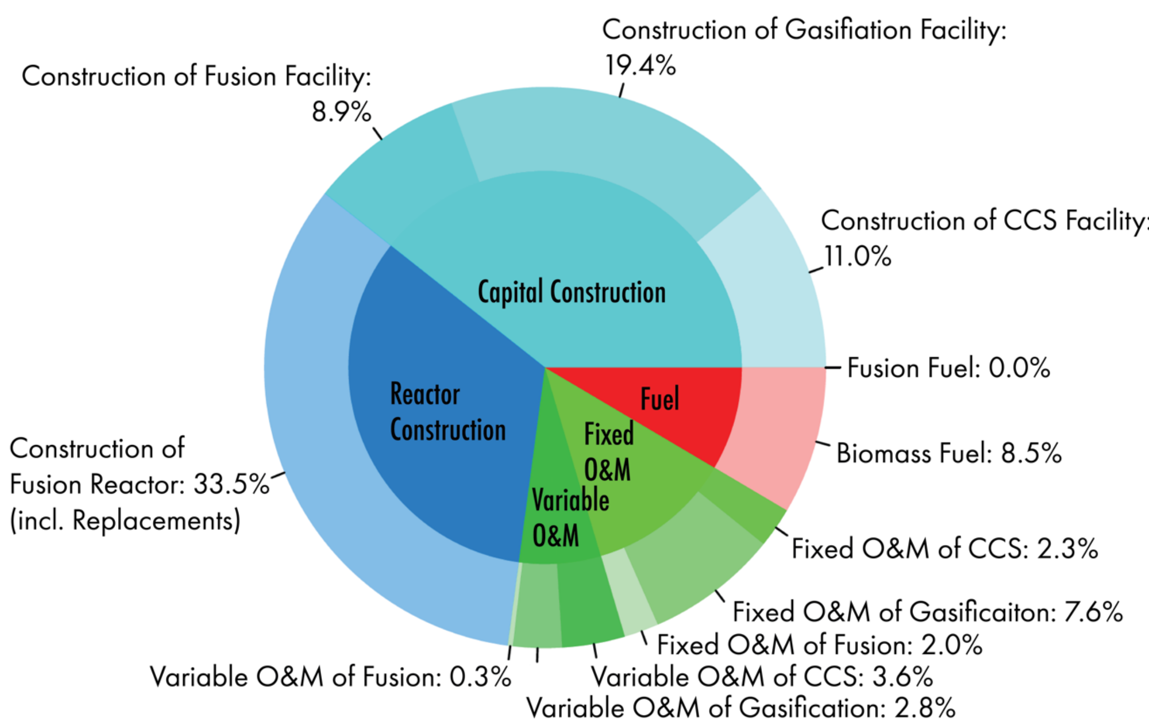


Figure 25. Cost Breakdown of LCOE for Nuclear Fusion BECCS (by author).

Table 16. Cost Breakdown of LCOE for Nuclear Fusion BECCS (by author).

Breakdown		**Cost [2018$/kWh]**
Capital Construction Costs	Construction Cost for Fusion	0.018
	Construction Cost for Gasification	0.039

	Construction for CCS	0.022
	GNOME Reactor Replacements	0.068
O&M Costs	Variable O&M for Fusion	0.001
	Variable O&M for Gasification	0.006
	Variable O&M for CCS	0.007
	Fixed O&M for Fusion	0.004
	Fixed O&M for Gasification	0.015
	Fixed O&M for CCS	0.005
Fuel Cost	Biomass Fuel	0.017
	Fusion Fuel	0.000
Total		**0.203**

This cost breakdown indicates that 72.8% of LCOE derives from the plant construction, 18.7% from O&M, and 8.5% from fuel. Or, from another angle, 44.9% from nuclear fusion facility, 38.2% from biomass gasification facility, and 16.9% from CCS facility.

Uncertainty Analysis. A Monte-Carlo simulation with 10,000 iterations was conducted for the LCOE of Nuclear Fusion BECCS plant. The result is illustrated in Figure 26. The estimated 90% Confidence Interval of the LCOE was from 0.150 to 0.275.

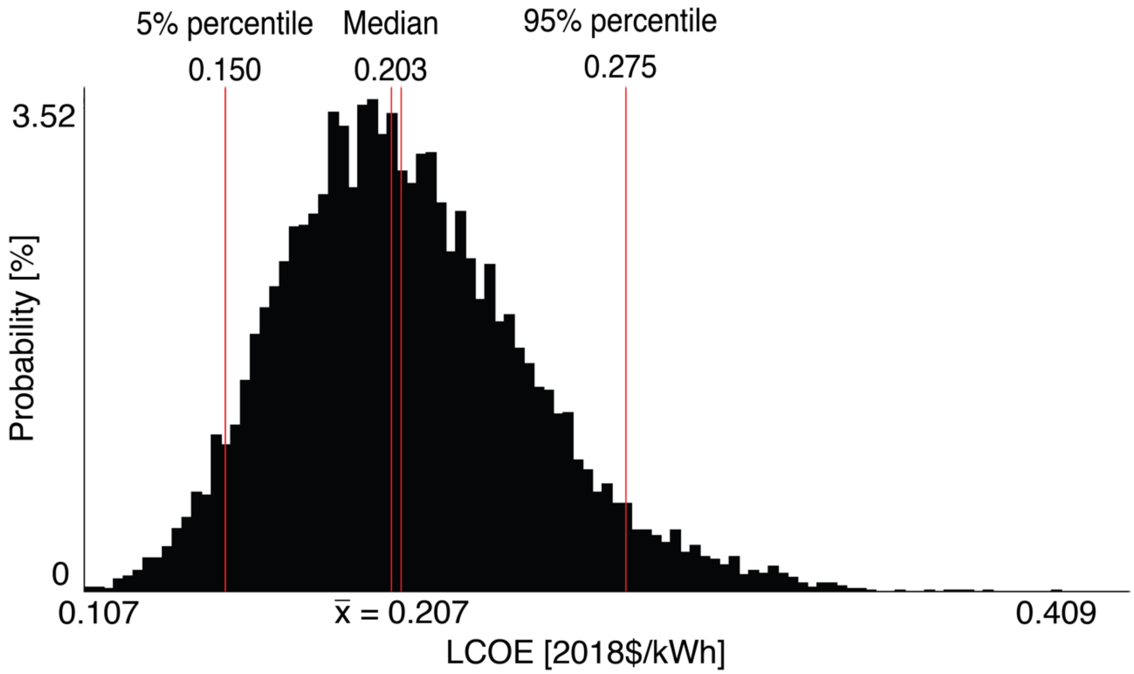


Figure 26. Uncertainly of the LCOE Estimation (by author).

Sensitivity Analysis. A series of sensitivity analyses were conducted for key plant design parameters to see the sensitivity to LCOE as illustrated in Figure 27.

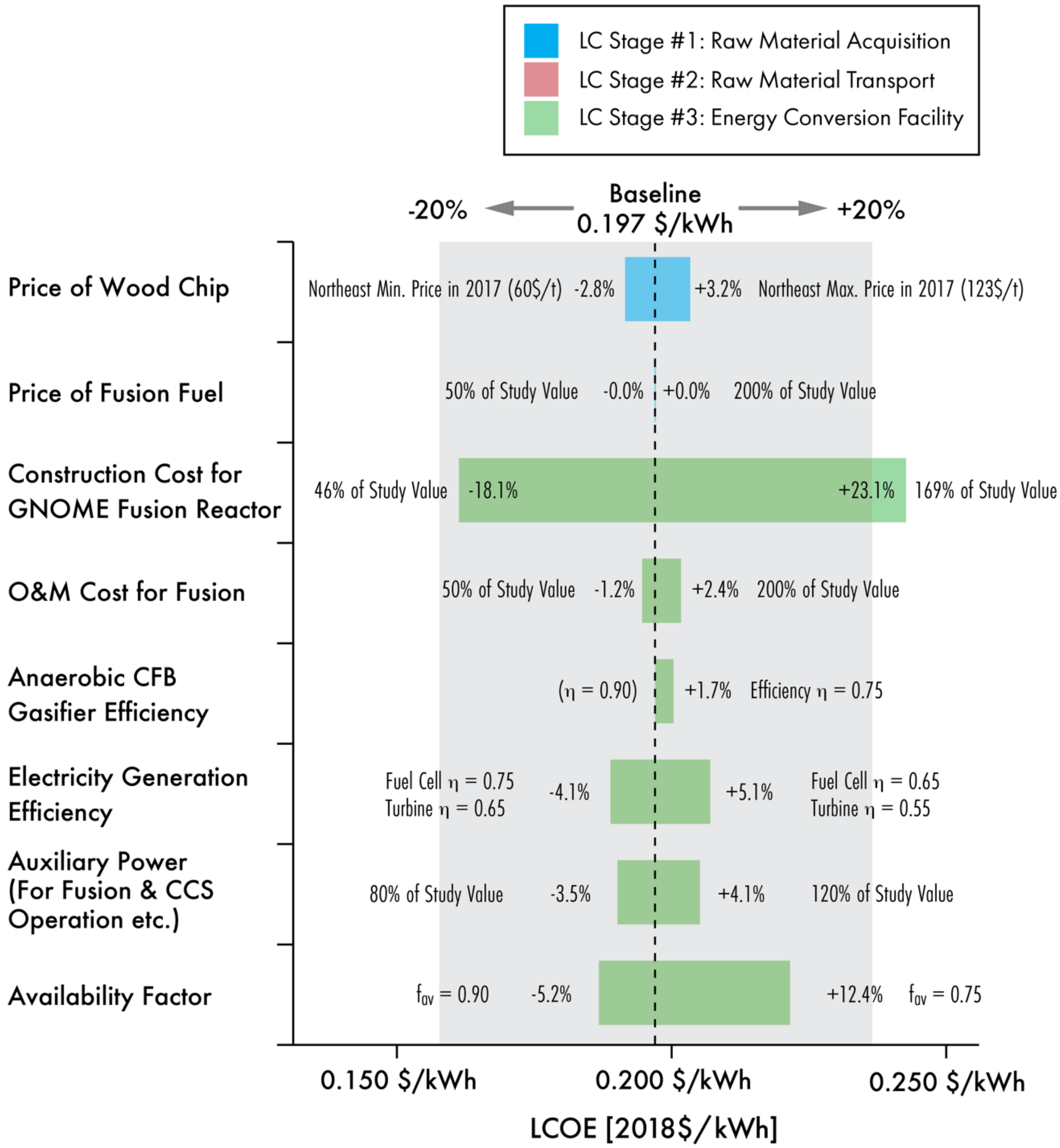


Figure 27. Sensitivity Analysis of the LCOE of Nuclear Fusion BECCS (by author).

For raw material acquisition, the price of wood chip showed considerable sensitivity. When the biomass feedstock price was changed from 89 $/t (market average in the U.S. northeast in 2017) to 123 $/t (market maximum), the LCOE was increased by 3.2%. On the other hand, the raw material acquisition for fusion fuel showed almost no sensitivity. This is an expected result since the fusion fuel cost amounts only for 0.000061 USD/kWh.

The largest sensitivity observed for the construction was the GNOME Nuclear Fusion Reactor construction (including the replacements). This brings a significant uncertainty to the LCOE of Nuclear Fusion BECCS plant, as the cost of construction for fusion plants is still unclear. This point is reflected in the uncertainty analysis results.

Finally, as expected, the efficiencies of the plant components showed significant sensitivity to the LCOE. Among them, the availability factor of the plant was identified to have the largest sensitivity. This is an important point to note, as first-of-a-kind power plants usually have lower availability factors than conventional plants.

Carbon Pricing

As described in Chapter II, a sensitivity analysis was conducted for the price of carbon. For this sensitivity analysis, LCOEs after factoring in the price of carbon were calculated for each power plant. Here, it was assumed that the price of carbon will be added to the base LCOE in proportional to the life cycle GHG emissions shown in Figure 20. Uncertainty was considered for Nuclear Fusion BECCS plant as 95% Confidence Interval, assuming the LCOE and life cycle GHG emissions of the plant are independent.

Figure 28 illustrates the result of the sensitivity analysis, where the y-axis shows the LCOE [$/kWh] while the x-axis represents the price of carbon [$/t CO2-eq].

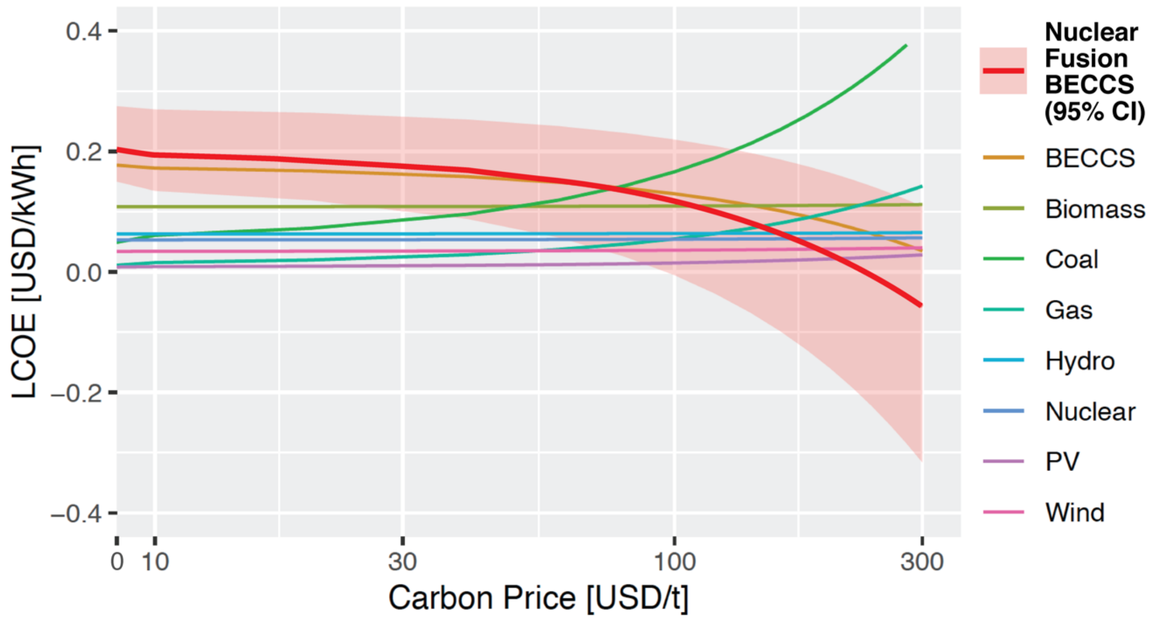


Figure 28. LCOE vs. the Carbon Price (by author).

As can be seen, LCOE of Nuclear Fusion BECCS plant drops as the price of carbon rises. This is an expected result since Nuclear Fusion BBECS has a negative life cycle GHG emissions. As a result, the economic competency of Nuclear Fusion BECCS plant improves as the carbon price rises. While it cannot be definitively concluded due to the large uncertainty, at Carbon Price = 177 USD/t, the Nuclear Fusion BECCS (at the median) became the most economical plant in this comparison. This is a notable result; the assumption of Carbon Price = 177 USD/t is not illogical at all in the near future, as the Swedish carbon tax is already at 140 USD/t in 2018.

Chapter IV.

Discussion

In this thesis, I proposed a sustainable power plant concept that combines nuclear fusion plant with biomass Integrated Gasification Fuel Cell Cycle (IGFC) and Carbon Capture and Sequestration (CCS) for the first time. I hypothesized that this plant configuration could maximize the carbon removal capability of a Biomass Energy Carbon Capture and Sequestration (BECCCS) plant, and that the increased cost through the introduction of nuclear fusion could be offset by the enhanced carbon removal capacity.

Environmental impacts and the economic performance of Nuclear Fusion BECCS plan were analyzed and compared against other power sources, both renewable and fossil. The results were encouraging for this new plant concept.

Summary of the Findings

The key figures of the environmental impact and economic performance assessments for Nuclear Fusion BECCS plant are summarized in Figure 29.

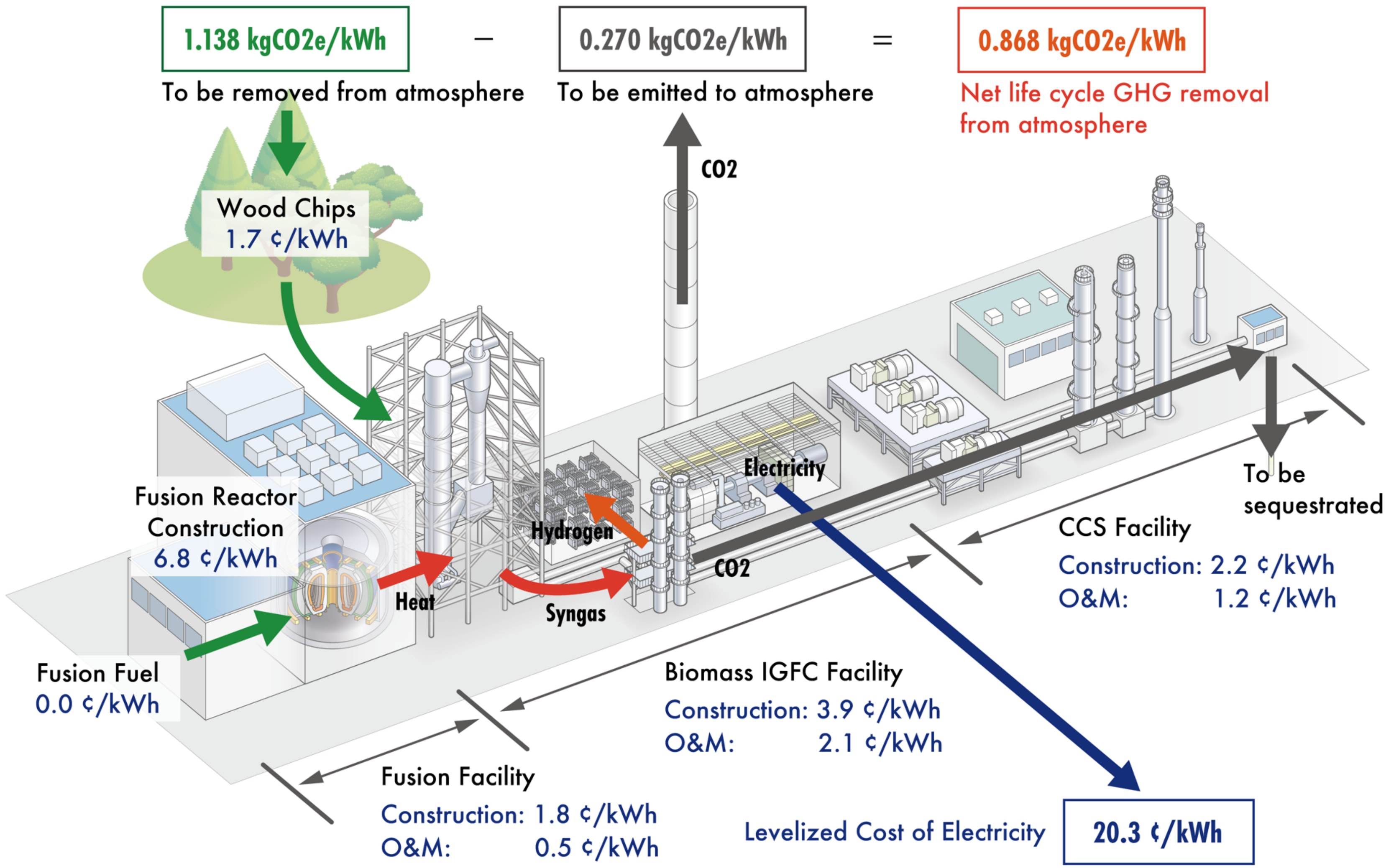


Figure 29. CO_2 Flow and the LCOE Breakdowns of Nuclear Fusion BECCS Plant (by author).

Identified Advantages of Nuclear Fusion BECCS Plant

Based on the analysis results, the following advantages and disadvantages were identified for Nuclear Fusion BECCS Plant.

Environmental Advantages. Electricity from Nuclear Fusion BECCS had the lowest Global Warming Potential (GWP) among all comparing power plants in this analysis at -0.868 kg CO_2-eq/kWh, even when the large uncertainty associated with fusion technology was considered. This is one of the greatest advantages of Nuclear Fusion BECCS plant.

Economic Advantages. The estimated levelized cost of electricity for Nuclear Fusion BECCS plant was the highest among nine comparing power plants in this study at 0.203 $/kWh. Due to this, Nuclear Fusion BECCS plant does not have economic competitiveness against other power sources in the current market. However, the sensitivity analysis on carbon price indicated that thanks to its net negative GHG emissions, the economic performance of Nuclear Fusion BECCS improves dramatically as the carbon price increases. Nuclear Fusion BECCS would even be the most economical power plant in the market when the carbon price is over 177 $/t CO_2. Therefore, in future markets, Nuclear Fusion BECCS plant could obtain a competitive edge economically.

Advantages from Fusion Engineering. The unique plant design of Nuclear Fusion BECCS also brings advantages over conventional nuclear fusion power plant from the engineering perspective.

One of the greatest advantages of Nuclear Fusion BECCS plant design is that the plant can produce 130% of electrical energy from the fusion reactor. This brings the seeming thermal efficiency of the plant to over 100%. This is due to the additional input of chemical energy from the biomass feedstock. This "multiplication" in electricity production leads to a much lower engineering break-even condition (a condition where the output energy exceeds the input) for fusion, which enables small-scale nuclear fusion reactors to produce net electricity. And, most importantly, lower engineering break-even condition means the faster realization of the commercial fusion.

Limitations of this Study

The primary limitation of this thesis is that this study is solely based on modeling. Although I had frequent discussions with industry professionals, adopted background data from peer-reviewed publications, and carried out uncertainty analysis and sensitivity analyses to improve the validity, the results can only be assumptive. This is an unavoidable limitation for a conceptual study for a first-of-a-kind plant.

For the environmental LCA, I intentionally focused solely on the GHG emissions in this thesis, in the aim of streamlining the logical flow. Due to this decision, other environmental impacts of the Nuclear Fusion BECCS plant went undiscussed. My preliminary calculations suggest that Nuclear Fusion BECCS might have larger impacts than other renewable energy sources in eutrophication and ozone depletion. In addition, this study disregards one of the core advantages of nuclear fusion: the fuel abundance. These points should further be studied in the future.

It should also be noted that the economic assessment in this thesis did not factor in other forms of subsidies than the carbon pricing, e.g. Feed-in-Tariff. Because of this assumption, the economic performance of low-carbon energy sources may be higher in certain electricity markets.

Conclusions

In this thesis, I proposed and assessed Nuclear Fusion BECCS plant, an innovative sustainable energy concept, for the first time. The obtained analyses results were encouraging: both environmental and economic analyses indicated Nuclear Fusion BECCS plant may have the potential to play a significant role in the future.

Conclusions on the Hypothesis

- Hypothesis 1: Nuclear Fusion BECCS plant can achieve life cycle GHG emissions of < 0 (life cycle net negative emissions).
  - 1.1: Nuclear Fusion BECCS can achieve larger carbon removal than plain BECCS plant per electricity production.

The estimated net GHG emissions (-0.868 kg CO2-eq/kWh; 90%CI: -1.154 – -0.555 kg CO2-eq/kWh) was lower than any other comparing power plants in this study, even when the large uncertainty was taken into account (Figure 20). Based on this finding, I conclude that Hypothesis 1 and 1.1 are proven.

- Hypothesis 2: The increased cost of Nuclear Fusion BECCS plant over other proposed BECCS plants can be offset by the enhanced carbon removal capacity under a reasonable carbon price (< 200 USD/tCO2e).

On the other hand, due to the large uncertainty associated with nuclear fusion-related construction costs, it is difficult to give a definitive verdict on Hypothesis 2. The economic assessment result showed that at Carbon Price = 170 USD/t, the Nuclear Fusion BECCS (at the median) became the most economical plant in this comparison.

This indicates that the increased cost of Nuclear Fusion BECCS is more likely to be offset by the enhanced carbon removal capacity under carbon price of > 170 USD/t; however, even at Carbon Price = 200 USD/t, the LCOEs of other power plants are within the 95% CI for Nuclear Fusion BECCS Plant. Based on these observations, I conclude that Hypothesis 2 is plausible.

Nuclear Fusion BECCS – A Promising Option for Future Energy Sustainability?

Timing is everything for sustainable energy conversion plants, especially in the post-Paris Agreement world. Multiple recent analyses suggest we may have a shorter time-window to achieve the 2-degree target. With the advantages of this plant concept in fusion engineering, this plant could be commercialized even sooner than the current projection shown in Figure 6, before 2030. For this reason, as a conclusion of the thesis, this section will analyze if Nuclear Fusion BECCS could play a significant role in the future energy market before 2050.

Figure 30 illustrates the projections of LCOEs for various power plants until 2050. Projections for conventional power plants are based on Mid projections of EIA (2019) with the carbon pricing scenario by S&P Global (2017) until 2050. I added the projected LCOE of Nuclear Fusion BECCS into the figure, based on the calculated LCOE and the life cycle GHG emissions with the assumption that the construction cost of Nuclear Fusion BECCS plant would decrease by 3%/10years.

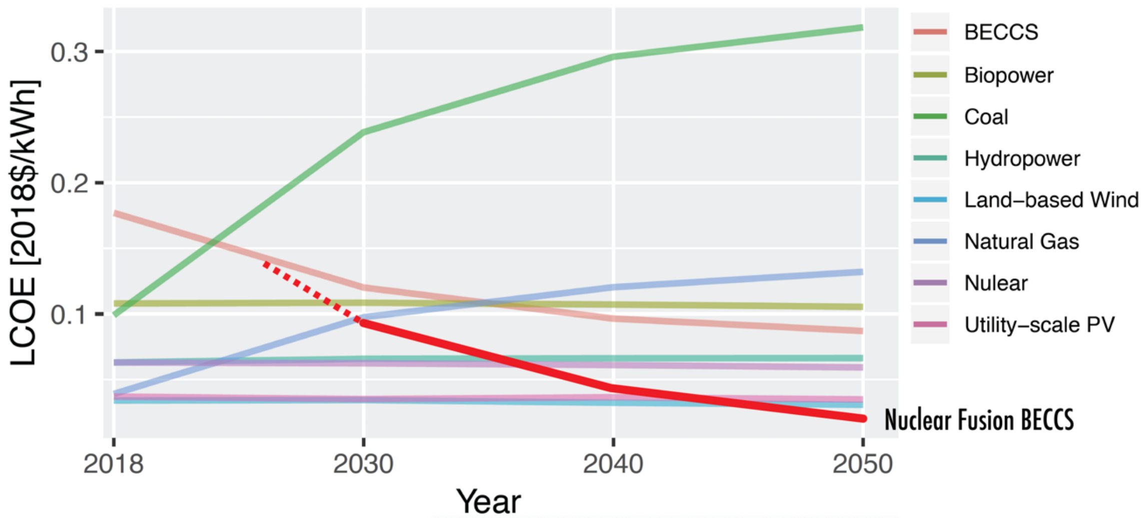


Figure 30. Projected LCOEs for Various Power Plants (by author; based on EIA (2019) and S&P Global (2017)).

The indication of this LCOE projection is clear: Nuclear Fusion BECCS can, in fact, compete against other renewable energy sources in the future market as a sustainable energy option. Nuclear fusion can sustain terra-watts of energy for more than ten million years (Bradshaw et al., 2011). By realizing this plant concept, we may be able to remove carbon dioxide from the atmosphere while producing electricity economically for generations to come. *Is Nuclear Fusion BECCS a promising option for future energy sustainability?* I conclude the answer is, "*yes*."

Appendix I.

Life Cycle Inventory Result

This appendix reports the life cycle inventory of the 1 kWh electricity production from Nuclear Fusion BECCS plant.

Table A1. Life Cycle Inventory of 1 kWh Electricity Production from Nuclear Fusion BECCS (by author).

(a) Inputs

Flow	**Category**	**Sub-category**	**Unit**	**Result**
Energy, gross calorific value, in biomass	Resource	biotic	MJ	14.38326
Energy, gross calorific value, in biomass, primary forest	Resource	biotic	MJ	0.00267
Peat, in ground	Resource	biotic	kg	4.2E-05
Wood, hard, standing	Resource	biotic	m3	2.34E-05
Wood, soft, standing	Resource	biotic	m3	0.000349
Wood, unspecified, standing	Resource	biotic	m3	2.66E-12
Argon-40	Resource	in air	kg	9.91E-06
Carbon dioxide, in air	Resource	in air	kg	1.307082
Energy, kinetic (in wind), converted	Resource	in air	MJ	0.015322
Energy, solar, converted	Resource	in air	MJ	0.00028
Krypton, in air	Resource	in air	kg	1.11E-17
Nitrogen	Resource	in air	kg	0.000535
Oxygen	Resource	in air	kg	0.000288
Xenon, in air	Resource	in air	kg	1.3E-18
Aluminium, 24% in bauxite, 11% in crude ore, in ground	Resource	in ground	kg	1.31E-08
Aluminium, in ground	Resource	in ground	kg	0.001626
Anhydrite, in ground	Resource	in ground	kg	4.24E-09
Barite, 15% in crude ore, in ground	Resource	in ground	kg	7.78E-05
Basalt, in ground	Resource	in ground	kg	2.56E-05
Borax, in ground	Resource	in ground	kg	4.15E-08
Cadmium, 0.30% in sulfide, Cd 0.18%, Pb, Zn, Ag, In, in ground	Resource	in ground	kg	4.57E-07
Calcite, in ground	Resource	in ground	kg	0.003255
Carbon, in organic matter, in soil	Resource	in ground	kg	0.000167

Cerium, 24% in bastnasite, 2.4% in crude ore, in ground	Resource	in ground	kg	9.34E-06
Chromium, 25.5% in chromite, 11.6% in crude ore, in ground	Resource	in ground	kg	0.000133
Chrysotile, in ground	Resource	in ground	kg	9.57E-08
Cinnabar, in ground	Resource	in ground	kg	7.16E-10
Clay, bentonite, in ground	Resource	in ground	kg	4.98E-05
Clay, unspecified, in ground	Resource	in ground	kg	0.001491
Coal, brown, in ground	Resource	in ground	kg	0.009044
Coal, hard, unspecified, in ground	Resource	in ground	kg	0.018979
Cobalt, Co 5.0E-2%, in mixed ore, in ground	Resource	in ground	kg	1.57E-06
Cobalt, in ground	Resource	in ground	kg	3.98E-10
Colemanite, in ground	Resource	in ground	kg	6.36E-07
Copper, 0.52% in sulfide, Cu 0.27% and Mo 8.2E-3% in crude ore, in ground	Resource	in ground	kg	1.72E-05
Copper, 0.59% in sulfide, Cu 0.22% and Mo 8.2E-3% in crude ore, in ground	Resource	in ground	kg	1.06E-05
Copper, 0.97% in sulfide, Cu 0.36% and Mo 4.1E-2% in crude ore, in ground	Resource	in ground	kg	1.84E-06
Copper, 0.99% in sulfide, Cu 0.36% and Mo 8.2E-3% in crude ore, in ground	Resource	in ground	kg	2.37E-05
Copper, 1.13% in sulfide, Cu 0.76% and Ni 0.76% in crude ore, in ground	Resource	in ground	kg	2.41E-06
Copper, 1.18% in sulfide, Cu 0.39% and Mo 8.2E-3% in crude ore, in ground	Resource	in ground	kg	1.46E-05
Copper, 1.42% in sulfide, Cu 0.81% and Mo 8.2E-3% in crude ore, in ground	Resource	in ground	kg	2.09E-06
Copper, 2.19% in sulfide, Cu 1.83% and Mo 8.2E-3% in crude ore, in ground	Resource	in ground	kg	6.75E-06
Copper, Cu 0.2%, in mixed ore, in ground	Resource	in ground	kg	3.44E-09
Copper, Cu 0.38%, Au 9.7E-4%, Ag 9.7E-4%, Zn 0.63%, Pb 0.014%, in ore, in ground	Resource	in ground	kg	2.22E-05
Copper, Cu 6.8E-1%, in mixed ore, in ground	Resource	in ground	kg	2.14E-05
Cu, Cu 3.2E+0%, Pt 2.5E-4%, Pd 7.3E-4%, Rh 2.0E-5%, Ni 2.3E+0% in ore, in ground	Resource	in ground	kg	1.75E-06
Cu, Cu 5.2E-2%, Pt 4.8E-4%, Pd 2.0E-4%, Rh 2.4E-5%, Ni 3.7E-2% in ore, in ground	Resource	in ground	kg	2.91E-08
Diatomite, in ground	Resource	in ground	kg	2.86E-11
Dolomite, in ground	Resource	in ground	kg	0.015429
Energy, geothermal, converted	Resource	in ground	MJ	0.001597
Europium, 0.06% in bastnasite, 0.006% in crude ore, in ground	Resource	in ground	kg	2.34E-08
Feldspar, in ground	Resource	in ground	kg	1.08E-10
Fluorine, 4.5% in apatite, 1% in crude ore, in ground	Resource	in ground	kg	5.76E-07
Fluorine, 4.5% in apatite, 3% in crude ore, in ground	Resource	in ground	kg	3.22E-07
Fluorspar, 92%, in ground	Resource	in ground	kg	1.28E-05

Gadolinium, 0.15% in bastnasite, 0.015% in crude ore, in ground	Resource	in ground	kg	5.84E-08
Gallium, 0.014% in bauxite, in ground	Resource	in ground	kg	7.33E-13
Gallium, in ground	Resource	in ground	kg	5.05E-07
Gangue, bauxite, in ground	Resource	in ground	kg	0.017276
Gas, mine, off-gas, process, coal mining	Resource	in ground	m3	0.000162
Gas, natural, in ground	Resource	in ground	m3	0.011961
Gold, Au 1.0E-7%, in mixed ore, in ground	Resource	in ground	kg	3.24E-10
Gold, Au 1.1E-4%, Ag 4.2E-3%, in ore, in ground	Resource	in ground	kg	1.96E-10
Gold, Au 1.3E-4%, Ag 4.6E-5%, in ore, in ground	Resource	in ground	kg	1.97E-10
Gold, Au 1.4E-4%, in ore, in ground	Resource	in ground	kg	5.81E-10
Gold, Au 1.8E-4%, in mixed ore, in ground	Resource	in ground	kg	4.11E-12
Gold, Au 2.1E-4%, Ag 2.1E-4%, in ore, in ground	Resource	in ground	kg	4.31E-11
Gold, Au 4.3E-4%, in ore, in ground	Resource	in ground	kg	1.13E-10
Gold, Au 4.9E-5%, in ore, in ground	Resource	in ground	kg	5.69E-10
Gold, Au 5.4E-4%, Ag 1.5E-5%, in ore, in ground	Resource	in ground	kg	3.25E-12
Gold, Au 6.7E-4%, in ore, in ground	Resource	in ground	kg	6.07E-10
Gold, Au 6.8E-4%, Ag 1.5E-4%, in ore, in ground	Resource	in ground	kg	4.42E-12
Gold, Au 7.1E-4%, in ore, in ground	Resource	in ground	kg	2.81E-10
Gold, Au 9.7E-4%, Ag 9.7E-4%, Zn 0.63%, Cu 0.38%, Pb 0.014%, in ore, in ground	Resource	in ground	kg	5.41E-10
Gold, Au 9.7E-5%, Ag 7.6E-5%, in ore, in ground	Resource	in ground	kg	1.6E-11
Granite, in ground	Resource	in ground	kg	2.59E-14
Gravel, in ground	Resource	in ground	kg	0.115743
Gypsum, in ground	Resource	in ground	kg	5.69E-05
Indium, 0.005% in sulfide, In 0.003%, Pb, Zn, Ag, Cd, in ground	Resource	in ground	kg	7.62E-09
Iron, 46% in ore, 25% in crude ore, in ground	Resource	in ground	kg	0.002709
Iron, 72% in magnetite, 14% in crude ore, in ground	Resource	in ground	kg	2.93E-07
Kaolinite, 24% in crude ore, in ground	Resource	in ground	kg	6.97E-07
Kieserite, 25% in crude ore, in ground	Resource	in ground	kg	5.31E-09
Lanthanum, 7.2% in bastnasite, 0.72% in crude ore, in ground	Resource	in ground	kg	2.8E-06
Lead, 5.0% in sulfide, Pb 3.0%, Zn, Ag, Cd, In, in ground	Resource	in ground	kg	7.62E-06
Lead, Pb 0.014%, Au 9.7E-4%, Ag 9.7E-4%, Zn 0.63%, Cu 0.38%, in ore, in ground	Resource	in ground	kg	2.69E-06
Lead, Pb 3.6E-1%, in mixed ore, in ground	Resource	in ground	kg	6.19E-09
Lithium, 0.15% in brine, in ground	Resource	in ground	kg	1.18E-08
Magnesite, 60% in crude ore, in ground	Resource	in ground	kg	2.05E-05
Manganese, 35.7% in sedimentary deposit, 14.2% in crude ore, in ground	Resource	in ground	kg	2.21E-05
Metamorphous rock, graphite containing, in ground	Resource	in ground	kg	9.27E-08
Molybdenum, 0.010% in sulfide, Mo 8.2E-3% and Cu 1.83% in crude ore, in ground	Resource	in ground	kg	1.96E-07

Molybdenum, 0.014% in sulfide, Mo 8.2E-3% and Cu 0.81% in crude ore, in ground	Resource	in ground	kg	4.29E-08
Molybdenum, 0.016% in sulfide, Mo 8.2E-3% and Cu 0.27% in crude ore, in ground	Resource	in ground	kg	4.12E-07
Molybdenum, 0.022% in sulfide, Mo 8.2E-3% and Cu 0.22% in crude ore, in ground	Resource	in ground	kg	2.37E-07
Molybdenum, 0.022% in sulfide, Mo 8.2E-3% and Cu 0.36% in crude ore, in ground	Resource	in ground	kg	3.21E-07
Molybdenum, 0.025% in sulfide, Mo 8.2E-3% and Cu 0.39% in crude ore, in ground	Resource	in ground	kg	2.92E-07
Molybdenum, 0.11% in sulfide, Mo 4.1E-2% and Cu 0.36% in crude ore, in ground	Resource	in ground	kg	2.1E-07
Neodymium, 4% in bastnasite, 0.4% in crude ore, in ground	Resource	in ground	kg	1.54E-06
Ni, Ni 2.3E+0%, Pt 2.5E-4%, Pd 7.3E-4%, Rh 2.0E-5%, Cu 3.2E+0% in ore, in ground	Resource	in ground	kg	1.26E-06
Ni, Ni 3.7E-2%, Pt 4.8E-4%, Pd 2.0E-4%, Rh 2.4E-5%, Cu 5.2E-2% in ore, in ground	Resource	in ground	kg	4.15E-08
Nickel, 1.13% in sulfide, Ni 0.76% and Cu 0.76% in crude ore, in ground	Resource	in ground	kg	4.68E-06
Nickel, 1.98% in silicates, 1.04% in crude ore, in ground	Resource	in ground	kg	7.83E-05
Nickel, Ni 2.5E+0%, in mixed ore, in ground	Resource	in ground	kg	7.69E-05
niobium	Resource	in ground	kg	9.76E-05
Oil, crude, in ground	Resource	in ground	kg	0.015412
Olivine, in ground	Resource	in ground	kg	1.48E-09
Palladium, Pd 1.6E-6%, in mixed ore, in ground	Resource	in ground	kg	5.14E-09
Pd, Pd 2.0E-4%, Pt 4.8E-4%, Rh 2.4E-5%, Ni 3.7E-2%, Cu 5.2E-2% in ore, in ground	Resource	in ground	kg	8.1E-11
Pd, Pd 7.3E-4%, Pt 2.5E-4%, Rh 2.0E-5%, Ni 2.3E+0%, Cu 3.2E+0% in ore, in ground	Resource	in ground	kg	3.98E-10
Perlite, in ground	Resource	in ground	kg	6.04E-09
Phosphorus, 18% in apatite, 12% in crude ore, in ground	Resource	in ground	kg	1.29E-06
Phosphorus, 18% in apatite, 4% in crude ore, in ground	Resource	in ground	kg	2.3E-06
Platinum, Pt 4.7E-7%, in mixed ore, in ground	Resource	in ground	kg	1.49E-09
Praseodymium, 0.42% in bastnasite, 0.042% in crude ore, in ground	Resource	in ground	kg	1.63E-07
Pt, Pt 2.5E-4%, Pd 7.3E-4%, Rh 2.0E-5%, Ni 2.3E+0%, Cu 3.2E+0% in ore, in ground	Resource	in ground	kg	1.36E-10
Pt, Pt 4.8E-4%, Pd 2.0E-4%, Rh 2.4E-5%, Ni 3.7E-2%, Cu 5.2E-2% in ore, in ground	Resource	in ground	kg	1.91E-10
Rh, Rh 2.0E-5%, Pt 2.5E-4%, Pd 7.3E-4%, Ni 2.3E+0%, Cu 3.2E+0% in ore, in ground	Resource	in ground	kg	1.09E-11
Rh, Rh 2.4E-5%, Pt 4.8E-4%, Pd 2.0E-4%, Ni 3.7E-2%, Cu 5.2E-2% in ore, in ground	Resource	in ground	kg	9.55E-12
Rhenium, in crude ore, in ground	Resource	in ground	kg	4.12E-12
Rhodium, Rh 1.6E-7%, in mixed ore, in ground	Resource	in ground	kg	5.05E-10

Samarium, 0.3% in bastnasite, 0.03% in crude ore, in ground	Resource	in ground	kg	1.17E-07
Sand, unspecified, in ground	Resource	in ground	kg	2.61E-07
Shale, in ground	Resource	in ground	kg	0.004833
Silver, 0.007% in sulfide, Ag 0.004%, Pb, Zn, Cd, In, in ground	Resource	in ground	kg	1.11E-08
Silver, 3.2ppm in sulfide, Ag 1.2ppm, Cu and Te, in crude ore, in ground	Resource	in ground	kg	2.84E-12
Silver, Ag 1.5E-4%, Au 6.8E-4%, in ore, in ground	Resource	in ground	kg	9.92E-13
Silver, Ag 1.5E-5%, Au 5.4E-4%, in ore, in ground	Resource	in ground	kg	9.08E-14
Silver, Ag 1.8E-6%, in mixed ore, in ground	Resource	in ground	kg	5.74E-09
Silver, Ag 2.1E-4%, Au 2.1E-4%, in ore, in ground	Resource	in ground	kg	4.39E-11
Silver, Ag 4.2E-3%, Au 1.1E-4%, in ore, in ground	Resource	in ground	kg	7.36E-09
Silver, Ag 4.6E-5%, Au 1.3E-4%, in ore, in ground	Resource	in ground	kg	7.04E-11
Silver, Ag 5.4E-3%, in mixed ore, in ground	Resource	in ground	kg	9.36E-11
Silver, Ag 7.6E-5%, Au 9.7E-5%, in ore, in ground	Resource	in ground	kg	1.25E-11
Silver, Ag 9.7E-4%, Au 9.7E-4%, Zn 0.63%, Cu 0.38%, Pb 0.014%, in ore, in ground	Resource	in ground	kg	2.74E-08
Sodium chloride, in ground	Resource	in ground	kg	0.004361
Sodium nitrate, in ground	Resource	in ground	kg	1.19E-13
Sodium sulphate, various forms, in ground	Resource	in ground	kg	3.3E-07
Spodumene, in ground	Resource	in ground	kg	3.58E-09
Stibnite, in ground	Resource	in ground	kg	2.97E-12
strontium, in ground	Resource	in ground	kg	7.66E-09
Sulfur, in ground	Resource	in ground	kg	8.85E-08
Sylvite, 25 % in sylvinite, in ground	Resource	in ground	kg	1.61E-05
Talc, in ground	Resource	in ground	kg	5.19E-08
Tantalum, 81.9% in tantalite, 1.6E-4% in crude ore, in ground	Resource	in ground	kg	4.05E-08
Tellurium, 0.5ppm in sulfide, Te 0.2ppm, Cu and Ag, in crude ore, in ground	Resource	in ground	kg	4.26E-13
Tin	Resource	in ground	kg	4.16E-05
Tin, 79% in cassiterite, 0.1% in crude ore, in ground	Resource	in ground	kg	1.85E-07
TiO2, 54% in ilmenite, 18% in crude ore, in ground	Resource	in ground	kg	2.2E-07
TiO2, 54% in ilmenite, 2.6% in crude ore, in ground	Resource	in ground	kg	7.96E-06
TiO2, 95% in rutile, 0.40% in crude ore, in ground	Resource	in ground	kg	1.23E-06
Ulexite, in ground	Resource	in ground	kg	1.97E-08
Uranium, in ground	Resource	in ground	kg	6.65E-07
Volume occupied, final repository for low-active radioactive waste	Resource	in ground	m3	1.77E-08
Volume occupied, final repository for radioactive waste	Resource	in ground	m3	2.02E-09
Volume occupied, underground deposit	Resource	in ground	m3	1.9E-09
Water, unspecified natural origin	Resource	in ground	m3	1.77E-07

Zinc, 9.0% in sulfide, Zn 5.3%, Pb, Ag, Cd, In, in ground	Resource	in ground	kg	1.37E-05
Zinc, Zn 0.63%, Au 9.7E-4%, Ag 9.7E-4%, Cu 0.38%, Pb 0.014%, in ore, in ground	Resource	in ground	kg	3.48E-06
Zinc, Zn 3.1%, in mixed ore, in ground	Resource	in ground	kg	5.31E-08
Zirconium, 50% in zircon, 0.39% in crude ore, in ground	Resource	in ground	kg	1.17E-06
Bromine, 0.23% in water	Resource	in water	kg	2.33E-08
Carnallite	Resource	in water	kg	2.43E-07
Energy, potential (in hydropower reservoir), converted	Resource	in water	MJ	0.146625
Fish, pelagic, in ocean	Resource	in water	kg	3.5E-18
Iodine, 0.03% in water	Resource	in water	kg	5.4E-09
Volume occupied, reservoir	Resource	in water	m3*a	0.00239
Water, cooling, unspecified natural origin	Resource	in water	m3	0.022205
Water, lake	Resource	in water	m3	5.61E-05
Water, river	Resource	in water	m3	0.001209
Water, salt, ocean	Resource	in water	m3	9.25E-06
Water, salt, sole	Resource	in water	m3	9.23E-06
Water, turbine use, unspecified natural origin	Resource	in water	m3	1.064862
Water, unspecified natural origin	Resource	in water	m3	0.000326
Water, well, in ground	Resource	in water	m3	0.000206
Occupation, annual crop	Resource	land	m2*a	0.000498
Occupation, annual crop, irrigated	Resource	land	m2*a	3.12E-05
Occupation, annual crop, irrigated, intensive	Resource	land	m2*a	2.45E-09
Occupation, annual crop, non-irrigated	Resource	land	m2*a	7.09E-09
Occupation, annual crop, non-irrigated, extensive	Resource	land	m2*a	3.62E-08
Occupation, annual crop, non-irrigated, intensive	Resource	land	m2*a	0.000255
Occupation, construction site	Resource	land	m2*a	2.97E-05
Occupation, dump site	Resource	land	m2*a	0.000317
Occupation, forest, extensive	Resource	land	m2*a	0.917316
Occupation, forest, intensive	Resource	land	m2*a	0.825362
Occupation, grassland, natural (non-use)	Resource	land	m2*a	1.45E-05
Occupation, industrial area	Resource	land	m2*a	0.000958
Occupation, inland waterbody, unspecified	Resource	land	m2*a	4.39E-08
Occupation, lake, artificial	Resource	land	m2*a	0.000246
Occupation, mineral extraction site	Resource	land	m2*a	0.000109
Occupation, pasture, man made, extensive	Resource	land	m2*a	1.43E-11
Occupation, pasture, man made, intensive	Resource	land	m2*a	6.62E-08
Occupation, permanent crop	Resource	land	m2*a	0.000192
Occupation, permanent crop, irrigated	Resource	land	m2*a	1.09E-05
Occupation, permanent crop, irrigated, intensive	Resource	land	m2*a	5.78E-20
Occupation, river, artificial	Resource	land	m2*a	0.000129

Occupation, seabed, drilling and mining	Resource	land	m2*a	2.84E-06
Occupation, seabed, infrastructure	Resource	land	m2*a	3.03E-08
Occupation, shrub land, sclerophyllous	Resource	land	m2*a	1.65E-05
Occupation, traffic area, rail network	Resource	land	m2*a	4.79E-05
Occupation, traffic area, rail/road embankment	Resource	land	m2*a	0.026413
Occupation, traffic area, road network	Resource	land	m2*a	0.000831
Occupation, unknown	Resource	land	m2*a	2.68E-06
Occupation, urban, discontinuously built	Resource	land	m2*a	6.28E-07
Occupation, urban/industrial fallow (non-use)	Resource	land	m2*a	1.46E-08
Transformation, from annual crop	Resource	land	m2	0.000647
Transformation, from annual crop, non-irrigated	Resource	land	m2	6.33E-08
Transformation, from annual crop, non-irrigated, extensive	Resource	land	m2	3.12E-08
Transformation, from annual crop, non-irrigated, intensive	Resource	land	m2	0.00013
Transformation, from cropland fallow (non-use)	Resource	land	m2	3.26E-07
Transformation, from dump site, inert material landfill	Resource	land	m2	2.53E-06
Transformation, from dump site, residual material landfill	Resource	land	m2	5.59E-07
Transformation, from dump site, sanitary landfill	Resource	land	m2	2.9E-08
Transformation, from dump site, slag compartment	Resource	land	m2	1.68E-07
Transformation, from forest, extensive	Resource	land	m2	0.008446
Transformation, from forest, intensive	Resource	land	m2	0.00871
Transformation, from forest, primary (non-use)	Resource	land	m2	5.03E-06
Transformation, from forest, secondary (non-use)	Resource	land	m2	7.04E-06
Transformation, from forest, unspecified	Resource	land	m2	1.89E-05
Transformation, from grassland, natural (non-use)	Resource	land	m2	3.83E-08
Transformation, from grassland, natural, for livestock grazing	Resource	land	m2	1.04E-07
Transformation, from heterogeneous, agricultural	Resource	land	m2	7.84E-09
Transformation, from industrial area	Resource	land	m2	5.12E-06
Transformation, from mineral extraction site	Resource	land	m2	3.3E-06
Transformation, from pasture, man made	Resource	land	m2	6.11E-06
Transformation, from pasture, man made, extensive	Resource	land	m2	2.86E-13
Transformation, from pasture, man made, intensive	Resource	land	m2	3.01E-08
Transformation, from permanent crop	Resource	land	m2	1.12E-05
Transformation, from permanent crop, irrigated	Resource	land	m2	5.27E-07
Transformation, from permanent crop, irrigated, intensive	Resource	land	m2	7.22E-22
Transformation, from seabed, infrastructure	Resource	land	m2	1.62E-10
Transformation, from seabed, unspecified	Resource	land	m2	2.85E-06
Transformation, from shrub land, sclerophyllous	Resource	land	m2	3.94E-06

Transformation, from traffic area, rail/road embankment	Resource	land	m2	0.000173
Transformation, from traffic area, road network	Resource	land	m2	3E-21
Transformation, from unknown	Resource	land	m2	3.21E-05
Transformation, from unspecified, natural (non-use)	Resource	land	m2	3.51E-09
Transformation, from wetland, inland (non-use)	Resource	land	m2	9.32E-10
Transformation, to annual crop	Resource	land	m2	7.7E-05
Transformation, to annual crop, irrigated, intensive	Resource	land	m2	2.5E-09
Transformation, to annual crop, non-irrigated	Resource	land	m2	1.93E-08
Transformation, to annual crop, non-irrigated, extensive	Resource	land	m2	4.39E-08
Transformation, to annual crop, non-irrigated, intensive	Resource	land	m2	0.000497
Transformation, to arable land, unspecified use	Resource	land	m2	0.000214
Transformation, to cropland fallow (non-use)	Resource	land	m2	3.41E-07
Transformation, to dump site	Resource	land	m2	2.16E-06
Transformation, to dump site, inert material landfill	Resource	land	m2	2.53E-06
Transformation, to dump site, residual material landfill	Resource	land	m2	5.59E-07
Transformation, to dump site, sanitary landfill	Resource	land	m2	2.9E-08
Transformation, to dump site, slag compartment	Resource	land	m2	1.68E-07
Transformation, to forest	Resource	land	m2	4.22E-06
Transformation, to forest, extensive	Resource	land	m2	0.007056
Transformation, to forest, intensive	Resource	land	m2	0.01003
Transformation, to forest, secondary (non-use)	Resource	land	m2	3.54E-21
Transformation, to grassland, natural (non-use)	Resource	land	m2	1.94E-07
Transformation, to heterogeneous, agricultural	Resource	land	m2	5.46E-07
Transformation, to industrial area	Resource	land	m2	2.57E-05
Transformation, to inland waterbody, unspecified	Resource	land	m2	4.39E-10
Transformation, to lake, artificial	Resource	land	m2	2.53E-06
Transformation, to mineral extraction site	Resource	land	m2	2.33E-05
Transformation, to pasture, man made	Resource	land	m2	4.4E-08
Transformation, to pasture, man made, extensive	Resource	land	m2	2.86E-13
Transformation, to pasture, man made, intensive	Resource	land	m2	3.33E-09
Transformation, to permanent crop	Resource	land	m2	1.27E-05
Transformation, to permanent crop, irrigated	Resource	land	m2	5.27E-07
Transformation, to permanent crop, irrigated, intensive	Resource	land	m2	7.22E-22
Transformation, to permanent crop, non-irrigated	Resource	land	m2	3.54E-21
Transformation, to river, artificial	Resource	land	m2	1.5E-06
Transformation, to seabed, drilling and mining	Resource	land	m2	2.84E-06
Transformation, to seabed, infrastructure	Resource	land	m2	1.09E-08
Transformation, to seabed, unspecified	Resource	land	m2	1.62E-10

Transformation, to shrub land, sclerophyllous	Resource	land	m2	3.29E-06
Transformation, to traffic area, rail network	Resource	land	m2	1.11E-07
Transformation, to traffic area, rail/road embankment	Resource	land	m2	0.000243
Transformation, to traffic area, road network	Resource	land	m2	3.2E-06
Transformation, to unknown	Resource	land	m2	1.2E-06
Transformation, to urban, discontinuously built	Resource	land	m2	1.25E-08
Transformation, to urban/industrial fallow (non-use)	Resource	land	m2	1.95E-10
Transformation, to wetland, inland (non-use)	Resource	land	m2	1.12E-20

(b) Outputs

Flow	**Category**	**Sub-category**	**Unit**	**Result**
1,4-Butanediol	Emission to air	high population density	kg	9.46E-12
1-Pentanol	Emission to air	high population density	kg	8.37E-13
1-Pentene	Emission to air	high population density	kg	5.5E-11
2-Aminopropanol	Emission to air	high population density	kg	8.03E-13
2-Methyl pentane	Emission to air	high population density	kg	2E-09
2-Methyl-1-propanol	Emission to air	high population density	kg	2.48E-12
2-Methyl-2-butene	Emission to air	high population density	kg	3.86E-14
2-Nitrobenzoic acid	Emission to air	high population density	kg	1.43E-12
2-Propanol	Emission to air	high population density	kg	1.3E-08
Acetaldehyde	Emission to air	high population density	kg	7.57E-08
Acetic acid	Emission to air	high population density	kg	1.99E-07
Acetone	Emission to air	high population density	kg	8.07E-08
Acrolein	Emission to air	high population density	kg	2.15E-10
Acrylic acid	Emission to air	high population density	kg	1.34E-10
Aldehydes, unspecified	Emission to air	high population density	kg	3.44E-10
Aluminium	Emission to air	high population density	kg	6.74E-07
Ammonia	Emission to air	high population density	kg	1.47E-05
Ammonium carbonate	Emission to air	high population density	kg	2.59E-10
Aniline	Emission to air	high population density	kg	1.6E-11
Anthranilic acid	Emission to air	high population density	kg	1.12E-12
Antimony	Emission to air	high population density	kg	6.41E-10
Arsenic	Emission to air	high population density	kg	3.59E-09
Arsine	Emission to air	high population density	kg	1.56E-15
Barium	Emission to air	high population density	kg	8.75E-09
Benzaldehyde	Emission to air	high population density	kg	6.67E-11
Benzene	Emission to air	high population density	kg	1.84E-06
Benzene, dichloro	Emission to air	high population density	kg	1E-11
Benzene, ethyl-	Emission to air	high population density	kg	6.09E-08
Benzene, hexachloro-	Emission to air	high population density	kg	4.87E-13

Benzene, pentachloro-	Emission to air	high population density	kg	1.21E-12
Benzo(a)pyrene	Emission to air	high population density	kg	4.1E-10
Beryllium	Emission to air	high population density	kg	8.09E-11
Boric acid	Emission to air	high population density	kg	2.55E-19
Boron	Emission to air	high population density	kg	3.4E-08
Boron trifluoride	Emission to air	high population density	kg	1.74E-15
Bromine	Emission to air	high population density	kg	5.05E-08
Butadiene	Emission to air	high population density	kg	3.64E-13
Butane	Emission to air	high population density	kg	1.36E-06
Butanol	Emission to air	high population density	kg	5.57E-12
Butene	Emission to air	high population density	kg	2.05E-08
Cadmium	Emission to air	high population density	kg	2.9E-09
Calcium	Emission to air	high population density	kg	4.68E-06
Carbon dioxide, biogenic	Emission to air	high population density	kg	0.051705
Carbon dioxide, fossil	Emission to air	high population density	kg	0.024736
Carbon disulfide	Emission to air	high population density	kg	2.58E-12
Carbon monoxide, biogenic	Emission to air	high population density	kg	0.000288
Carbon monoxide, fossil	Emission to air	high population density	kg	3.91E-05
Chloramine	Emission to air	high population density	kg	6.19E-12
Chlorine	Emission to air	high population density	kg	2.89E-07
Chloroacetic acid	Emission to air	high population density	kg	5.67E-11
Chloroform	Emission to air	high population density	kg	2.95E-10
Chlorosilane, trimethyl-	Emission to air	high population density	kg	2.49E-11
Chlorosulfonic acid	Emission to air	high population density	kg	2.84E-12
Chromium	Emission to air	high population density	kg	6.87E-09
Chromium IV	Emission to air	high population density	kg	2.96E-15
Chromium VI	Emission to air	high population density	kg	2.24E-10
Cobalt	Emission to air	high population density	kg	3.6E-09
Copper	Emission to air	high population density	kg	3.38E-08
Cumene	Emission to air	high population density	kg	5.07E-07
Cyanide	Emission to air	high population density	kg	3.72E-09
Cyanoacetic acid	Emission to air	high population density	kg	2.33E-12
Cyclohexane	Emission to air	high population density	kg	9.01E-18
Cyclohexane (for all cycloalkanes)	Emission to air	high population density	kg	1.13E-10
Diethyl ether	Emission to air	high population density	kg	2.12E-17
Diethylamine	Emission to air	high population density	kg	7.42E-12
Diethylene glycol	Emission to air	high population density	kg	1.22E-08
Dimethyl malonate	Emission to air	high population density	kg	2.92E-12
Dimethylamine	Emission to air	high population density	kg	3.92E-14
Dinitrogen monoxide	Emission to air	high population density	kg	3.38E-06

Dioxins, measured as 2,3,7,8-tetrachlorodibenzo-p-dioxin	Emission to air	high population density	kg	4.43E-14
Dipropylamine	Emission to air	high population density	kg	4.28E-12
Elemental carbon	Emission to air	high population density	kg	1.67E-09
Ethane	Emission to air	high population density	kg	3.19E-07
Ethane, 1,1,1,2-tetrafluoro-, HFC-134a	Emission to air	high population density	kg	1.81E-11
Ethane, 1,1,2-trichloro-1,2,2-trifluoro-, CFC-113	Emission to air	high population density	kg	6.35E-12
Ethane, 1,1-difluoro-, HFC-152a	Emission to air	high population density	kg	6.15E-10
Ethane, 1,2-dichloro-	Emission to air	high population density	kg	1.8E-09
Ethane, hexafluoro-, HFC-116	Emission to air	high population density	kg	4.4E-10
Ethanol	Emission to air	high population density	kg	2.2E-07
Ethene	Emission to air	high population density	kg	2.61E-07
Ethene, chloro-	Emission to air	high population density	kg	8.99E-10
Ethene, tetrachloro-	Emission to air	high population density	kg	2.17E-08
Ethyl acetate	Emission to air	high population density	kg	2.39E-07
Ethyl cellulose	Emission to air	high population density	kg	1.44E-10
Ethylamine	Emission to air	high population density	kg	2.61E-12
Ethylene diamine	Emission to air	high population density	kg	9.28E-13
Ethylene oxide	Emission to air	high population density	kg	1.55E-09
Ethyne	Emission to air	high population density	kg	3.33E-08
Fluorine	Emission to air	high population density	kg	3.92E-08
Fluosilicic acid	Emission to air	high population density	kg	1.22E-09
Formaldehyde	Emission to air	high population density	kg	5.02E-06
Formamide	Emission to air	high population density	kg	1.53E-12
Formic acid	Emission to air	high population density	kg	7.62E-11
Heat, waste	Emission to air	high population density	MJ	0.003626
Heptane	Emission to air	high population density	kg	1.99E-07
Hexane	Emission to air	high population density	kg	9.65E-07
Hydrocarbons, aliphatic, alkanes, cyclic	Emission to air	high population density	kg	1.96E-08
Hydrocarbons, aliphatic, alkanes, unspecified	Emission to air	high population density	kg	1.24E-06
Hydrocarbons, aliphatic, unsaturated	Emission to air	high population density	kg	2.51E-06
Hydrocarbons, aromatic	Emission to air	high population density	kg	7.37E-08
Hydrocarbons, chlorinated	Emission to air	high population density	kg	1.12E-09
Hydrogen	Emission to air	high population density	kg	1.67E-06
Hydrogen chloride	Emission to air	high population density	kg	2.97E-06
Hydrogen fluoride	Emission to air	high population density	kg	1.05E-07
Hydrogen peroxide	Emission to air	high population density	kg	2.16E-10
Hydrogen sulfide	Emission to air	high population density	kg	6.67E-08

Iodine	Emission to air	high population density	kg	2.09E-09
Iron	Emission to air	high population density	kg	2.99E-07
Isocyanic acid	Emission to air	high population density	kg	3.62E-06
Isopropylamine	Emission to air	high population density	kg	1.18E-12
Lactic acid	Emission to air	high population density	kg	3.35E-12
Lead	Emission to air	high population density	kg	3.09E-08
Lead-210	Emission to air	high population density	kBq	3.5E-06
Lithium	Emission to air	high population density	kg	2.85E-13
m-Xylene	Emission to air	high population density	kg	9.49E-08
Magnesium	Emission to air	high population density	kg	5.21E-07
Manganese	Emission to air	high population density	kg	1.35E-07
Mercury	Emission to air	high population density	kg	7.4E-10
Methane	Emission to air	high population density	kg	7.33E-09
Methane, biogenic	Emission to air	high population density	kg	9.48E-06
Methane, bromo-, Halon 1001	Emission to air	high population density	kg	1.48E-23
Methane, bromotrifluoro-, Halon 1301	Emission to air	high population density	kg	1.36E-15
Methane, chlorodifluoro-, HCFC-22	Emission to air	high population density	kg	4.91E-11
Methane, dichloro-, HCC-30	Emission to air	high population density	kg	1.53E-11
Methane, dichlorodifluoro-, CFC-12	Emission to air	high population density	kg	9.14E-12
Methane, dichlorofluoro-, HCFC-21	Emission to air	high population density	kg	9.41E-14
Methane, fossil	Emission to air	high population density	kg	1.34E-05
Methane, tetrachloro-, R-10	Emission to air	high population density	kg	5.44E-09
Methane, tetrafluoro-, R-14	Emission to air	high population density	kg	4.42E-12
Methane, trichlorofluoro-, CFC-11	Emission to air	high population density	kg	1.04E-13
Methane, trifluoro-, HFC-23	Emission to air	high population density	kg	2.99E-11
Methanesulfonic acid	Emission to air	high population density	kg	2.35E-12
Methanol	Emission to air	high population density	kg	3.31E-07
Methyl acetate	Emission to air	high population density	kg	3.32E-13
Methyl acrylate	Emission to air	high population density	kg	1.52E-10
Methyl amine	Emission to air	high population density	kg	2.98E-12
Methyl borate	Emission to air	high population density	kg	8.15E-13
Methyl ethyl ketone	Emission to air	high population density	kg	2.39E-07
Methyl formate	Emission to air	high population density	kg	7.1E-13
Methyl lactate	Emission to air	high population density	kg	3.68E-12
Molybdenum	Emission to air	high population density	kg	1.67E-09
Monoethanolamine	Emission to air	high population density	kg	8.13E-08
Nickel	Emission to air	high population density	kg	5.58E-08
Nitrate	Emission to air	high population density	kg	2.29E-11
Nitrobenzene	Emission to air	high population density	kg	1.15E-09

Nitrogen fluoride	Emission to air	high population density	kg	4.98E-18
Nitrogen oxides	Emission to air	high population density	kg	0.000153
NMVOC, non-methane volatile organic compounds, unspecified origin	Emission to air	high population density	kg	2.31E-05
o-Nitrotoluene	Emission to air	high population density	kg	1.24E-12
o-Xylene	Emission to air	high population density	kg	2.21E-10
Organic carbon	Emission to air	high population density	kg	4.15E-09
Ozone	Emission to air	high population density	kg	6.43E-13
PAH, polycyclic aromatic hydrocarbons	Emission to air	high population density	kg	2.5E-08
Particulates, < 2.5 um	Emission to air	high population density	kg	8.08E-05
Particulates, > 10 um	Emission to air	high population density	kg	6.18E-06
Particulates, > 2.5 um, and < 10um	Emission to air	high population density	kg	8.08E-06
Pentane	Emission to air	high population density	kg	2.07E-06
Phenol	Emission to air	high population density	kg	1.01E-06
Phenol, 2,4-dichloro	Emission to air	high population density	kg	1.05E-11
Phenol, pentachloro-	Emission to air	high population density	kg	6.45E-12
Phosphine	Emission to air	high population density	kg	1.27E-13
Phosphoric acid	Emission to air	high population density	kg	9.01E-18
Phosphorus	Emission to air	high population density	kg	2.4E-07
Phosphorus trichloride	Emission to air	high population density	kg	9.86E-13
Platinum	Emission to air	high population density	kg	3.21E-17
Polonium-210	Emission to air	high population density	kBq	6.23E-06
Polychlorinated biphenyls	Emission to air	high population density	kg	2.91E-12
Potassium	Emission to air	high population density	kg	1.84E-05
Potassium-40	Emission to air	high population density	kBq	9.91E-07
Propanal	Emission to air	high population density	kg	2.4E-11
Propane	Emission to air	high population density	kg	1.05E-06
Propanol	Emission to air	high population density	kg	2.59E-11
Propene	Emission to air	high population density	kg	4.43E-07
Propionic acid	Emission to air	high population density	kg	1.45E-08
Propylamine	Emission to air	high population density	kg	8.56E-13
Propylene oxide	Emission to air	high population density	kg	2.19E-09
Radioactive species, other beta emitters	Emission to air	high population density	kBq	4.58E-05
Radium-226	Emission to air	high population density	kBq	8.79E-07
Radium-228	Emission to air	high population density	kBq	4.02E-06
Radon-220	Emission to air	high population density	kBq	3.05E-06
Radon-222	Emission to air	high population density	kBq	1.75E-06
Scandium	Emission to air	high population density	kg	7.93E-11
Selenium	Emission to air	high population density	kg	1.67E-09
Silicon	Emission to air	high population density	kg	1.01E-06

Silver	Emission to air	high population density	kg	1.38E-11
Sodium	Emission to air	high population density	kg	1.12E-06
Sodium chlorate	Emission to air	high population density	kg	2.05E-10
Sodium dichromate	Emission to air	high population density	kg	3.28E-12
Sodium formate	Emission to air	high population density	kg	5.18E-12
Sodium hydroxide	Emission to air	high population density	kg	5.76E-10
Sodium tetrahydroborate	Emission to air	high population density	kg	3.31E-15
Strontium	Emission to air	high population density	kg	1.23E-08
Styrene	Emission to air	high population density	kg	1.43E-08
Sulfate	Emission to air	high population density	kg	2.16E-05
Sulfur dioxide	Emission to air	high population density	kg	0.00011
Sulfur hexafluoride	Emission to air	high population density	kg	1.99E-17
Sulfuric acid	Emission to air	high population density	kg	1.96E-10
Sulphur trioxide	Emission to air	high population density	kg	1.71E-10
t-Butyl methyl ether	Emission to air	high population density	kg	2.16E-08
t-Butylamine	Emission to air	high population density	kg	2.38E-12
Tetramethyl ammonium hydroxide	Emission to air	high population density	kg	1.19E-13
Thallium	Emission to air	high population density	kg	9.96E-11
Thorium	Emission to air	high population density	kg	1.19E-10
Thorium-228	Emission to air	high population density	kBq	3.6E-07
Thorium-232	Emission to air	high population density	kBq	2.5E-07
Tin	Emission to air	high population density	kg	9.5E-11
Titanium	Emission to air	high population density	kg	2.41E-08
Toluene	Emission to air	high population density	kg	5.45E-07
Toluene, 2-chloro	Emission to air	high population density	kg	1.24E-11
Trimethylamine	Emission to air	high population density	kg	6.96E-13
Uranium	Emission to air	high population density	kg	1.53E-10
Uranium-238	Emission to air	high population density	kBq	7.32E-07
Vanadium	Emission to air	high population density	kg	1.75E-07
Water	Emission to air	high population density	m3	3.56E-05
Xylene	Emission to air	high population density	kg	1.45E-07
Zinc	Emission to air	high population density	kg	3.02E-07
2,4-D	Emission to air	low population density	kg	4.45E-10
2,4-D dimethylamine salt	Emission to air	low population density	kg	4.77E-21
2,4-D polypropoxybutyl ester	Emission to air	low population density	kg	3.71E-20
2,4-DB	Emission to air	low population density	kg	5.39E-20
2-Propanol	Emission to air	low population density	kg	3.71E-13
4-Methyl-2-pentanone	Emission to air	low population density	kg	8.11E-15
Acenaphthene	Emission to air	low population density	kg	1.19E-12
Acephate	Emission to air	low population density	kg	4.73E-11

Acetaldehyde	Emission to air	low population density	kg	3.83E-07
Acetamide	Emission to air	low population density	kg	1.16E-11
Acetic acid	Emission to air	low population density	kg	1.57E-07
Acetone	Emission to air	low population density	kg	1.5E-07
Acetonitrile	Emission to air	low population density	kg	1.17E-08
Acifluorfen	Emission to air	low population density	kg	6.5E-12
Acrolein	Emission to air	low population density	kg	2.14E-08
Actinides, radioactive, unspecified	Emission to air	low population density	kBq	4.3E-06
Aerosols, radioactive, unspecified	Emission to air	low population density	kBq	1.23E-07
Alachlor	Emission to air	low population density	kg	4.6E-11
Aldehydes, unspecified	Emission to air	low population density	kg	5.25E-09
Aluminium	Emission to air	low population density	kg	8.94E-09
Ammonia	Emission to air	low population density	kg	2.42E-05
Antimony	Emission to air	low population density	kg	6.4E-09
Antimony-124	Emission to air	low population density	kBq	1.46E-10
Antimony-125	Emission to air	low population density	kBq	6.39E-09
Argon-41	Emission to air	low population density	kBq	4.88E-05
Arsenic	Emission to air	low population density	kg	5.18E-08
Atrazine	Emission to air	low population density	kg	3.64E-11
Azoxystrobin	Emission to air	low population density	kg	2.15E-11
Barium	Emission to air	low population density	kg	1.45E-08
Barium-140	Emission to air	low population density	kBq	1.45E-08
Bentazone	Emission to air	low population density	kg	1.99E-11
Benzaldehyde	Emission to air	low population density	kg	2.17E-07
Benzene	Emission to air	low population density	kg	1.04E-06
Benzene, ethyl-	Emission to air	low population density	kg	1.52E-08
Benzene, hexachloro-	Emission to air	low population density	kg	4.99E-21
Benzo(a)pyrene	Emission to air	low population density	kg	6.74E-09
Beryllium	Emission to air	low population density	kg	6.87E-11
Boron	Emission to air	low population density	kg	2.47E-07
Bromine	Emission to air	low population density	kg	7.37E-08
Bromoxynil	Emission to air	low population density	kg	1.42E-20
Butadiene	Emission to air	low population density	kg	4.92E-15
Butane	Emission to air	low population density	kg	2.26E-07
Cadmium	Emission to air	low population density	kg	1.63E-08
Calcium	Emission to air	low population density	kg	1.34E-08
Carbaryl	Emission to air	low population density	kg	5.43E-12
Carbon dioxide, biogenic	Emission to air	low population density	kg	8.86E-05
Carbon dioxide, fossil	Emission to air	low population density	kg	0.33046
Carbon dioxide, from soil or biomass stock	Emission to air	low population density	kg	0.000874

Carbon disulfide	Emission to air	low population density	kg	9.13E-07
Carbon monoxide, biogenic	Emission to air	low population density	kg	7.06E-07
Carbon monoxide, fossil	Emission to air	low population density	kg	0.000538
Carbon monoxide, from soil or biomass stock	Emission to air	low population density	kg	6.76E-06
Carbon-14	Emission to air	low population density	kBq	0.001094
Carfentrazone-ethyl	Emission to air	low population density	kg	5.96E-13
Cerium-141	Emission to air	low population density	kBq	3.34E-09
Cesium-134	Emission to air	low population density	kBq	1.6E-10
Cesium-137	Emission to air	low population density	kBq	2.85E-09
Chlorimuron-ethyl	Emission to air	low population density	kg	1.08E-11
Chlorinated solvents, unspecified	Emission to air	low population density	kg	1.93E-11
Chlorine	Emission to air	low population density	kg	9.71E-10
Chloroform	Emission to air	low population density	kg	2.04E-10
Chlorpyrifos	Emission to air	low population density	kg	2.16E-10
Chromium	Emission to air	low population density	kg	4.58E-07
Chromium VI	Emission to air	low population density	kg	1.17E-08
Chromium-51	Emission to air	low population density	kBq	2.25E-10
Clethodim	Emission to air	low population density	kg	3.21E-11
Cloransulam-methyl	Emission to air	low population density	kg	5.65E-12
Cobalt	Emission to air	low population density	kg	1.3E-08
Cobalt-58	Emission to air	low population density	kBq	4.63E-09
Cobalt-60	Emission to air	low population density	kBq	2.27E-08
Copper	Emission to air	low population density	kg	1.6E-07
Cumene	Emission to air	low population density	kg	1.13E-11
Cyanide	Emission to air	low population density	kg	2.34E-07
Cyfluthrin	Emission to air	low population density	kg	1.13E-12
Cyhalothrin, gamma-	Emission to air	low population density	kg	1.3E-11
Dicamba	Emission to air	low population density	kg	3.64E-12
Dichlorprop	Emission to air	low population density	kg	6.02E-21
Diflubenzuron	Emission to air	low population density	kg	5.96E-13
Dimethenamid	Emission to air	low population density	kg	4.02E-18
Dinitrogen monoxide	Emission to air	low population density	kg	1.92E-06
Dioxins, measured as 2,3,7,8-tetrachlorodibenzo-p-dioxin	Emission to air	low population density	kg	8.62E-15
Esfenvalerate	Emission to air	low population density	kg	6.77E-12
Ethane	Emission to air	low population density	kg	1.7E-06
Ethane, 1,1,1,2-tetrafluoro-, HFC-134a	Emission to air	low population density	kg	1.5E-09
Ethane, 1,1,1-trichloro-, HCFC-140	Emission to air	low population density	kg	4.16E-11
Ethane, 1,1-difluoro-, HFC-152a	Emission to air	low population density	kg	5.53E-10

Ethane, 1,2-dichloro-	Emission to air	low population density	kg	8.29E-11
Ethane, 1,2-dichloro-1,1,2,2-tetrafluoro-, CFC-114	Emission to air	low population density	kg	3.16E-08
Ethanol	Emission to air	low population density	kg	2.56E-08
Ethene	Emission to air	low population density	kg	1.39E-07
Ethene, tetrachloro-	Emission to air	low population density	kg	8.92E-11
Ethephon	Emission to air	low population density	kg	9.7E-22
Ethylene oxide	Emission to air	low population density	kg	4.75E-14
Ethyne	Emission to air	low population density	kg	2.62E-09
Fenoxaprop	Emission to air	low population density	kg	8.87E-12
Fluazifop-p-butyl	Emission to air	low population density	kg	1.27E-11
Flufenacet	Emission to air	low population density	kg	4.77E-12
Flumetsulam	Emission to air	low population density	kg	1.12E-12
Flumiclorac-pentyl	Emission to air	low population density	kg	1.91E-12
Flumioxazin	Emission to air	low population density	kg	1.93E-11
Fluorine	Emission to air	low population density	kg	5.49E-09
Fomesafen	Emission to air	low population density	kg	7.18E-11
Formaldehyde	Emission to air	low population density	kg	1.66E-05
Formic acid	Emission to air	low population density	kg	7.16E-08
Furan	Emission to air	low population density	kg	3.12E-07
Glyphosate	Emission to air	low population density	kg	1.44E-08
Heat, waste	Emission to air	low population density	MJ	2.53E-06
Helium	Emission to air	low population density	kg	2.67E-08
Hexane	Emission to air	low population density	kg	3.39E-07
Hydrocarbons, aliphatic, alkanes, cyclic	Emission to air	low population density	kg	1.2E-09
Hydrocarbons, aliphatic, alkanes, unspecified	Emission to air	low population density	kg	7.11E-08
Hydrocarbons, aliphatic, unsaturated	Emission to air	low population density	kg	5.16E-08
Hydrocarbons, aromatic	Emission to air	low population density	kg	8.99E-09
Hydrocarbons, chlorinated	Emission to air	low population density	kg	4.21E-10
Hydrocarbons, unspecified	Emission to air	low population density	kg	1.84E-08
Hydrogen chloride	Emission to air	low population density	kg	6.57E-06
Hydrogen fluoride	Emission to air	low population density	kg	9.35E-07
Hydrogen sulfide	Emission to air	low population density	kg	3.21E-07
Hydrogen-3, Tritium	Emission to air	low population density	kBq	0.010749
Imazamox	Emission to air	low population density	kg	2.86E-12
Imazaquin	Emission to air	low population density	kg	9.11E-12
Imazethapyr	Emission to air	low population density	kg	1.89E-11
Iodine	Emission to air	low population density	kg	3.83E-08
Iodine-129	Emission to air	low population density	kBq	2.69E-07
Iodine-131	Emission to air	low population density	kBq	1.11E-05

Iodine-133	Emission to air	low population density	kBq	2.04E-08
Iron	Emission to air	low population density	kg	4.95E-09
Isoprene	Emission to air	low population density	kg	1.04E-09
Krypton-85	Emission to air	low population density	kBq	0.000161
Krypton-85m	Emission to air	low population density	kBq	0.002809
Krypton-87	Emission to air	low population density	kBq	4.73E-05
Krypton-88	Emission to air	low population density	kBq	6.21E-05
Krypton-89	Emission to air	low population density	kBq	2.61E-05
Lactofen	Emission to air	low population density	kg	9.17E-12
Lambda-cyhalothrin	Emission to air	low population density	kg	3.07E-23
Lanthanum-140	Emission to air	low population density	kBq	1.24E-09
Lead	Emission to air	low population density	kg	1.47E-07
Lead-210	Emission to air	low population density	kBq	2.22E-05
m-Xylene	Emission to air	low population density	kg	1.78E-13
Magnesium	Emission to air	low population density	kg	3.07E-08
Manganese	Emission to air	low population density	kg	2.77E-08
Manganese-54	Emission to air	low population density	kBq	1.15E-10
MCPA	Emission to air	low population density	kg	1.1E-20
MCPB	Emission to air	low population density	kg	1.09E-20
Mercury	Emission to air	low population density	kg	1.56E-09
Methane, biogenic	Emission to air	low population density	kg	1.15E-05
Methane, bromochlorodifluoro-, Halon 1211	Emission to air	low population density	kg	2.45E-10
Methane, bromotrifluoro-, Halon 1301	Emission to air	low population density	kg	7.68E-10
Methane, chlorodifluoro-, HCFC-22	Emission to air	low population density	kg	3.51E-09
Methane, dichloro-, HCC-30	Emission to air	low population density	kg	6.02E-10
Methane, dichlorodifluoro-, CFC-12	Emission to air	low population density	kg	3E-13
Methane, fossil	Emission to air	low population density	kg	0.0002
Methane, from soil or biomass stock	Emission to air	low population density	kg	4.86E-07
Methane, monochloro-, R-40	Emission to air	low population density	kg	1.1E-09
Methanol	Emission to air	low population density	kg	1.32E-06
Methomyl	Emission to air	low population density	kg	3.32E-21
Methyl ethyl ketone	Emission to air	low population density	kg	9.71E-14
Methyl parathion	Emission to air	low population density	kg	7.34E-12
Metolachlor	Emission to air	low population density	kg	1.5E-10
Metribuzin	Emission to air	low population density	kg	5.95E-11
Molybdenum	Emission to air	low population density	kg	3.79E-10
Nickel	Emission to air	low population density	kg	1.13E-07
Niobium-95	Emission to air	low population density	kBq	1.28E-05

Nitrate	Emission to air	low population density	kg	1.18E-08
Nitrogen oxides	Emission to air	low population density	kg	0.000175
NMVOC, non-methane volatile organic compounds, unspecified origin	Emission to air	low population density	kg	0.000172
Noble gases, radioactive, unspecified	Emission to air	low population density	kBq	23.22627
PAH, polycyclic aromatic hydrocarbons	Emission to air	low population density	kg	6.06E-08
Paraquat	Emission to air	low population density	kg	3.83E-11
Particulates, < 2.5 um	Emission to air	low population density	kg	6.86E-05
Particulates, > 10 um	Emission to air	low population density	kg	8.64E-05
Particulates, > 2.5 um, and < 10um	Emission to air	low population density	kg	2.8E-05
Pendimethalin	Emission to air	low population density	kg	4.03E-10
Pentane	Emission to air	low population density	kg	1.63E-05
Permethrin	Emission to air	low population density	kg	5.99E-12
Phenol	Emission to air	low population density	kg	4.85E-09
Phenol, pentachloro-	Emission to air	low population density	kg	2.88E-09
Phosphorus	Emission to air	low population density	kg	4.35E-10
Platinum	Emission to air	low population density	kg	7.34E-14
Plutonium-238	Emission to air	low population density	kBq	3.67E-14
Plutonium-alpha	Emission to air	low population density	kBq	8.41E-14
Polonium-210	Emission to air	low population density	kBq	2.64E-05
Polychlorinated biphenyls	Emission to air	low population density	kg	4.58E-12
Potassium	Emission to air	low population density	kg	1.79E-09
Potassium-40	Emission to air	low population density	kBq	5.22E-06
Propanal	Emission to air	low population density	kg	5.83E-08
Propane	Emission to air	low population density	kg	4.64E-07
Propanol	Emission to air	low population density	kg	2.34E-17
Propene	Emission to air	low population density	kg	3.96E-08
Propiconazole	Emission to air	low population density	kg	7.04E-12
Propionic acid	Emission to air	low population density	kg	2.63E-09
Protactinium-234	Emission to air	low population density	kBq	3.98E-07
Prothioconazol	Emission to air	low population density	kg	8.47E-23
Pyraclostrobin	Emission to air	low population density	kg	1.66E-11
Quizalofop-ethyl	Emission to air	low population density	kg	2.22E-12
Radioactive species, other beta emitters	Emission to air	low population density	kBq	2.5E-08
Radium-226	Emission to air	low population density	kBq	8.12E-06
Radium-228	Emission to air	low population density	kBq	1.31E-06
Radon-220	Emission to air	low population density	kBq	0.000125
Radon-222	Emission to air	low population density	kBq	0.353077
Ruthenium-103	Emission to air	low population density	kBq	3E-12

Scandium	Emission to air	low population density	kg	2.28E-11
Selenium	Emission to air	low population density	kg	1E-08
Sethoxydim	Emission to air	low population density	kg	4.79E-12
Silicon	Emission to air	low population density	kg	7.17E-09
Silicon tetrafluoride	Emission to air	low population density	kg	1.39E-11
Silver	Emission to air	low population density	kg	9.98E-13
Silver-110	Emission to air	low population density	kBq	8.54E-10
Sodium	Emission to air	low population density	kg	3.6E-09
Strontium	Emission to air	low population density	kg	1.43E-08
Styrene	Emission to air	low population density	kg	2.17E-08
Sulfate	Emission to air	low population density	kg	7.62E-08
Sulfentrazone	Emission to air	low population density	kg	4.58E-11
Sulfur dioxide	Emission to air	low population density	kg	0.0003
Sulfur hexafluoride	Emission to air	low population density	kg	4.35E-11
Sulfuric acid	Emission to air	low population density	kg	2.28E-09
Tebuconazole	Emission to air	low population density	kg	2.26E-22
Tefluthrin	Emission to air	low population density	kg	1.03E-18
Terpenes	Emission to air	low population density	kg	9.76E-09
Thallium	Emission to air	low population density	kg	1.32E-12
Thifensulfuron	Emission to air	low population density	kg	6.52E-13
Thiodicarb	Emission to air	low population density	kg	2.33E-12
Thorium	Emission to air	low population density	kg	6.78E-14
Thorium-228	Emission to air	low population density	kBq	7.34E-07
Thorium-230	Emission to air	low population density	kBq	6.42E-07
Thorium-232	Emission to air	low population density	kBq	2.08E-06
Thorium-234	Emission to air	low population density	kBq	3.98E-07
Tin	Emission to air	low population density	kg	9.16E-09
Titanium	Emission to air	low population density	kg	7.83E-10
Toluene	Emission to air	low population density	kg	1.57E-05
Trifloxystrobin	Emission to air	low population density	kg	4.17E-13
Trifluralin	Emission to air	low population density	kg	6.59E-10
Tungsten	Emission to air	low population density	kg	3.02E-12
Uranium	Emission to air	low population density	kg	4.75E-14
Uranium alpha	Emission to air	low population density	kBq	6.65E-06
Uranium-234	Emission to air	low population density	kBq	1.7E-06
Uranium-235	Emission to air	low population density	kBq	5.78E-08
Uranium-238	Emission to air	low population density	kBq	4.56E-06
Vanadium	Emission to air	low population density	kg	5.06E-09
Water	Emission to air	low population density	m3	5.3E-05
Xenon-131m	Emission to air	low population density	kBq	0.000238
Xenon-133	Emission to air	low population density	kBq	0.009964

Xenon-133m	Emission to air	low population density	kBq	9.19E-06
Xenon-135	Emission to air	low population density	kBq	0.003807
Xenon-135m	Emission to air	low population density	kBq	0.002171
Xenon-137	Emission to air	low population density	kBq	6.82E-05
Xenon-138	Emission to air	low population density	kBq	0.000509
Xylene	Emission to air	low population density	kg	2.31E-07
Zeta-cypermethrin	Emission to air	low population density	kg	2.75E-12
Zinc	Emission to air	low population density	kg	1.37E-07
Zinc-65	Emission to air	low population density	kBq	5.75E-10
Zirconium	Emission to air	low population density	kg	4.03E-13
Zirconium-95	Emission to air	low population density	kBq	1.58E-08
Aluminium	Emission to air	low population density, long-term	kg	3.42E-06
Ammonia	Emission to air	low population density, long-term	kg	3.69E-11
Antimony	Emission to air	low population density, long-term	kg	3.09E-10
Arsenic	Emission to air	low population density, long-term	kg	1.81E-08
Barium	Emission to air	low population density, long-term	kg	1.98E-08
Beryllium	Emission to air	low population density, long-term	kg	4.31E-10
Boron	Emission to air	low population density, long-term	kg	5.74E-09
Bromine	Emission to air	low population density, long-term	kg	9.97E-12
Cadmium	Emission to air	low population density, long-term	kg	4.76E-10
Calcium	Emission to air	low population density, long-term	kg	1.11E-06
Chlorine	Emission to air	low population density, long-term	kg	4.23E-08
Chromium	Emission to air	low population density, long-term	kg	3.91E-13
Chromium VI	Emission to air	low population density, long-term	kg	2.2E-09
Cobalt	Emission to air	low population density, long-term	kg	2.74E-09
Copper	Emission to air	low population density, long-term	kg	2.92E-08
Dinitrogen monoxide	Emission to air	low population density, long-term	kg	2.65E-11
Dioxins, measured as 2,3,7,8-tetrachlorodibenzo-p-dioxin	Emission to air	low population density, long-term	kg	2.32E-19
Ethane, 1,1,2-trichloro-1,2,2-trifluoro-, CFC-113	Emission to air	low population density, long-term	kg	4.44E-12
Fluorine	Emission to air	low population density, long-term	kg	2.08E-07
Hydrogen chloride	Emission to air	low population density, long-term	kg	8.92E-09

Hydrogen fluoride	Emission to air	low population density, long-term	kg	2.24E-11
Hydrogen sulfide	Emission to air	low population density, long-term	kg	1.39E-08
Iodine	Emission to air	low population density, long-term	kg	8.08E-16
Iron	Emission to air	low population density, long-term	kg	3.72E-06
Lead	Emission to air	low population density, long-term	kg	3.07E-08
Magnesium	Emission to air	low population density, long-term	kg	3.41E-07
Manganese	Emission to air	low population density, long-term	kg	7.68E-08
Mercury	Emission to air	low population density, long-term	kg	2.36E-10
Molybdenum	Emission to air	low population density, long-term	kg	5.94E-09
Nickel	Emission to air	low population density, long-term	kg	6.29E-09
Nitrate	Emission to air	low population density, long-term	kg	3.7E-08
Nitrogen oxides	Emission to air	low population density, long-term	kg	5.56E-12
Particulates, < 2.5 um	Emission to air	low population density, long-term	kg	2.86E-06
Particulates, > 10 um	Emission to air	low population density, long-term	kg	7.14E-06
Particulates, > 2.5 um, and < 10um	Emission to air	low population density, long-term	kg	4.28E-06
Phosphorus	Emission to air	low population density, long-term	kg	5.75E-09
Potassium	Emission to air	low population density, long-term	kg	5.84E-07
Radon-222	Emission to air	low population density, long-term	kBq	12.63961
Scandium	Emission to air	low population density, long-term	kg	1.22E-08
Selenium	Emission to air	low population density, long-term	kg	1.71E-09
Silicon	Emission to air	low population density, long-term	kg	7.6E-07
Silver	Emission to air	low population density, long-term	kg	5.11E-10
Sodium	Emission to air	low population density, long-term	kg	2.02E-07
Strontium	Emission to air	low population density, long-term	kg	1.24E-08
Sulfate	Emission to air	low population density, long-term	kg	3.14E-06
Thallium	Emission to air	low population density, long-term	kg	8.25E-14
Tin	Emission to air	low population density, long-term	kg	7.34E-10
Titanium	Emission to air	low population density, long-term	kg	2.23E-07

Tungsten	Emission to air	low population density, long-term	kg	1.38E-09
Vanadium	Emission to air	low population density, long-term	kg	2.12E-08
Water	Emission to air	low population density, long-term	m3	2.48E-21
Zinc	Emission to air	low population density, long-term	kg	2.23E-08
Benzene	Emission to air	lower stratosphere + upper troposphere	kg	1.92E-14
Butadiene	Emission to air	lower stratosphere + upper troposphere	kg	1.82E-14
Cadmium	Emission to air	lower stratosphere + upper troposphere	kg	9.6E-18
Carbon dioxide, fossil	Emission to air	lower stratosphere + upper troposphere	kg	3.03E-09
Carbon monoxide, fossil	Emission to air	lower stratosphere + upper troposphere	kg	3.55E-12
Chromium	Emission to air	lower stratosphere + upper troposphere	kg	4.8E-17
Copper	Emission to air	lower stratosphere + upper troposphere	kg	1.63E-15
Dinitrogen monoxide	Emission to air	lower stratosphere + upper troposphere	kg	2.88E-14
Ethylene oxide	Emission to air	lower stratosphere + upper troposphere	kg	1.75E-13
Formaldehyde	Emission to air	lower stratosphere + upper troposphere	kg	1.51E-13
Hydrogen chloride	Emission to air	lower stratosphere + upper troposphere	kg	8.26E-16
Lead	Emission to air	lower stratosphere + upper troposphere	kg	1.92E-17
Mercury	Emission to air	lower stratosphere + upper troposphere	kg	6.72E-20
Methane, fossil	Emission to air	lower stratosphere + upper troposphere	kg	4.8E-14
Nickel	Emission to air	lower stratosphere + upper troposphere	kg	6.72E-17
Nitrogen oxides	Emission to air	lower stratosphere + upper troposphere	kg	3.28E-09
NMVOC, non-methane volatile organic compounds, unspecified origin	Emission to air	lower stratosphere + upper troposphere	kg	6.44E-13
Particulates, < 2.5 um	Emission to air	lower stratosphere + upper troposphere	kg	3.65E-14
Selenium	Emission to air	lower stratosphere + upper troposphere	kg	9.6E-18
Sulfur dioxide	Emission to air	lower stratosphere + upper troposphere	kg	9.6E-13
Water	Emission to air	lower stratosphere + upper troposphere	m3	1.19E-12
Zinc	Emission to air	lower stratosphere + upper troposphere	kg	9.6E-16
2,2,4-Trimethyl pentane	Emission to air	unspecified	kg	2.17E-14
2-Propanol	Emission to air	unspecified	kg	3.21E-08
Acenaphthene	Emission to air	unspecified	kg	2.08E-12

Acenaphthylene	Emission to air	unspecified	kg	2.04E-13
Acetaldehyde	Emission to air	unspecified	kg	1.87E-07
Acetic acid	Emission to air	unspecified	kg	7.41E-08
Acetone	Emission to air	unspecified	kg	2.12E-09
Acrolein	Emission to air	unspecified	kg	2.29E-08
Aldehydes, unspecified	Emission to air	unspecified	kg	3.05E-10
Aluminium	Emission to air	unspecified	kg	5.38E-06
Ammonia	Emission to air	unspecified	kg	3.32E-06
Anthracene	Emission to air	unspecified	kg	8.78E-18
Antimony	Emission to air	unspecified	kg	2.63E-07
Argon-40	Emission to air	unspecified	kg	1.31E-06
Arsenic	Emission to air	unspecified	kg	2.28E-10
Barium	Emission to air	unspecified	kg	1.02E-07
Benz(a)anthracene	Emission to air	unspecified	kg	3.92E-15
Benzal chloride	Emission to air	unspecified	kg	5.26E-15
Benzaldehyde	Emission to air	unspecified	kg	1.77E-08
Benzene	Emission to air	unspecified	kg	3.03E-07
Benzene, ethyl-	Emission to air	unspecified	kg	1.02E-08
Benzene, hexachloro-	Emission to air	unspecified	kg	1.36E-11
Benzo(a)pyrene	Emission to air	unspecified	kg	1.09E-10
Benzo(b)fluoranthene	Emission to air	unspecified	kg	4.63E-15
Benzo(ghi)perylene	Emission to air	unspecified	kg	2.89E-16
Benzo(k)fluoranthene	Emission to air	unspecified	kg	3.35E-15
Beryllium	Emission to air	unspecified	kg	2.98E-12
Boron	Emission to air	unspecified	kg	1.25E-10
Bromine	Emission to air	unspecified	kg	3.02E-10
Butadiene	Emission to air	unspecified	kg	9.86E-14
Butane	Emission to air	unspecified	kg	1.95E-09
Cadmium	Emission to air	unspecified	kg	2.01E-10
Calcium	Emission to air	unspecified	kg	2.47E-08
Carbon dioxide, biogenic	Emission to air	unspecified	kg	1.67E-05
Carbon dioxide, fossil	Emission to air	unspecified	kg	0.018285
Carbon dioxide, from soil or biomass stock	Emission to air	unspecified	kg	0.00012
Carbon disulfide	Emission to air	unspecified	kg	9.75E-16
Carbon monoxide, biogenic	Emission to air	unspecified	kg	8.04E-09
Carbon monoxide, fossil	Emission to air	unspecified	kg	0.000121
Carbonyl sulfide	Emission to air	unspecified	kg	5.87E-09
Chlorine	Emission to air	unspecified	kg	1E-08
Chloroform	Emission to air	unspecified	kg	4.44E-16
Chlorosulfonic acid	Emission to air	unspecified	kg	2.87E-15
Chromium	Emission to air	unspecified	kg	2.41E-09

Chromium VI	Emission to air	unspecified	kg	2.06E-12
Chrysene	Emission to air	unspecified	kg	4.65E-16
Cobalt	Emission to air	unspecified	kg	8.82E-11
Copper	Emission to air	unspecified	kg	1.44E-07
Cumene	Emission to air	unspecified	kg	3.98E-17
Cyanide	Emission to air	unspecified	kg	1.88E-14
Dibenz(a,h)anthracene	Emission to air	unspecified	kg	2.17E-15
Dimethyl carbonate	Emission to air	unspecified	kg	2.41E-08
Dinitrogen monoxide	Emission to air	unspecified	kg	1.42E-06
Dinitrogen tetroxide	Emission to air	unspecified	kg	7.84E-12
Dioxins, measured as 2,3,7,8-tetrachlorodibenzo-p-dioxin	Emission to air	unspecified	kg	3.52E-14
Ethane	Emission to air	unspecified	kg	5.35E-10
Ethane, 1,1,1,2-tetrafluoro-, HFC-134a	Emission to air	unspecified	kg	3.47E-11
Ethane, 1,1,1-trichloro-, HCFC-140	Emission to air	unspecified	kg	8.21E-16
Ethane, 1,1,2-trichloro-1,2,2-trifluoro-, CFC-113	Emission to air	unspecified	kg	9.32E-12
Ethane, 2-chloro-1,1,1,2-tetrafluoro-, HCFC-124	Emission to air	unspecified	kg	9.32E-12
Ethane, hexafluoro-, HFC-116	Emission to air	unspecified	kg	1.85E-10
Ethanol	Emission to air	unspecified	kg	1.31E-13
Ethene	Emission to air	unspecified	kg	1.81E-11
Ethene, chloro-	Emission to air	unspecified	kg	3.01E-16
Ethene, tetrachloro-	Emission to air	unspecified	kg	6.5E-13
Ethylene	Emission to air	unspecified	kg	3.91E-08
Ethylene oxide	Emission to air	unspecified	kg	1.44E-09
Ethyne	Emission to air	unspecified	kg	1.01E-09
Fluoranthene	Emission to air	unspecified	kg	3.6E-14
Fluorene	Emission to air	unspecified	kg	3.44E-14
Fluorine	Emission to air	unspecified	kg	2.19E-12
Formaldehyde	Emission to air	unspecified	kg	4.43E-06
Furan	Emission to air	unspecified	kg	6.39E-17
Heat, waste	Emission to air	unspecified	MJ	0.000144
Helium	Emission to air	unspecified	kg	4.21E-09
Heptane	Emission to air	unspecified	kg	3.87E-09
Hexane	Emission to air	unspecified	kg	4.86E-14
Hydrocarbons, aliphatic, alkanes, unspecified	Emission to air	unspecified	kg	3.04E-07
Hydrocarbons, aliphatic, unsaturated	Emission to air	unspecified	kg	6.93E-11
Hydrocarbons, aromatic	Emission to air	unspecified	kg	3.46E-07
Hydrocarbons, chlorinated	Emission to air	unspecified	kg	2E-09

Hydrochloric acid	Emission to air	unspecified	kg	1.93E-13
Hydrogen	Emission to air	unspecified	kg	7.11E-09
Hydrogen chloride	Emission to air	unspecified	kg	6.9E-07
Hydrogen fluoride	Emission to air	unspecified	kg	5.68E-08
Hydrogen sulfide	Emission to air	unspecified	kg	2.42E-08
Indeno(1,2,3-cd)pyrene	Emission to air	unspecified	kg	8.56E-16
Iodine	Emission to air	unspecified	kg	4.94E-11
Iron	Emission to air	unspecified	kg	5.71E-07
Isoprene	Emission to air	unspecified	kg	8.53E-16
Lead	Emission to air	unspecified	kg	2.63E-08
Lead-210	Emission to air	unspecified	kBq	2.05E-08
m-Xylene	Emission to air	unspecified	kg	1.27E-08
Magnesium	Emission to air	unspecified	kg	1.64E-10
Manganese	Emission to air	unspecified	kg	9E-09
Mercury	Emission to air	unspecified	kg	2.06E-09
Methane, biogenic	Emission to air	unspecified	kg	4.17E-12
Methane, bromo-, Halon 1001	Emission to air	unspecified	kg	1.2E-15
Methane, chlorodifluoro-, HCFC-22	Emission to air	unspecified	kg	3.01E-23
Methane, dichloro-, HCC-30	Emission to air	unspecified	kg	3.91E-11
Methane, dichlorodifluoro-, CFC-12	Emission to air	unspecified	kg	8E-16
Methane, fossil	Emission to air	unspecified	kg	2.61E-05
Methane, tetrachloro-, R-10	Emission to air	unspecified	kg	3.58E-13
Methane, tetrafluoro-, R-14	Emission to air	unspecified	kg	3.13E-09
Methanol	Emission to air	unspecified	kg	8.92E-08
Methylamine	Emission to air	unspecified	kg	4.83E-12
Molybdenum	Emission to air	unspecified	kg	2.63E-08
Naphtalene	Emission to air	unspecified	kg	1.29E-12
Naphthalene	Emission to air	unspecified	kg	9.39E-15
Nickel	Emission to air	unspecified	kg	2.28E-09
Nitrate	Emission to air	unspecified	kg	1.16E-08
Nitric oxide	Emission to air	unspecified	kg	5.41E-11
Nitrogen	Emission to air	unspecified	kg	7.34E-05
Nitrogen oxides	Emission to air	unspecified	kg	0.000132
NMVOC, non-methane volatile organic compounds, unspecified origin	Emission to air	unspecified	kg	3.42E-05
o-Xylene	Emission to air	unspecified	kg	5.17E-09
Ozone	Emission to air	unspecified	kg	5.61E-07
PAH, polycyclic aromatic hydrocarbons	Emission to air	unspecified	kg	7.03E-09
Particulates, < 2.5 um	Emission to air	unspecified	kg	9.66E-06

Particulates, > 10 um	Emission to air	unspecified	kg	2.19E-05
Particulates, > 2.5 um, and < 10um	Emission to air	unspecified	kg	7.28E-06
Pentane	Emission to air	unspecified	kg	8.15E-10
Phenanthrene	Emission to air	unspecified	kg	5.03E-13
Phenol	Emission to air	unspecified	kg	1.11E-10
Phenol, 2,4-dichloro	Emission to air	unspecified	kg	1.4E-14
Phenol, pentachloro-	Emission to air	unspecified	kg	1.22E-11
Phosgene	Emission to air	unspecified	kg	2.24E-10
Phosphorus	Emission to air	unspecified	kg	8.52E-12
Platinum	Emission to air	unspecified	kg	7.32E-11
Polonium-210	Emission to air	unspecified	kBq	3.68E-08
Polychlorinated biphenyls	Emission to air	unspecified	kg	2.84E-11
Potassium	Emission to air	unspecified	kg	3.07E-09
Potassium-40	Emission to air	unspecified	kBq	5.05E-09
Propanal	Emission to air	unspecified	kg	3.6E-13
Propane	Emission to air	unspecified	kg	1.31E-09
Propene	Emission to air	unspecified	kg	7.33E-11
Propionic acid	Emission to air	unspecified	kg	2.61E-13
Pyrene	Emission to air	unspecified	kg	2.61E-14
Radium-226	Emission to air	unspecified	kBq	5.19E-09
Radium-228	Emission to air	unspecified	kBq	1.56E-09
Radon-220	Emission to air	unspecified	kBq	1.08E-07
Radon-222	Emission to air	unspecified	kBq	6.05E-08
Scandium	Emission to air	unspecified	kg	7.86E-16
Selenium	Emission to air	unspecified	kg	1.94E-10
Silicon	Emission to air	unspecified	kg	1.87E-07
Silver	Emission to air	unspecified	kg	5.6E-13
Sodium	Emission to air	unspecified	kg	2.36E-08
Strontium	Emission to air	unspecified	kg	1.46E-09
Styrene	Emission to air	unspecified	kg	7.25E-09
Sulfate	Emission to air	unspecified	kg	1E-07
Sulfur dioxide	Emission to air	unspecified	kg	1.32E-05
Sulfur hexafluoride	Emission to air	unspecified	kg	1.08E-08
Sulfur oxides	Emission to air	unspecified	kg	5.05E-10
Sulfuric acid	Emission to air	unspecified	kg	4.01E-11
Sulphur trioxide	Emission to air	unspecified	kg	7.26E-11
Thallium	Emission to air	unspecified	kg	1.5E-11
Thorium	Emission to air	unspecified	kg	2.37E-15
Thorium-228	Emission to air	unspecified	kBq	8.32E-10
Thorium-232	Emission to air	unspecified	kBq	1.3E-09
Tin	Emission to air	unspecified	kg	1.87E-08

Titanium	Emission to air	unspecified	kg	1.14E-08
Toluene	Emission to air	unspecified	kg	4.31E-07
Trichloroethylene	Emission to air	unspecified	kg	3.32E-11
Uranium	Emission to air	unspecified	kg	3.73E-15
Uranium-238	Emission to air	unspecified	kBq	4.33E-09
Vanadium	Emission to air	unspecified	kg	1.83E-09
VOC, volatile organic compounds, unspecified origin	Emission to air	unspecified	kg	3.4E-15
Water	Emission to air	unspecified	m3	0.002586
Xylene	Emission to air	unspecified	kg	2.61E-07
Zinc	Emission to air	unspecified	kg	9.1E-08
2,4-D	Emission to soil	agricultural	kg	3.09E-08
2,4-D dimethylamine salt	Emission to soil	agricultural	kg	8.96E-19
2,4-D polypropoxybutyl ester	Emission to soil	agricultural	kg	4.38E-19
2,4-DB	Emission to soil	agricultural	kg	8.38E-19
Acephate	Emission to soil	agricultural	kg	6.96E-10
Acetamide	Emission to soil	agricultural	kg	9.76E-11
Acetochlor	Emission to soil	agricultural	kg	2.12E-12
Acifluorfen	Emission to soil	agricultural	kg	2.78E-13
Aclonifen	Emission to soil	agricultural	kg	3.86E-14
Acrinathrin	Emission to soil	agricultural	kg	4.42E-23
Alachlor	Emission to soil	agricultural	kg	2.12E-12
Aldicarb	Emission to soil	agricultural	kg	2.33E-09
Aldrin	Emission to soil	agricultural	kg	1.04E-11
Aluminium	Emission to soil	agricultural	kg	6.58E-05
Amidosulfuron	Emission to soil	agricultural	kg	1.83E-15
Anthraquinone	Emission to soil	agricultural	kg	3.82E-15
Antimony	Emission to soil	agricultural	kg	2.35E-13
Arsenic	Emission to soil	agricultural	kg	2.12E-08
Asulam	Emission to soil	agricultural	kg	3.68E-17
Atrazine	Emission to soil	agricultural	kg	2.4E-11
Azoxystrobin	Emission to soil	agricultural	kg	1.08E-11
Barium	Emission to soil	agricultural	kg	1.38E-11
Benomyl	Emission to soil	agricultural	kg	1.79E-11
Bensulfuron methyl ester	Emission to soil	agricultural	kg	3.96E-15
Bentazone	Emission to soil	agricultural	kg	1.22E-11
Bifenox	Emission to soil	agricultural	kg	2.55E-15
Bifenthrin	Emission to soil	agricultural	kg	7.74E-15
Bitertanol	Emission to soil	agricultural	kg	5.69E-17
Boron	Emission to soil	agricultural	kg	4.08E-12
Boscalid	Emission to soil	agricultural	kg	1.26E-21

Bromoxynil	Emission to soil	agricultural	kg	3.29E-14
Bromuconazole	Emission to soil	agricultural	kg	1.72E-16
Cadmium	Emission to soil	agricultural	kg	4.5E-08
Calcium	Emission to soil	agricultural	kg	0.000897
Carbaryl	Emission to soil	agricultural	kg	2.54E-13
Carbendazim	Emission to soil	agricultural	kg	7.08E-11
Carbetamide	Emission to soil	agricultural	kg	1.47E-12
Carbofuran	Emission to soil	agricultural	kg	9.81E-09
Carbon	Emission to soil	agricultural	kg	5.78E-05
Carfentrazone ethyl ester	Emission to soil	agricultural	kg	2.56E-14
Chloridazon	Emission to soil	agricultural	kg	1.54E-14
Chloride	Emission to soil	agricultural	kg	1.01E-05
Chlorimuron-ethyl	Emission to soil	agricultural	kg	1.11E-11
Chlormequat	Emission to soil	agricultural	kg	2.47E-12
Chloropicrin	Emission to soil	agricultural	kg	4.72E-19
Chlorothalonil	Emission to soil	agricultural	kg	1.86E-10
Chlorotoluron	Emission to soil	agricultural	kg	5.08E-14
Chlorpyrifos	Emission to soil	agricultural	kg	1.85E-09
Chlorpyrifos methyl	Emission to soil	agricultural	kg	9.55E-09
Chlorsulfuron	Emission to soil	agricultural	kg	2.37E-16
Choline chloride	Emission to soil	agricultural	kg	3.27E-14
Chromium	Emission to soil	agricultural	kg	6.16E-07
Cinidon-ethyl	Emission to soil	agricultural	kg	2.22E-15
Clethodim	Emission to soil	agricultural	kg	1.68E-11
Clodinafop-propargyl	Emission to soil	agricultural	kg	3.51E-15
Clomazone	Emission to soil	agricultural	kg	1.68E-12
Clopyralid	Emission to soil	agricultural	kg	4E-14
Cloquintocet-mexyl	Emission to soil	agricultural	kg	8.49E-16
Cloransulam-methyl	Emission to soil	agricultural	kg	4.81E-12
Cobalt	Emission to soil	agricultural	kg	5.69E-08
Copper	Emission to soil	agricultural	kg	5.13E-07
Cyfluthrin	Emission to soil	agricultural	kg	5.81E-12
Cyhalothrin, gamma-	Emission to soil	agricultural	kg	5.57E-13
Cypermethrin	Emission to soil	agricultural	kg	2.86E-09
Cyproconazole	Emission to soil	agricultural	kg	2.86E-14
Cyprodinil	Emission to soil	agricultural	kg	1.57E-12
Deltamethrin	Emission to soil	agricultural	kg	6.97E-14
Desmedipham	Emission to soil	agricultural	kg	3.18E-15
Dicamba	Emission to soil	agricultural	kg	2.21E-13
Dichlorprop	Emission to soil	agricultural	kg	4.56E-19
Dichlorprop-P	Emission to soil	agricultural	kg	8.31E-14

Diclofop	Emission to soil	agricultural	kg	5.19E-15
Diclofop-methyl	Emission to soil	agricultural	kg	5.87E-15
Dicrotophos	Emission to soil	agricultural	kg	1.27E-10
Difenoconazole	Emission to soil	agricultural	kg	1.24E-10
Diflubenzuron	Emission to soil	agricultural	kg	1.62E-08
Diflufenican	Emission to soil	agricultural	kg	8.62E-14
Diflufenzopyr-sodium	Emission to soil	agricultural	kg	6.88E-15
Dimethachlor	Emission to soil	agricultural	kg	3.95E-12
Dimethenamid	Emission to soil	agricultural	kg	1.81E-13
Dimethoate	Emission to soil	agricultural	kg	1.9E-13
Diquat	Emission to soil	agricultural	kg	3.11E-12
Dithianon	Emission to soil	agricultural	kg	1.83E-14
Diuron	Emission to soil	agricultural	kg	1.97E-10
Endosulfan	Emission to soil	agricultural	kg	4.9E-09
Endothall	Emission to soil	agricultural	kg	4.05E-14
Epoxiconazole	Emission to soil	agricultural	kg	2.8E-14
Esfenvalerate	Emission to soil	agricultural	kg	2.91E-13
Ethalfluralin	Emission to soil	agricultural	kg	1.32E-12
Ethephon	Emission to soil	agricultural	kg	2.66E-10
Ethofumesate	Emission to soil	agricultural	kg	3.34E-13
Fenbuconazole	Emission to soil	agricultural	kg	4.78E-15
Fenoxaprop	Emission to soil	agricultural	kg	9.49E-12
Fenoxaprop ethyl ester	Emission to soil	agricultural	kg	4.32E-16
Fenoxaprop-P ethyl ester	Emission to soil	agricultural	kg	1.07E-15
Fenpiclonil	Emission to soil	agricultural	kg	7.32E-12
Fenpropidin	Emission to soil	agricultural	kg	9.36E-14
Fenpropimorph	Emission to soil	agricultural	kg	1.6E-13
Fipronil	Emission to soil	agricultural	kg	7.62E-10
Florasulam	Emission to soil	agricultural	kg	1.61E-17
Fluazifop-P-butyl	Emission to soil	agricultural	kg	4.56E-12
Flucarbazone sodium salt	Emission to soil	agricultural	kg	1.48E-17
Fludioxonil	Emission to soil	agricultural	kg	1.14E-13
Flufenacet	Emission to soil	agricultural	kg	2.06E-13
Flumetsulam	Emission to soil	agricultural	kg	5.99E-14
Flumiclorac-pentyl	Emission to soil	agricultural	kg	8.18E-14
Flumioxazin	Emission to soil	agricultural	kg	6.14E-12
Flupyrsulfuron-methyl	Emission to soil	agricultural	kg	2.3E-17
Fluquinconazole	Emission to soil	agricultural	kg	4.16E-15
Fluroxypyr	Emission to soil	agricultural	kg	1.55E-14
Flurtamone	Emission to soil	agricultural	kg	5.01E-14
Flusilazole	Emission to soil	agricultural	kg	1.67E-14

Fomesafen	Emission to soil	agricultural	kg	3.8E-11
Foramsulfuron	Emission to soil	agricultural	kg	1.29E-15
Fungicides, unspecified	Emission to soil	agricultural	kg	2.65E-14
Glufosinate	Emission to soil	agricultural	kg	1.59E-11
Glyphosate	Emission to soil	agricultural	kg	3.4E-08
Halosulfuron-methyl	Emission to soil	agricultural	kg	1.12E-15
Herbicides, unspecified	Emission to soil	agricultural	kg	3.02E-11
Imazamox	Emission to soil	agricultural	kg	4.69E-12
Imazapyr	Emission to soil	agricultural	kg	1.72E-16
Imazaquin	Emission to soil	agricultural	kg	3.9E-13
Imazethapyr	Emission to soil	agricultural	kg	1.22E-11
Imidacloprid	Emission to soil	agricultural	kg	7.45E-10
Insecticides, unspecified	Emission to soil	agricultural	kg	2.19E-19
Iodosulfuron	Emission to soil	agricultural	kg	2.77E-16
Iodosulfuron-methyl-sodium	Emission to soil	agricultural	kg	1.44E-17
Ioxynil	Emission to soil	agricultural	kg	1.09E-13
Iprodion	Emission to soil	agricultural	kg	1.76E-12
Iron	Emission to soil	agricultural	kg	7.28E-05
Isoproturon	Emission to soil	agricultural	kg	9.38E-13
Isoxaflutole	Emission to soil	agricultural	kg	3.93E-14
Kresoxim-methyl	Emission to soil	agricultural	kg	3.11E-14
Lactofen	Emission to soil	agricultural	kg	3.93E-13
Lambda-cyhalothrin	Emission to soil	agricultural	kg	5.28E-12
Lead	Emission to soil	agricultural	kg	2.06E-07
Lenacil	Emission to soil	agricultural	kg	1.73E-15
Linuron	Emission to soil	agricultural	kg	2.14E-09
Magnesium	Emission to soil	agricultural	kg	0.000101
Malathion	Emission to soil	agricultural	kg	3.31E-10
Mancozeb	Emission to soil	agricultural	kg	2.42E-10
Manganese	Emission to soil	agricultural	kg	6.32E-05
MCPA	Emission to soil	agricultural	kg	1.17E-13
MCPB	Emission to soil	agricultural	kg	2.83E-15
Mecoprop	Emission to soil	agricultural	kg	1.36E-14
Mecoprop-P	Emission to soil	agricultural	kg	5.02E-14
Mefenpyr	Emission to soil	agricultural	kg	1.7E-15
Mefenpyr-diethyl	Emission to soil	agricultural	kg	5.76E-20
Mepiquat chloride	Emission to soil	agricultural	kg	1.72E-11
Mercury	Emission to soil	agricultural	kg	3.25E-10
Mesosulfuron-methyl (prop)	Emission to soil	agricultural	kg	7.93E-17
Mesotrione	Emission to soil	agricultural	kg	5.59E-14
Metalaxil	Emission to soil	agricultural	kg	3.98E-11

Metaldehyde	Emission to soil	agricultural	kg	3.62E-12
Metam-sodium	Emission to soil	agricultural	kg	1.05E-10
Metamitron	Emission to soil	agricultural	kg	9E-14
Metazachlor	Emission to soil	agricultural	kg	9.31E-12
Metconazole	Emission to soil	agricultural	kg	3.89E-13
Methomyl	Emission to soil	agricultural	kg	1.05E-20
Methyl parathion	Emission to soil	agricultural	kg	3.15E-13
Metolachlor	Emission to soil	agricultural	kg	1.56E-08
Metosulam	Emission to soil	agricultural	kg	4.54E-17
Metribuzin	Emission to soil	agricultural	kg	3.65E-10
Metsulfuron-methyl	Emission to soil	agricultural	kg	1.53E-10
Molinate	Emission to soil	agricultural	kg	3.37E-13
Molybdenum	Emission to soil	agricultural	kg	1.17E-08
Monocrotophos	Emission to soil	agricultural	kg	1.97E-09
MSMA	Emission to soil	agricultural	kg	6.5E-11
Napropamide	Emission to soil	agricultural	kg	5.49E-12
Nickel	Emission to soil	agricultural	kg	1.74E-07
Nicosulfuron	Emission to soil	agricultural	kg	9.46E-15
Oils, unspecified	Emission to soil	agricultural	kg	3.01E-12
Orbencarb	Emission to soil	agricultural	kg	4.59E-11
Oxydemeton-methyl	Emission to soil	agricultural	kg	1.94E-14
Paraquat	Emission to soil	agricultural	kg	6.4E-11
Parathion	Emission to soil	agricultural	kg	4.16E-13
Pendimethalin	Emission to soil	agricultural	kg	4.36E-10
Permethrin	Emission to soil	agricultural	kg	2.61E-13
Pesticides, unspecified	Emission to soil	agricultural	kg	3.3E-09
Phenmedipham	Emission to soil	agricultural	kg	1.08E-14
Phosphorus	Emission to soil	agricultural	kg	3.09E-05
Picloram	Emission to soil	agricultural	kg	2.97E-17
Picoxystrobin	Emission to soil	agricultural	kg	5.6E-16
Pirimicarb	Emission to soil	agricultural	kg	1.17E-12
Potassium	Emission to soil	agricultural	kg	0.000172
Primisulfuron	Emission to soil	agricultural	kg	4.3E-15
Prochloraz	Emission to soil	agricultural	kg	4.61E-14
Procymidone	Emission to soil	agricultural	kg	6.3E-13
Profenofos	Emission to soil	agricultural	kg	1.01E-10
Prohexadione-calcium	Emission to soil	agricultural	kg	1.79E-17
Prometryn	Emission to soil	agricultural	kg	5.43E-11
Propanil	Emission to soil	agricultural	kg	8.73E-13
Propiconazole	Emission to soil	agricultural	kg	3.31E-13
Propoxycarbazone-sodium (prop)	Emission to soil	agricultural	kg	9.91E-17

Prosulfuron	Emission to soil	agricultural	kg	8.06E-16
Prothioconazol	Emission to soil	agricultural	kg	1.88E-12
Pyraclostrobin (prop)	Emission to soil	agricultural	kg	8.36E-13
Pyrithiobac sodium salt	Emission to soil	agricultural	kg	3.63E-12
Quinclorac	Emission to soil	agricultural	kg	1.46E-14
Quinoxyfen	Emission to soil	agricultural	kg	8.67E-16
Quizalofop ethyl ester	Emission to soil	agricultural	kg	1.76E-13
Quizalofop-P	Emission to soil	agricultural	kg	9.07E-14
Rimsulfuron	Emission to soil	agricultural	kg	4.3E-15
Sethoxydim	Emission to soil	agricultural	kg	6.14E-13
Silicon	Emission to soil	agricultural	kg	0.000261
Silthiofam	Emission to soil	agricultural	kg	1.33E-15
Silver	Emission to soil	agricultural	kg	7.5E-19
Simazine	Emission to soil	agricultural	kg	8.69E-14
Spinosad	Emission to soil	agricultural	kg	3.4E-22
Spiroxamine	Emission to soil	agricultural	kg	8.33E-13
Strontium	Emission to soil	agricultural	kg	3.43E-11
Sulfentrazone	Emission to soil	agricultural	kg	5.67E-11
Sulfosate	Emission to soil	agricultural	kg	2.26E-10
Sulfosulfuron	Emission to soil	agricultural	kg	3.56E-16
Sulfur	Emission to soil	agricultural	kg	2.91E-05
Sulfuric acid	Emission to soil	agricultural	kg	1.74E-13
Tebuconazole	Emission to soil	agricultural	kg	3.09E-12
Tebupirimphos	Emission to soil	agricultural	kg	3.61E-14
Tebutam	Emission to soil	agricultural	kg	4.08E-12
Teflubenzuron	Emission to soil	agricultural	kg	5.67E-13
Tefluthrin	Emission to soil	agricultural	kg	2.84E-14
Terbufos	Emission to soil	agricultural	kg	9.66E-14
Thiamethoxam	Emission to soil	agricultural	kg	6.24E-12
Thidiazuron	Emission to soil	agricultural	kg	6.36E-12
Thifensulfuron-methyl	Emission to soil	agricultural	kg	2.86E-14
Thiobencarb	Emission to soil	agricultural	kg	1.87E-13
Thiodicarb	Emission to soil	agricultural	kg	9.97E-14
Thiram	Emission to soil	agricultural	kg	2.23E-10
Tin	Emission to soil	agricultural	kg	1.02E-10
Titanium	Emission to soil	agricultural	kg	4.36E-06
Tralkoxydim	Emission to soil	agricultural	kg	1.05E-16
Tri-allate	Emission to soil	agricultural	kg	8.01E-16
Triadimenol	Emission to soil	agricultural	kg	1.02E-14
Triasulfuron	Emission to soil	agricultural	kg	2.37E-16
Tribenuron	Emission to soil	agricultural	kg	1.04E-15

Tribenuron-methyl	Emission to soil	agricultural	kg	1.61E-14
Tribufos	Emission to soil	agricultural	kg	5.95E-11
Triclopyr	Emission to soil	agricultural	kg	2.59E-11
Trifloxystrobin	Emission to soil	agricultural	kg	1.99E-14
Trifluralin	Emission to soil	agricultural	kg	6.5E-10
Trinexapac-ethyl	Emission to soil	agricultural	kg	8.57E-14
Vanadium	Emission to soil	agricultural	kg	1.25E-07
Vinclozolin	Emission to soil	agricultural	kg	2.1E-13
Zeta-cypermethrin	Emission to soil	agricultural	kg	1.18E-13
Zinc	Emission to soil	agricultural	kg	5.24E-06
Oils, biogenic	Emission to soil	forestry	kg	2.7E-05
Oils, unspecified	Emission to soil	forestry	kg	4.89E-05
Aluminium	Emission to soil	industrial	kg	5.36E-07
Antimony	Emission to soil	industrial	kg	4.79E-10
Arsenic	Emission to soil	industrial	kg	1.98E-10
Barium	Emission to soil	industrial	kg	2.12E-07
Beryllium	Emission to soil	industrial	kg	5.24E-12
Boron	Emission to soil	industrial	kg	4.29E-09
Bromine	Emission to soil	industrial	kg	5.16E-10
Cadmium	Emission to soil	industrial	kg	7.65E-10
Calcium	Emission to soil	industrial	kg	1.83E-06
Carbon	Emission to soil	industrial	kg	4.49E-06
Chloride	Emission to soil	industrial	kg	1.67E-06
Chromium	Emission to soil	industrial	kg	4.63E-09
Cobalt	Emission to soil	industrial	kg	2.64E-10
Copper	Emission to soil	industrial	kg	7.52E-09
Dioxins, measured as 2,3,7,8-tetrachlorodibenzo-p-dioxin	Emission to soil	industrial	kg	4.61E-15
Fluoride	Emission to soil	industrial	kg	2.18E-08
Glyphosate	Emission to soil	industrial	kg	2.91E-09
Heat, waste	Emission to soil	industrial	MJ	0.000119
Iodide	Emission to soil	industrial	kg	5.06E-14
Iron	Emission to soil	industrial	kg	1.02E-06
Lead	Emission to soil	industrial	kg	8.51E-09
Magnesium	Emission to soil	industrial	kg	3.7E-07
Manganese	Emission to soil	industrial	kg	2.04E-08
Mercury	Emission to soil	industrial	kg	1.44E-11
Molybdenum	Emission to soil	industrial	kg	2.68E-11
Nickel	Emission to soil	industrial	kg	1.19E-09
Nitrogen	Emission to soil	industrial	kg	2.36E-08
Oils, biogenic	Emission to soil	industrial	kg	2.59E-15

Oils, unspecified	Emission to soil	industrial	kg	2.69E-08
Phosphorus	Emission to soil	industrial	kg	2.85E-08
Potassium	Emission to soil	industrial	kg	1.66E-07
Selenium	Emission to soil	industrial	kg	1.98E-11
Silicon	Emission to soil	industrial	kg	4.68E-07
Silver	Emission to soil	industrial	kg	6.25E-12
Sodium	Emission to soil	industrial	kg	9.2E-07
Strontium	Emission to soil	industrial	kg	5.05E-09
Sulfur	Emission to soil	industrial	kg	2.67E-07
Thallium	Emission to soil	industrial	kg	4.7E-12
Tin	Emission to soil	industrial	kg	9.95E-10
Titanium	Emission to soil	industrial	kg	9.44E-09
Vanadium	Emission to soil	industrial	kg	4.7E-09
Zinc	Emission to soil	industrial	kg	2.32E-08
Aluminium	Emission to soil	unspecified	kg	1.28E-06
Antimony	Emission to soil	unspecified	kg	8.3E-11
Arsenic	Emission to soil	unspecified	kg	2.35E-10
Barium	Emission to soil	unspecified	kg	7.72E-09
Beryllium	Emission to soil	unspecified	kg	7.62E-11
Boron	Emission to soil	unspecified	kg	4.28E-09
Bromine	Emission to soil	unspecified	kg	3.03E-10
Cadmium	Emission to soil	unspecified	kg	7.79E-11
Calcium	Emission to soil	unspecified	kg	2.47E-07
Carbon	Emission to soil	unspecified	kg	1.31E-07
Carbon dioxide, to soil or biomass stock	Emission to soil	unspecified	kg	3.29E-06
Chloride	Emission to soil	unspecified	kg	7.03E-07
Chlorine	Emission to soil	unspecified	kg	7.87E-09
Chromium	Emission to soil	unspecified	kg	1.22E-09
Chromium VI	Emission to soil	unspecified	kg	1.32E-08
Cobalt	Emission to soil	unspecified	kg	4.86E-10
Copper	Emission to soil	unspecified	kg	1.17E-08
Dioxins, measured as 2,3,7,8-tetrachlorodibenzo-p-dioxin	Emission to soil	unspecified	kg	6.91E-17
Elemental carbon	Emission to soil	unspecified	kg	5.72E-09
Fluoride	Emission to soil	unspecified	kg	8.96E-09
Hydrocarbons, unspecified	Emission to soil	unspecified	kg	3.78E-10
Iron	Emission to soil	unspecified	kg	2.79E-06
Lead	Emission to soil	unspecified	kg	3.25E-09
Lithium	Emission to soil	unspecified	kg	1.97E-11
Magnesium	Emission to soil	unspecified	kg	6.04E-08
Manganese	Emission to soil	unspecified	kg	3.98E-09

Mercury	Emission to soil	unspecified	kg	2.76E-12
Molybdenum	Emission to soil	unspecified	kg	1.29E-10
Nickel	Emission to soil	unspecified	kg	9.82E-10
Nitrate	Emission to soil	unspecified	kg	2.27E-08
Nitrogen	Emission to soil	unspecified	kg	4.07E-09
Oils, biogenic	Emission to soil	unspecified	kg	3.13E-08
Oils, unspecified	Emission to soil	unspecified	kg	8.99E-08
Organic carbon	Emission to soil	unspecified	kg	1.35E-08
PAH, polycyclic aromatic hydrocarbons	Emission to soil	unspecified	kg	5.92E-11
Phenol, pentachloro-	Emission to soil	unspecified	kg	4.05E-13
Phosphorus	Emission to soil	unspecified	kg	1.02E-08
Potassium	Emission to soil	unspecified	kg	9.97E-08
Scandium	Emission to soil	unspecified	kg	2.14E-10
Selenium	Emission to soil	unspecified	kg	4.83E-10
Silicon	Emission to soil	unspecified	kg	2.04E-06
Silver	Emission to soil	unspecified	kg	3.24E-11
Sodium	Emission to soil	unspecified	kg	5.04E-07
Strontium	Emission to soil	unspecified	kg	8.05E-09
Sulfate	Emission to soil	unspecified	kg	3.8E-08
Sulfur	Emission to soil	unspecified	kg	4.34E-07
Thallium	Emission to soil	unspecified	kg	1.32E-11
Tin	Emission to soil	unspecified	kg	1.51E-10
Titanium	Emission to soil	unspecified	kg	7.76E-08
Vanadium	Emission to soil	unspecified	kg	1.66E-09
Zinc	Emission to soil	unspecified	kg	1.15E-07
2,4-D dimethylamine salt	Emission to water	ground water	kg	2.79E-20
2,4-D polypropoxybutyl ester	Emission to water	ground water	kg	1.27E-20
2,4-DB	Emission to water	ground water	kg	2.23E-20
Aluminium	Emission to water	ground water	kg	1.18E-07
Ammonium, ion	Emission to water	ground water	kg	1.25E-07
Antimony	Emission to water	ground water	kg	5.58E-09
Arsenic, ion	Emission to water	ground water	kg	5.56E-08
Atrazine	Emission to water	ground water	kg	1.39E-16
Barium	Emission to water	ground water	kg	4.1E-09
Bentazone	Emission to water	ground water	kg	4.15E-13
Beryllium	Emission to water	ground water	kg	2.34E-10
BOD5, Biological Oxygen Demand	Emission to water	ground water	kg	3.24E-08
Boron	Emission to water	ground water	kg	8.16E-07
Bromine	Emission to water	ground water	kg	6.13E-09
Bromoxynil	Emission to water	ground water	kg	2.39E-20

Cadmium, ion	Emission to water	ground water	kg	6.5E-10
Calcium, ion	Emission to water	ground water	kg	1.33E-05
Carbaryl	Emission to water	ground water	kg	1.61E-20
Chloride	Emission to water	ground water	kg	0.000186
Chlorine	Emission to water	ground water	kg	7.87E-09
Chromium VI	Emission to water	ground water	kg	7.19E-09
Chromium, ion	Emission to water	ground water	kg	1.77E-09
Cobalt	Emission to water	ground water	kg	2.44E-09
COD, Chemical Oxygen Demand	Emission to water	ground water	kg	1.31E-07
Copper, ion	Emission to water	ground water	kg	6.11E-09
Dicamba	Emission to water	ground water	kg	1.47E-17
Dichlorprop	Emission to water	ground water	kg	1.31E-20
Dimethenamid	Emission to water	ground water	kg	1.42E-18
Dissolved solids	Emission to water	ground water	kg	2.16E-06
DOC, Dissolved Organic Carbon	Emission to water	ground water	kg	1.19E-07
Elemental carbon	Emission to water	ground water	kg	5.72E-09
Ethephon	Emission to water	ground water	kg	6.4E-23
Fluoride	Emission to water	ground water	kg	1.27E-07
Glyphosate	Emission to water	ground water	kg	1.01E-11
Hydrogen sulfide	Emission to water	ground water	kg	2.68E-10
Iodide	Emission to water	ground water	kg	6.8E-10
Iron	Emission to water	ground water	kg	2.59E-08
Iron, ion	Emission to water	ground water	kg	1.48E-05
Lambda-cyhalothrin	Emission to water	ground water	kg	1.55E-26
Lead	Emission to water	ground water	kg	4.2E-09
Lead-210	Emission to water	ground water	kBq	4.45E-09
Lithium	Emission to water	ground water	kg	1.97E-11
Magnesium	Emission to water	ground water	kg	4.76E-06
Manganese	Emission to water	ground water	kg	2.33E-07
MCPA	Emission to water	ground water	kg	4.25E-22
MCPB	Emission to water	ground water	kg	1.12E-22
Mercury	Emission to water	ground water	kg	2.34E-11
Methomyl	Emission to water	ground water	kg	5.12E-23
Metolachlor	Emission to water	ground water	kg	5.99E-14
Molybdenum	Emission to water	ground water	kg	7.53E-08
Nickel, ion	Emission to water	ground water	kg	9.08E-09
Nitrate	Emission to water	ground water	kg	2.54E-05
Nitrite	Emission to water	ground water	kg	6.01E-09
Nitrogen, organic bound	Emission to water	ground water	kg	2.25E-07
Organic carbon	Emission to water	ground water	kg	1.35E-08

PAH, polycyclic aromatic hydrocarbons	Emission to water	ground water	kg	5.92E-11
Pendimethalin	Emission to water	ground water	kg	1.95E-18
Phosphate	Emission to water	ground water	kg	2.95E-05
Phosphorus	Emission to water	ground water	kg	3.92E-09
Polonium-210	Emission to water	ground water	kBq	6.52E-09
Potassium	Emission to water	ground water	kg	4.94E-09
Potassium, ion	Emission to water	ground water	kg	1.96E-06
Potassium-40	Emission to water	ground water	kBq	5.37E-10
Propiconazole	Emission to water	ground water	kg	2.25E-21
Prothioconazol	Emission to water	ground water	kg	8.7E-24
Pyraclostrobin	Emission to water	ground water	kg	5.99E-18
Radium-226	Emission to water	ground water	kBq	1.25E-08
Scandium	Emission to water	ground water	kg	1.71E-09
Selenium	Emission to water	ground water	kg	7.46E-09
Silicon	Emission to water	ground water	kg	1.43E-06
Silver, ion	Emission to water	ground water	kg	1.03E-10
Sodium	Emission to water	ground water	kg	9.77E-09
Sodium chlorate	Emission to water	ground water	kg	1.49E-11
Sodium, ion	Emission to water	ground water	kg	6.45E-06
Solids, inorganic	Emission to water	ground water	kg	3.24E-05
Strontium	Emission to water	ground water	kg	1.84E-07
Sulfate	Emission to water	ground water	kg	0.000309
Sulfur	Emission to water	ground water	kg	3.33E-08
Suspended solids, unspecified	Emission to water	ground water	kg	1.54E-08
Tebuconazole	Emission to water	ground water	kg	6.97E-23
Tefluthrin	Emission to water	ground water	kg	5.05E-24
Thallium	Emission to water	ground water	kg	3.74E-11
Thorium-228	Emission to water	ground water	kBq	5.25E-11
Thorium-232	Emission to water	ground water	kBq	3.9E-08
Tin, ion	Emission to water	ground water	kg	3.3E-10
Titanium, ion	Emission to water	ground water	kg	6.98E-09
TOC, Total Organic Carbon	Emission to water	ground water	kg	1.19E-07
Trifloxystrobin	Emission to water	ground water	kg	2.57E-24
Tungsten	Emission to water	ground water	kg	5.58E-09
Uranium-238	Emission to water	ground water	kBq	2.3E-09
Vanadium, ion	Emission to water	ground water	kg	3.36E-09
Water	Emission to water	ground water	m3	4.98E-05
Zinc, ion	Emission to water	ground water	kg	1.39E-07
Aluminium	Emission to water	ground water, long-term	kg	0.000333
Ammonium, ion	Emission to water	ground water, long-term	kg	3.57E-06

Antimony	Emission to water	ground water, long-term	kg	1.52E-07
Arsenic, ion	Emission to water	ground water, long-term	kg	6.51E-07
Barium	Emission to water	ground water, long-term	kg	2.03E-06
Beryllium	Emission to water	ground water, long-term	kg	1.08E-07
BOD5, Biological Oxygen Demand	Emission to water	ground water, long-term	kg	8.85E-05
Boron	Emission to water	ground water, long-term	kg	9.36E-06
Bromine	Emission to water	ground water, long-term	kg	3.96E-08
Cadmium, ion	Emission to water	ground water, long-term	kg	2.97E-07
Calcium, ion	Emission to water	ground water, long-term	kg	0.001977
Chloride	Emission to water	ground water, long-term	kg	9.86E-05
Chromium VI	Emission to water	ground water, long-term	kg	1.1E-06
Cobalt	Emission to water	ground water, long-term	kg	1.92E-06
COD, Chemical Oxygen Demand	Emission to water	ground water, long-term	kg	0.000315
Copper, ion	Emission to water	ground water, long-term	kg	7.21E-06
DOC, Dissolved Organic Carbon	Emission to water	ground water, long-term	kg	0.000213
Fluoride	Emission to water	ground water, long-term	kg	2.67E-05
Heat, waste	Emission to water	ground water, long-term	MJ	0.007042
Hydrogen sulfide	Emission to water	ground water, long-term	kg	1.32E-06
Iodide	Emission to water	ground water, long-term	kg	4.05E-10
Iron, ion	Emission to water	ground water, long-term	kg	0.000234
Lead	Emission to water	ground water, long-term	kg	8.88E-07
Magnesium	Emission to water	ground water, long-term	kg	0.000652
Manganese	Emission to water	ground water, long-term	kg	0.000113
Mercury	Emission to water	ground water, long-term	kg	1.2E-08
Molybdenum	Emission to water	ground water, long-term	kg	4.05E-07
Nickel, ion	Emission to water	ground water, long-term	kg	5.9E-06
Nitrate	Emission to water	ground water, long-term	kg	7.92E-05
Nitrite	Emission to water	ground water, long-term	kg	1.94E-07
Nitrogen, organic bound	Emission to water	ground water, long-term	kg	5.84E-06
Phosphate	Emission to water	ground water, long-term	kg	0.000129
Potassium, ion	Emission to water	ground water, long-term	kg	0.000493
Scandium	Emission to water	ground water, long-term	kg	2.84E-07
Selenium	Emission to water	ground water, long-term	kg	2.95E-07
Silicon	Emission to water	ground water, long-term	kg	0.00161
Silver, ion	Emission to water	ground water, long-term	kg	1.72E-08
Sodium, ion	Emission to water	ground water, long-term	kg	0.000496
Strontium	Emission to water	ground water, long-term	kg	1.51E-05
Sulfate	Emission to water	ground water, long-term	kg	0.004033
Thallium	Emission to water	ground water, long-term	kg	2.75E-08
Tin, ion	Emission to water	ground water, long-term	kg	2.35E-07

Titanium, ion	Emission to water	ground water, long-term	kg	4.71E-05
TOC, Total Organic Carbon	Emission to water	ground water, long-term	kg	0.000213
Tungsten	Emission to water	ground water, long-term	kg	3.16E-07
Vanadium, ion	Emission to water	ground water, long-term	kg	2.21E-06
Zinc, ion	Emission to water	ground water, long-term	kg	2.09E-05
Acenaphthene	Emission to water	ocean	kg	2.21E-13
Acenaphthylene	Emission to water	ocean	kg	1.38E-14
Actinides, radioactive, unspecified	Emission to water	ocean	kBq	3.92E-06
Aluminium	Emission to water	ocean	kg	6.23E-08
Ammonium, ion	Emission to water	ocean	kg	3.64E-08
AOX, Adsorbable Organic Halogen as Cl	Emission to water	ocean	kg	9.88E-11
Arsenic, ion	Emission to water	ocean	kg	2.39E-10
Barite	Emission to water	ocean	kg	1.77E-06
Barium	Emission to water	ocean	kg	3.15E-08
Benzene	Emission to water	ocean	kg	7.14E-09
Benzene, ethyl-	Emission to water	ocean	kg	8.52E-10
BOD5, Biological Oxygen Demand	Emission to water	ocean	kg	1.79E-05
Boron	Emission to water	ocean	kg	4.42E-09
Bromine	Emission to water	ocean	kg	2.48E-08
Cadmium, ion	Emission to water	ocean	kg	1.09E-10
Calcium, ion	Emission to water	ocean	kg	1.9E-06
Carbonate	Emission to water	ocean	kg	5.19E-10
Carboxylic acids, unspecified	Emission to water	ocean	kg	5.55E-07
Cesium	Emission to water	ocean	kg	3.5E-11
Cesium-137	Emission to water	ocean	kBq	5E-05
Chloride	Emission to water	ocean	kg	2.74E-05
Chromium, ion	Emission to water	ocean	kg	1.43E-09
Cobalt	Emission to water	ocean	kg	1.35E-11
COD, Chemical Oxygen Demand	Emission to water	ocean	kg	1.82E-05
Copper, ion	Emission to water	ocean	kg	2.21E-09
Cyanide	Emission to water	ocean	kg	4.26E-09
Dibutyltin	Emission to water	ocean	kg	1.64E-29
Diphenyltin	Emission to water	ocean	kg	1.04E-27
Discarded fish, pelagic, to ocean	Emission to water	ocean	kg	1.31E-19
Dissolved solids	Emission to water	ocean	kg	1.04E-15
DOC, Dissolved Organic Carbon	Emission to water	ocean	kg	5.12E-06
Fluoride	Emission to water	ocean	kg	5.15E-08
Glutaraldehyde	Emission to water	ocean	kg	2.19E-10

Hydrocarbons, aliphatic, alkanes, unspecified	Emission to water	ocean	kg	4.61E-09
Hydrocarbons, aliphatic, unsaturated	Emission to water	ocean	kg	4.26E-10
Hydrocarbons, aromatic	Emission to water	ocean	kg	2.54E-08
Hydrocarbons, unspecified	Emission to water	ocean	kg	3.44E-08
Hydrogen carbonate	Emission to water	ocean	kg	6.23E-08
Hydrogen-3, Tritium	Emission to water	ocean	kBq	0.932923
Hypochlorite	Emission to water	ocean	kg	8.89E-09
Iodide	Emission to water	ocean	kg	3.55E-09
Iron, ion	Emission to water	ocean	kg	4.67E-09
Lead	Emission to water	ocean	kg	2.15E-09
Lead-210	Emission to water	ocean	kBq	7.17E-12
Magnesium	Emission to water	ocean	kg	9.48E-07
Manganese	Emission to water	ocean	kg	2.65E-09
Mercury	Emission to water	ocean	kg	1.63E-11
Methanol	Emission to water	ocean	kg	1.37E-09
Molybdenum	Emission to water	ocean	kg	6.14E-11
Monobutyltin	Emission to water	ocean	kg	2.83E-27
Monophenyltin	Emission to water	ocean	kg	3.1E-30
Nickel, ion	Emission to water	ocean	kg	5.76E-10
Nitrate	Emission to water	ocean	kg	3.43E-07
Nitrite	Emission to water	ocean	kg	6.08E-09
Nitrogen	Emission to water	ocean	kg	1.88E-10
Nitrogen, organic bound	Emission to water	ocean	kg	7.95E-08
Oils, non-fossil	Emission to water	ocean	kg	1.12E-20
Oils, unspecified	Emission to water	ocean	kg	5.71E-06
PAH, polycyclic aromatic hydrocarbons	Emission to water	ocean	kg	9.08E-10
Phenol	Emission to water	ocean	kg	1.32E-08
Phosphate	Emission to water	ocean	kg	1.46E-08
Phosphorus	Emission to water	ocean	kg	2.49E-09
Polonium-210	Emission to water	ocean	kBq	1.28E-06
Potassium, ion	Emission to water	ocean	kg	3.89E-07
Potassium-40	Emission to water	ocean	kBq	1.05E-07
Radioactive species, Nuclides, unspecified	Emission to water	ocean	kBq	0.002343
Radium-224	Emission to water	ocean	kBq	1.75E-06
Radium-226	Emission to water	ocean	kBq	3.74E-06
Radium-228	Emission to water	ocean	kBq	3.5E-06
Rubidium	Emission to water	ocean	kg	3.55E-10
Selenium	Emission to water	ocean	kg	9.2E-11
Silicon	Emission to water	ocean	kg	9.76E-11

Silver, ion	Emission to water	ocean	kg	2.13E-11
Sodium, ion	Emission to water	ocean	kg	1.73E-05
Solids, inorganic	Emission to water	ocean	kg	3.21E-28
Strontium	Emission to water	ocean	kg	7.43E-08
Strontium-90	Emission to water	ocean	kBq	5.56E-06
Sulfate	Emission to water	ocean	kg	3.18E-06
Sulfide	Emission to water	ocean	kg	1.12E-09
Sulfur	Emission to water	ocean	kg	5.23E-10
Suspended solids, unspecified	Emission to water	ocean	kg	6.32E-06
t-Butyl methyl ether	Emission to water	ocean	kg	5.88E-10
Thorium-228	Emission to water	ocean	kBq	7.01E-06
Tin, ion	Emission to water	ocean	kg	7.11E-27
Titanium, ion	Emission to water	ocean	kg	1.6E-11
TOC, Total Organic Carbon	Emission to water	ocean	kg	5.27E-06
Toluene	Emission to water	ocean	kg	1.48E-08
Tributyltin compounds	Emission to water	ocean	kg	1.81E-09
Triethylene glycol	Emission to water	ocean	kg	1.55E-09
Trioctyltin	Emission to water	ocean	kg	7.29E-28
Triphenyltin	Emission to water	ocean	kg	3.1E-28
Uranium-238	Emission to water	ocean	kBq	4.29E-07
Vanadium, ion	Emission to water	ocean	kg	1.85E-10
VOC, volatile organic compounds, unspecified origin	Emission to water	ocean	kg	1.24E-08
Water	Emission to water	ocean	m3	2.64E-06
Xylene	Emission to water	ocean	kg	8.82E-09
Zinc, ion	Emission to water	ocean	kg	1.02E-07
1,4-Butanediol	Emission to water	surface water	kg	2.18E-11
1-Pentanol	Emission to water	surface water	kg	2.01E-12
1-Pentene	Emission to water	surface water	kg	1.52E-12
2,4-D dimethylamine salt	Emission to water	surface water	kg	1.14E-22
2,4-D polypropoxybutyl ester	Emission to water	surface water	kg	5.09E-23
2,4-DB	Emission to water	surface water	kg	9.2E-23
2-Aminopropanol	Emission to water	surface water	kg	1.93E-12
2-Methyl-1-propanol	Emission to water	surface water	kg	5.94E-12
2-Methyl-2-butene	Emission to water	surface water	kg	9.27E-14
2-Propanol	Emission to water	surface water	kg	6.51E-12
4-Methyl-2-pentanol	Emission to water	surface water	kg	1.13E-18
Acenaphthene	Emission to water	surface water	kg	6E-12
Acenaphthylene	Emission to water	surface water	kg	2.76E-13
Acetaldehyde	Emission to water	surface water	kg	6.22E-09

Acetic acid	Emission to water	surface water	kg	1.81E-08
Acetone	Emission to water	surface water	kg	1.81E-09
Acetonitrile	Emission to water	surface water	kg	1.95E-12
Acetyl chloride	Emission to water	surface water	kg	1.58E-12
Acidity, unspecified	Emission to water	surface water	kg	2.11E-09
Acrylate, ion	Emission to water	surface water	kg	3.17E-10
Aluminium	Emission to water	surface water	kg	1.25E-05
Ammonium, ion	Emission to water	surface water	kg	3.14E-06
Aniline	Emission to water	surface water	kg	3.84E-11
Anthracene	Emission to water	surface water	kg	3.53E-13
Antimony	Emission to water	surface water	kg	1.27E-08
Antimony-122	Emission to water	surface water	kBq	2.47E-07
Antimony-124	Emission to water	surface water	kBq	2.28E-05
Antimony-125	Emission to water	surface water	kBq	1.15E-05
AOX, Adsorbable Organic Halogen as Cl	Emission to water	surface water	kg	2.07E-08
Arsenic, ion	Emission to water	surface water	kg	1.5E-07
Atrazine	Emission to water	surface water	kg	5.36E-19
Barium	Emission to water	surface water	kg	6.16E-07
Barium-140	Emission to water	surface water	kBq	3.76E-08
Bentazone	Emission to water	surface water	kg	2.57E-16
Benzene	Emission to water	surface water	kg	1.69E-06
Benzene, chloro-	Emission to water	surface water	kg	3.07E-08
Benzene, ethyl-	Emission to water	surface water	kg	1.68E-08
Benzo(a)anthracene	Emission to water	surface water	kg	1.33E-15
Benzo(a)pyrene	Emission to water	surface water	kg	1.62E-16
Benzo(b)fluoranthene	Emission to water	surface water	kg	1.58E-16
Benzo(ghi)perylene	Emission to water	surface water	kg	2.22E-17
Benzo(k)fluoranthene	Emission to water	surface water	kg	7.43E-17
Beryllium	Emission to water	surface water	kg	7.16E-11
BOD5, Biological Oxygen Demand	Emission to water	surface water	kg	0.000159
Borate	Emission to water	surface water	kg	2.33E-10
Boron	Emission to water	surface water	kg	3.29E-08
Bromate	Emission to water	surface water	kg	6.62E-07
Bromide	Emission to water	surface water	kg	2.16E-08
Bromine	Emission to water	surface water	kg	6.77E-07
Bromoxynil	Emission to water	surface water	kg	8.68E-23
Butanol	Emission to water	surface water	kg	1.63E-09
Butene	Emission to water	surface water	kg	2.28E-09
Butyl acetate	Emission to water	surface water	kg	2.1E-09
Cadmium, ion	Emission to water	surface water	kg	9.1E-10

Calcium, ion	Emission to water	surface water	kg	5.46E-05
Carbaryl	Emission to water	surface water	kg	2.01E-22
Carbon disulfide	Emission to water	surface water	kg	4.71E-12
Carbon-14	Emission to water	surface water	kBq	1.24E-06
Carbonate	Emission to water	surface water	kg	2.28E-07
Carboxylic acids, unspecified	Emission to water	surface water	kg	2.57E-06
Cerium-141	Emission to water	surface water	kBq	1.47E-08
Cerium-144	Emission to water	surface water	kBq	5.4E-09
Cesium	Emission to water	surface water	kg	6.9E-10
Cesium-134	Emission to water	surface water	kBq	2.14E-07
Cesium-136	Emission to water	surface water	kBq	3.15E-09
Cesium-137	Emission to water	surface water	kBq	4.65E-06
Chloramine	Emission to water	surface water	kg	5.52E-11
Chlorate	Emission to water	surface water	kg	5.06E-06
Chloride	Emission to water	surface water	kg	0.000458
Chlorinated solvents, unspecified	Emission to water	surface water	kg	2.35E-09
Chlorine	Emission to water	surface water	kg	3.33E-10
Chloroacetic acid	Emission to water	surface water	kg	3.49E-09
Chloroacetyl chloride	Emission to water	surface water	kg	2.57E-12
Chloroform	Emission to water	surface water	kg	1.94E-11
Chlorosulfonic acid	Emission to water	surface water	kg	7.09E-12
Chromium VI	Emission to water	surface water	kg	2.49E-07
Chromium, ion	Emission to water	surface water	kg	6.33E-09
Chromium-51	Emission to water	surface water	kBq	4.77E-06
Chrysene	Emission to water	surface water	kg	8.59E-16
Cobalt	Emission to water	surface water	kg	2.59E-09
Cobalt-57	Emission to water	surface water	kBq	2.43E-06
Cobalt-58	Emission to water	surface water	kBq	0.000312
Cobalt-60	Emission to water	surface water	kBq	0.000115
COD, Chemical Oxygen Demand	Emission to water	surface water	kg	0.000157
Copper, ion	Emission to water	surface water	kg	8.42E-09
Cumene	Emission to water	surface water	kg	1.22E-06
Cyanide	Emission to water	surface water	kg	4.28E-08
Dibenz(a,h)anthracene	Emission to water	surface water	kg	1.56E-17
Dicamba	Emission to water	surface water	kg	5.88E-20
Dichlorprop	Emission to water	surface water	kg	5.41E-23
Dichromate	Emission to water	surface water	kg	2.73E-12
Diethylamine	Emission to water	surface water	kg	1.78E-11
Dimethenamid	Emission to water	surface water	kg	1.77E-20
Dimethylamine	Emission to water	surface water	kg	3.6E-11

Dipropylamine	Emission to water	surface water	kg	1.03E-11
Dissolved solids	Emission to water	surface water	kg	1.05E-05
DOC, Dissolved Organic Carbon	Emission to water	surface water	kg	6.04E-05
Ethane, 1,1,1-trichloro-, HCFC-140	Emission to water	surface water	kg	4.25E-21
Ethane, 1,2-dichloro-	Emission to water	surface water	kg	5.27E-10
Ethanol	Emission to water	surface water	kg	7.52E-09
Ethene	Emission to water	surface water	kg	4.16E-08
Ethene, chloro-	Emission to water	surface water	kg	1.83E-11
Ethephon	Emission to water	surface water	kg	3.88E-25
Ethyl acetate	Emission to water	surface water	kg	1.94E-11
Ethylamine	Emission to water	surface water	kg	6.26E-12
Ethylene diamine	Emission to water	surface water	kg	2.23E-12
Ethylene oxide	Emission to water	surface water	kg	7.83E-10
Fluoranthene	Emission to water	surface water	kg	6.99E-12
Fluorene	Emission to water	surface water	kg	2.58E-12
Fluoride	Emission to water	surface water	kg	3.56E-07
Fluosilicic acid	Emission to water	surface water	kg	2.19E-09
Formaldehyde	Emission to water	surface water	kg	1.45E-07
Formamide	Emission to water	surface water	kg	3.67E-12
Formate	Emission to water	surface water	kg	7.32E-10
Formic acid	Emission to water	surface water	kg	1.07E-12
Fresh water (obsolete)	Emission to water	surface water	m3	4.14E-08
Glyphosate	Emission to water	surface water	kg	6.57E-14
Heat, waste	Emission to water	surface water	MJ	0.00089
Hydrocarbons, aliphatic, alkanes, unspecified	Emission to water	surface water	kg	9.08E-08
Hydrocarbons, aliphatic, unsaturated	Emission to water	surface water	kg	8.39E-09
Hydrocarbons, aromatic	Emission to water	surface water	kg	3.67E-07
Hydrocarbons, unspecified	Emission to water	surface water	kg	3.37E-08
Hydrogen peroxide	Emission to water	surface water	kg	4.13E-09
Hydrogen sulfide	Emission to water	surface water	kg	2.46E-09
Hydrogen-3, Tritium	Emission to water	surface water	kBq	0.585299
Hydroxide	Emission to water	surface water	kg	1.83E-08
Hypochlorite	Emission to water	surface water	kg	9.22E-09
Indeno(1,2,3-cd)pyrene	Emission to water	surface water	kg	2.44E-16
Iodide	Emission to water	surface water	kg	8.07E-08
Iodine-131	Emission to water	surface water	kBq	2.3E-06
Iodine-133	Emission to water	surface water	kBq	2.34E-08
Iron, ion	Emission to water	surface water	kg	1.27E-06
Iron-59	Emission to water	surface water	kBq	1.05E-05

Isopropylamine	Emission to water	surface water	kg	2.82E-12
Lactic acid	Emission to water	surface water	kg	8.05E-12
Lambda-cyhalothrin	Emission to water	surface water	kg	3.89E-29
Lanthanum-140	Emission to water	surface water	kBq	1.7E-07
Lead	Emission to water	surface water	kg	6.68E-08
Lead-210	Emission to water	surface water	kBq	2.67E-06
Lithium, ion	Emission to water	surface water	kg	1.25E-09
m-Xylene	Emission to water	surface water	kg	1E-11
Magnesium	Emission to water	surface water	kg	5.88E-06
Manganese	Emission to water	surface water	kg	2.22E-07
Manganese-54	Emission to water	surface water	kBq	4.17E-06
MCPA	Emission to water	surface water	kg	2.41E-20
MCPB	Emission to water	surface water	kg	2.41E-20
Mercury	Emission to water	surface water	kg	1.37E-10
Methane, dichloro-, HCC-30	Emission to water	surface water	kg	1.03E-08
Methanol	Emission to water	surface water	kg	7.05E-09
Methomyl	Emission to water	surface water	kg	5.74E-25
Methyl acetate	Emission to water	surface water	kg	7.96E-13
Methyl acrylate	Emission to water	surface water	kg	2.97E-09
Methyl amine	Emission to water	surface water	kg	7.15E-12
Methyl formate	Emission to water	surface water	kg	2.84E-13
Metolachlor	Emission to water	surface water	kg	8.04E-16
Molybdenum	Emission to water	surface water	kg	8.7E-08
Molybdenum-99	Emission to water	surface water	kBq	1.54E-08
Naphthalene	Emission to water	surface water	kg	5.17E-13
Nickel, ion	Emission to water	surface water	kg	1.24E-08
Niobium-95	Emission to water	surface water	kBq	8.58E-07
Nitrate	Emission to water	surface water	kg	1.2E-05
Nitrite	Emission to water	surface water	kg	8.3E-08
Nitrobenzene	Emission to water	surface water	kg	4.6E-09
Nitrogen	Emission to water	surface water	kg	7.77E-07
Nitrogen, organic bound	Emission to water	surface water	kg	3.36E-07
o-Dichlorobenzene	Emission to water	surface water	kg	2.04E-08
Oils, non-fossil	Emission to water	surface water	kg	3.45E-08
Oils, unspecified	Emission to water	surface water	kg	3.97E-05
PAH, polycyclic aromatic hydrocarbons	Emission to water	surface water	kg	4.26E-09
Pendimethalin	Emission to water	surface water	kg	3.27E-21
Phenanthrene	Emission to water	surface water	kg	5.8E-12
Phenol	Emission to water	surface water	kg	9.73E-07
Phosphate	Emission to water	surface water	kg	6.17E-07
Phosphorus	Emission to water	surface water	kg	5.37E-08

Polonium-210	Emission to water	surface water	kBq	2.56E-06
Potassium, ion	Emission to water	surface water	kg	2.99E-05
Potassium-40	Emission to water	surface water	kBq	3.35E-06
Propanal	Emission to water	surface water	kg	2.42E-12
Propanol	Emission to water	surface water	kg	7.57E-12
Propene	Emission to water	surface water	kg	8.89E-07
Propiconazole	Emission to water	surface water	kg	2.15E-25
Propionic acid	Emission to water	surface water	kg	3.44E-11
Propylamine	Emission to water	surface water	kg	2.06E-12
Propylene oxide	Emission to water	surface water	kg	4.18E-09
Protactinium-234	Emission to water	surface water	kBq	2.8E-06
Prothioconazol	Emission to water	surface water	kg	1.36E-25
Pyraclostrobin	Emission to water	surface water	kg	9.52E-20
Pyrene	Emission to water	surface water	kg	5.27E-12
Radioactive species, alpha emitters	Emission to water	surface water	kBq	2.95E-08
Radioactive species, Nuclides, unspecified	Emission to water	surface water	kBq	2.79E-06
Radium-224	Emission to water	surface water	kBq	3.45E-05
Radium-226	Emission to water	surface water	kBq	0.000981
Radium-228	Emission to water	surface water	kBq	6.9E-05
Rubidium	Emission to water	surface water	kg	6.98E-09
Ruthenium-103	Emission to water	surface water	kBq	7.8E-08
Scandium	Emission to water	surface water	kg	7.09E-09
Selenium	Emission to water	surface water	kg	1.78E-08
Silicon	Emission to water	surface water	kg	2.62E-05
Silver, ion	Emission to water	surface water	kg	6.4E-10
Silver-110	Emission to water	surface water	kBq	1.16E-05
Sodium formate	Emission to water	surface water	kg	1.24E-11
Sodium, ion	Emission to water	surface water	kg	0.000315
Sodium-24	Emission to water	surface water	kBq	2.73E-06
Solids, inorganic	Emission to water	surface water	kg	8E-06
Strontium	Emission to water	surface water	kg	1.26E-06
Strontium-89	Emission to water	surface water	kBq	2.3E-07
Strontium-90	Emission to water	surface water	kBq	0.000289
Sulfate	Emission to water	surface water	kg	0.000182
Sulfide	Emission to water	surface water	kg	8.48E-09
Sulfite	Emission to water	surface water	kg	5.18E-08
Sulfur	Emission to water	surface water	kg	2.33E-07
Suspended solids, unspecified	Emission to water	surface water	kg	2.97E-05
t-Butyl methyl ether	Emission to water	surface water	kg	3.39E-10
t-Butylamine	Emission to water	surface water	kg	5.7E-12

Tebuconazole	Emission to water	surface water	kg	1.68E-25
Technetium-99m	Emission to water	surface water	kBq	1.06E-06
Tefluthrin	Emission to water	surface water	kg	8.39E-26
Tellurium-123m	Emission to water	surface water	kBq	4.4E-07
Tellurium-132	Emission to water	surface water	kBq	2.3E-08
Thallium	Emission to water	surface water	kg	1.28E-10
Thorium-228	Emission to water	surface water	kBq	0.000138
Thorium-230	Emission to water	surface water	kBq	0.000237
Thorium-232	Emission to water	surface water	kBq	1.88E-06
Thorium-234	Emission to water	surface water	kBq	2.8E-06
Tin, ion	Emission to water	surface water	kg	4.59E-10
Titanium, ion	Emission to water	surface water	kg	7.53E-08
TOC, Total Organic Carbon	Emission to water	surface water	kg	6.1E-05
Toluene	Emission to water	surface water	kg	7.94E-08
Toluene, 2-chloro	Emission to water	surface water	kg	2.54E-11
Triethylene glycol	Emission to water	surface water	kg	3.37E-11
Trifloxystrobin	Emission to water	surface water	kg	4.2E-26
Trimethylamine	Emission to water	surface water	kg	1.67E-12
Tungsten	Emission to water	surface water	kg	6.56E-09
Uranium alpha	Emission to water	surface water	kBq	0.000109
Uranium-234	Emission to water	surface water	kBq	3.24E-06
Uranium-235	Emission to water	surface water	kBq	3.61E-06
Uranium-238	Emission to water	surface water	kBq	7.78E-06
Urea	Emission to water	surface water	kg	3.14E-12
Vanadium, ion	Emission to water	surface water	kg	2.73E-08
VOC, volatile organic compounds, unspecified origin	Emission to water	surface water	kg	3.09E-07
Water	Emission to water	surface water	m3	7.69E-05
Xylene	Emission to water	surface water	kg	6.6E-08
Zinc, ion	Emission to water	surface water	kg	1.04E-07
Zinc-65	Emission to water	surface water	kBq	2.31E-06
Zirconium-95	Emission to water	surface water	kBq	5.62E-06
1,3-Dioxolan-2-one	Emission to water	unspecified	kg	2.48E-07
2-Propanol	Emission to water	unspecified	kg	5.43E-10
4-Methyl-2-pentanone	Emission to water	unspecified	kg	3.11E-11
Acetone	Emission to water	unspecified	kg	7.42E-11
Acidity, unspecified	Emission to water	unspecified	kg	1.56E-09
Allyl chloride	Emission to water	unspecified	kg	2.08E-12
Aluminium	Emission to water	unspecified	kg	1.38E-07
Aluminium hydroxide	Emission to water	unspecified	kg	1.37E-12
Ammonium, ion	Emission to water	unspecified	kg	9.27E-08

Aniline	Emission to water	unspecified	kg	1.05E-09
Antimony	Emission to water	unspecified	kg	8.37E-11
AOX, Adsorbable Organic Halogen as Cl	Emission to water	unspecified	kg	2.23E-09
Arsenic, ion	Emission to water	unspecified	kg	1.82E-09
Barite	Emission to water	unspecified	kg	1.04E-06
Barium	Emission to water	unspecified	kg	1.07E-06
Benzene	Emission to water	unspecified	kg	1.74E-08
Benzene, ethyl-	Emission to water	unspecified	kg	7E-10
Beryllium	Emission to water	unspecified	kg	7.46E-11
Bisphenol A	Emission to water	unspecified	kg	1.62E-09
BOD5, Biological Oxygen Demand	Emission to water	unspecified	kg	1.04E-05
Borate	Emission to water	unspecified	kg	4.18E-10
Boron	Emission to water	unspecified	kg	2.33E-08
Bromine	Emission to water	unspecified	kg	1.59E-06
Butyrolactone	Emission to water	unspecified	kg	2.23E-12
Cadmium, ion	Emission to water	unspecified	kg	8.07E-10
Calcium, ion	Emission to water	unspecified	kg	2.39E-05
Carbonate	Emission to water	unspecified	kg	7.25E-12
Carboxylic acids, unspecified	Emission to water	unspecified	kg	8.43E-13
Chloride	Emission to water	unspecified	kg	0.00027
Chloride, ion	Emission to water	unspecified	kg	2.06E-08
Chlorides, unspecified	Emission to water	unspecified	kg	4.04E-07
Chlorine	Emission to water	unspecified	kg	1.29E-12
Chromium VI	Emission to water	unspecified	kg	3.11E-10
Chromium, ion	Emission to water	unspecified	kg	6.07E-09
Cobalt	Emission to water	unspecified	kg	1.65E-10
COD, Chemical Oxygen Demand	Emission to water	unspecified	kg	1.2E-05
Copper, ion	Emission to water	unspecified	kg	3.62E-09
Cu-HDO	Emission to water	unspecified	kg	1.76E-15
Cumene	Emission to water	unspecified	kg	5.91E-07
Cyanide	Emission to water	unspecified	kg	1.77E-09
Dichromate	Emission to water	unspecified	kg	3.95E-10
Diethanolamine	Emission to water	unspecified	kg	3.28E-11
Dissolved solids	Emission to water	unspecified	kg	0.00033
DOC, Dissolved Organic Carbon	Emission to water	unspecified	kg	3.87E-06
Epichlorohydrin	Emission to water	unspecified	kg	7.21E-10
Ethanol	Emission to water	unspecified	kg	8.79E-14
Fluoride	Emission to water	unspecified	kg	1.14E-08
Fluosilicic acid	Emission to water	unspecified	kg	8.97E-10

Formaldehyde	Emission to water	unspecified	kg	2.22E-07
Hydrocarbons, aliphatic, unsaturated	Emission to water	unspecified	kg	2.54E-17
Hydrocarbons, unspecified	Emission to water	unspecified	kg	4.95E-09
Hydrochloric acid	Emission to water	unspecified	kg	3.93E-08
Hydroxide	Emission to water	unspecified	kg	1.2E-12
Iron, ion	Emission to water	unspecified	kg	5.56E-07
Lauric acid	Emission to water	unspecified	kg	7.3E-11
Lead	Emission to water	unspecified	kg	4.41E-09
Lead-210	Emission to water	unspecified	kBq	2.15E-06
Lithium, ion	Emission to water	unspecified	kg	7.98E-06
m-Xylene	Emission to water	unspecified	kg	2.25E-10
Magnesium	Emission to water	unspecified	kg	4.66E-06
Manganese	Emission to water	unspecified	kg	9.26E-09
Mercury	Emission to water	unspecified	kg	9.92E-11
Methanol	Emission to water	unspecified	kg	6.93E-08
Molybdenum	Emission to water	unspecified	kg	1.71E-10
Monoethanolamine	Emission to water	unspecified	kg	6.32E-12
Nickel, ion	Emission to water	unspecified	kg	5.28E-09
Nitrate	Emission to water	unspecified	kg	1.41E-08
Nitrite	Emission to water	unspecified	kg	4.32E-11
Nitrogen	Emission to water	unspecified	kg	2.47E-10
Nitrogen, organic bound	Emission to water	unspecified	kg	8.25E-14
o-Xylene	Emission to water	unspecified	kg	1.64E-10
Oils, unspecified	Emission to water	unspecified	kg	5.59E-06
PAH, polycyclic aromatic hydrocarbons	Emission to water	unspecified	kg	2.47E-11
Phenol	Emission to water	unspecified	kg	2.56E-08
Phosphate	Emission to water	unspecified	kg	4.71E-12
Phosphorus	Emission to water	unspecified	kg	2.23E-08
Polychlorinated biphenyls	Emission to water	unspecified	kg	1.61E-14
Potassium, ion	Emission to water	unspecified	kg	1.06E-13
Radium-226	Emission to water	unspecified	kBq	9.46E-06
Radium-228	Emission to water	unspecified	kBq	1.33E-05
Selenium	Emission to water	unspecified	kg	2.07E-11
Silver, ion	Emission to water	unspecified	kg	1.56E-08
Sodium, ion	Emission to water	unspecified	kg	8.12E-05
Solids, inorganic	Emission to water	unspecified	kg	9.6E-13
Strontium	Emission to water	unspecified	kg	4.05E-07
Sulfate	Emission to water	unspecified	kg	1.05E-06
Sulfate, ion	Emission to water	unspecified	kg	1.77E-09
Sulfur	Emission to water	unspecified	kg	3.16E-08

Suspended solids, unspecified	Emission to water	unspecified	kg	0.000259
Thallium	Emission to water	unspecified	kg	1.76E-11
Tin, ion	Emission to water	unspecified	kg	8.17E-10
Titanium, ion	Emission to water	unspecified	kg	5.67E-09
TOC, Total Organic Carbon	Emission to water	unspecified	kg	4.55E-06
Toluene	Emission to water	unspecified	kg	1.18E-08
Triethylene glycol	Emission to water	unspecified	kg	3.4E-11
Vanadium, ion	Emission to water	unspecified	kg	2.02E-10
VOC, volatile organic compounds, unspecified origin	Emission to water	unspecified	kg	4.3E-11
Water	Emission to water	unspecified	m3	1.085924
Xylene	Emission to water	unspecified	kg	5.95E-09
Zinc, ion	Emission to water	unspecified	kg	1.06E-08

References

Bradshaw, A. M., Hamacher, T., & Fischer, U. (2011). Is nuclear fusion a sustainable energy form? *Fusion Engineering and Design, 86*(9-11), 2770-2773. doi:10.1016/j.fusengdes.2010.11.040

Browne, E., Dairiki, J. M., & Doebler, R. E. (1978). *Table of isotopes*. Retrieved from

Ciroth, A. (2007). ICT for environment in life cycle applications openLCA—A new open source software for life cycle assessment. *The International Journal of Life Cycle Assessment, 12*(4), 209.

Climate Action Tracker. (2018). *Warming Projections Global Update*. Retrieved from New York:

Corsten, M., Ramírez, A., Shen, L., Koornneef, J., & Faaij, A. (2013). Environmental impact assessment of CCS chains–Lessons learned and limitations from LCA literature. *International Journal of Greenhouse Gas Control, 13*, 59-71.

Durmayaz, A., & Sogut, O. S. (2006). Influence of cooling water temperature on the efficiency of a pressurized ‐ water reactor nuclear ‐ power plant. *International Journal of Energy Research, 30*(10), 799-810.

E4tech. (2009). *Review of Technologies for Gasification of Biomass and Wastes*. Retrieved from York:

EIA. (2019). *Capital Cost Estimates for Utility Scale Electricity Generating Plants*. Retrieved from Washington, D.C.: https://www.eia.gov/analysis/studies/powerplants/capitalcost/pdf/capcost_assumption.pdf

Fosgitt, R. L. (2010). GASIFICATION USING ROTARY KILN TECHNOLOGY [Press release]

Frischknecht, R., Jungbluth, N., Althaus, H.-J., Doka, G., Dones, R., Heck, T., . . . Rebitzer, G. (2005). The ecoinvent database: overview and methodological framework (7 pp). *The International Journal of Life Cycle Assessment, 10*(1), 3-9.

Fuss, S., Canadell, J. G., Peters, G. P., Tavoni, M., Andrew, R. M., Ciais, P., . . . Nakicenovic, N. (2014). Betting on negative emissions. *Nature Climate Change, 4*(10), 850.

Gaurina-Medimurec, N., Novak-Mavar, K., & Majic, M. (2018). Carbon Capture and Storage (CCS): Technology, Projects and Monitoring Review. *The Mining-Geology-Petroleum Engineering Bulletin*, 1-14.

Guan, G. (2017). Clean coal technologies in Japan: A review. *Chinese Journal of Chemical Engineering, 25*(6), 689-697.

Herrera-Velázquez, J. E. (2007). Nuclear Fusion as an Energy Option for the 21 st Century. In *Towards a Cleaner Planet* (pp. 405-419): Springer.

Ibano, K. (2012). *Design Study Of Small Power Tokamak Nuclear Fusion Reactor For The Biomass-Fusion Hybird Concept.* (Doctor of Energy), Kyoto University, Kyoto.

Ibano, K., Utoh, H., Tobita, K., Yamamoto, Y., & Konishi, S. (2011). Design studies of innovatively small fusion reactor based on biomass-fusion hybrid concept: GNOME. *Fusion Engineering and Design, 86*(9-11), 2779-2782. doi:10.1016/j.fusengdes.2010.12.011

IEA/NEA. (2015). *Projected Costs of Generating Electricity*. Retrieved from Paris:

IEA/NEA. (2018). *The Full Cost of Electricity Provision*. Retrieved from Paris:

Ishida, K. (2017). *Out Line of the Osaki CoolGen Project.* Paper presented at the ASME 2017 Power Conference Joint With ICOPE-17 collocated with the ASME 2017 11th International Conference on Energy Sustainability, the ASME 2017 15th International Conference on Fuel Cell Science, Engineering and Technology, and the ASME 2017 Nuclear Forum.

ITER. (2016). ITER Tokamak and Plant Systems. Retrieved from https://www.iter.org/album/media/

Japan Coal Energy Center. (2007). Clean coal technologies in Japan. *Technology Innovation in the Coal Industry*.

Kemper, J. (2015). Biomass and carbon dioxide capture and storage: A review. *International Journal of Greenhouse Gas Control, 40*, 401-430.

Kenji, A. (2015). *The Situation and Progress of the Osaki COOLGEN Blowing-Oxygen IGCC Project.* Paper presented at the Nineth Sino Japanese Energy Saving and Environmental Protection Comprehensive Forum.

Kobori, H., Kasada, R., Hiwatari, R., & Konishi, S. (2016). Improvement of system code importing evaluation of Life Cycle Analysis of tokamak fusion power reactors. *Fusion Engineering and Design, 109*, 760-763.

Kumar, A., Jones, D. D., & Hanna, M. A. (2009). Thermochemical Biomass Gasification: A Review of the Current Status of the Technology. *Energies, 2*(3), 556-581. doi:10.3390/en20300556

Kwon, S., Kasada, R., & Konishi, S. (2013). *Operation scenario of DT fusion plant without external initial tritium.* Paper presented at the Fusion Engineering (SOFE), 2013 IEEE 25th Symposium on.

Maisonnier, D., Campbell, D., Cook, I., Di Pace, L., Giancarli, L., Hayward, J., . . . Roccella, M. (2007). Power plant conceptual studies in Europe. *Nuclear Fusion, 47*(11), 1524.

Mathy, S., Menanteau, P., & Criqui, P. (2018). After the Paris Agreement: measuring the global decarbonization wedges from national energy scenarios. *Ecological Economics, 150*, 273-289.

Matin, M. A. A., Takeda, S., Tanaka, Y., Sakurai, S., & Tezuka, T. (2019). *LCOE Analysis for Grid-Connected PV Systems of Utility Scale Across Selected ASEAN Countries*. Retrieved from Jakarta:

Nam, H., Kasada, R., & Konishi, S. (2017). Feasibility of Waste to Bio-Diesel Production via Nuclear-Biomass Hybrid Model; System Dynamics Analysis. *Proceedings of ICAPP2017, 17674*.

Nobukawa, H. (1997). Technology on the Lihium Recovery from Seawaer (2) Extraction System and Simulation. *Bulletin of the Society of Sea Water Science, Japan, 51*(5), 289-292.

Oiwa, T. (2014). Economic evaluations of biomass power generation. *Chuden Technology Development, 151*, 35-36.

Ooi, K. (1997). Technology on the Lihium Recovery from Seawaer (1) Adsorbent for Lithium. *Bulletin of the Society of Sea Water Science, Japan, 51*(5), 285-288.

Perrault, D. (2016). Safety issues to be taken into account in designing future nuclear fusion facilities. *Fusion Engineering and Design, 109-111*, 1733-1738. Retrieved from http://www.sciencedirect.com/science/article/pii/S0920379615302994. doi:https://doi.org/10.1016/j.fusengdes.2015.10.012

Psarras, P., Krutka, H., Fajardy, M., Zhang, Z., Liguori, S., Dowell, N. M., & Wilcox, J. (2017). Slicing the pie: how big could carbon dioxide removal be? *Wiley Interdisciplinary Reviews: Energy and Environment, 6*(5), e253.

Quader, M., & Ahmed, S. (2017). Bioenergy With Carbon Capture and Storage (BECCS): Future Prospects of Carbon-Negative Technologies. In *Clean Energy for Sustainable Development* (pp. 91-140): Elsevier.

Robertson, R. (1956). *Heat-Power Cycles and Prime Movers for Nuclear Power Plants*. Retrieved from

Rüegsegger, M. (2014). Thermal Gasification of Biomass Country Report Switzerland. *IEA Bioenergy, Task 33*.

S&P Global. (2017). Carbon Pricing Is Essential for Effective Climate-Related Financial Disclosure. Retrieved from https://www.trucost.com/trucost-blog/carbon-pricing-is-essential-for-effective-climate-related-financial-disclosure/

Schleicher, R., Raffray, A., & Wong, C. (2001). An assessment of the Brayton cycle for high performance power plants. *Fusion Technology, 39*(2P2), 823-827.

Shu-jian, J. (2009). Review and Prospect on Development of IGCC Technology. *Electric Power Construction, 1*, 004.

Skone, T. J. (2014). *Understanding the Life Cycle Environmental Footprint of the Natural Gas Value Chain*. Retrieved from Bruceton:

Skone, T. J., Cooney, G., & Marriott, J. (2016). *A Life Cycle Analysis Perspective of CCS*. Retrieved from Washington D.C.:

Stocker, T. (2014). *Climate change 2013: the physical science basis: Working Group I contribution to the Fifth assessment report of the Intergovernmental Panel on Climate Change*: Cambridge University Press.

Takeda, S., & Pearson, R. (2019). Nuclear Fusion Power Plants. In *Power Plants in the Industry* (pp. 101-121). London: IntechOpen.

Tanaka, Y., Abe, M., Sawada, Y., Tanase, D., Ito, T., & Kasukawa, T. (2014). Tomakomai CCS demonstration project in Japan, 2014 update. *Energy Procedia, 63*, 6111-6119.

The Japan Society of Plasma Science and Nuclear Fusion Research. (2011). *Text - Fusion Reactors - Tokamak Reactor Designs and their Basis on Plasma Physics and Reactor Technology* - (Vol. 87 Supplement). Nagoya: JSPF.

Tijmensen, M. J., Faaij, A. P., Hamelinck, C. N., & van Hardeveld, M. R. (2002). Exploration of the possibilities for production of Fischer Tropsch liquids and power via biomass gasification. *Biomass and Bioenergy, 23*(2), 129-152.

Tobita, K., Nishio, S., Enoeda, M., Nakamura, H., Hayashi, T., Asakura, N., . . . Isono, T. (2010). *Conceptual design of the SlimCS fusion DEMO reactor*. Retrieved from Naka:

Tokimatsu, K., Konishi, S., Ishihara, K., Tezuka, T., Yasuoka, R., & Nishio, M. (2016). Role of innovative technologies under the global zero emissions scenarios. *Applied Energy, 162*, 1483-1493.

Turn, S., Kinoshita, C., Zhang, Z., Ishimura, D., & Zhou, J. (1998). An experimental investigation of hydrogen production from biomass gasification. *International Journal of Hydrogen Energy, 23*(8), 641-648.

U.S. Department of Energy National Renewable Energy Laboratory. (2018). Annual Technology Baseline. Retrieved from https://atb.nrel.gov/

Ueda, Y., Inoue, T., & Kurihara, K. (2004). Intelligible Seminor on Fusion Reactors - (1) Introduction to Fusion Reactors. *Journal of the Atomic Energy Society of Japan, 46*(12), 27-34.

UNFCCC. (2018). The Paris Agreement. Retrieved from https://unfccc.int/process-and-meetings/the-paris-agreement/the-paris-agreement

USGS. (2018). Lithium. Retrieved from https://minerals.usgs.gov/minerals/pubs/commodity/lithium/mcs-2018-lithi.pdf

van der Meijden, C. M., Veringa, H. J., & Rabou, L. P. (2010). The production of synthetic natural gas (SNG): A comparison of three wood gasification systems for energy balance and overall efficiency. *Biomass bioenergy, 34*(3), 302-311.

Vesely, L., Dostal, V., & Entler, S. (2017). Study of the cooling systems with S-CO2 for the DEMO fusion power reactor. *Fusion Engineering and Design, 124*, 244-247.

Watanabe, K., & Naruse, K. (2012). Continuous Operation of a Fluidezed-Bed Gasification and Ash Melting Plant for 226 Days. *Ebara Journal, 236*, 17-20.

Wernet, G., Bauer, C., Steubing, B., Reinhard, J., Moreno-Ruiz, E., & Weidema, B. (2016). The ecoinvent database version 3 (part I): overview and methodology. *The International Journal of Life Cycle Assessment, 21*(9), 1218-1230.

Wood Resources International. (2016). *North American Wood Fiber Review*. Retrieved from Vancouver, WA:

Yamamoto, H., Sekino, K., Amari, T., Terasawa, Y., Honda, H., & Ichinose, T. (2005). Commercialization of Woody Biomass Gasification Power Generating System with Indirectly Heating Kiln. *Mitsubishi Heavy Industry Technology Review, 42*(4), 160-163.