Article

Comparative Life-Cycle Assessment of Electricity-Generation Technologies: West Texas Case Study

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Abstract: This comparison of five power plants in West Texas is intended to provide various decision-makers and stakeholders with a holistic picture of the life-cycle environmental impacts associated with these power plants. A key contribution of this analysis is that we assumed all power plants generate the same amount of electricity over a 30-year life, taking a 500 MW combined-cycle gas turbine (CCGT) plant as a benchmark. Also, in two cases, we added battery storage to wind and solar PV facilities to render them nearly as dispatchable as the CCGT. We included the entire supply chain supporting electricity generation, which encompassed raw material sourcing, processing, manufacturing, operations, and product end of life, also called "cradle to grave". We report on 18 environmental impacts using ReCiPe midpoint (H) impact assessment. The supply chains are global, and impacts are felt differently by host communities across the world. The results can help stakeholders identify hotspots across numerous supply chains with the highest environmental impacts. We discuss some remedial measures and challenges to inform future analysis by the research community.

Keywords: wind turbines; combined-cycle gas turbines; solar photovoltaic; life-cycle assessment; lithium-ion battery; battery energy storage system; critical materials; sustainability

1. Introduction

Sustainable development is defined as "development that meets the needs of the present without compromising the ability of future generations to meet their own needs" [1]. This concept has evolved from environmental and economic domains to cater to institutional, political, societal, and technological needs of the world [2]. Although electric-power generation is essential for meeting basic needs of the world's population, it is also responsible for a diverse set of negative environmental impacts associated with resource extraction and processing; manufacturing of gas turbines, solar panels, wind turbines, and other power plant equipment; transportation of minerals, fuels, and equipment; and combustion of fossil fuels at thermal power plants. Nearly all impacts to air, water, and land resources occur locally, where supply chain activities take place, except for greenhouse gas (GHG) emissions that cause global climate change.

The Intergovernmental Panel on Climate Change (IPCC) has identified decarbonization of electricity systems around the world as a significant measure for reducing GHG emissions. The goal is to keep global warming below 1.5 °C to 2 °C [3]. At the same time, the United Nations Sustainable Development Goals (SDG) (specifically, Goal #7-Affordable and Clean Energy) suggest ensuring access to affordable, reliable, sustainable, and modern energy for all [4]. This follows directly from SDG #1 (no poverty). Other SDGs aim at enhancing ecosystems and halting biodiversity loss (#15) and ensuring the availability and sustainability of water and sanitation (#6). How electricity is generated touches on

these SDGs and others. Sustainable electricity production can improve the quality of life, economy, and social well-being of a nation [5], but most environmental impacts of electricity, which is supplied locally, are distributed across the globe—because supply chains are global.

Reliability is a critical aspect of sustainable development (in the context of energy availability). Reliability is defined here as the "ability of the power system to withstand instability, uncontrolled events, or unanticipated loss of system components" [6]. Ensuring reliable and affordable access to electricity while simultaneously mitigating climate change, minimizing local environmental impacts, and realizing other SDGs is a significant challenge. One widely accepted method of assessing most aspects of sustainability is conducting a life-cycle assessment (LCA) [7]. LCA impact categories, which relate to an array of environmental characteristics, such as climate, water stress, biodiversity, aquatic toxicity, and eutrophication, are linked directly to numerous SDGs (#3, #6, #13–15). Many LCA impact categories address broad targets related to integrated water management and protecting and restoring water-related ecosystems. For example, as presented in [8], environmental impact pathways such as climate, water stress, toxicity, and eutrophication can impact local communities, users, and small-scale entrepreneurs, which is directly linked to the SDG #6 target of clean water and sanitation.

When comparing electricity-generation facilities at any location, we need to rely on global supply chains. For example, the extraction and processing of mineral resources and manufacturing of equipment, in many cases, occur in developing economies that are working to achieve SDG goals, whereas the deployment and operation of advanced technologies often occur in developed countries on different continents. The electricity system in Texas is an example of this paradox. Although the grid is dominated by natural-gas-fired generation (43% of installed capacity and 42% of generation in 2022; Figure 1, [9]) using natural gas sourced in Texas, wind and solar equipment is imported mostly from Asia. Wind energy in Texas has been growing and in 2022, accounted for 29% of installed capacity and 25% of generation. Although Texas leads the U.S. in wind generation (nearly 26% of U.S. capacity), solar has been growing faster and in 2022, accounted for 11% of installed capacity and 6% of generation. The interconnection queue includes mostly solar projects, followed by wind and a few gas-fired power plants. Announced capacities can more than double the installed capacity of solar (~15 GW capacity at end of 2022, [9]). Texas has also been adding battery storage at a fast pace and may have more than 10 GW of grid-scale battery storage within several years. Since natural gas supplied to the gas-fired plant is produced in Texas, environmental impacts of the whole supply chain are relatively localized. In contrast, the wind, solar, and battery equipment that will be installed in Texas will have environmental impacts across many geographies of the world, given the global supply chains of this equipment, including the mining and processing of minerals needed for their manufacturing.
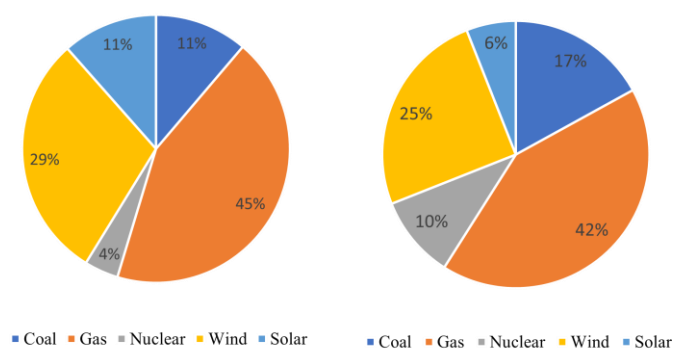

Figure 1. Installed capacity and actual generation in Texas [9].

Many studies have been conducted on sustainable electricity production with different levels of comprehensiveness; technological, temporal, and geographical levels; and in

current and future generation scenarios. For decades, minimizing environmental impacts from electricity generation has been the focus, starting with sulfur dioxide (SO_2), particulate-matter formation (PMFP), mercury, and GHG, particularly carbon dioxide (CO2). In 2020, fossil-fuel combustion accounted for 31% of total CO_2 emissions and 24% of GHG emissions in the U.S. [10], whereas the transportation sector accounted for 33% of CO_2 emissions. Other environmental impacts influence land, water, and air quality, with attendant impacts on human health across the entire supply chain and life cycle of the extraction and processing of natural resources (e.g., natural gas and a long list of minerals, including copper, cobalt, lithium, and nickel); manufacturing materials such as cement, aluminum, and steel used in building power plants; and equipment such as gas turbines, wind turbines, solar PV panels, and batteries.

LCA is an internationally standardized approach used to measure the broader environmental impacts of any product or process in question [11]. Pertaining to this study, a comparative LCA on impacts from generating electricity using several different technologies could identify environmental hotspots in both time and space and along the full supply chain from raw material sourcing to product end of life (or cradle to grave). LCA identifies the distribution of environmental burden between processing stages, different geographic areas, and different environmental media (air, land, water). For complex, multidimensional problems, such as comparing electricity generation options, detailed modeling of all processes, applied dynamically, can require extensive data and many assumptions. The ability to compare different LCA studies is improved using standardized approaches such as ReCiPe 2016 [12] and TRACI [13]. Standardization allows researchers and practitioners to identify limitations, overlaps, gaps, or differences in system boundaries between studies, facilitating a meaningful comparison. Researchers have also studied the environmental impacts extensively—GHG emissions in particular—associated with natural gas production, gathering, boosting, storage, transmission, and processing, all of which are needed before combustion at a combined-cycle gas plant (CCGT). In general, commercially available databases (e.g., Ecoinvent) lack site specificity and, on occasion, the comprehensiveness needed to compare different technologies fully, especially those recently developed and/or without substantial operational experience. Other studies include significant levels of data and detail (e.g., [14–16]) on life-cycle impacts of natural gas extraction and power generation and impacts from gas flaring and leakage. Spath and Mann (2000) [17] discussed basic details such as the land usage and bill of materials for constructing a CCGT plant as they generated their life cycle inventory. Toscano et al. (2019) [18] focused on environmental impacts due to water-conditioning methods in CCGT plants, as well as impacts on water depletion and freshwater, marine, and terrestrial ecotoxicity. Agrawal et al. (2014) [19] pointed out that natural gas extraction, treatment, and transmission lead to additional adverse effects such as carcinogenic and respiratory impacts.

For onshore wind generation, Alsaleh and Sattler (2019) [20] presented a comprehensive LCA of turbines deployed in the U.S., including each turbine life-cycle phase and a consideration of a broad number of environmental impact pathways. They also studied the sensitivity of the impacts to turbine life span. The end of life of wind turbines is generally not well studied, although recent studies [21,22] identify a need for broader environmental audits of wind turbine component disposal by landfilling and recycling. McKenna et al. (2016) [23] reviewed over 300 studies on wind potential assessment and identified geographical and technical limitations of wind energy operation. Jordaan et al. (2021) [16] conducted a meta-analysis of LCAs on electricity generation, focusing on Europe, Asia, and North America. The authors reviewed 251 studies and concluded that, whereas most studies have historically focused on GHG, an increasing number of studies have begun investigating acidification, eutrophication, and human-health impacts. The authors also recommended the better characterization of spatial and temporal drivers of impacts such as transport needs, local environmental conditions (e.g., hydrology), temporal changes in plant operations (intraday, across seasons, over the years), degradation of equipment, and other characteristics that may be unique to any given location. Guidi et al. (2023) [24] also

conducted a review of LCA studies of power generation systems from around the world published in the past ten years, comparing energy technologies solely by global warming potential. Nuclear and wind had the lowest GHG emissions, followed by hydro, solar, and geothermal. These emissions were 1–2 orders of magnitude larger than the emissions from thermal plants using coal and natural gas. The authors identified the need for reducing the environmental footprint of the PV supply chain for this technology to be truly sustainable.

Many studies have presented LCAs of utility-scale PV generation systems. Krebs et al. (2020) [25] reported the GHG emissions and cumulative energy demand of a 10 kW$_p$ multicrystalline silicon PV panel with batteries and control systems. They pointed out that environmental burdens vary across battery types and increase proportionally to battery capacity. Differences across PV panel technologies (chemistries, production processes) and how to account for them in LCAs were addressed by the International Energy Agency [25]. Subsequently, Krebs et al. (2020) [25] identified only one comprehensive life-cycle inventory (LCI) for manufacturing of five different types of PV modules. They also incorporated the global supply chain for different components based in North America, China, the Asia–Pacific region, and Europe. Established companies focusing on solar energy generation were consulted to provide land-use, operational, and installation guidelines, as well as commercial photovoltaic cell types. Singh et al. (2023) [26] recently conducted an LCA of end-of-life options for crystalline silicon and cadmium telluride PV modules and concluded that the environmental impacts of crystalline silicon modules are greater than those of cadmium telluride modules. Ali et al. (2022) [27] conducted an LCA of distributed solar generation in New York based on operational data from 120 facilities. The system starts from raw material extraction and ends with the complete recycling of PV panels at the end of operational life. Results of 10 environmental impacts varied by site location (hence, capacity factor) and system design (panel type, power ratio) were used to estimate all major environmental impacts.

The literature suggests that locations of generation facilities and global supply chains are important for LCA studies, especially for local impacts on air, land, and water. We add to the literature by comparing electricity-generation technology options located in West Texas, a sparsely populated, arid region with natural gas production and high wind and solar resources but a limited capacity to transmit electricity to demand centers in the east. We considered five power plant technologies: combined-cycle gas turbine (CCGT), wind, wind with battery storage, solar photovoltaic (PV), and PV with battery storage. In each option, the comparison assumed equal generation of electricity over the life of the power plant. To approximate equivalency of intermittent and variable wind and solar resources to a thermal plant, which can be dispatched at the request of the electric system operator to ensure real-time balancing of demand and supply, we added battery storage to mimic the dispatchability of the CCGT unit. We are unaware of studies that pursue such generation equivalency, which we consider a key contribution of this paper. In summary, this study focused on addressing the following research questions.

Q1: What is the side-by-side comparison of the life-cycle environmental impacts of five electricity generation options for the facility generating the same amount of electricity annually in West Texas?
Q2: What is the change in environmental impacts, when storage is added to wind and solar plants, to mimic dispatchability of CCGT?
Q3: What is the cradle-to-grave breakdown of environmental impacts at each life-cycle stage across global supply chains?
Q4: What is the sensitivity of environmental impacts to capacity factors for each generation option?

2. Materials and Methods

According to the International Organization for Standardization (ISO) 14040 [28] and ISO 14044 [29], the LCA approach consists of four main phases: (1) goal and scope definition, (2) life-cycle inventory, (3) life-cycle impact assessment, and (4) interpretation

and inferences. These phases are described next. The LCA model calculations used in this study were carried out using the OpenLCA software package (version 1.10.3, Green Delta, Berlin, Germany).
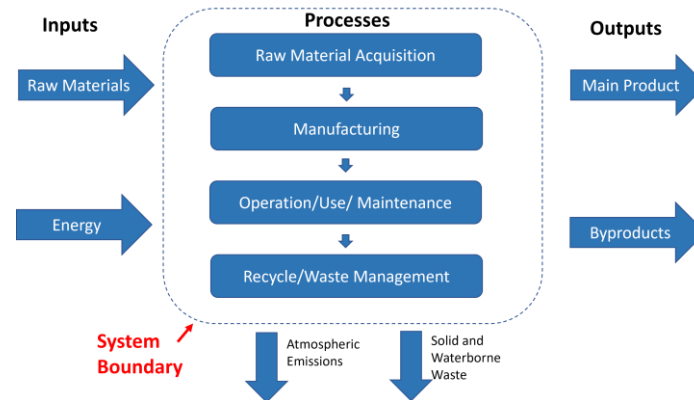
A unit process is represented in Figure 2.

Figure 2. Definition of a unit process.

We define a cradle-to-gate burden vector {B} for a life-cycle inventory per-unit production as in (1):

$$\{B\}ctg = \{B\}mp + \{B\}mnf + \{B\}tr + \{B\}oper \tag{1}$$

where *ctg* stands for cradle to gate, *mp* is material production stage, *mnf* is manufacturing stage, *tr* is transportation, and *oper* is operation. We further define the material production energy of any process or product *{PEj}* as the sum of the input energy of the *j*th component, including materials, fuel, and electricity, as in (2):

$$E_{mp} = \sum PE_j * m_j / C_j \tag{2}$$

where E_{mp} is the material production energy, *j* is the number of components in the process or system, PE_j is the production energy of the *j*th component, m_j is the number of components, and C_j is the production efficiency of incorporating an amount m_j of material *j* into the unit.

We then sum the cradle-to-grave environmental impact of the system for each step within the system boundary for each generating option, as in (3):

$$EI_{ctgrave} = EI_{(sourcing)} + EI_{(processing)} + EI_{(manufacturing)} + EI_{(transportation)} \\ + EI_{(operations)} + EI_{(end\ of\ life)} \tag{3}$$

where *EI* stands for environmental impact, and *ctgrave* stands for cradle to grave.

2.1. Area of Interest (AOI)

The area of interest (AOI) lies in the Permian Basin region of West Texas, U.S.A. (Figure 3), a region with a century-long history of oil and gas development and currently the most prolific hydrocarbon basin in North America. The region, 194,250 km^2 (75,000 mi^2) in area, hosts significant wind and solar resources. The electricity-generation infrastructure is connected to a power grid that is managed by ERCOT (Electricity Reliability Council of Texas), separately from other system operations in the U.S.
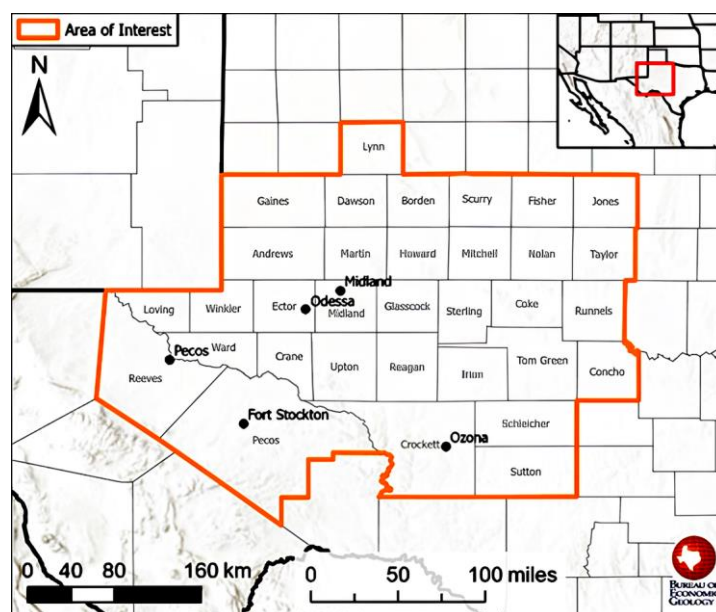
Figure 3. Area of interest.

2.2. Goal and Scope Definition

The goal of this work was to compare life-cycle environmental impacts of three electricity-generating technologies (CCGT, wind, solar PV), along with the use of a battery energy storage system (BESS) paired with wind and solar. The comparative LCA assumed that each generation technology generates an average of 3 terawatt hours (TWh) per year (Table 1). To mimic the dispatchability of the CCGT plant, BESS was used to store electricity from wind and solar and to discharge this electricity on demand. The functional unit was 1 MWh of generation from the system under consideration.

Table 1. Summary of the base case of five power plants assessed in this study.

EGO	Variables	Values
CCGT	Capacity	500 MW
	Capacity factor	68%
Wind	Installed capacity in year 0	1273 MW
	Capacity factor	31%
	Annual degradation	1%/year of turbine efficiency
Solar PV	Technology	Monocrystalline
	Installed capacity in year 0	1435 MW
	Capacity factor	26%
	Annual degradation	0.6%/year of decay of panels
Wind + BESS	Wind system as defined above	
	Battery	Lithium iron phosphate (LFP)
	Storage capacity	500 MWh
Solar PV + BESS	Solar PV system as defined above	
	Battery	Lithium iron phosphate (LFP)
	Storage capacity	500 MWh

The base case was generation from a 500 MW capacity CCGT power plant operating as a baseload facility at a 68% capacity factor for a period of 30 years (~90 TWh). The capacity factor is the average of two CCGT power plants operating as baseload facilities in the AOI over the 2018–2022 (according to EIA, the nationwide average capacity factor for CCGT power plants built between 2010 and 2022 was 64% [30]) period. Wind and solar-PV power plants are sized for generating 90 TWh of electricity over 30 years at 31% and 26%

capacity factors, respectively, again based on the performance of wind and solar facilities in the AOI (see the Sensitivity Analysis Section for details). Plants are oversized to allow for annual degradation of equipment so that the average annual generation would be 3 TWh (described in further detail in Sections 2.3.2 and 2.3.3).

LCA system boundaries encompass the extraction of natural resources (natural gas, mining of minerals needed to manufacture PV panels, wind turbines, and batteries) and processing of extracted resources. Many of these activities, such as separation of hydrocarbon molecules and processing of ore and mixing of chemicals, use heat or other combinations of energy to produce a specific refined product or to obtain a product to help in further processing of a product needed. Manufacturing includes all processes needed to build power plants, including the building of gas turbines, a wind-turbine gearbox, nacelle and blades, solar cells, and panels and batteries. We included a grid mix at the location where the equipment was assembled and different modes of transporting materials to the facility and equipment from the manufacturing facility to the deployment site. After deployment, operations then include those processes involved in the generation of electricity and maintenance of the power plants, including replenishment of the fuel cycle (e.g., new wells needed to produce natural gas) and components (e.g., new battery packs to address degradation of battery capacity).We also captured the environmental impacts associated with transporting ore from source to processing, processed ore to manufacturing, manufactured equipment to the power plant site, and equipment to landfills after end of life. In each segment, detailed processes were considered. We also considered end-of-life disposal of power plant components. Owing to the considerable inconsistency across recycling practices of different technologies and the limited data available on emerging recycling practices, we did not consider the recycling of any component.

2.3. Life-Cycle Inventory

Data for processes and products studied in the life-cycle inventory (LCI) analysis were sourced from the U.S. Department of Energy (DOE), National Energy Technology Laboratory (NETL), and National Renewable Energy Lab (NREL), reports from the United Nations (e.g., United Nations Environment Programme), company reports, and peer-reviewed research. LCIs for secondary processes and their upstream processes were filled in using the Ecoinvent database (v. 3.8, [31]). Individual elementary flows were verified for all upstream processes to avoid missing an association of impacts for any category. OpenLCA software (v. 1.10.3, GreenDelta, Berlin, Germany) was used for carrying out LCA analysis.

In this study, we built the inventory for the LCA using references and assumptions, as well as Ecoinvent (Table 2). The following sections details the LCI of the energy-generating options that were studied.

Table 2. Data/information sources of the life cycle-inventory (in addition to Ecoinvent).

EGO	Process	Reference for LCI	Notes
CCGT	Production	[14]	Same LCI with addition of water and land based on [32–34].
	Gathering, boosting	[14]	
	Processing	[14]	LCI is the same as that presented by authors in various works for the Permian region.
	Transmission	[14]	
	Storage, distribution, and production	[14]	
	CCGT plant operation	[14]	
	CCGT plant decommissioning	[17]	Same numbers as referenced; bulk density for concrete = 2400 kg/m³. Mass numbers are the same as cited in document. End of life (decommissioning) carried out by converting metals and concrete to scrap.
	CCGT plant construction	[17]	
Wind	Tower	[35]	Same LCIs as presented in the paper. LCI unit items were based and modelled as independent of location. Total number of wind turbine units depends on the capacity factor to produce 3 TWh.
	Nacelle	[35]	

Table 2. *Cont.*

EGO	Process	Reference for LCI	Notes
	Foundation	[35]	
	Operation	[35]	
	Rotor	[35]	
	Operation	[35]	
Solar	Metallurgical-grade silicon	[32]	LCIs modelled as presented for the U.S.-based energy-generation options for the monocrystalline and Cd-Tl types of solar panels. Scaling based on two independent consultants working in solar-field applications in U.S. land usage assumed 5 ac per MW of installed capacity, with 3 million panels needed to produce 90 TWh over 30 yr of life.
	Solar-grade silicon	[32]	
	Single-crystalline silicon	[32]	
	Solar-panel frames	[32]	
	Inverters and transformers	[32]	
	Silicon wafers	[32]	
	Photovoltaic cells	[32]	
	Solar-farm operation	[32]	
Lithium-Ion Battery	Lithium concentrate	[33]	Inventory for battery based on electric vehicle and upscaled to match grid-scale battery storage system.
	Lithium carbonate	[33]	
	Cathode	[33]	
	Active material	[33]	
	Battery pack	[33]	
	Iron phosphate	[33]	
	End of life	[33]	

2.3.1. Combined-Cycle Gas Turbine (CCGT)

Inventories associated with plant construction were based on [17], whereas those of natural gas were based on [14]. These LCIs target GWP and are comprehensive, with numerous scenarios covering almost all natural-ga- producing regions in the U.S. The area per pad of 15,000 m^2 was taken from [34,36–38], and we assumed a base case of five wells per pad as the midpoint for the Permian region. Along with the pads themselves, we accounted for support infrastructure (e.g., roads, pipelines, ancillary setups) using a multiplier of 2.2 × the pad area for land usage per unit of natural gas produced [34]. Water needed to hydraulically fracture each natural gas well was estimated using a well-by-well analysis in the Permian Basin and was within the range of Du et al. (2022) [39]. We used a proportion-weighted, average water volume to extract the gas, assuming an AG–NAG mix in the Permian Basin of 79% to 21%. A detailed LCI system boundary can be found in the Supplementary Materials (Figure S1). We accounted for the transportation of materials between life-cycle phases. We also assumed that the total weight of the CCGT facility was 381 tons, 90% of which is sourced outside the U.S., mainly low-alloyed steel, aluminum, and cast iron from Canada, South Korea, and Mexico, 31% (106 tons) of which is through sea transport of 11,400 km, and 69% (236 tons) of which is over land spanning 2000 km. The amount of material carried over the land route is almost 2.5 times that of the material carried over the sea.

2.3.2. Wind Turbine (WT)

A 3 MW capacity wind turbine was used in this work, given that the average turbine capacity installed in Texas in 2021 was 2.9 MW, with about 18,552 actively operating turbines in the state ranging in capacity from 2.0 to 4.8 MW [40]. Using a base case capacity factor of 31% (Table 1), we assumed construction of 424 3 MW turbines. Staffell and Green (2014) [41] suggested 1.6% degradation using a UK database, and Hamilton et al. (2020) [42] suggested 0.5% for older vintages and 0.2% for newer vintages. We overbuilt the facility in year 0 to account for 1% annual degradation (considering earlier references) in turbine performance so that the total generation over 30 years would be about 90 TWh. The base case capacity factor was assumed to be 31%. Inventory was modelled separately, with

the quantitative reference being the turbine unit itself, with recently published literature being used (e.g., [20,22,32,43,44]). The distance of sea and land transport was assumed to be the same as that of the CCGT. We estimated that 28% of the material for each turbine was sourced from outside the U.S., including chromium steel, aluminum, and cast iron from Canada and Mexico [45], 39% of which was transported over land and 61% over sea. The weight of material for each turbine to be transported was 1384 tons.

We then estimated the LCI for a single unit and multiplied the values by the total number of units needed in year 0. The concrete used in each tower foundation (125 m^3 of concrete per MW [46]) was 50 MPa, high-strength material, with an assumed concrete density of 2400 kg/m^3. The operation of wind turbines requires nominal maintenance and repair that includes crew travel; we assumed a 50 km travel distance per year. At the end of 30 years, all parts are decommissioned, with metal parts turned into scrap, concrete into waste concrete, and blades incinerated. A detailed LCI system boundary is included in the Supplementary Materials (Figure S2).

2.3.3. Solar-Photovoltaic (PV) Systems

Solar-PV system capacity was rated at 1435 MW, accounting for an annual degradation of 0.6% [47] and a base case capacity factor of 26%. A total of 3,262,117 panels (440 W each) were needed, and major processes were the growing of silicon from mining of quartz to mono- and multicrystalline forms. These were then transformed into wafers and cells and followed by panel and laminate assembly, with monocrystalline and cadmium telluride technologies being considered for power generation. These were the most efficient, commercially viable options being deployed around the world at the time of this analysis. The LCI for these processes was taken from Frischknecht et al. (2016) [32], and land use was 2.02 hectares (5 acres) per MW of generation capacity [48]. Each panel area measured around 7.02 km^2, with each panel weighing 18.1 kg (40 lb), and all were imported from China. Most (98%) of the panels were transported by sea, the remaining over rail and road. Based on feedback from solar industry experts, we assumed that five full-time technicians would be needed for site maintenance. Also, a total of 10,000 km of driving per year per technician was assumed as an operational cost, and landscaping in the solar generating plant was the only other maintenance activity considered (i.e., periodic cleaning of solar modules was not considered). At end of life (decommissioning), we assumed that removing one solar module, stacking it on pallets, and loading by forklift would take about 10 min and would be followed by shipping to landfill. A detailed LCI system boundary is included in Supplementary Materials (Figure S3).

2.3.4. Battery Energy Storage Systems

Lithium-iron phosphate (LFP) batteries with 500 MW capacity were the energy storage system used for this study. BESS delivers energy for 4 h daily for 30 years or about ~22 TWh. To account for battery degradation and maintain the same dispatch capability, the original battery was augmented with additional storage capacity in the 3rd, 7th, and 14th year before a complete replacement in the 21st year (Table 3). For wind + BESS and solar + BESS systems, we assumed that batteries would be charged from solar and wind sources during excess generation hours (and not from the grid). The battery installed capacity was higher than the required capacity, with cell degradation and efficiency being considered. Augmentation ensured that the usable capacity of the battery would be retained at 100% in each time interval. A detailed LCI system boundary is included in Supplementary Materials (Figure S4).

Table 3. Battery-augmentation rate used for the analysis.

Year End	Battery Capacity (% of Rating)	Augmentation (% of Rating)	Battery-Installed Capacity (% of Rating)	Usable Capacity (% of Rating)
0	100	-	120.5	100
3	88.7	10	118.0	100
7	82.0	10	119.3	100
14	74.5	15	123.3	100
21	64.9	112 (Battery replacement)	122	100

2.4. Life-Cycle Impact Assessment

With the LCI established for each process, life-cycle impact assessment (LCIA) then quantifies and groups the effects of LCI throughout the product life cycle into a tractable number of impact categories, which can then be either ranked or weighted based on the relative importance and nature of the specific questions being asked.

We used the characterization factors from ReCiPe 2016 [12] to quantify the environmental impact relative to a baseline condition per unit of functional unit (in our case, MWh of electricity generation) (Table S1). The ReCiPe 2016 midpoint H (hierarchist) LCIA method used in this study is based on a scientific consensus of time frame and likelihood of impact mechanisms. Impact categories included in the analysis are shown in Table 4.

Table 4. Impact categories considered in this study.

Impact Category	Abbreviation	Unit	Damage Pathways
Fine particulate-matter formation	PMFP	kg PM2.5$_{eq}$	Increased respiratory illness
Fossil resource scarcity	FFP	kg oil$_{eq}$	Scarcity in fossil resources on Earth
Freshwater ecotoxicity	FETP	kg 1,4-DCB	Loss of plant and aquatic life; increased risk of cancer
Freshwater eutrophication potential	FEP	kg P$_{eq}$	Loss of aquatic species
Global warming potential	GWP	kg CO$_{2eq}$	Increased flood risk, human disease, species decline
Human carcinogenic toxicity	HTP$_c$	kg 1,4-DCB	Increased toxicity and human disease
Human noncarcinogenic toxicity	HTP$_{nc}$	kg 1,4-DCB	Increased toxicity and human disease that are noncarcinogenic
Ionizing radiation	IRP	kBq Co-60$_{eq}$	Increased DNA damage
Land use	LOP	m^{2}a crop$_{eq}$	Increased land footprint
Marine ecotoxicity	METP	kg 1,4-DCB	Loss of plant and aquatic life; increased risk of cancer
Marine eutrophication potential	MEP	kg N$_{eq}$	Loss of aquatic species
Mineral resource scarcity	SOP	kg Cu$_{eq}$	Scarcity of minerals on Earth
Ozone formation/human health	OFHH	kg NOx$_{eq}$	Increased threat to human health
Ozone formation/ Terrestrial ecosystems	OFTE	kg NOx$_{eq}$	Increased threat to terrestrial ecosystems
Stratospheric ozone depletion	ODP	kg CFC-11$_{eq}$	Increased risk of disease
Terrestrial acidification potential	TAP	kg SO$_{2eq}$	Loss of plant life
Terrestrial ecotoxicity	TETP	kg 1,4-DCB	Loss of plant species
Water consumption potential	WCP	m^3	Loss of aquatic species; malnutrition

2.5. Sensitivity Analysis

Although a strong rationale or sufficient data were not always available to assess the sensitivities of all inputs, data were available on the capacity factor of power plants in the AOI over the 2018–2022 period. The capacity factor will impact the installed capacity of facilities needed to meet our research design requirement of lifetime generation equivalency. Thus, given the strong connection between facility capacity and the environmental load for sourcing and constructing the facilities themselves, as well as an uncertain capacity factor of our facility in question, we conducted a sensitivity analysis to determine environmental impact. Fluctuations in capacity factor (from year to year and facility to facility) were due to several factors, including changes in electricity load in the region versus export needs, the availability of transmission capacity to export, plant operational issues, and market conditions. In our assessment, the wind capacity factor was based on the average performance of wind power plants in the AOI during the 2018–2022 period and excluded facilities performing below/above two standard deviations of the mean capacity factor. To

determine the mean solar-PV capacity factor, with a large sample size, we considered only facilities in the AOI that generated electricity for a full year in 2022 (The number of solar power plants that generated electricity for a full year were 7, 12, 16, 28 and 45 in 2018, 2019, 2020, 2021, and 2022, respectively) and excluded facilities performing below/above two standard deviations of the mean capacity factor. The resulting analyses of all power plants in the AOI led to a mean and upper/lower values of capacity factors of CCGT (mean 68% and range between 56% and 76%), wind (mean 31% and range between 14% and 48%), and solar PV (mean 26% and range between 21% and 31%) (Table 5).

Table 5. Sensitivity scenarios for the three energy-generating options.

EGO	Scenario	Capacity Factor (CF)	EGO Capacity (MW)
CCGT	Minimum CF	56%	612
	Base case	68%	500
	Maximum CF	76%	451
Wind Turbine	Minimum CF	14%	2819
	Base case	31%	1273
	Maximum CF	48%	822
Solar PV	Minimum CF	21%	1777
	Base case	26%	1435
	Maximum CF	31%	1204

3. Life-Cycle Assessment Results

The detailed LCA results with all 18 impacts on each power plant can be found in the Supplementary Materials (Figures S5–S12, Table S2). Here, we compare the five power plant options to answer our first three research questions (per MWh impacts tabulated in Table S3) and we compare environmental impacts (Figure 3) to help answer Q1 and Q2. The results showed that the impacts from CCGT were the highest in fossil-fuel resource scarcity, global warming potential, ozone formation (both types), terrestrial acidification, and water consumption. For GWP, CCGT emissions were orders of magnitude larger than those of all four of the other options. When compared with those of wind and solar facilities without battery storage, emissions of particulate matter from CCGT operations were also higher. Land use for CCGT was higher than that of wind use but less than that of solar.

Adding battery storage to wind and solar facilities increased their impacts significantly. Without battery storage, wind, solar, and CCGT facilities had similar impacts in human noncarcinogenic toxicity and land use. Although the absolute levels were significantly lower than those of plants with BESS added, human carcinogenic toxicity, ionizing radiation, marine ecotoxicity, marine eutrophication, mineral resource scarcity, and stratospheric ozone depletion of wind and solar facilities were orders of magnitude larger than those of CCGT. The charts for the 18 environmental impacts are shown in Figure 4.

Battery storage, because of current technology and the global supply chain, magnifies certain impacts (Q2). For example, when wind and BESS are combined, GWP increases 208%, and water consumption and PMFM increase 249%. Also, sourcing and processing of batteries significantly impact noncarcinogenic emissions and marine and terrestrial ecotoxicity. Impacts from BESS manufacturing are prominent in noncarcinogenic emissions, while other impacts are prominent in the PV storage system, with a 167% increase in GWP and 210% in PMFM. Other impacts are also increased due to BESS integration.
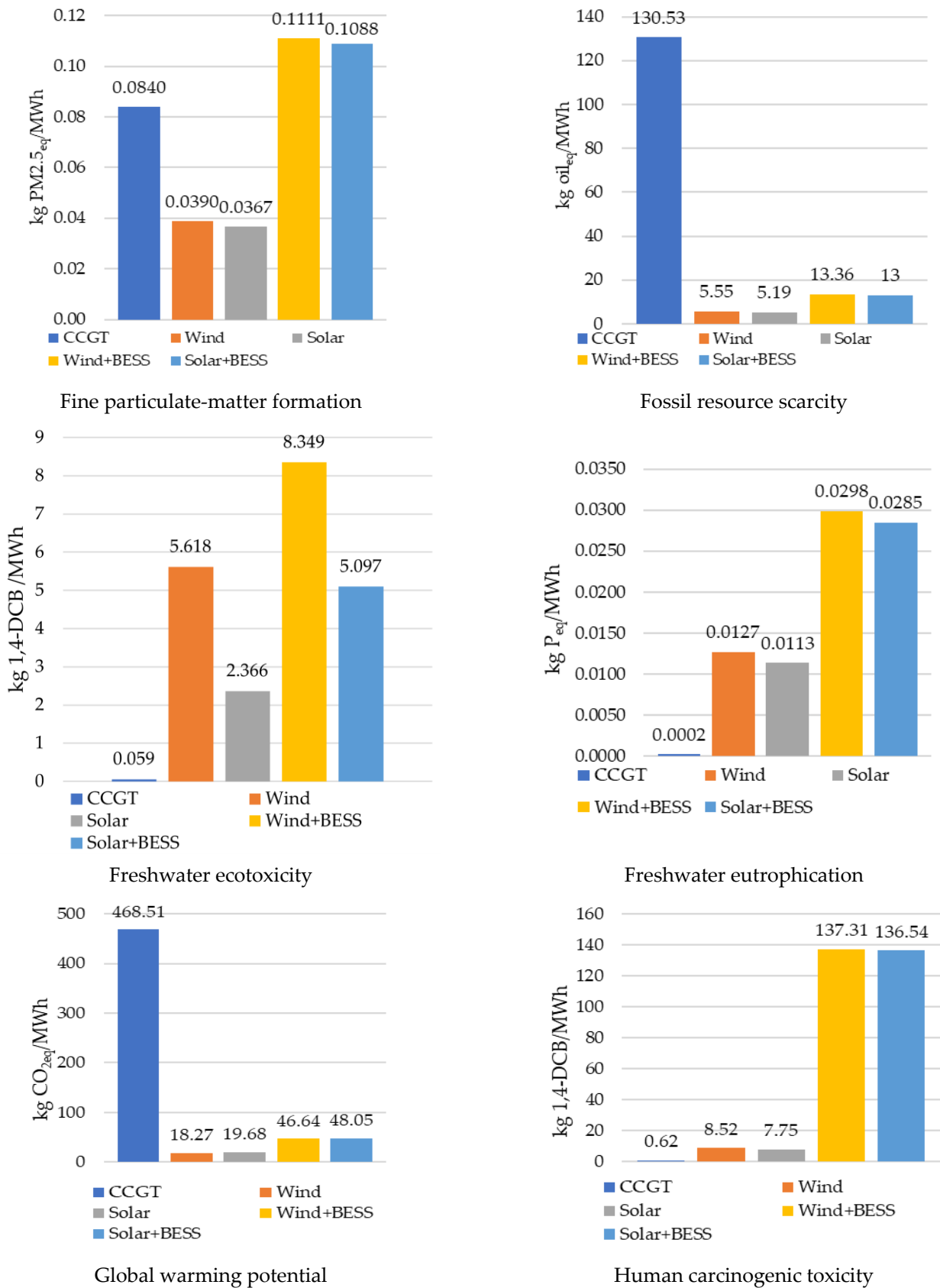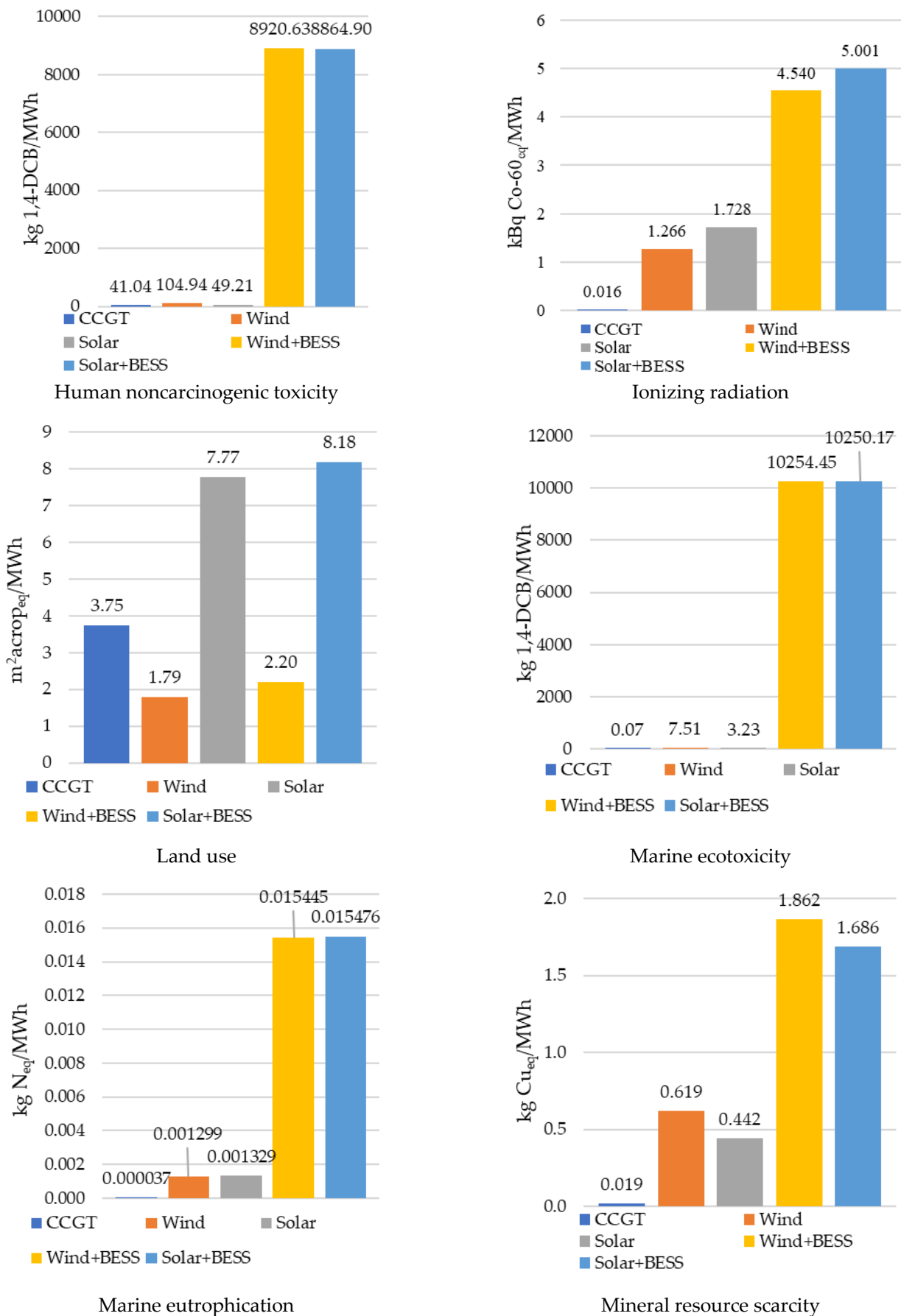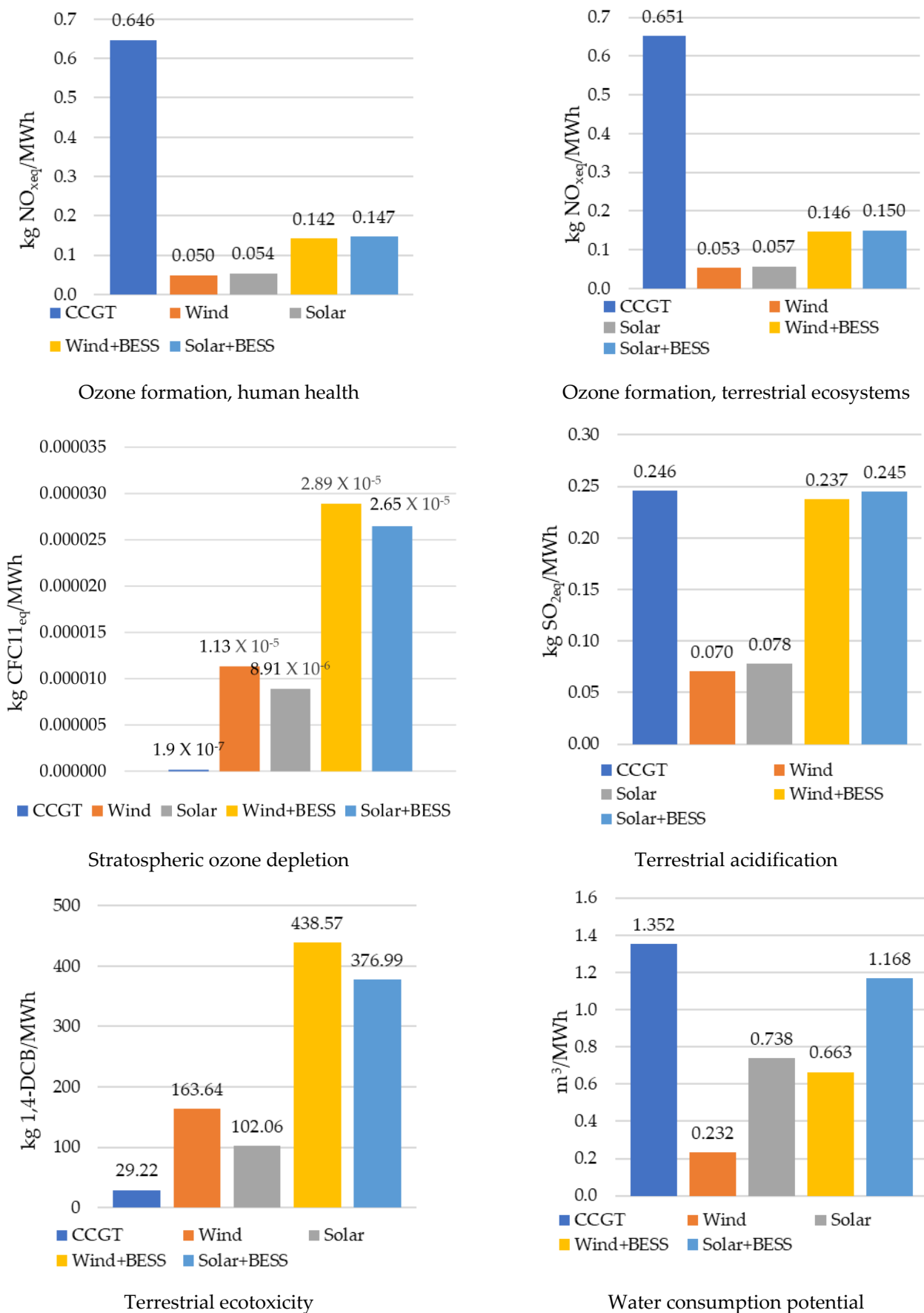
Fine particulate-matter formation

Fossil resource scarcity

Freshwater ecotoxicity

Freshwater eutrophication

Global warming potential

Human carcinogenic toxicity

Figure 4. *Cont.*

Human noncarcinogenic toxicity

Ionizing radiation

Land use

Marine ecotoxicity

Marine eutrophication

Mineral resource scarcity

Figure 4. *Cont.*

Ozone formation, human health

Ozone formation, terrestrial ecosystems

Stratospheric ozone depletion

Terrestrial acidification

Terrestrial ecotoxicity

Water consumption potential

Figure 4. Environmental impact comparison for the five electricity-generation options under study.

At the same time, opportunities are available for reducing impacts. Comparison of the distribution of impacts across life-cycle phases is a useful step for focusing attention on identifying these opportunities and answering Q3. Note that most of the impacts associated with CCGT occurred during sourcing and operations phases (Figure 5). Increasing combustion efficiency and adding carbon capture can reduce many of these impacts. Moreover, increasing flaring efficiency while reducing venting and fugitive methane emissions across the natural gas supply chain will reduce GWP and other air emissions. Note that most impacts associated with wind energy generation occurred during the processing of raw materials needed to manufacture wind turbines, blades, and other equipment (Figure 6).
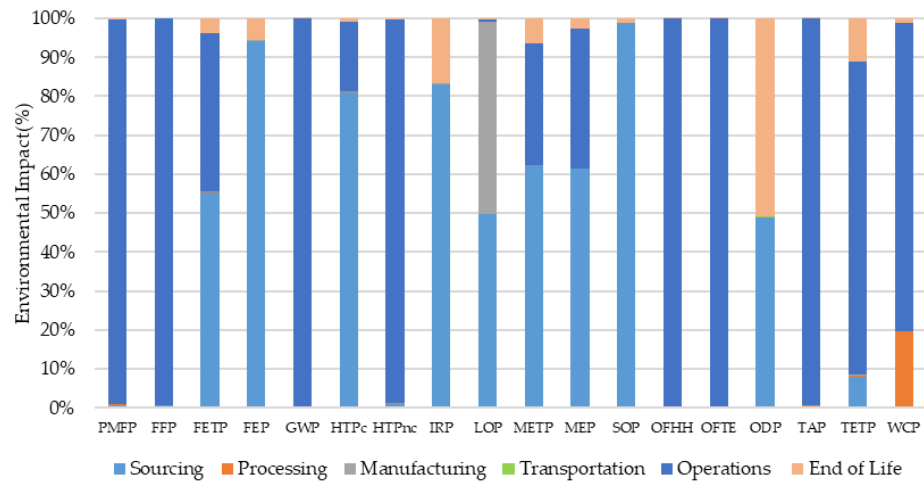
Figure 5. Percentage environmental impacts for CCGT.
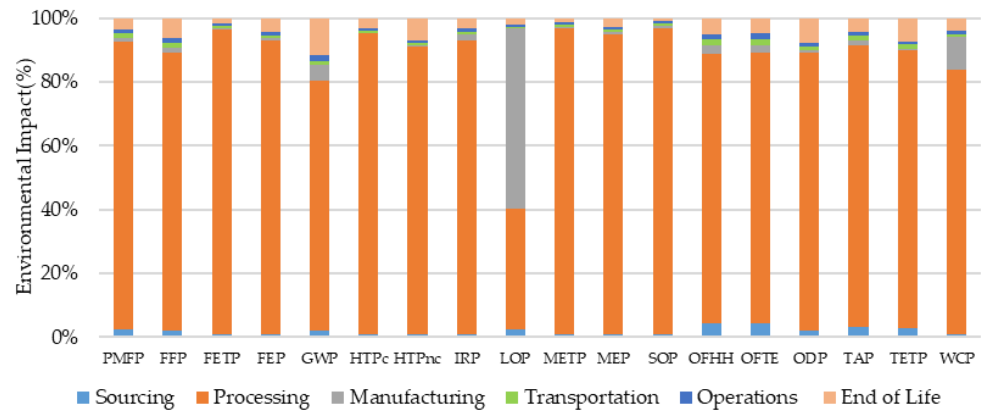
Figure 6. Percentage environmental impacts for wind-turbine generation (WTG).

Increasing efficiency of ore processing and switching to lower-emission energy sources at these facilities will reduce many of these impacts. Impacts associated with solar PV facilities (Figure 7) were distributed across three life-cycle phases in a somewhat declining order: sourcing, processing, and manufacturing. This distribution suggests opportunities to reduce the impacts across all three phases and the transportation that connects them with an increase in process efficiencies and a switch to lower-emission fuels where feasible. Sourcing of materials for BESS dominated impacts in wind + BESS and solar + BESS systems (Figures 8 and 9). Improving process efficiencies at mining sites and metallurgical processing facilities while switching to lower emissions fuels can offer real solutions, and observations from industry news seem to substantiate these recommendations.
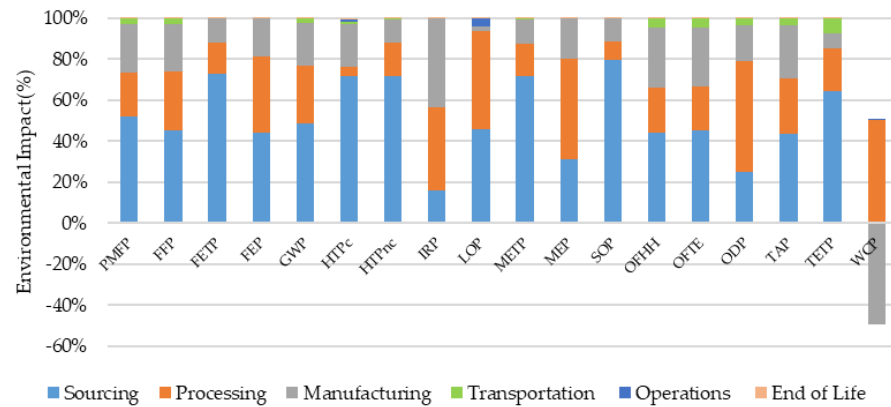
Figure 7. Percentage environmental impacts for PV panels.
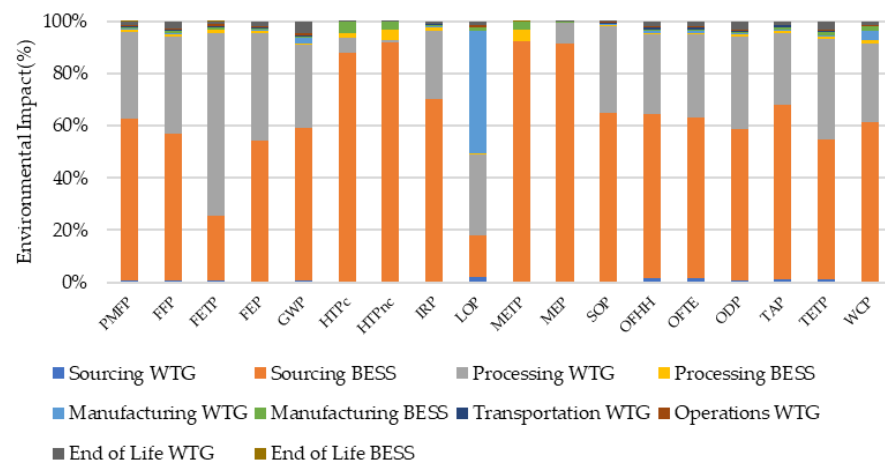
Figure 8. Percentage life-cycle environmental impacts of the WTG and BESS combination, phase wise.
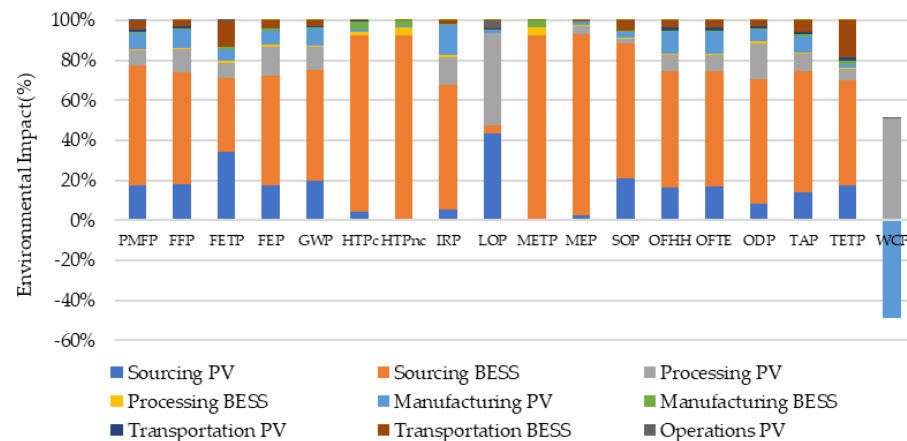
Figure 9. Percentage life-cycle environmental impacts of the PV and BESS combination, phase wise.

In the sensitivity analysis, we could also answer Q4. As discussed earlier, most environmental impacts associated with a CCGT power plant occurred during sourcing of natural gas and the operation of power plant phases (Figure 5). Regardless of the installed capacity of the power plant, our requirement of 3 TWh annual generation requires the same supply and combustion of gas across the scenarios and, hence, the same number of wells and other upstream activities. Changes in many emissions (e.g., PMFP, GWP) are therefore due to construction of the facility and differences in the amount of cement, steel, and other materials for finalizing the plant. Results showed a decline in facility capacity of 18.3% when the CF increased from 56% to 68% (a 21.4% increase) and a 9.8% decline in facility

capacity when the CF increased further from 68% to 76% (11.7% increase). The decline in facility capacity was directly proportional to the increase in CF, translating to reductions in several, but not all, environmental impacts. For example, PMFP, GWP, FFP, and other emissions directly related to combustion were essentially unchanged. Only those pathways related to facility construction were proportionally reduced (Figure 10).
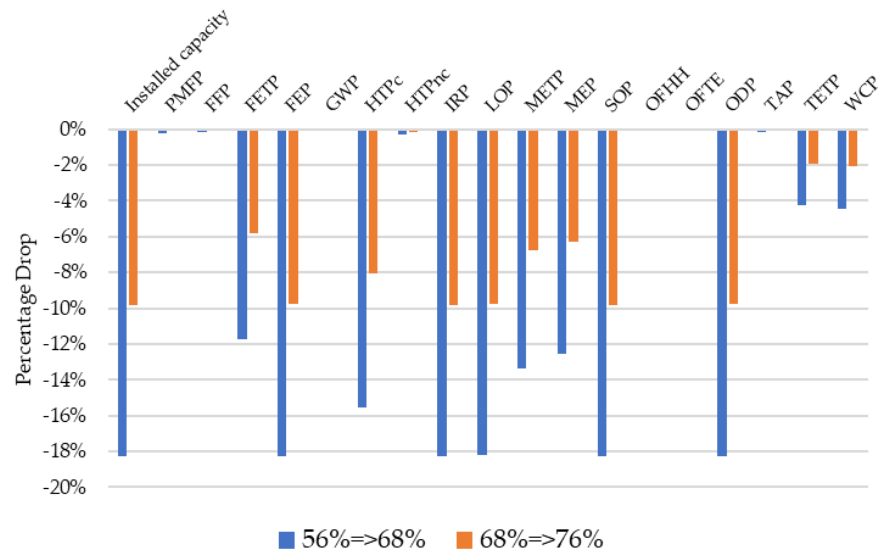
Figure 10. Percentage decrease in per-MWh impacts of CCGT with an increase in capacity factor.

Most environmental impacts associated with the solar-PV power plant occurred during the sourcing and processing of raw materials and equipment manufacturing and facility construction (Figure 6). As such, reducing the installed capacity because of higher CF led to about a 10% decline in most impacts, except for water consumption, which declined 20% when CF rose from 21% to 26%. These declines were less than the decline in installed capacity (~19%), except for water consumption. A similar pattern emerged when CF increases from 26% to 31%, and installed capacity needed declined by about 16%. Strikingly, water consumption declined by 35% (Figure 11). The detailed numbers are shown in Supplementary Materials (Tables S4–S8).
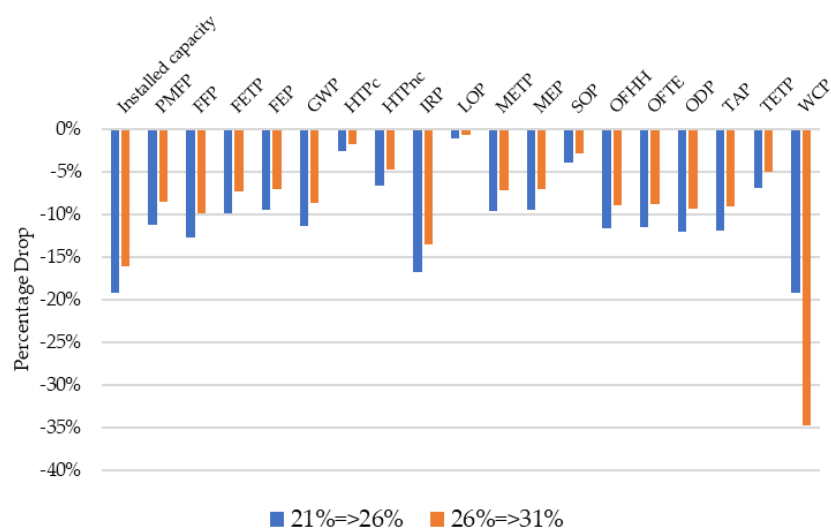
Figure 11. Percentage decrease in per-MWh impacts of solar PV system with an increase in capacity factor.

The processing phase dominated impacts of the wind power plant, accounting for 80% to 95% of all impacts, except for land use (Figure 6). As a result, impacts declined proportionally to the decline in the installed number of turbines as we tested higher CFs. As an artifact of our modelling of an individual 3 MW turbine, proportionality was the same: results showed a 55% decline in the installed number of turbines and all impacts when CF increased from 14% to 31% and 35% decline in all impacts when CF increased from 31% to 48%. Hence, we do not provide a graphic analogous to Figures 10 and 11. Our approach to this analysis probably missed the economies of scale associated with building larger numbers of turbines, but the higher-level conclusion that environmental impacts associated with wind power plants are more sensitive to CF changes than CCGT and solar-PV plants seems justified.

4. Interpretation and Inferences

The results suggest that different generation technologies impose various environmental burdens across their life cycles and associated global supply chains. Trade-offs across geographies and over time were identified: these are weak points because mining, drilling, processing, transportation, manufacturing, and generation facilities needed to supply future electricity depend on procuring a social license to operate from host communities. A focus on environmental, social, and governance (ESG) factors are growing among the financial community, who may become increasingly reticent to fund projects that lack host community approval [49]. Increasingly, companies are expected to disclose nature-related impacts in financial or other reporting [50]. The cradle-to-grave LCAs of our energy options allow us to identify, albeit at a high level, weak points across global supply chains. These weak points can help direct resources toward in-depth environmental and social impact assessments of individual projects based on location- and project-specific data. In particular, the tolerance of host communities to any of the impacts need to be surveyed. In fact, early engagement with host communities has become a best practice for most energy and extractive companies, especially where civil society and regulatory frameworks are well established. Fortunately, trade-offs often suggest opportunities to reduce or even mitigate impacts where they occur while also ensuring that progress toward achieving most SDGs is maintained for communities around the world.

In this section, we want to focus on these opportunities and offer a selection of possible mitigation options across the global supply chains of the five power plants we analyzed. Several developments present opportunities to reduce emissions along the natural gas supply chain and during gas combustion in a CCGT facility for power generation. Many countries now pursue regulations to reduce flaring, venting, and fugitive methane emissions [51]. For example, the U.S. Inflation Reduction Act imposes large fines on fugitive methane emissions that do not comply with new regulations from the U. S. EPA. A Global Methane Pledge was signed by 155 countries as of early 2024 [52]. Several other initiatives, including those by the U.N. and large oil and gas companies, intend to reduce emissions from their operations. Some technologies that reduce methane emissions are already available, and others are under development [53]. Reduced flaring, venting, and fugitive methane emissions from the Permian Basin would, in turn, reduce our GWP and PM calculations. However, most emissions stemming from the full life cycle of a CCGT plant occur during the combustion of natural gas for power generation not from the upstream production side. Modern gas turbines and combined-cycle designs have lower heat rates (higher efficiency in converting fuel to electricity) [54], which reduce per-MWh emissions commensurately with decline in heat rate.

A much larger reduction in GWP emissions can be achieved by including carbon-capture technologies and sequestering the carbon below ground (known as CCS). However, geologic storage may not be available near a CCGT plant, adding a CO_2 transportation cost. Also, alternative uses of captured CO_2 are under development and if they can be scaled up, offer a revenue stream that could support CCS investment (see Cameron Hepburn et al. (2019) [55] for a review of CO_2 utilization options). For our CCGT case, geologic storage

opportunities were easier to identify in the Permian Basin than elsewhere. On the other hand, CCS added a parasitic load to the power plant (~30%), which needs to be considered for CCGT economics and for reliable operation of the electricity grid.

As reported above, most environmental impacts associated with wind, solar, and BESS facilities occur during sourcing of raw materials, their processing and refining, and, to a lesser extent, the manufacturing of equipment. Many of these impacts are associated directly with local air emissions of particulate matter, NO_x, and SO_x but also the use of water resources and discharges to land and waterways. Mitigation or reduction of these impacts is possible by following best resource extraction and processing practices, including using new technologies to increase resource recovery, reduce energy and water use for mining and processing, and mitigate impacts to host community environments. Transportation of resources between life-cycle phases could also add significantly to certain impacts because of the large distances and dominant use of diesel fuel.

Mitigation opportunities can therefore be found by increasing the efficiency of energy-dense mining and processing operations and switching to lower-emission fuels for processing, manufacturing, and transportation. For example, in New Caledonia, efforts are under way to increase the share of solar electricity to power nickel-mining operations [56]. Changes to lithium-ion battery (LIB) chemistries and alternatives to LIBs [57] are being pursued, partly to reduce the environmental impacts associated with some inputs, such as cobalt [58]. The shipping industry is pursuing LNG, methanol, ammonia, and other fuels to reduce emissions, but all options include trade-offs across cost, performance, and environmental impact dimensions (e.g., see Chin Law et al. (2021) [59]).

Environmental impacts from mining, processing, and manufacturing are often larger when these activities occur in locations with weak regulations or coal-heavy electric power generation and/or by private or partly or fully state-owned companies that are not publicly traded in major exchanges around the world (hence, not subject to as much public or financier scrutiny as publicly traded companies) [60]. As such, onshoring or friend-shoring some of these supply chains has become a strategy, especially in the U.S. [61].

This work adds to the discussion of technological developments that will continue to change the technological landscape and supply chains for power-generation alternatives. Future LCAs will continue to be needed to account for these changes and, thus, to identify and shed light on weak links and opportunities that further reduce impacts on all host communities involved.

5. Conclusions and Recommendations

Sustainable development of electricity-generating options should be effectively assessed for present and future systems, at both global and local spatial scales. To meet this need, the LCA method has been applied in accordance with ISO standards to quantify and compare environmental impact profiles for electricity-generating options. We used facilities located in West Texas as a case study site. The novelty and contributions of this study to address the research gaps are the following:

- Comprehensive LCA of five electricity generating options for West Texas: CCGT, wind, solar PV, wind + BESS, and solar PV + BESS. To approximate equal grid value for all options, our work did the following:
  - Compared environmental impacts on systems that generate approximately equal lifetime amounts of electricity;
  - Added electricity storage to wind and solar generation facilities, rendering them nearly as dispatchable as CCGTs.
- Detailed cradle-to-grave analysis of 18 environmental impacts of each option for discrete comparative assessment of different options across life-cycle phases, excluding recycling.

Throughout the study, our results highlight the importance of location when determining the level of each of the 18 impacts across each segment of the supply chains. We

considered and recognized the difference among communities bearing different environmental impacts (addressing Q1). Each technology led to the highest impacts in several categories, with differences being very large. For example, GWP from CCGT was orders of magnitude larger than the GWP of all the four other options. CCGT also had the highest impacts in fossil-fuel resource scarcity, ozone formation, terrestrial acidification, and water consumption. On the other hand, impacts from wind and solar technologies were orders of magnitude larger for human carcinogenic toxicity, ionizing radiation, marine ecotoxicity, marine eutrophication, mineral resource scarcity, and stratospheric ozone depletion when compared to CCGT. Adding battery storage increased impacts of wind and solar facilities; some impacts increased multifold (addressing Q2).

For answering Q3, a key distinction emerges between CCGT and other technologies. For CCGT, most impacts occurred during the sourcing of natural gas and electricity generation (operations). In contrast, operations of wind and solar technologies contributed little, with or without BESS. Sourcing and processing minerals, and, to a lesser extent, equipment manufacturing, dominated the environmental footprint of wind, solar, and BESS.

This contrast caused the divergence we observed when we assessed the sensitivity of impacts to the capacity factor of the power plants (addressing Q4). With CCGT, impacts that are almost exclusively caused by combustion of gas for power generation (GWP and other air emissions) did not change much with capacity factor because we assumed the same level of generation. Lower capacity factors for wind and solar led to mostly proportional increases in almost all impacts because they were caused by an increase in sourcing and processing of materials and equipment manufacturing. Naturally, higher capacity factors for wind and solar reduce impacts because less capacity is needed to generate the same amount of electricity. Hence, it is highly desirable to site wind and solar facilities where wind speeds and solar irradiance are high quality, grid interconnection is seamless, and transmission congestion is unlikely to lead to curtailment.

Finally, we recognize that the absolute levels of impacts and relative ranking of technologies may become secondary considerations to community acceptance. The ability to develop mining, drilling, processing, transportation, manufacturing, and generation facilities needed to supply future electricity needs depend on procuring and maintaining the social license to operate from communities hosting these facilities. Local opposition can deter investment from private and public lenders who use ESG criteria to allocate their capital funds. Furthermore, delays in one segment of global supply chains may create costly bottlenecks and alter environmental outcomes, especially when resources and equipment are procured from locations with weaker regulatory infrastructure. The cradle-to-grave LCAs of our energy options allowed us to identify, albeit at a high level, weak points across global supply chains. Policy and investment decision makers, although not explicitly addressed here, can target their efforts to these weak points.

Supplementary Materials: The following supporting information can be downloaded at https://www.mdpi.com/article/10.3390/en17050992/s1: Figure S1: System boundary of the CCGT plant under study; Figure S2: System boundary of the wind turbine under study; Figure S3: System boundary of the PV system under study; Figure S4: System boundary of the BESS under study; Figure S5: Per-MWh environmental impacts of CCGT (500 MW); Figure S6: (a) Single-score environmental impacts of CCGT; (b) Single-score environmental impacts of sea and land transport for CCGT; Figure S7: Per-MWh environmental impacts of the 3 MW (424 nos) wind turbine; Figure S8: (a) Per-MWh single score results/life-cycle phase for the WTG. (b) Single-score environmental impacts of sea and land transport for the WTG; Figure S9: PV panel production process; Figure S10: Per-MWh environmental impacts of 1435 MW PV power generation; Figure S11: (a) Per-MWh single-score results/life cycle-phase for the 1435 MW solar panels. (b) Single-score environmental impacts of sea and land transport for solar panels; Figure S12: Percentage life-cycle phase-wise environmental impacts of 1 MWh BESS; Table S1: Normalization factors used in ReCiPe midpoint (H); Table S2: Environmental impact for sea and land transport in per tkm; Table S3: Per-MWh environmental impacts for the five electricity-generating options; Table S4: Per-MWh sensitivity of CF to impact pathways of a CCGT; Table S5: Per-MWh sensitivity of CF to impact pathways of the wind turbine

generation; Table S6: Per-MWh sensitivity of CF to impact pathways of the solar-PV generation; Table S7: Per-MWh sensitivity of CF to impact pathways of wind + BESS generation; Table S8: Per-MWh sensitivity of CF to impact pathways of solar PV + BESS generation.

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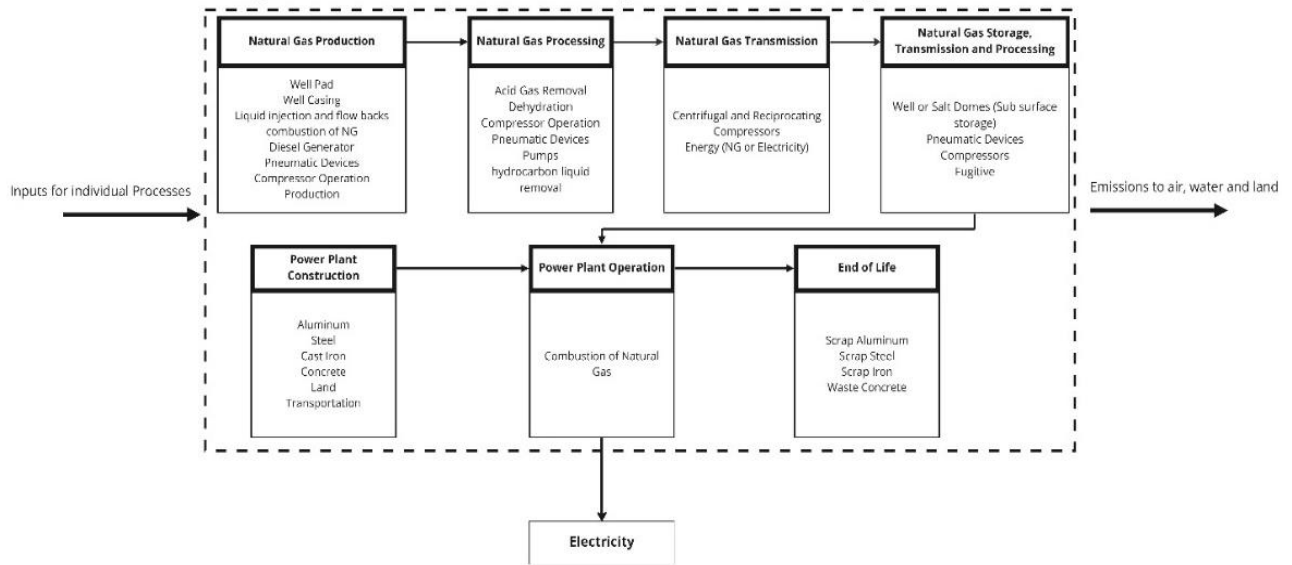
FIGURES

Figure S1. System boundary of the CCGT plant under study

Figure S2. System boundary of the wind turbine under study

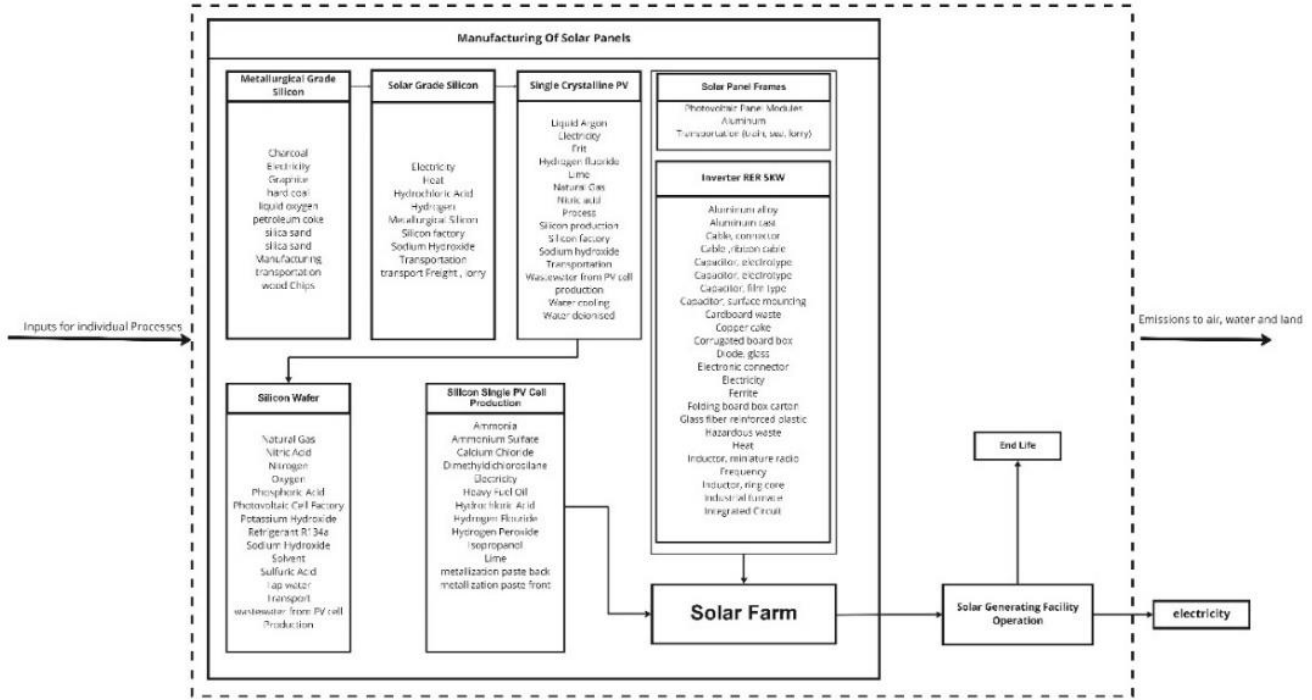**Manufacturing Of Solar Panels**

Metallurgical Grade Silicon

Charcoal
Electricity
Graphite
hard coal
liquid oxygen
petroleum coke
silica sand
silica sand
Manufacturing
transportation
wood Chips

Solar Grade Silicon

Electricity
heat
Hydrochloric Acid
Hydrogen
Metallurgical Silicon
Silicon factory
Sodium Hydroxide
Transportation
transport Freight, lorry

Single Crystalline PV

Liquid Argon
Electricity
Frit
Hydrogen fluoride
Lime
Natural Gas
Nitric acid
Process
Silicon production
Silicon factory
Sodium hydroxide
Transportation
Wastewater from PV cell production
Water cooling
Water deionised

Solar Panel Frames

Photovoltaic Panel Modules
Aluminum
Transportation (truck, sea, lorry)

Inverter RER 5KW

Aluminum alloy
Aluminum cast
Cable, connector
Cable, ribbon cable
Capacitor, electrolype
Capacitor, electrolype
Capacitor, film type
Capacitor, surface mounting
Cardboard waste
Copper cake
Corrugated board box carton
Diode, glass
Electronic connector
Electricity
Ferrite
Folding board box carton
Glass fiber reinforced plastic
Hazardous waste
Heat
Inductor, miniature radio frequency
Inductor, ring core
Industrial furnace
Integrated Circuit

Silicon Wafer

Natural Gas
Nitric Acid
Nitrogen
Oxygen
Phosphoric Acid
Photovoltaic Cell Factory
Potassium Hydroxide
Refrigerant R134a
Sodium Hydroxide
Solvent
Sulfuric Acid
Tap water
Transport
wastewater from PV cell Production

Silicon Single PV Cell Production

Ammonia
Ammonium Sulfate
Calcium Chloride
Dimethyldichlorosilane
Electricity
Heavy Fuel Oil
Hydrochloric Acid
Hydrogen fluoride
Hydrogen Peroxide
Isopropanol
Lime
metallization paste back
metallization paste front

Solar Farm

End Life

Solar Generating Facility Operation

Inputs for individual Processes

Emissions to air, water and land

electricity

Figure S3. System boundary of the PV system under study

System Boundaries: Battery Energy

Electricity to Charge Battery

Manufacturing Of Batteries

Lithium Concentrate

Diesel
Electricity
Lithium
Paraffin
Soda ash
Sodium hypochlorite

Lithium Carbonate

Calcium carbonate
Electricity
Hard coal
Heat
Lithium concentrate
Quicklime
Soda ash
Sodium hypochlorite
Sulfuric acid

LFP Battery Pack

Acrylic binder
Battery management
Battery operator
Carbon black
Dimethyl carbonate
Electricity
Electronics
Ethylene carbonate
Ethylene glycol
Glass fiber
graphite
heat

Iron Phosphate

Electricity
Heat
Hydrogen peroxide
Iron sulfate
Phosphoric acid
Sodium hydroxide
Water

LFP Cathode

Lithium
Hexaflourophosphate
Packing film
Polyethylene terephthalate
Polypropylene
Sheet rolling
Water
Wire drawing copper
Wire drawing steel

Battery Operation

Electricity

End Of Life

Inputs for individual Processes

Emissions to air, water and land

Figure S4. System boundary of BESS under study

Fine particulate matter formation
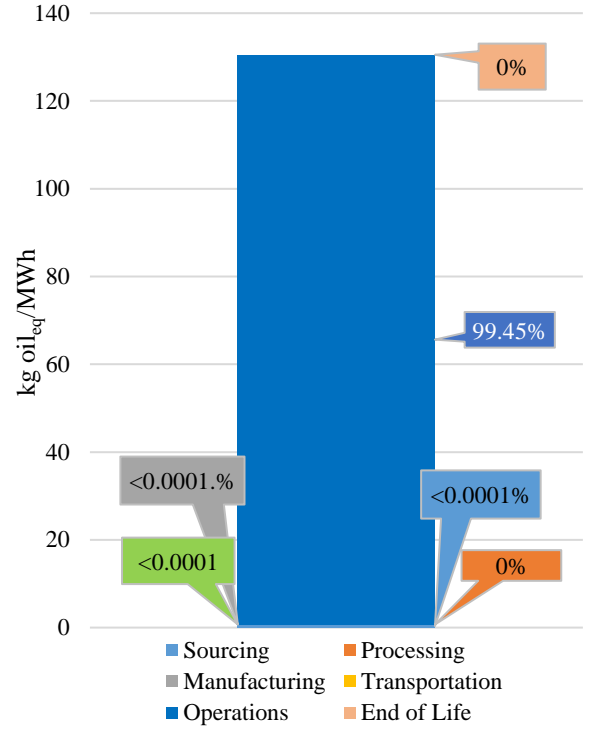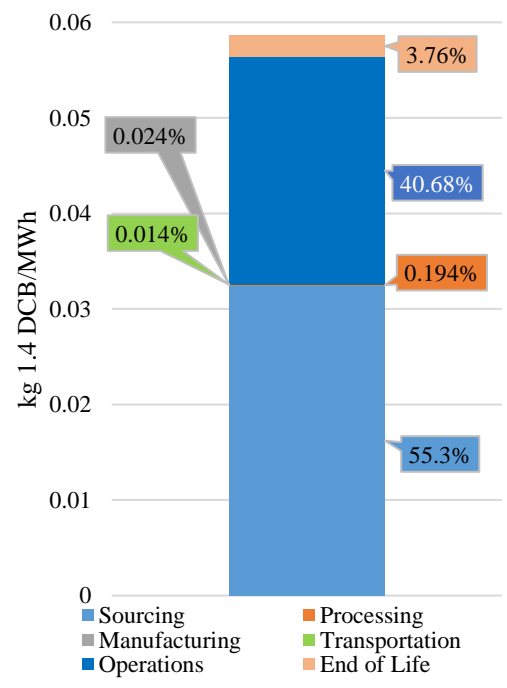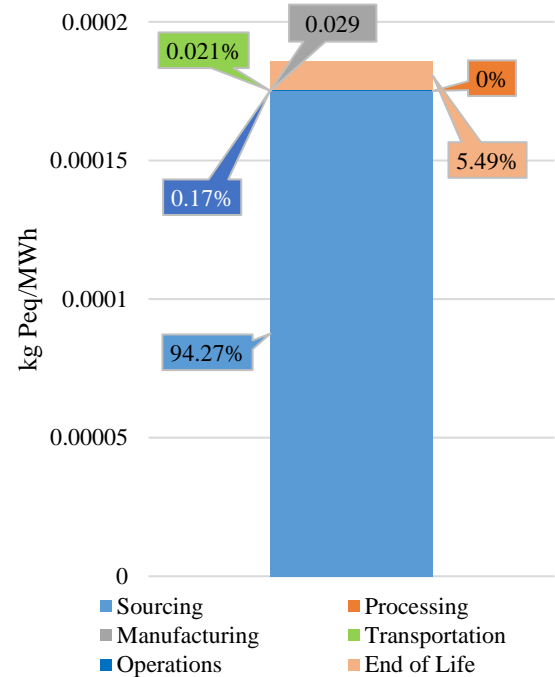
Fossil Resource Scarcity

Freshwater Ecotoxicity

Freshwater Eutrophication

Global Warming Potential

Human carcinogenic toxicity

Human non-carcinogenic toxicity

Ionizing radiation

Land Use

Ozone Formation, Terrestrial Ecosystems
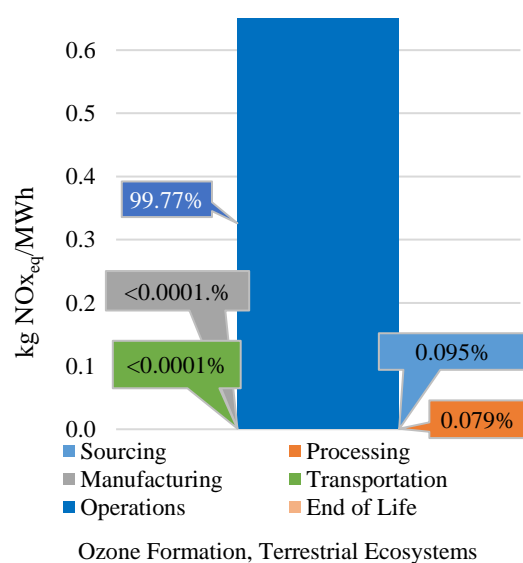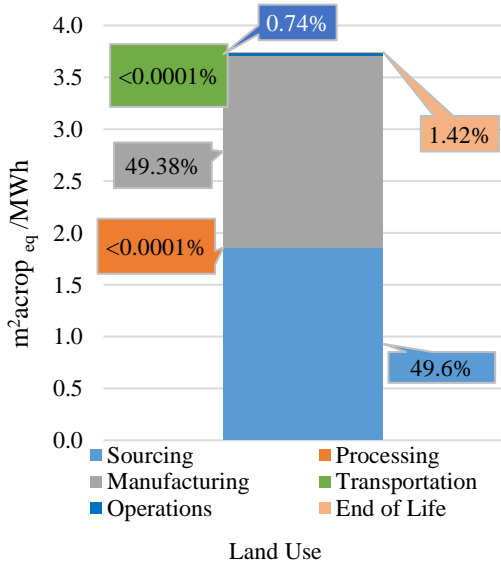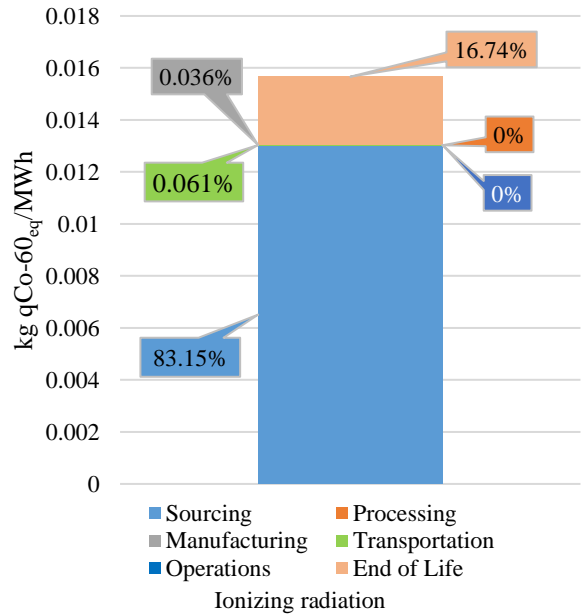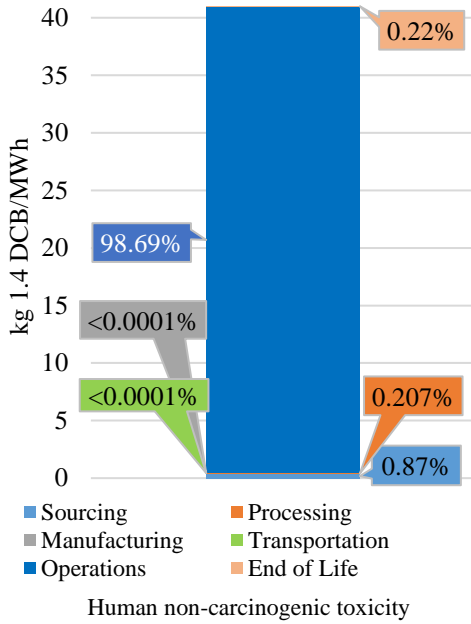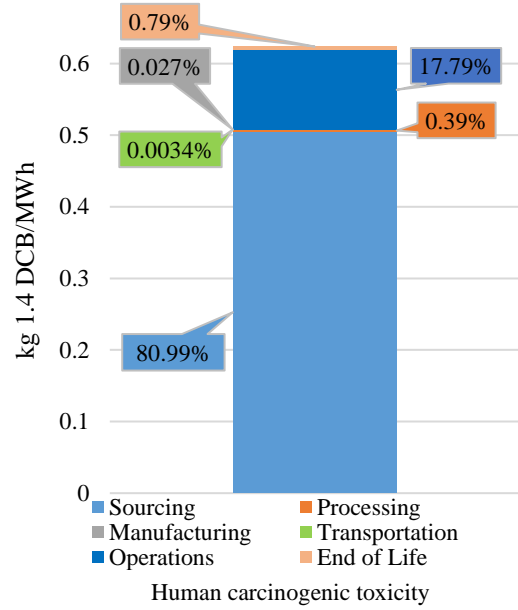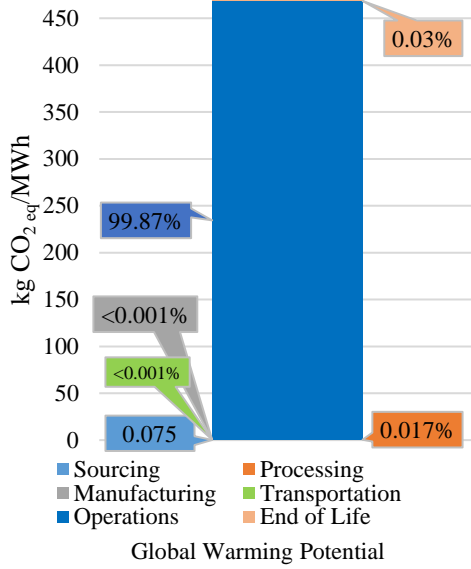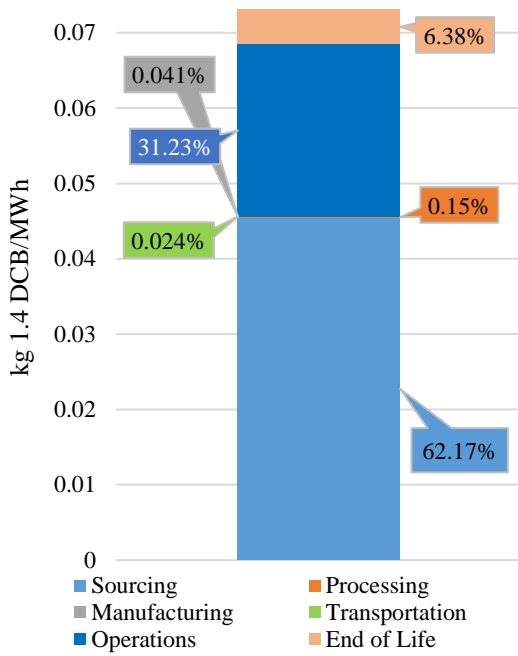
Marine ecotoxicity
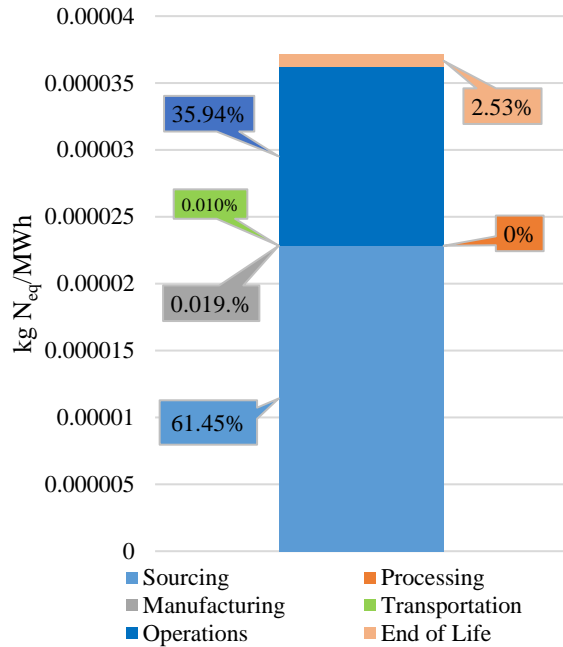
Marine Eutrophication
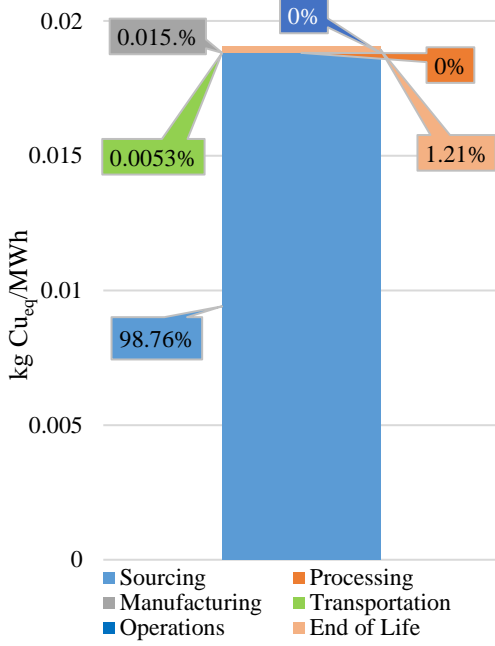
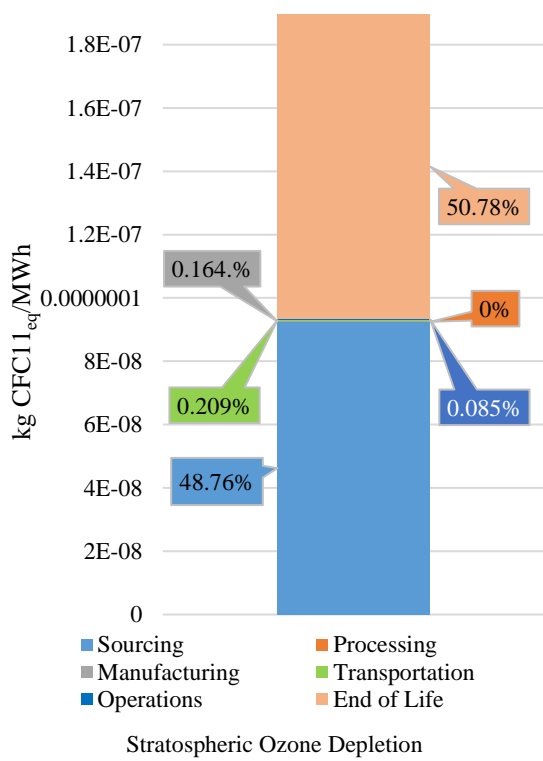Mineral Resource Scarcity
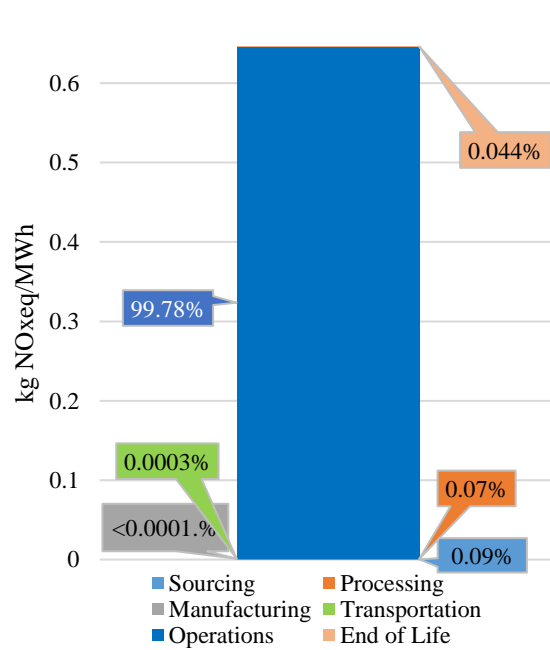
Ozone Formation, Human Health
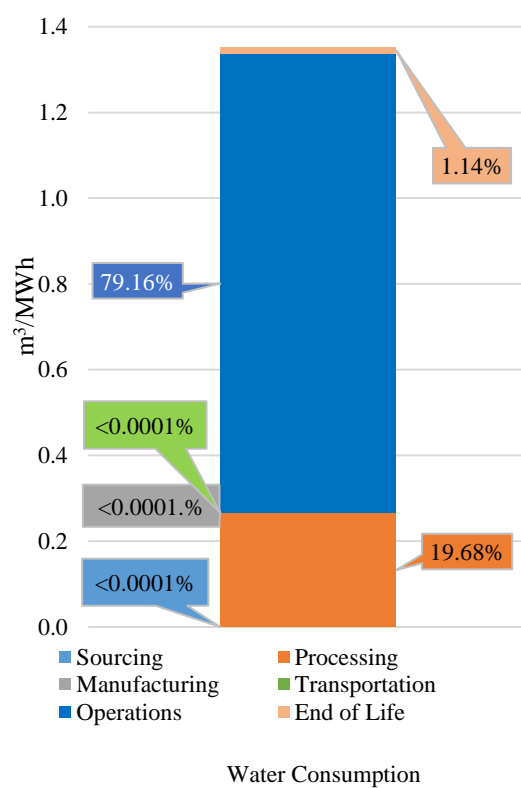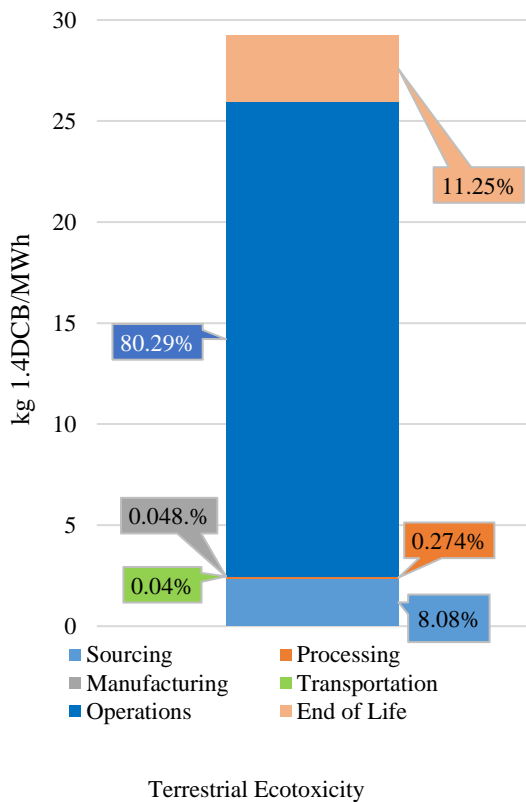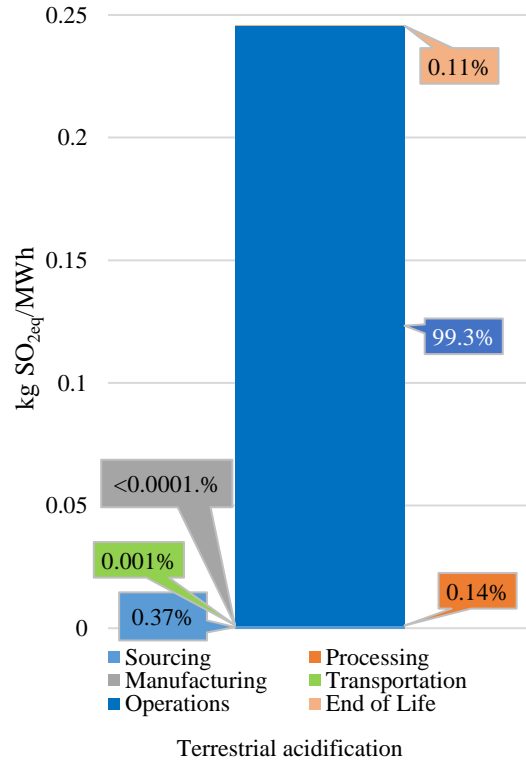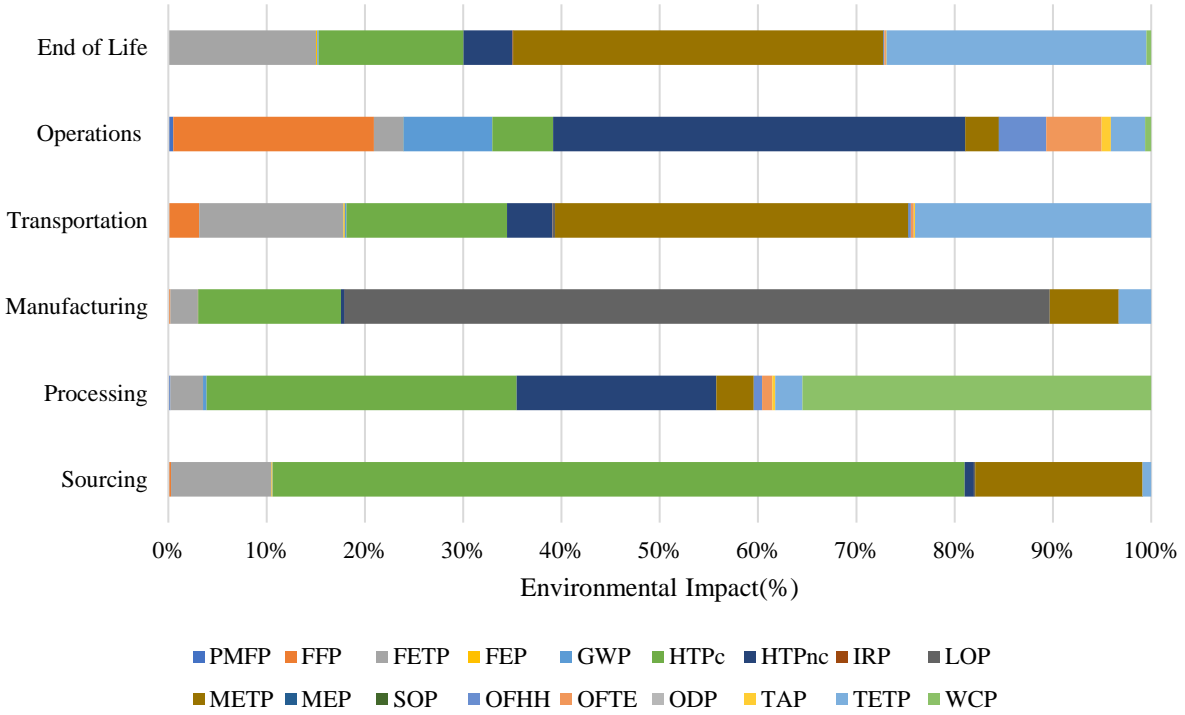
Figure S5. Per MWh environmental impacts of CCGT (500 MW)
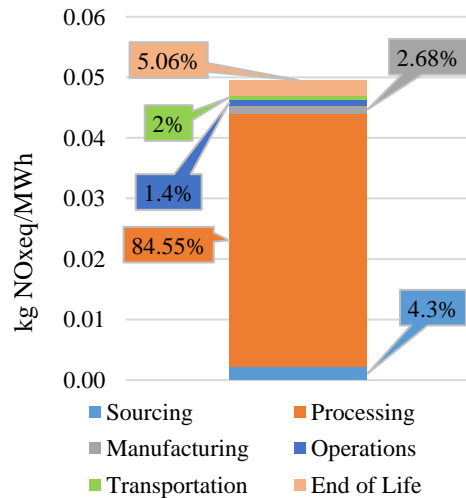
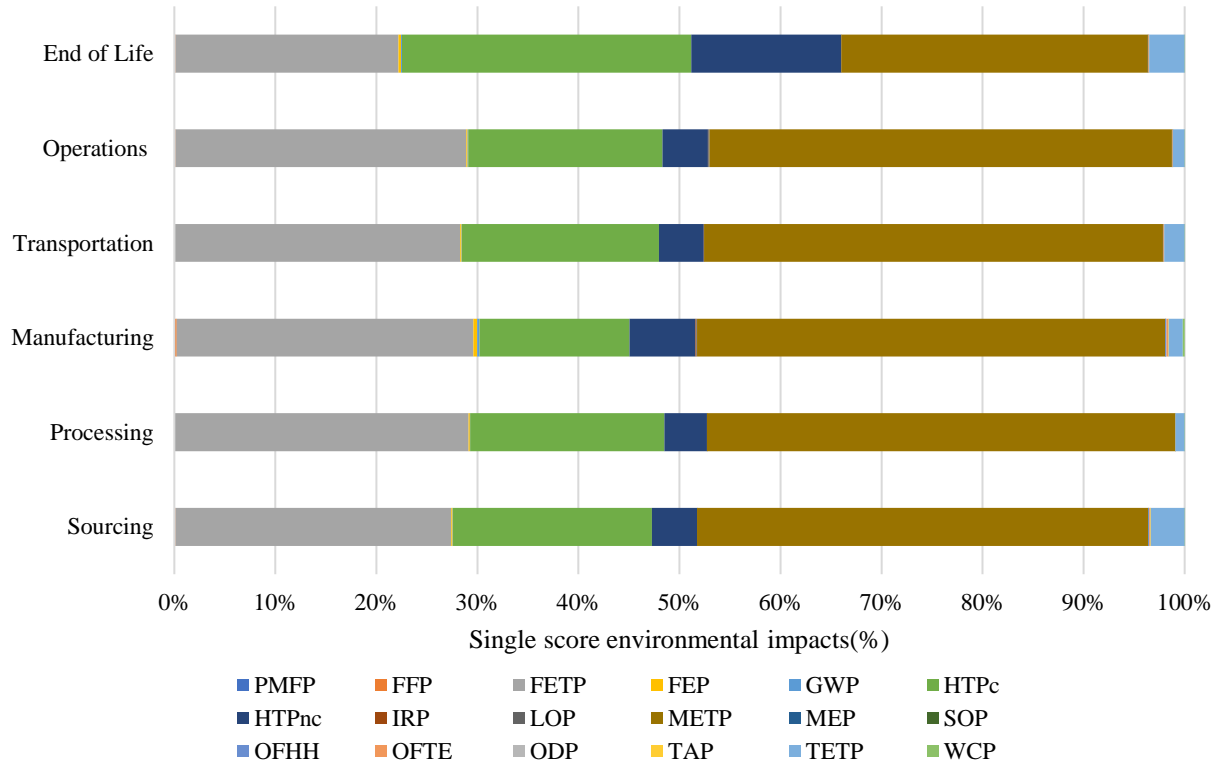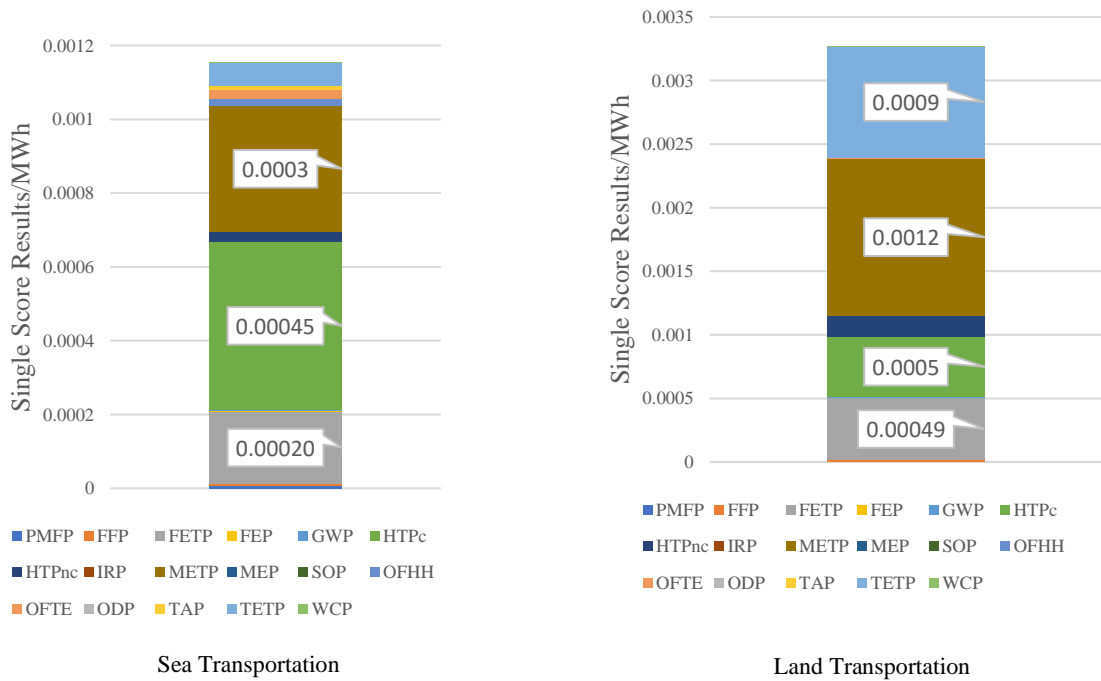**Figure S6(a).** Single score environmental impacts of CCGT
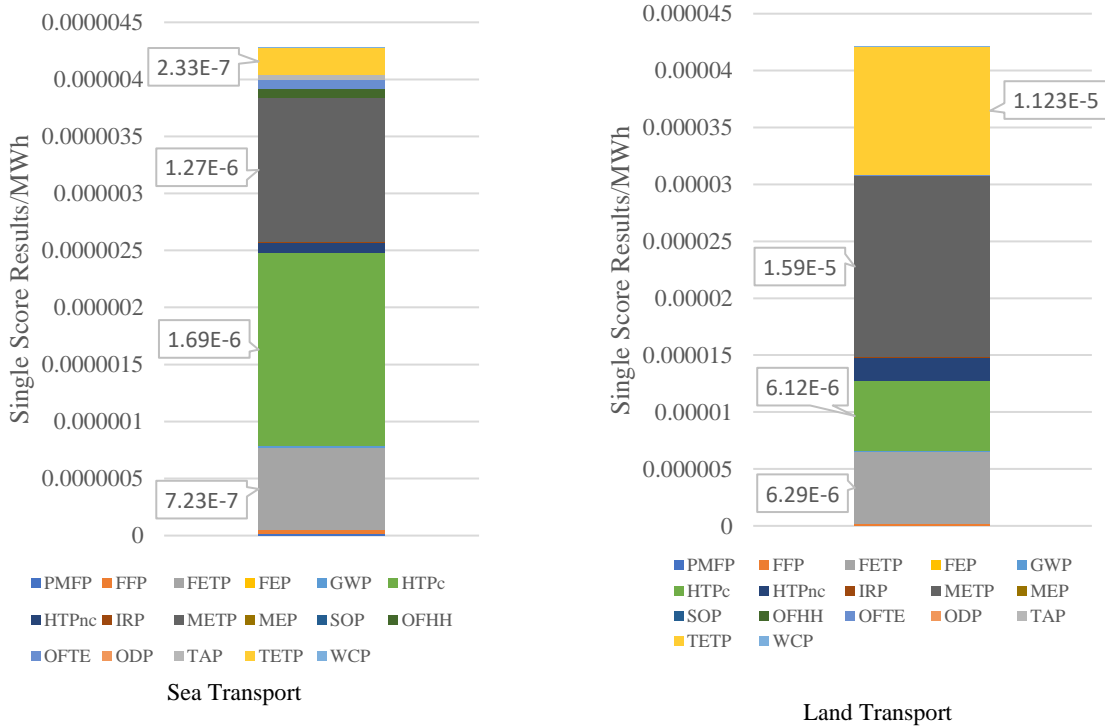
Figure S6(b). Single score environmental impacts of sea and land transport for CCGT
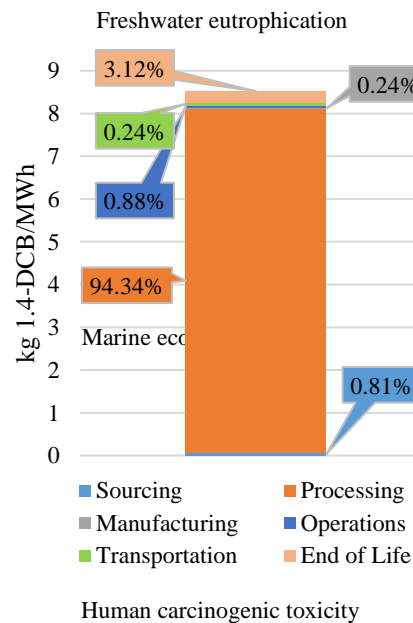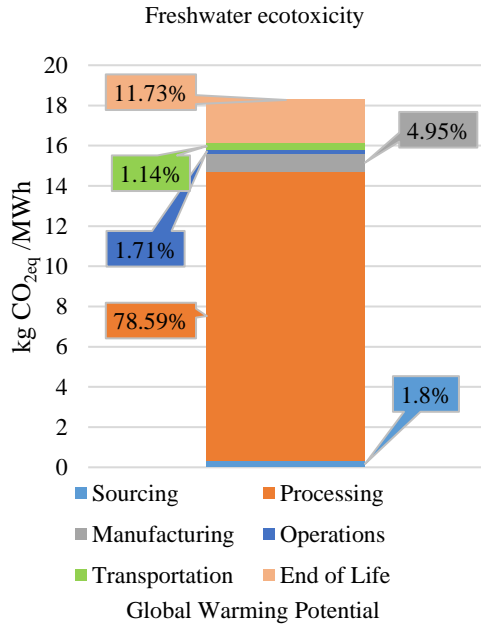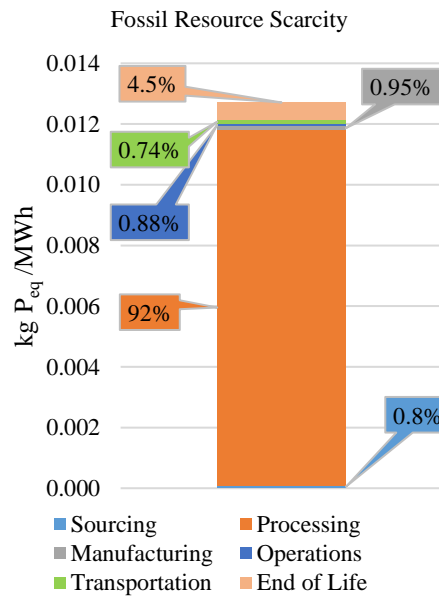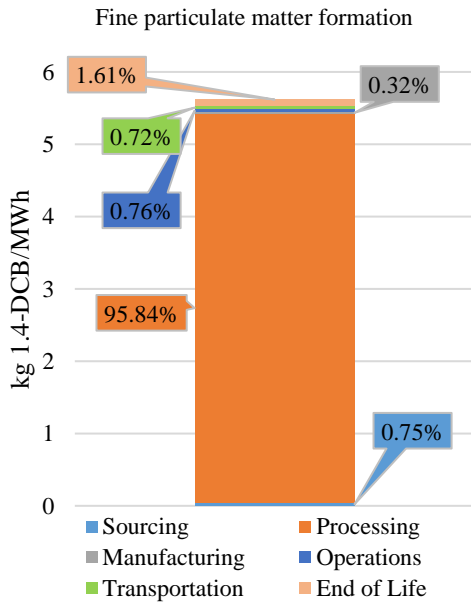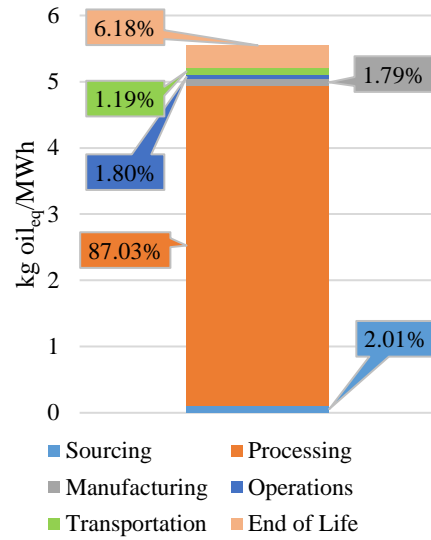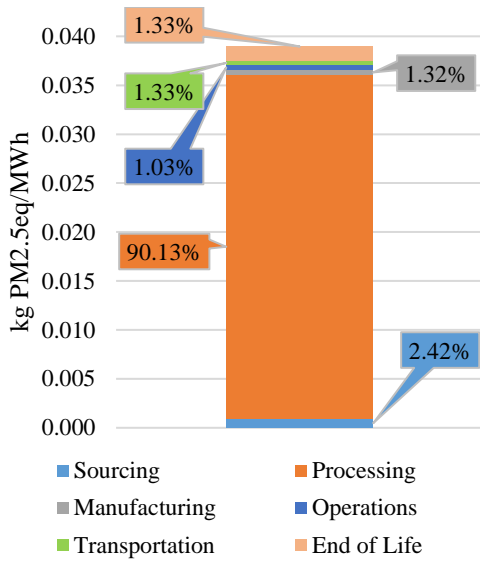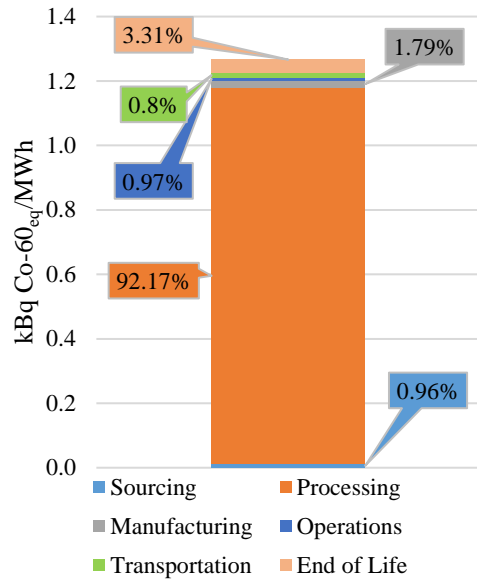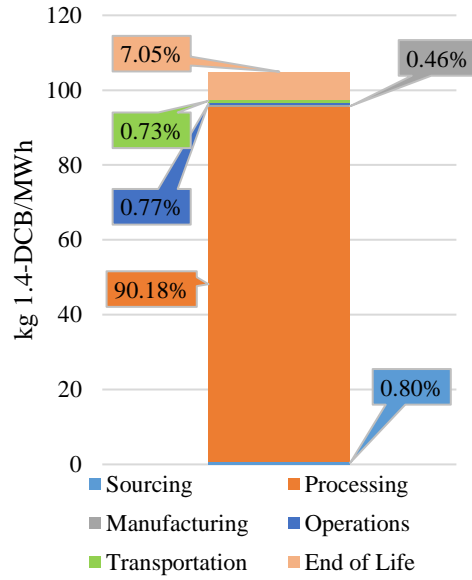
Fine particulate matter formation

Fossil Resource Scarcity

Freshwater ecotoxicity

Freshwater eutrophication

Global Warming Potential

Human carcinogenic toxicity

Human non-carcinogenic toxicity
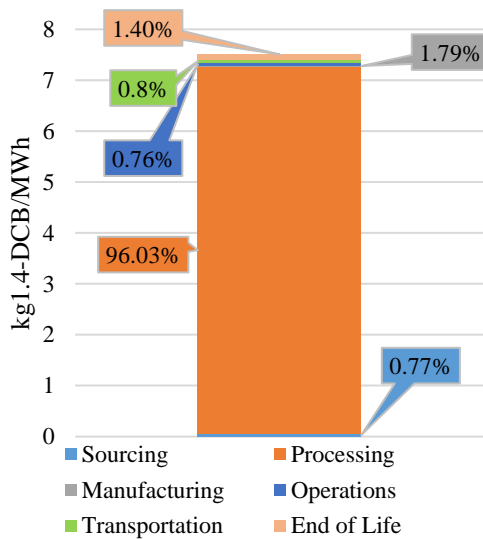
Ionizing radiation
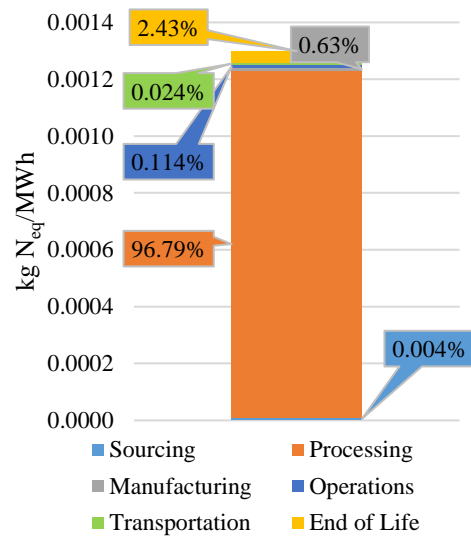
Marine ecotoxicity
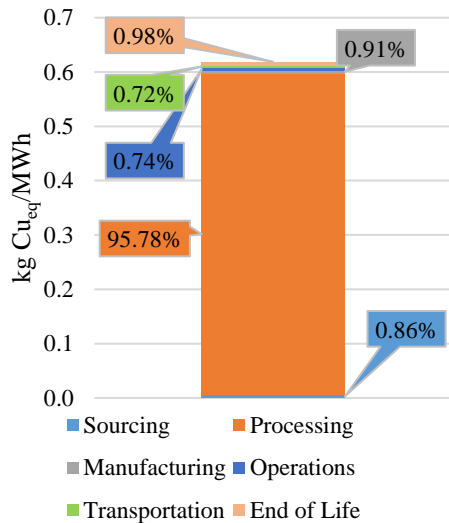
Marine Eutrophication

Mineral resource scarcity

Ozone formation, Human health
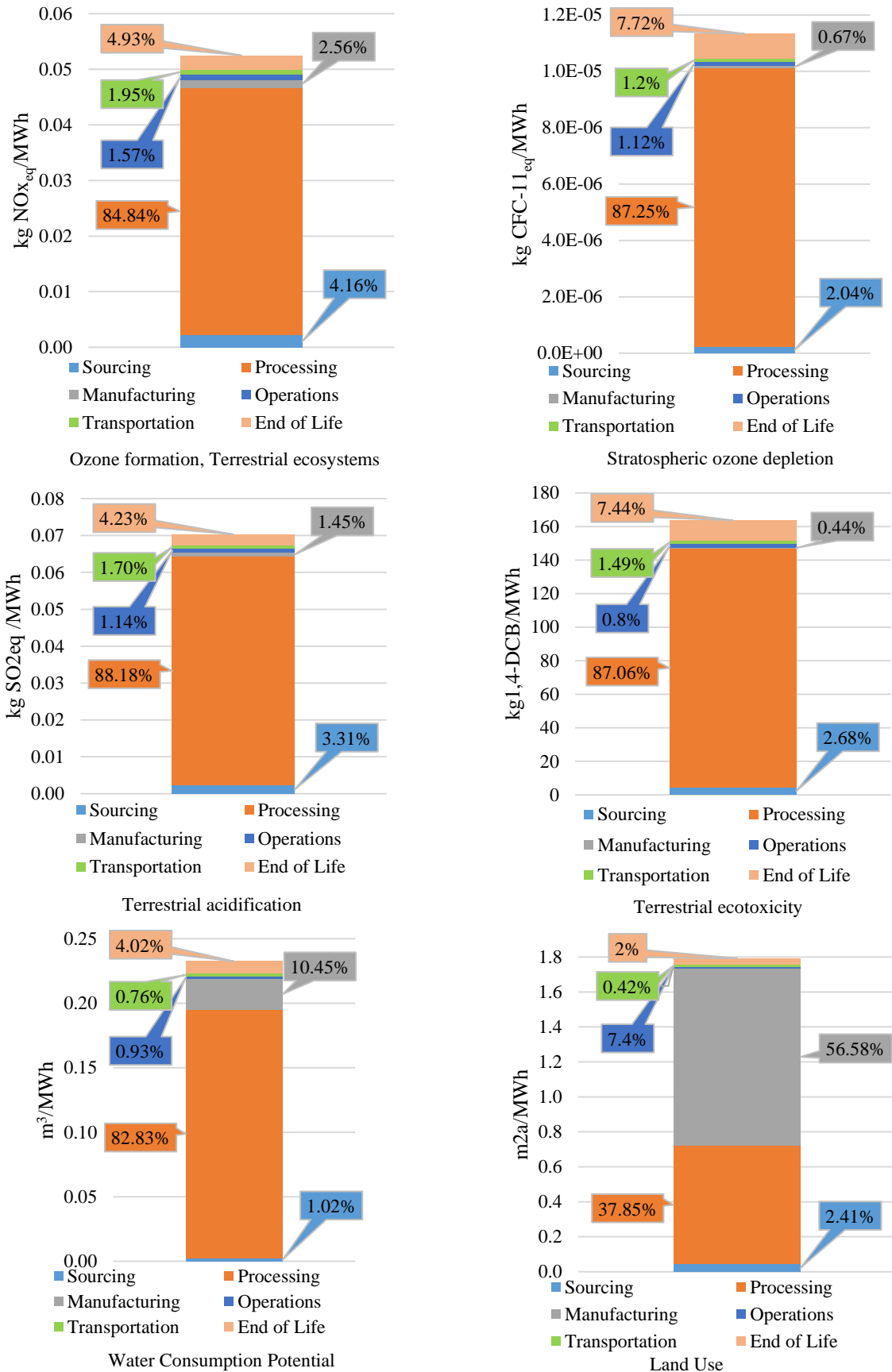
Figure S7. Per MWh environmental impacts of 3 MW (424 nos) Wind Turbine

Figure S8(a). Per MWh Single Score Results/ life cycle phase for the WTG

Sea Transportation

Land Transportation

Figure S8(b). Single score environmental impacts of sea and land transport for the WTG
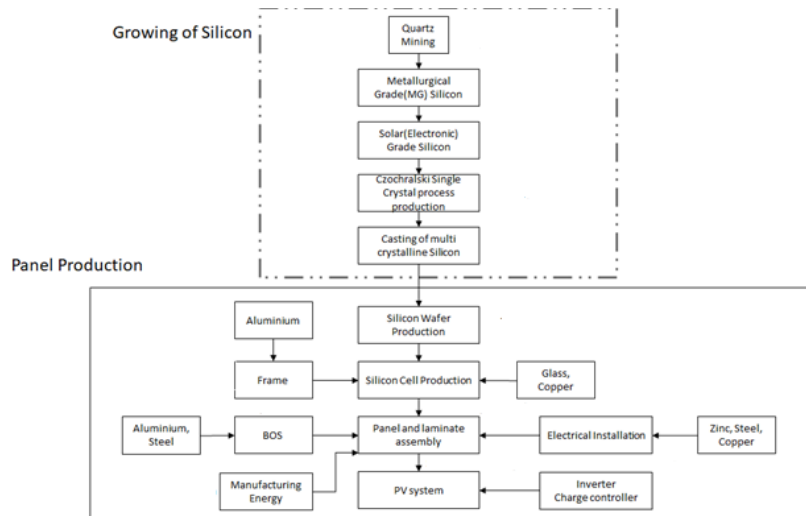
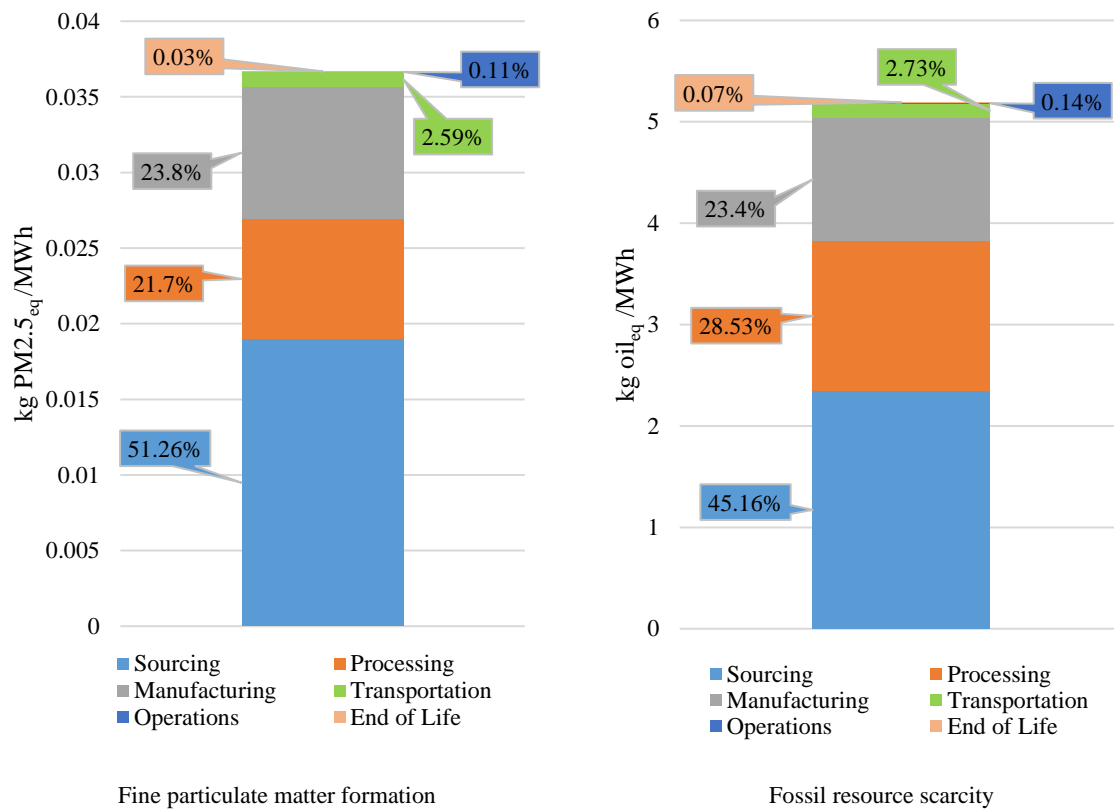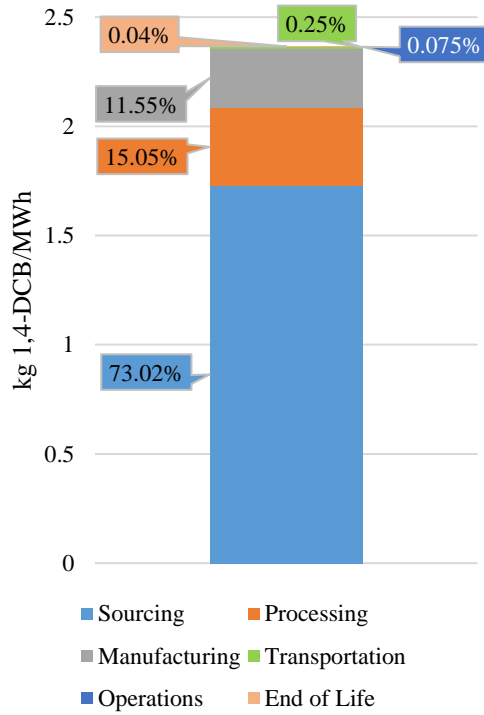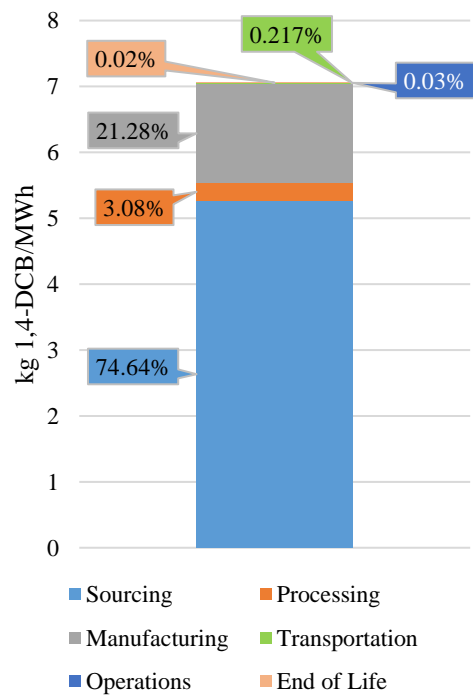**Figure S9**. PV panel production process

Fine particulate matter formation

Fossil resource scarcity
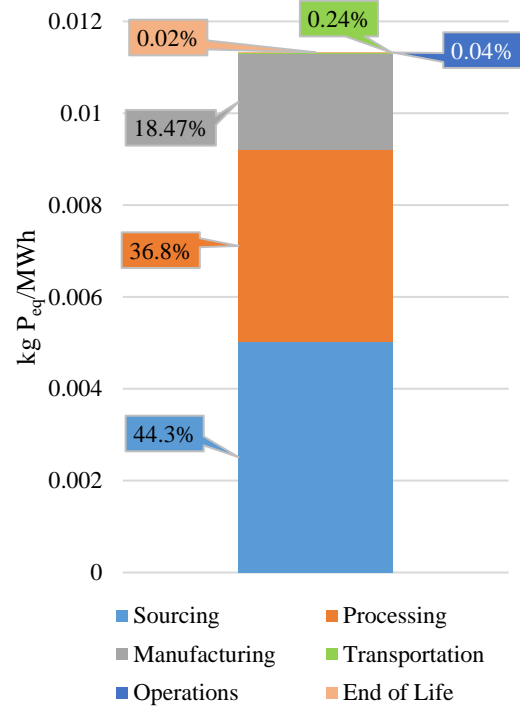
Freshwater Ecotoxicity
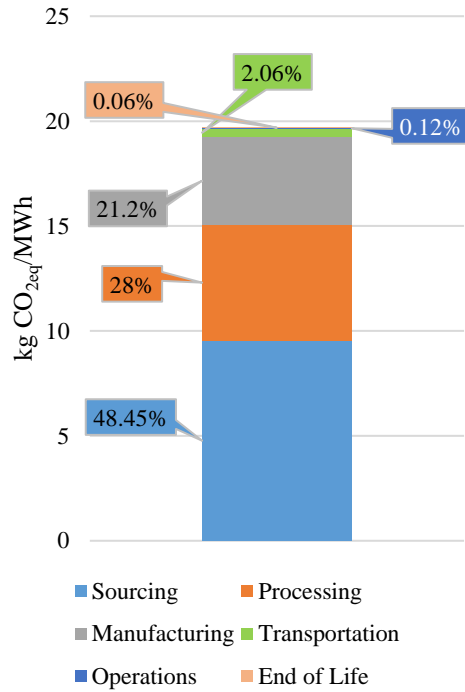
Freshwater Eutrophication

Global Warming

Human Carcinogenic Toxicity
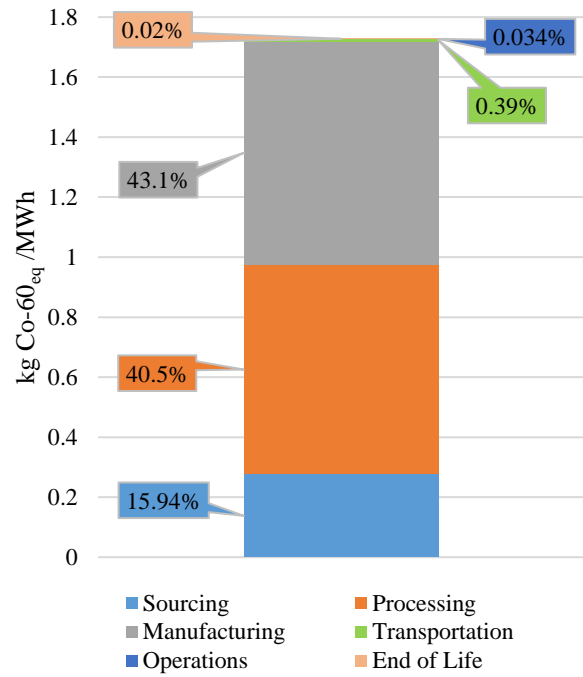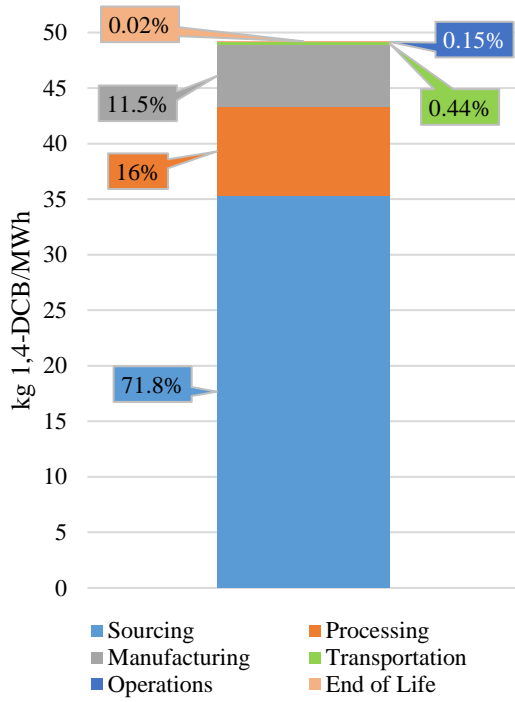
Human Non-Carcinogenic Toxicity

Ionization Radiation Potential
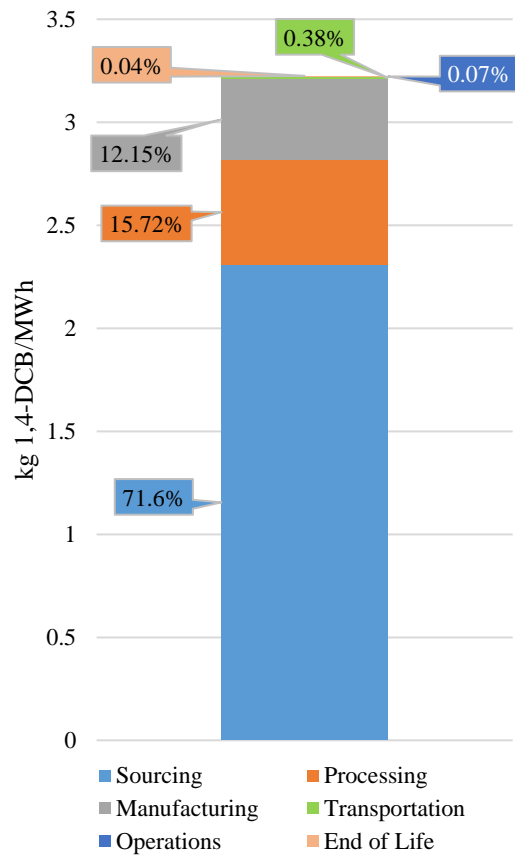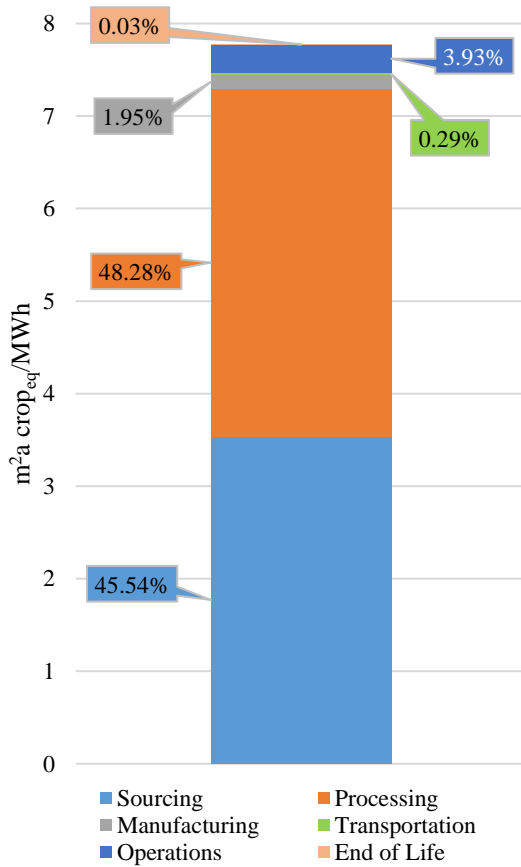
Land Use Potential

Marine Ecotoxicity
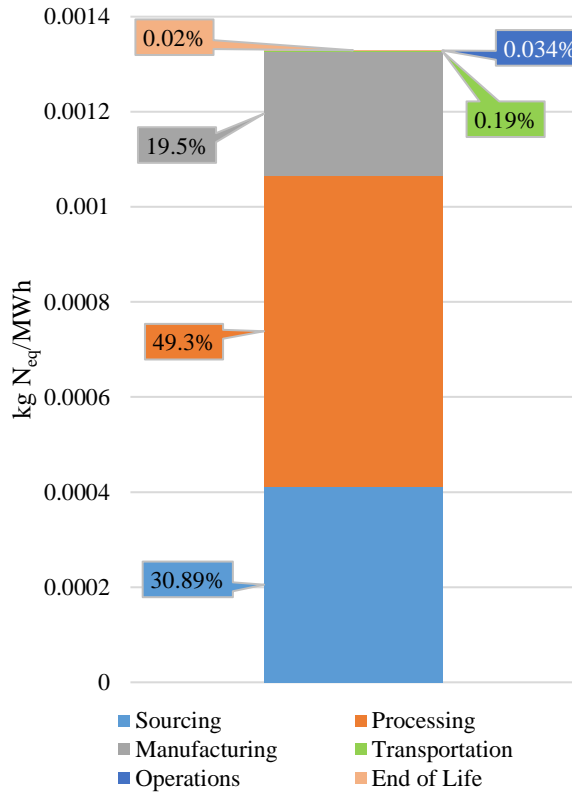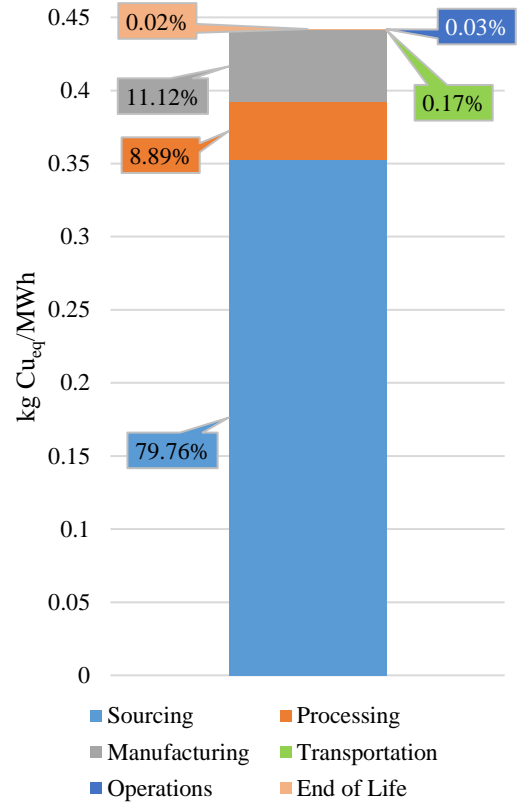
Marine Eutrophication

Mineral Resource Scarcity
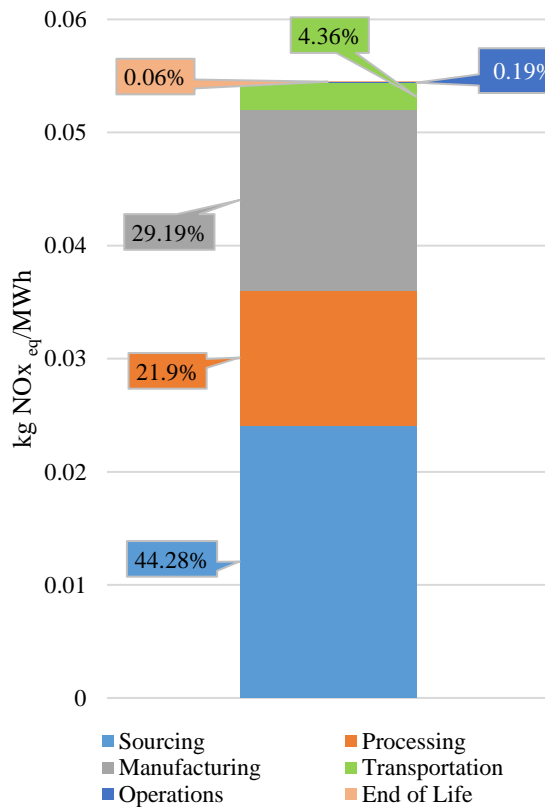
Ozone formation, Human health
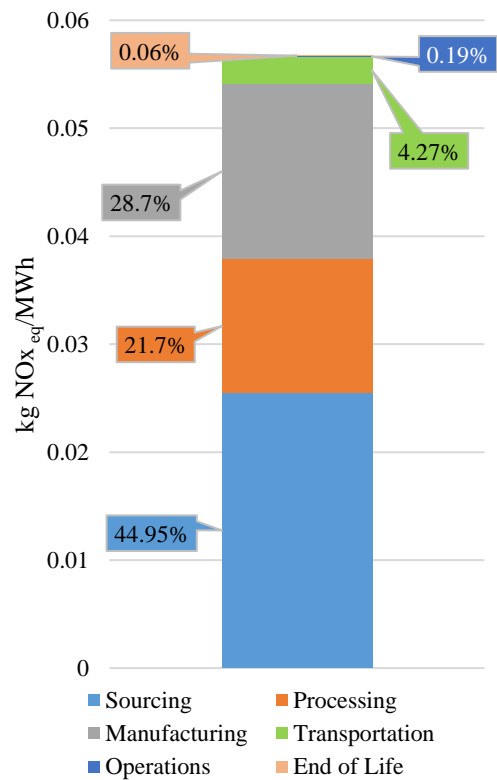
Ozone formation, Terrestrial Ecosystems

Figure S10. Per MWh environmental impacts of 1435 MW PV Power generation

Figure S11(a). Per MWh Single Score Results/ life cycle phase for the 1435 MW solar panels

Sea Transportation
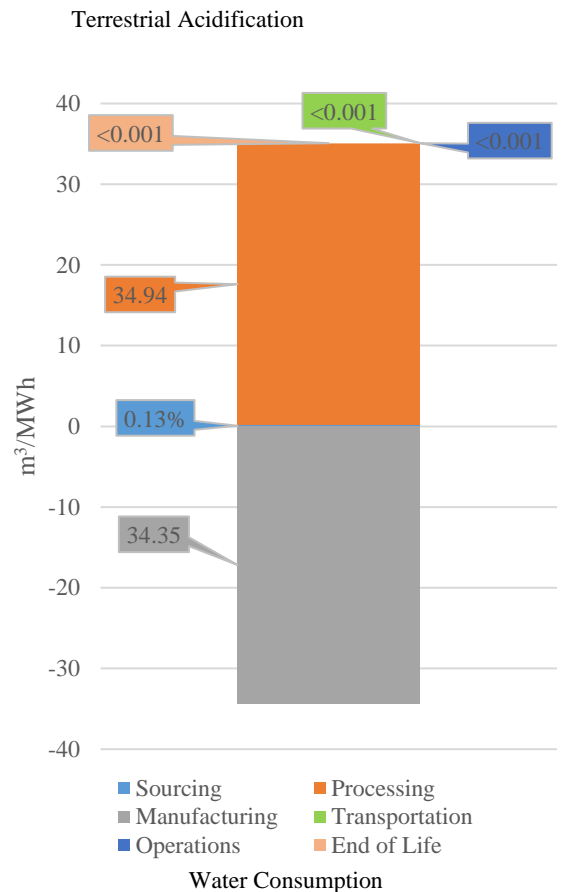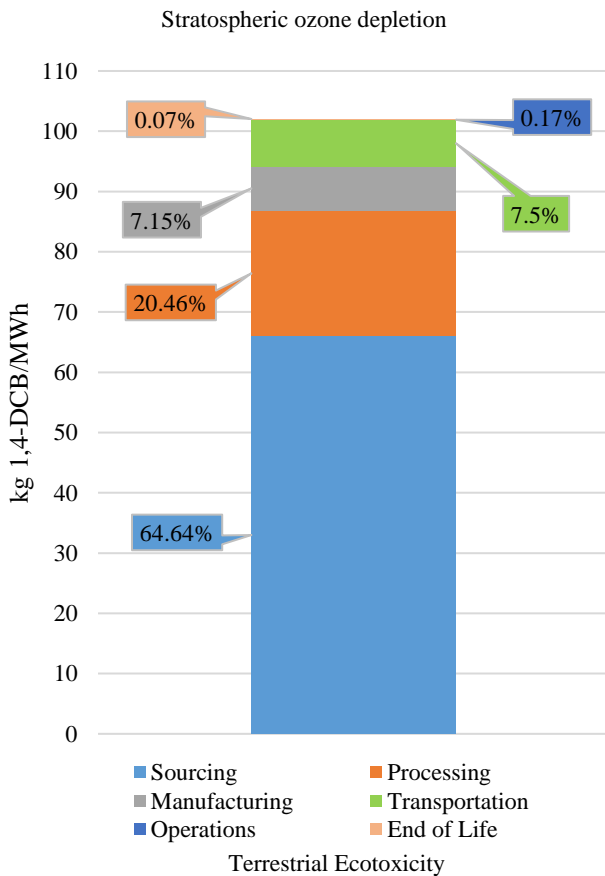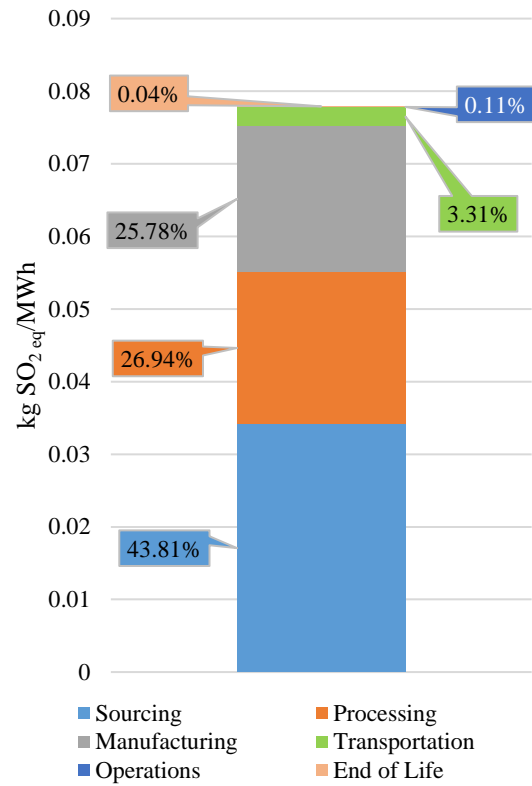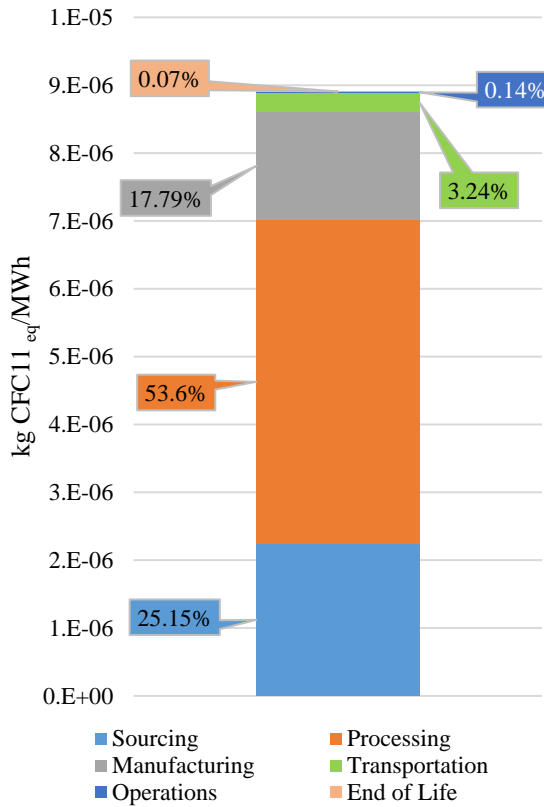
Land Transportation
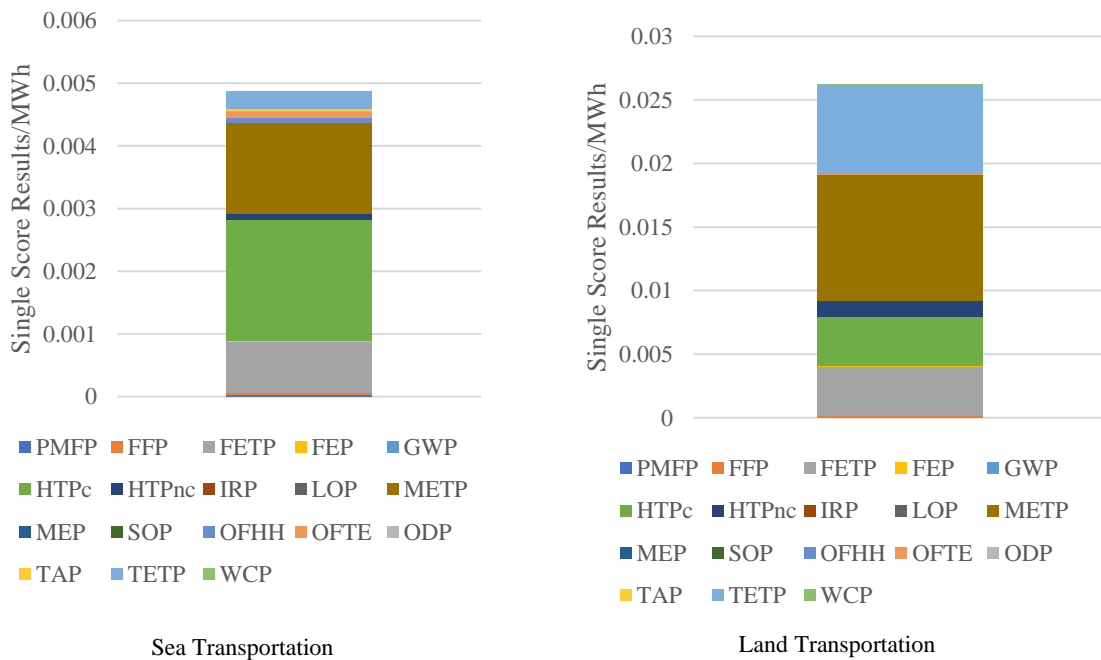
Figure S11(b). Single score environmental impacts of sea and land transport for solar panels
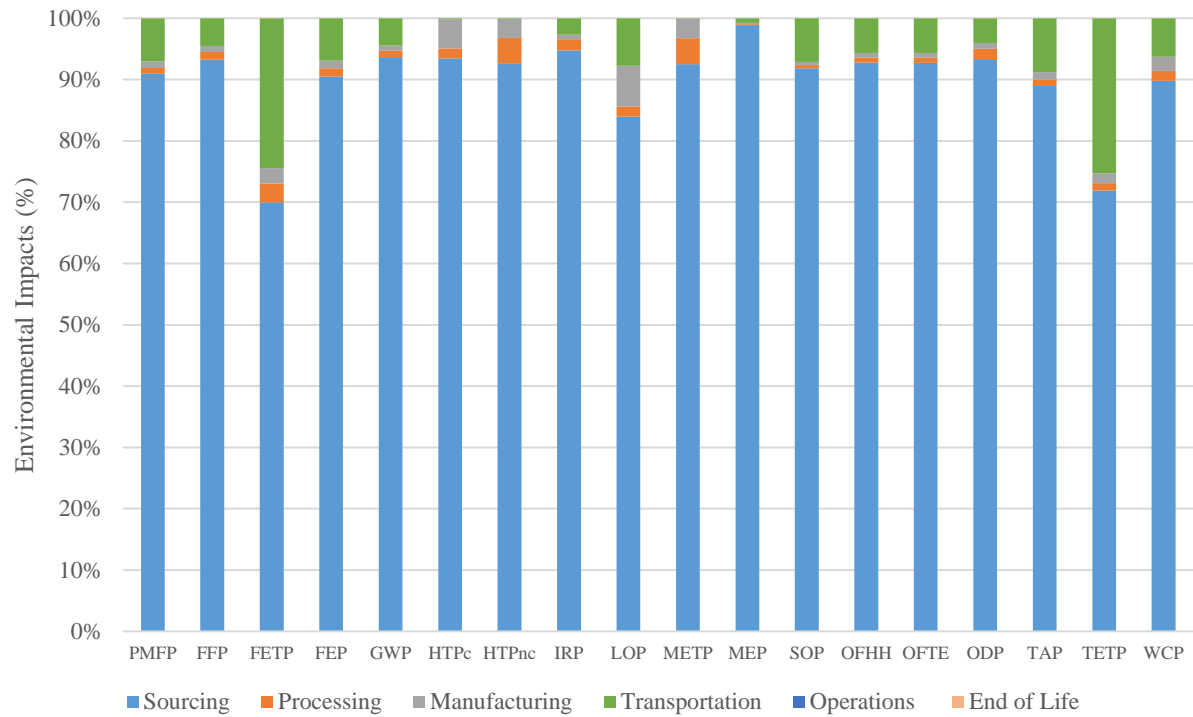
Figure S12. Percentage life cycle phase wise environmental impacts of 1MWh BESS

TABLES

Table S1. Normalization Factors used in ReCiPe Midpoint (H)

Reference unit	Factor
Fine particulate matter formation	25.6
Fossil resource scarcity	980.4
Freshwater ecotoxicity	1.2
Freshwater eutrophication	0.6
Global warming	7987.2
Human carcinogenic toxicity	2.8
Human non-carcinogenic toxicity	149.0
Ionizing radiation	480.8
Land use	6172.8
Marine ecotoxicity	1.0
Marine eutrophication	4.6
Mineral resource scarcity	120048
Ozone formation, Human health	20.6
Ozone formation, Terrestrial ecosystems	17.8
Stratospheric ozone depletion	0.1
Terrestrial acidification	41.0
Terrestrial ecotoxicity	1036.3
Water consumption	266.7

Table S2. Environmental Impact for sea and land transport in per tkm

Environmental Parameter	Unit	Transport Raw Material	
		Sea (per tkm)	Land (per tkm)
Fine particulate matter formation	kg PM2.5$_{eq}$	0.00004	0.00010
Fossil resource scarcity	kg oil$_{eq}$	0.00192	0.03286
Freshwater ecotoxicity	kg 1,4-DCB	0.00007	0.00147
Freshwater eutrophication	kg P$_{eq}$	0.00000	0.00001
Global warming	kg CO$_{2eq}$	0.00654	0.08975
Human carcinogenic toxicity	kg 1,4-DCB	0.00035	0.00322
Human non-carcinogenic toxicity	kg 1,4-DCB	0.00105	0.05982
Ionizing radiation	kBq Co-60$_{eq}$	0.00007	0.00165
Land use	m^{2}a crop$_{eq}$	0.00002	0.00665
Marine ecotoxicity	kg 1,4-DCB	0.00010	0.00312
Marine eutrophication	kg N$_{eq}$	0.00000	0.00000
Mineral resource scarcity	kg Cu$_{eq}$	0.00002	0.00015
Ozone formation, Human health	kg NOx eq	0.00011	0.00018
Ozone formation, Terrestrial ecosystems	kg NOx$_{eq}$	0.00011	0.00019
Stratospheric ozone depletion	kg CFC-11$_{eq}$	0.00000	0.00000
Terrestrial acidification	kg SO$_{2eq}$	0.00012	0.00019
Terrestrial ecotoxicity	kg 1,4-DCB	0.01790	2.21417
Water consumption	m^3	0.00001	0.00021

Table S3. Per MWh environmental impacts for the five electricity generating options

Reference unit		CCGT-500 MW	Wind-3MW (424 Nos)	Solar PV 1435 MW	Wind 3 (424 Nos) MW + BESS 500MWh	Solar 1435 MW +BESS 500MWh
kg PM$_{2.5eq}$	PMFP	0.084	0.039	0.037	0.111	0.109
kg oil$_{eq}$	FFP	130.5	5.5	5.2	13.4	13.0
kg 1,4-DCB	FETP	0.059	5.6	2.4	8.3	5.1
kg P$_{eq}$	FEP	0.0002	0.0127	0.0113	0.0298	0.0285
kg CO$_{2eq}$	GWP	468.5	18.3	19.7	46.6	48.0
kg 1,4-DCB	HTPc	0.6	8.5	7.7	137.3	136.5
kg 1,4-DCB	HTPnc	41.0	104.9	49.2	8920.6	8864.9
kBq Co-60$_{eq}$	IRP	0.016	1.3	1.7	4.5	5.0
m²a crop$_{eq}$	LOP	3.7	1.8	7.8	2.2	8.2
kg 1,4-DCB	METP	0.073	7.5	3.2	10254.5	10250.2
kg N$_{eq}$	MEP	0.00004	0.00130	0.00133	0.01545	0.01548
kg Cu$_{eq}$	SOP	0.019	0.6	0.4	1.9	1.7
kg NO$_{xeq}$	OFHH	0.6	0.0495	0.054	0.142	0.147
kg NO$_{xeq}$	OFTE	0.7	0.053	0.057	0.146	0.150
kg CFC11$_{eq}$	ODP	1.90E-07	1.13E-05	8.91E-06	2.89E-05	2.65E-05
kg SO$_{2eq}$	TAP	0.246	0.070	0.078	0.237	0.245
kg 1,4-DCB	TETP	29.2	163.6	102.1	438.6	377.0
m³	WCP	1.352	0.232	0.738	0.663	1.168

Table S4. Per MWh sensitivity of CF to impact pathways of a CCGT

	Environmental Impact	CF-56% 612 MW	CF-68% 500MW	CF-76% 451MW
kg PM2.5$_{eq}$	Fine particulate matter formation	0.0842	0.0840	0.0839
kg oil $_{eq}$	Fossil resource scarcity	130.69	130.53	130.46
kg 1,4-DCB	Freshwater ecotoxicity	0.066	0.059	0.055
kg P$_{eq}$	Freshwater eutrophication	2.27E-04	1.86E-04	1.68E-04
kg CO$_{2eq}$	Global warming	468.64	468.51	468.46
kg 1,4-DCB	Human carcinogenic toxicity	0.74	0.62	0.57
kg 1,4-DCB	Human non-carcinogenic toxicity	41.16	41.04	40.99
kBq Co-60 $_{eq}$	Ionizing radiation	0.019	0.016	0.014
m²a crop $_{eq}$	Land use	4.58	3.75	3.38
kg 1,4-DCB	Marine ecotoxicity	0.08	0.07	0.07
kg N$_{eq}$	Marine eutrophication	4.25E-05	3.71E-05	3.48E-05
kg Cu$_{eq}$	Mineral resource scarcity	0.02	0.02	0.02
kg NO$_{xeq}$	Ozone formation, Human health	0.65	0.65	0.65
kg NO$_{xeq}$	Ozone formation, Terrestrial ecosystems	0.65	0.65	0.65
kg CFC11$_{eq}$	Stratospheric ozone depletion	2.32E-07	1.90E-07	1.71E-07
kg SO$_{2eq}$	Terrestrial acidification	0.25	0.25	0.25
kg 1,4-DCB	Terrestrial ecotoxicity	30.51	29.22	28.66
m³	Water consumption	1.41	1.35	1.32

Table S5. Per MWh sensitivity of CF to impact pathways of the Wind turbine generation

	Environmental Impact	CF-14% 2819 MW	CF-31% 1273 MW	CF-48% 822 MW
kg PM2.5$_{eq}$	Fine particulate matter formation	0.09	0.04	0.03
kg oil $_{eq}$	Fossil resource scarcity	12.30	5.55	3.59
kg 1,4-DCB	Freshwater ecotoxicity	12.45	5.62	3.63
kg P$_{eq}$	Freshwater eutrophication	0.0282	0.0127	0.0082
kg CO$_{2eq}$	Global warming	40.51	18.27	11.81
kg 1,4-DCB	Human carcinogenic toxicity	18.89	8.52	5.51
kg 1,4-DCB	Human non-carcinogenic toxicity	232.65	104.94	67.82
kBq Co-60 $_{eq}$	Ionizing radiation	2.81	1.27	0.82
m²a crop $_{eq}$	Land use	1.19	0.53	0.35
kg 1,4-DCB	Marine ecotoxicity	16.64	7.51	4.85
kg N$_{eq}$	Marine eutrophication	0.00288	0.00130	0.00084
kg Cu$_{eq}$	Mineral resource scarcity	1.37	0.62	0.40
kg NO$_{xeq}$	Ozone formation, Human health	0.1098	0.0495	0.0320
kg NO$_{xeq}$	Ozone formation, Terrestrial ecosystems	0.1164	0.0525	0.0339
kg CFC11$_{eq}$	Stratospheric ozone depletion	2.51E-05	1.13E-05	7.32E-06
kg SO$_{2eq}$	Terrestrial acidification	0.16	0.07	0.05
kg 1,4-DCB	Terrestrial ecotoxicity	362.78	163.64	105.75
m³	Water consumption	0.52	0.23	0.15

Table S6. Per MWh sensitivity of CF to impact pathways of the solar PV generation

	Environmental Impact	CF-21% 1777 MW	CF-26% 1435 MW	CF-31% 1204 MW
kg PM2.5$_{eq}$	Fine particulate matter formation	0.041	0.037	0.034
kg oil $_{eq}$	Fossil resource scarcity	5.95	5.19	4.68
kg 1,4-DCB	Freshwater ecotoxicity	2.62	2.37	2.19
kg P$_{eq}$	Freshwater eutrophication	0.0125	0.0113	0.0105
kg CO$_{2eq}$	Global warming	22.22	19.68	17.97
kg 1,4-DCB	Human carcinogenic toxicity	7.24	7.06	6.93
kg 1,4-DCB	Human non-carcinogenic toxicity	52.68	49.21	46.86
kBq Co-60 $_{eq}$	Ionizing radiation	2.08	1.73	1.49
m²a crop $_{eq}$	Land use	7.86	7.77	7.72
kg 1,4-DCB	Marine ecotoxicity	3.57	3.23	2.99
kg N$_{eq}$	Marine eutrophication	1.47E-03	1.33E-03	1.24E-03
kg Cu$_{eq}$	Mineral resource scarcity	0.46	0.44	0.43
kg NO$_{xeq}$	Ozone formation, Human health	0.062	0.054	0.050
kg NO$_{xeq}$	Ozone formation, Terrestrial ecosystems	0.064	0.057	0.052
kg CFC11$_{eq}$	Stratospheric ozone depletion	1.01E-05	8.91E-06	8.08E-06
kg SO$_{2eq}$	Terrestrial acidification	0.088	0.078	0.071
kg 1,4-DCB	Terrestrial ecotoxicity	109.62	102.06	96.96
m³	Water consumption	0.85	0.76	0.70

Table S7. Per MWh sensitivity of CF to impact pathways of the wind + BESS generation

	Environmental Impact	CF-14% 2819 MW	CF-31% 1273 MW	CF-48% 822 MW
kg PM2.5$_{eq}$	Fine particulate matter formation	0.16	0.11	0.10
kg oil $_{eq}$	Fossil resource scarcity	20.11	13.36	11.40
kg 1,4-DCB	Freshwater ecotoxicity	15.19	8.35	6.36
kg P$_{eq}$	Freshwater eutrophication	0.045	0.030	0.025
kg CO$_{2eq}$	Global warming	68.87	46.64	40.17
kg 1,4-DCB	Human carcinogenic toxicity	147.68	137.31	134.29
kg 1,4-DCB	Human non-carcinogenic toxicity	9048.34	8920.63	8883.51
kBq Co-60 $_{eq}$	Ionizing radiation	6.08	4.54	4.09
m²a crop $_{eq}$	Land use	1.60	0.95	0.76
kg 1,4-DCB	Marine ecotoxicity	10263.59	10254.45	10251.79
kg N$_{eq}$	Marine eutrophication	0.0170	0.0154	0.0150
kg Cu$_{eq}$	Mineral resource scarcity	2.61	1.86	1.64
kg NO$_{xeq}$	Ozone formation, Human health	0.20	0.14	0.12
kg NO$_{xeq}$	Ozone formation, Terrestrial ecosystems	0.21	0.15	0.13
kg CFC11$_{eq}$	Stratospheric ozone depletion	4.27E-05	2.89E-05	2.49E-05
kg SO$_{2eq}$	Terrestrial acidification	0.32	0.24	0.21
kg 1,4-DCB	Terrestrial ecotoxicity	637.71	438.57	380.68
m³	Water consumption	0.95	0.66	0.58

Table S8. Per MWh sensitivity of CF to impact pathways of the solar PV +BESS generation

	Environmental Impact	CF-21% 1777 MW	CF-26% 1435 MW	CF-31% 1204 MW
kg PM2.5$_{eq}$	Fine particulate matter formation	0.113	0.109	0.106
kg oil $_{eq}$	Fossil resource scarcity	13.757	13.001	12.491
kg 1,4-DCB	Freshwater ecotoxicity	5.355	5.097	4.923
kg P$_{eq}$	Freshwater eutrophication	0.030	0.028	0.028
kg CO$_{2eq}$	Global warming	50.586	48.049	46.335
kg 1,4-DCB	Human carcinogenic toxicity	136.031	135.845	135.719
kg 1,4-DCB	Human non-carcinogenic toxicity	8868.372	8864.900	8862.556
kBq Co-60 $_{eq}$	Ionizing radiation	5.349	5.001	4.767
m²a crop $_{eq}$	Land use	8.266	8.184	8.128
kg 1,4-DCB	Marine ecotoxicity	10250.510	10250.168	10249.936
kg N$_{eq}$	Marine eutrophication	0.016	0.015	0.015
kg Cu$_{eq}$	Mineral resource scarcity	1.704	1.686	1.673
kg NO$_{xeq}$	Ozone formation, Human health	0.154	0.147	0.142
kg NO$_{xeq}$	Ozone formation, Terrestrial ecosystems	0.157	0.150	0.145
kg CFC11$_{eq}$	Stratospheric ozone depletion	2.77E-05	2.65E-05	2.56E-05
kg SO$_{2eq}$	Terrestrial acidification	0.255	0.245	0.238
kg 1,4-DCB	Terrestrial ecotoxicity	384.6	377.0	371.9
m³	Water consumption	1.284	1.193	1.126