

Article

External-Cost Estimation of Electricity Generation in G20 Countries: Case Study Using a Global Life-Cycle Impact-Assessment Method

Selim Karkour *, Yuki Ichisugi, Amila Abeynayaka  and Norihiro Itsubo

Graduate School of Environmental Studies, Tokyo City University, Yokohama 224-8551, Japan; g1793102@tcu.ac.jp (Y.I.); g1993101@tcu.ac.jp (A.A.); itsubo-n@tcu.ac.jp (N.I.)

* Correspondence: g1893103@tcu.ac.jp

Received: 9 February 2020; Accepted: 2 March 2020; Published: 5 March 2020



Abstract: The external costs derived from the environmental impacts of electricity generation can be significant and should not be underrated, as their consideration can be useful to establish a ranking between different electricity generation sources to inform decision-makers. The aim of this research is to transparently evaluate the recent external cost of electricity generation in G20 countries using a global life-cycle impact-assessment (LCIA) method: life cycle impact assessment method based on endpoint modeling (LIME3). The weighting factors developed in the LIME3 method for each G20 country enable one to convert the different environmental impacts (not only climate change and air pollution) resulting from the emissions and resources consumption during the full lifecycle of electricity generation—from resource extraction to electricity generation—into a monetary value. Moreover, in LIME3, not only the weighting factors are developed for each G20 country but also all the impact categories. Using this method, it was possible to determine accurately which resources or emission had an environmental impact in each country. This study shows that the countries relying heavily on coal, such as India (0.172 \$/kWh) or Indonesia (0.135 \$/kWh) have the highest external costs inside the G20, with air pollution and climate accounting together for more than 80% of the costs. In these two countries, the ratio of the external cost/market price was the highest in the G20, at 2.3 and 1.7, respectively. On the other hand, countries with a higher reliance on renewable energies, such as Canada (0.008 \$/kWh) or Brazil (0.012 \$/kWh) have lower induced costs. When comparing with the market price, it has to be noted also that for instance Canada is able to generate cheap electricity with a low-external cost. For most of the other G20 countries, this cost was estimated at between about 0.020\$ and 0.040 \$/kWh. By estimating the external cost of each electricity generation technology available in each G20 country, this study also highlighted that sometimes the external cost of the electricity generated from one specific technology can be significant even when using renewables due to resource scarcity—for example, the 0.068 \$/kWh of electricity generated from hydropower in India. This information, missing from most previous studies, should not be omitted by decision makers when considering which type of electricity generation source to prioritize.

Keywords: electricity generation; external cost; life-cycle assessment; life-cycle impact assessment; fossil fuels; renewables; G20; newly industrialized countries

1. Introduction

The management of energy systems has become a progressively more important topic in recent years. Under the growing concern of climate change consequences, decision makers are facing several types of challenges (economic, environmental, and social) to prioritize one source over another.

Electricity generation reached 26,615 TWh in 2018 [1], increasing by 3.7% from the previous year, as shown in Figure 1, with around 85% of consumption occurring in G20 countries [2] (Figure A1). About 65% of global electricity is generated from fossil fuels (coal, natural gas, and oil). As a result, combined with heat generation, the electricity sector globally represents 42% of total annual CO₂ emissions, with China (34%), the USA (13%), and India (8%) accounting for the highest share [3]. The heavy use of fossil-based sources, especially coal, also has an impact on airborne-substance emissions and on mineral-resource consumption. Regarding air pollution in India, the public-electricity and heat-production sector was responsible for 44% and 65% of total NO_x and SO₂ emissions in 2012, respectively [4]. For resource consumption, coal consumption in China and India has multiplied by 3.8 and 4.5 times since 1990 to reach 3770 and 982 Mt in 2018, respectively [5]. Globally, the consumption of natural gas has been also on the rise, especially in Asia, where some policies aim at replacing coal with natural gas, such as in China. The electricity sector is now responsible for 21% of the Chinese natural-gas consumption, and the sector was responsible for about 50% of the global annual consumption growth between 2011 and 2017 [6]. Only the generation of electricity by oil has been declining in recent years [7], especially in Japan and Korea, with the switch from oil to natural gas. One of the reasons is its emissions, especially in sulfur dioxide, which were estimated to be the highest among all power sources [8].

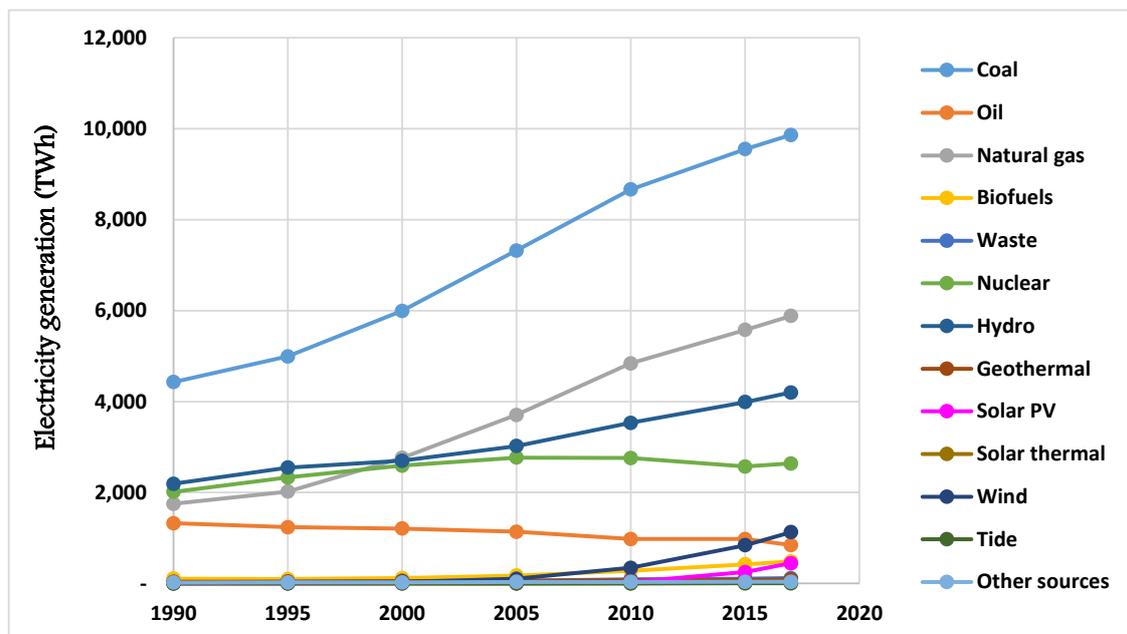


Figure 1. Global electricity generation by the source (1990–2017) [2].

For all the reasons mentioned previously, clean energy sources and carbon capture and storage (CCS, used acronyms presented in Table A1) methods are being focused on recently [9]. Biomass with carbon capture and storage (Bio-CCS or BECCS) is of particular interest, as negative emissions can be achieved [10,11]; thus, this technology could become very popular in the future. The building sector also accounts for a large amount of electricity consumption, therefore architecture design could also be another technique to reduce energy consumption [12].

1.1. Life-Cycle Assessment (LCA) of Electricity Generation

With the steadily growing economy of newly industrialized countries such as India or Indonesia, the damage caused in the environmental impact categories cited above could keep growing in the future if no measures are taken to mitigate the effect of population and economic growth on energy consumption.

Several life-cycle assessment (LCA) studies have tried to tackle the problems caused by the growing electricity consumption by estimating the emissions of different electricity generation sources. LCA is a useful technique to assess the environmental impacts of a product or services throughout its entire life-cycle, from the extraction of raw materials through to processing, transport, use and recycling/disposal. By considering several different impacts over the entire life-cycle, it is possible to identify potential tradeoffs from one life-cycle stage to another or from one environmental problem to another. These are major differences with the other assessment methods such as the carbon/water footprint (focusing only on one environmental aspect) or the methods focusing only on the direct emissions of products during operation. Each electricity generation source has a different lifecycle, so it is important to compare them at the same level. The main options are presented in Figure 2.

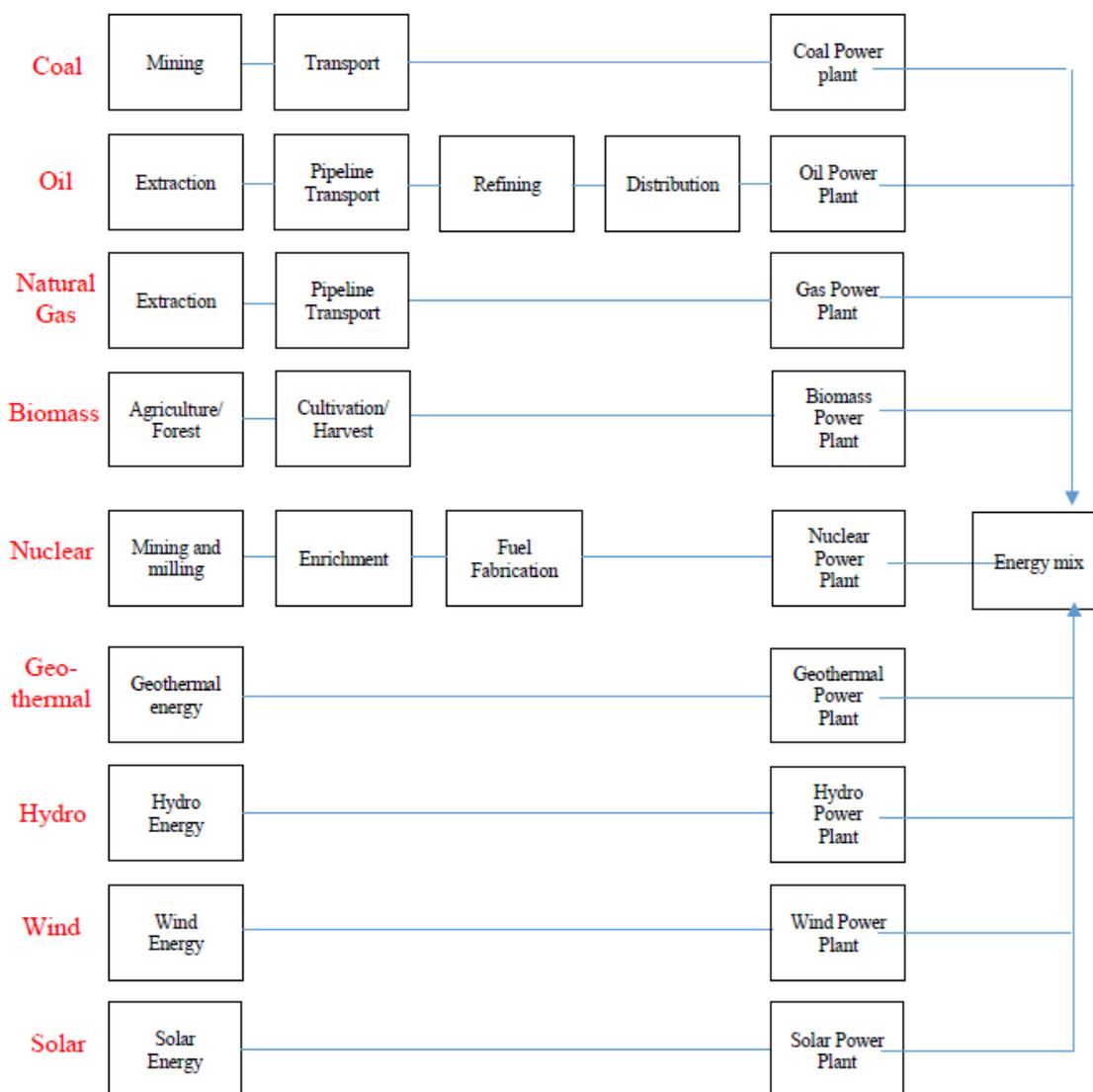


Figure 2. Lifecycle of the main electricity generation options (adapted from [13]).

Coal-based systems have various impacts: on water use, due to coal mining, washing, and processing [14]; on land use due to infrastructure [15]; and on fossil resources [16]. More importantly, coal has an impact during the operational stage of a plant, especially due to the combustion of coal emitting a large amount of greenhouse gases (GHGs) and air pollutants [8].

Oil and natural gas systems also have an impact on climate and air pollution during the operation stage [8], as well as on oil [17] and natural gas [18] scarcity due to fossil-fuel consumption.

Biomass systems have impacts during the cultivation/harvest stage, especially on land use and climate change [19] but also during combustion, depending on the type of biomass used [20].

Nuclear systems are proven to have a small impact on carbon dioxide emissions and air pollutants [21]; however impacts (land use and resource consumption) occur during the mining and enrichment of uranium and also due to the water required to create the steam needed for electricity generation and to cool the reactors during operation [22]. Nuclear waste may also contribute to ionizing radiation [23]. Other potential risks that have failed to be addressed by the LCA also exist, and various incidents can occur, such as in Chernobyl (1986) or, more recently, in Fukushima (2011).

Hydro systems have impacts on water use [24] and resource depletion due to the components required for their systems' construction [25]. Land transformation also occurs when using hydropower through infrastructure construction (namely, via power lines and access roads) [26].

Wind and solar systems have impacts on resource depletion due to the components required for photovoltaic panels and wind turbines, especially depletion of copper and chromium [25].

The latest findings for the LCA on electricity generation are summarized in Table A2. For conventional plants, such coal- and natural-gas-based systems, the literature has been focusing for example on the implementation of negative emissions technologies aimed at capturing carbon dioxide emissions or also on retrofitting existing coal power plants. For renewables, several systems (biomass, hydro, power, and solar) in different locations (China, Denmark, Spain, etc.) have been evaluated, an attention was given to infrastructural materials. Some assessments have been provided for developing countries as well (e.g., Bangladesh). Based on the environmental impacts raised in this recent review, it is still not intuitive to identify which technology has the overall best environmental performance.

For that purpose, Turconi et al. (2013) [8] conducted a review of 167 case studies found in the literature and reported that the range of values for carbon dioxide emissions was large depending on the source: between 2 (hydropower) and 1050 kg CO₂ eq/MWh (hard coal). Similarly, the same trend for these two technologies was observed for NO_x and SO₂ emissions: 0.004–3.9 kg NO_x/MWh and 0.001–6.7 kg SO₂/MWh; all these findings are shown in Table A3.

In a similar vein, Laurent et al. (2018) [27] identified the lifecycle environmental hotspots for electricity generation. They showed that fuel combustion during power-plants operation has the greatest impacts for fossil-based electricity; however, when using renewables, resource extraction stages for power-plants construction mainly influence the results. The main findings are shown in Table 1. The authors noted that it is important to consider all life cycles stages while dealing with energy system as for decision makers, it is important not to shift the environmental burden from one stage to another.

Table 1. Lifecycle environmental hotspots of electricity generation (adapted from [27]).

Impact Category	Coal	Natural Gas	Oil	Nuclear	Wind	Solar	Hydro	Geo-Thermal	Biomass
Climate Change	Operation	Operation	Operation	Operation	Resource	Resource	Resource	Resource	Operation
Particulate Matter	Operation	Operation	Operation	Operation	Resource	Resource	Resource	Resource	Operation
Water Use	Operation	Operation	Operation	Operation	Resource	Resource	Resource/ Operation	Resource	Operation
Land Use	Operation	Operation	Operation	Operation	Resource/ Operation	Resource/ Operation	Resource/ Operation	Resource/ Operation	Operation
Fossil Depletion	Operation	Operation	Operation	Operation	Resource	Resource	Resource	Resource	Operation
Metal Depletion	Resource/ Operation	Resource/ Operation	Resource/ Operation	Operation	Resource/ Disposal	Resource/ Disposal	Resource/ Disposal	Resource/ Disposal	Resource/ Disposal

1.2. External Cost of Electricity Generation

Another type of evaluation was performed by the European Environment Agency (EEA); the goal was to estimate the external cost of electricity generation in the EU [28]. According to the report, the external cost can be defined as the impact of an activity on an external group was not originally taken into account. Indeed, the costs associated with environmental damages for example on human health or ecosystems are not currently accounted for by the producers or the consumers of electricity, these costs can be significant and should not be underestimated. Their consideration can be useful to establish a ranking between different energy options and thereby support decision-making. In the EEA study, external cost was based on three major components: climate-change damage due to CO₂, air-pollutant emissions damage, and the nonenvironmental social cost for electricity not produced from fossil fuels. An environmental impact assessment expressed as a monetary value enables to increase the interest of decision makers, as it offers a more comprehensive approach to understand what the entire potential impact could be. It also allows us to establish a trade-off between different technologies to determine the pros and the cons of each one. The average external cost for EU25 in 2005 was found to be between 0.018 (low estimate) and 0.060 €/kWh (high estimate). A similar approach was applied on a city, country, or regional level in different case studies; a summary is provided in Table 2.

In this table, the external costs are between less than 0.001 and 0.375 \$/kWh. Coal and lignite technologies have the highest impact, whereas renewables have the lowest.

On a global scale, Rafaj and Kypreos (2007) [29] demonstrated that the external cost of electricity is usually found to be 20% higher when considering the impact of CO₂ emissions in addition to air pollutants. In contradiction to the common thinking that fossil fuels have the highest impacts, Stremikiene et al. (2014) [30] found that biomass (straw) CHP with an extraction–condensing turbine had the highest impact due to climate change. Although many studies focus on air-pollution’s impact, its magnitude is different in each study. By comparing Vrhocek et al. (2005) [31] and Dimitrijevic et al. (2011) [32], it can be observed that, even though both studies focused on countries located in the same region (the Balkans) and considered the same pollutants (PM, SO₂, and NO_x), the results were very different. The emissions inventory from power-plants for PM and NO_x showed many similarities; however, SO₂ emissions per kWh in some locations are up to 10 times higher in Bosnia than in Croatia due to the absence of abatement equipment for the mitigation of sulphur emissions. As shown by Czarnowska and Frangopoulos (2012) [33] and Klaassen (2007) [34], the damages caused by air pollution are directly linked to the amount of emissions and population density in the region. Mahapatra (2012) [35] also found that not only electricity generation had an impact on air substances emissions but also the energy supply.

Table 2. Overview of the previous studies’ estimates of external cost.

Impact Considered	Power-Plant Type	Low (\$/kWh)	High (\$/kWh)	Location	Year	Reference
CC, AP	C, Bio	0.009 (Bio)	0.026 (Coal)	China	2019	[36]
CC, AP	WTE	0.99	0.99	Spain	2019	[37]
CC, AP	C, L	0.041 (C)	0.082 (L)	Poland	2018	[38]
AP	C, NGC, NGCC	0.019	0.089	Iran	2015	[39]
AP, CC, R	Bio, C, Li, N, NGCC, O, S, W	0.001 (H)	0.078 (Bio)	Lithuania	2014	[30]
AP, CC, SOC	C	0.029	0.25	Northern Poland	2012	[33]
AP, CC	C	0.046	0.046	Western India	2012	[35]
AP	Li	0.002	0.035	Turkey	2011	[40]
AP	C	0.115	0.225	Bosnia and Herzegovina	2011	[3]

Table 2. Cont.

Impact Considered	Power-Plant Type	Low (\$/kWh)	High (\$/kWh)	Location	Year	Reference
CC	Li, NG, O	0.014 (NG)	0.034 (Li)	Greece	2010	[41]
AP, CC, SOC	Bio, C, H, Li, N, NGCC, O, P, S, W	<0.001 (H, W)	0.240 (Li)	EU25	2008	[28]
AP	C, O, NG, Bio, N, W, S	0.001 (S, W)	0.375 (C)	Global	2007	[34]
AP, CC	Bio, C, Geo, H, NG, O, N, S, W	0.001 (H, S, W)	0.177 (C)	Global	2007	[29]
AP	O	0.008	0.013	Cuba	2007	[42]
AP	C, NG, O	0.001 (NG)	0.007 (NG, O)	Croatia	2005	[31]
AP, CC	C	0.021	0.144	South Africa	2003	[43]

AP: air pollution; Bio: biofuel; CC: climate change; C: coal; Geo: geothermal; H: hydropower; Li: lignite; N: nuclear; NG: natural gas; NGC: NG conventional; NGCC: NG combined cycle; O: oil; P: peat; R: resource S: solar; SOC: Social cost; W: wind. WTE: Waste-to-Energy.

Several points can be observed from the previous table:

- Previous research has tended to only focus on the impact of air pollution or climate change, which could easily lead to an underestimation of the damages;
- Several studies only consider the operational stage (electricity generation stage), which is not adapted for the assessment of renewables;
- Only three studies covered the entire range of possibilities for different electricity generation sources;
- Rafaj and Kypreos (2007) [29] and Klaassen et al. (2007) [34] are the only studies to establish a comparison on a global scale. However, their models only estimate the external cost at the continental or global level, which is a serious limitation because, for example, the situation between western and eastern Europe is completely different (with a higher reliance on renewables in the former area and a higher reliance on coal (especially lignite) in the latter);
- The two previous studies were published more than 10 years ago, so they do not take into account current technological progress or the shift in the energy mix, which both have a strong influence on the results [28].

Thus, the different types of impact previously noted in this study, such as resource consumption (mineral, fossil, and water) and land transformation, have not been considered yet in the literature. Consequently, it is important to consider all available technologies and extend the number of environmental impact categories to properly assess the impacts of renewables. Differences between countries (efficiency of power plants, population density, and land-use planning) have important potential impact on the results, as highlighted in previous studies. Looking at the important differences of the results between studies with a range between less than 0.001 \$/kWh and 0.375 \$/kWh due to the different types of models applied, which are either only taking into account either one type of impact category, analyzing the impact of coal-power plant only, or the emissions at only one specific location. It would be better to compare different location using the same framework, considering for each location: a larger number of environmental impact categories, the differences of power-plant direct emissions, the difference of population density in each region but also considering the impacts of the mining stage and the following energy supply until electricity generation.

The aim of this paper is to fill the previous research gaps and to estimate, with transparency, the recent external costs of electricity generation at a global scale in G20 countries by considering a wider range of impact categories, including, for example land occupation and resource consumption and the full life-cycle of electricity generation, to provide a more accurate analysis of different electricity-generation technologies and evaluate most of the possibilities existing in the current market

in each country. Despite the recent rise of the environmental concerns, these external costs are still not considered when dealing with energy prices. One of the reasons might be the difficulty to understand the complex environment models but also the absence of tools specific to each region.

To achieve this transparent analysis, an approach based on life-cycle thinking was adopted: The life cycle impact assessment method based on endpoint modeling (LIME3) [44–46] was used to evaluate the environment impact assessment. For the choice of the global LCIA method, recently several studies provided regionalized-impact factors: Recipe2016 [47], ImpactWorld+ [48], and LIME3. In addition to the wide coverage of impact categories (climate change [49,50], air pollution [51], photochemical-oxidant creation [52], water consumption [53], land use [54], mineral-resources, fossil-fuels, forest-resource consumption, and solid waste) and their impacts on four areas of protection (human health, social assets, biodiversity, and primary production), the main advantage of LIME3 is the introduction of weighting factors that are specific to each country and help ultimately to provide a single indicator expressed in a monetary value (\$). This is particularly well-adapted for the evaluation of electricity, as a comparison can later be made between the market price and the external electricity cost. The two others global LCIA methods do not give any specific indications concerning weighting, and only provide the midpoint and endpoint characterization expressed as a specific unit of emissions or consumption for each impact category, for example, in disability-adjusted life year (DALY)/kgPM2.5. Therefore, these methods cannot be used to estimate an external cost contrary to LIME3.

2. Materials and Methods

2.1. Goal and Scope

The goal of the study was to evaluate the external cost of electricity generation in G20 countries using a global life-cycle impact-assessment (LCIA) method (LIME3) by considering 7 environmental impact categories: climate change, air pollution, photochemical oxidants, water consumption, land use, mineral resource consumption, and fossil fuel consumption. At first, an evaluation for each type of electricity-generation technology in each country was performed for the generation of 1 kWh (high voltage). Then, the evaluation of 1 kWh (low voltage) from the power generation mix of each country was assessed; system boundaries are provided in Figure 3. It includes the life cycle of the infrastructure, which generates electricity (including for example materials and their transport required to build the infrastructure) and the life cycle of fuels (not relevant for renewables) with the inclusion of the stages presented in Figure 2. The high-voltage processes describe the situation until the plant operation, before any further transformation, whereas the low-voltage processes describe the situation until the household level.

The European Union (EU) was excluded from our study, as several disparities (e.g., their reliance on fossil fuels, the efficiency of their power plants, etc.) currently exist between the member states. Therefore, the average external costs of the 27 nations would not be meaningful. However, France, Germany, and Italy, which are all individually G20 members, were included. The common targets in the EU have only been established in recent years: to increase the share of energy consumption from renewable sources and improve energy efficiency in order to reduce the use of primary energy [55].

The approach used in this study is detailed in Figure 4. Resources consumption and emissions that have an environmental impact during the electricity generation life-cycle are taken into account and later assigned to environmental impact categories (detailed in Section 2.3). These different impacts having damages on the area of protection such as human health or biodiversity. These damages are expressed in their own specific unit (e.g., DALY) therefore an economic weighting is applied to convert and aggregate these damages into a single monetary value: the external cost.

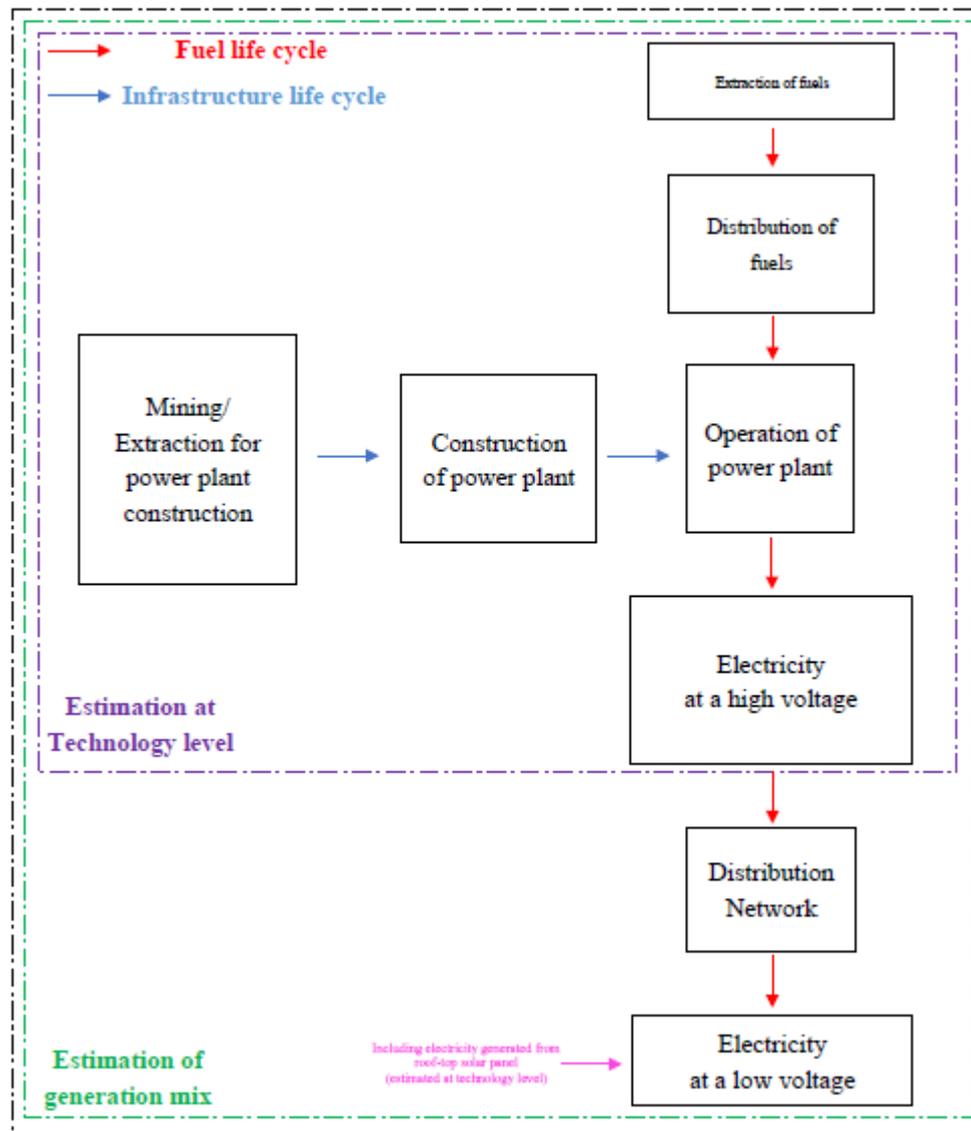


Figure 3. Studied system boundaries.

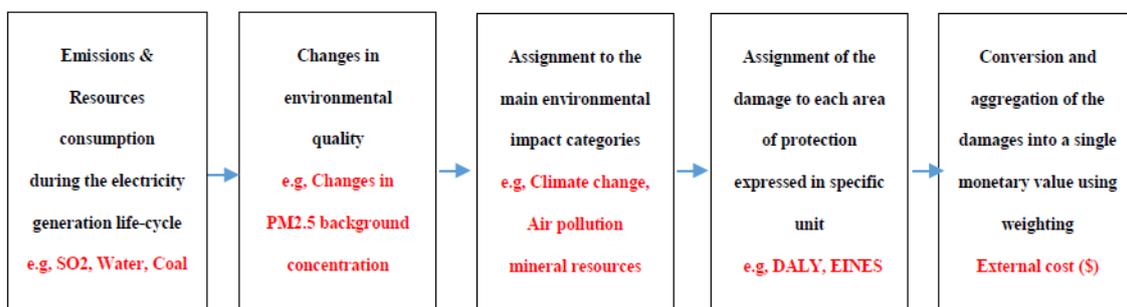


Figure 4. Pathway to estimate the external cost.

2.2. Inventory

IEA (International Energy Agency) data (2017) [56] were used as presented in Figure 5. These data are contained in the Ecoinvent Database v3.4, which is included in SimaPro 8. They correspond to global electricity generation in 2014 (for each country), and are the latest data available in the database. Ecoinvent database also provides a qualitative analysis of energy loss through the network and covers a

wider range of inventory flows than other available LCI databases. According to this information, Saudi Arabia, South Africa, and Indonesia have the highest dependence on fossil fuels (100%, 92%, and 86% of the energy mix, respectively). On the other hand, France, Canada, and Brazil have the lowest dependence (5%, 20%, and 24% of the mix, respectively). Concerning electricity generation from renewable energy (hydropower, solar, and wind energy), Brazil, Canada, and Italy are the leading G20 countries (65%, 62%, and 35% of the mix). Reliance on biofuels is quite low for the G20 (3% in the nonweighted average of the G20 energy mix), but Germany (9%), the UK (8%), Italy (8%), and Brazil (8%) still rely on them. This inventory provides electricity data for three types of voltages: low, medium, and high.

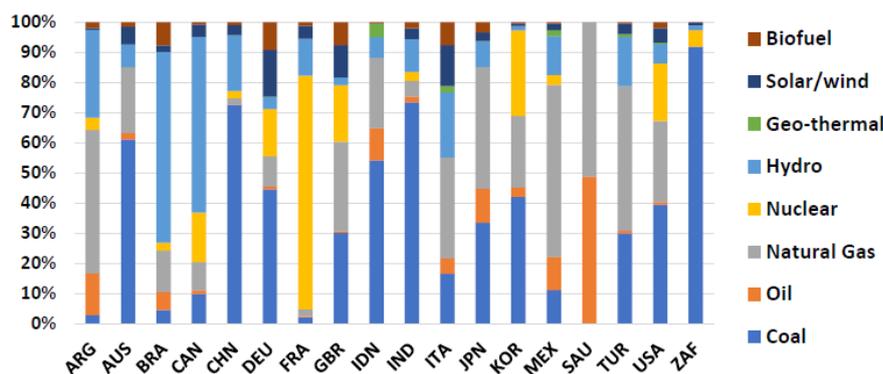


Figure 5. Electricity generation by source.

Following the Ecoinvent database structure, low-voltage processes were chosen to determine the impact of the grid mix for each country, and high voltage processes to determine the impact of each type of power plant. Almost all current possibilities available on the market were evaluated in this study, as shown in Table 3. Several types of plants were considered in this study, as shown in Table 3. Within each category, some differences can be briefly highlighted:

- Coal: In comparison to hard coal, lignite (also referred sometimes as brown coal) is the lowest grade coal with higher emissions of carbon dioxide and air pollutants during combustion.
- Natural gas: A combined cycle power plant combines both a gas and a steam turbine together for better efficiency than conventional plants.
- Wind: Both onshore and offshore options have pros and cons. Onshore wind farms are currently the most popular type of wind farm for economical reasons (with higher maintenance and supply costs for offshore turbines).
- Hydro: In run-of-river systems, water flows from a river through a canal or penstock to spin a turbine; in pumped-storage systems composed of a lower and upper reservoir, during high demand, the water is pumped from the upper reservoir to spin a turbine and produce electricity; in reservoir systems, a dam is used to store water, which is later released to spin turbines and produce electricity.
- Nuclear: Both boiling water and pressure water reactors use nuclear energy as fuel and water to generate steam and cool the reactors. However, a pressure water reactor uses two water circuits, while boiled water generates steam using only one water circuit.
- Solar: Open ground facilities can generate much more energy than simple roof-top panels; however, they require the occupation of land.

Table 3. Type of power plants considered in this study.

Category	Type 1	Type 2	Type 3
Coal	Hard Coal (HC)	Lignite	-
Natural Gas	Conventional (C)	Combined Cycle (CC)	-
Oil	Oil	-	-
Wind	Onshore (ON)	Offshore (OFF)	-
Geothermal	Geothermal (GEO)	-	-
Hydro	Run of River (RR)	Pumped Storage (PS)	Reservoir (R)
Nuclear	Boiling Water (BW)	Pressure Water (PW)	-
Solar	Open Ground (OG)	Roof	-

The following inventory items were chosen from the Ecoinvent database: carbon-dioxide emission (CO₂), sulfur-dioxide emission (SO₂), nitrogen-oxide emission (NO_x), nonmethane volatile organic compounds emission (NMVOC), particle-matter 2.5 emission (PM_{2.5}), oil consumption, coal consumption, natural-gas consumption, water consumption, land transformation and occupation, and mineral consumption.

2.3. Impact Assessment

LIME3 was utilized for external-cost evaluation. Nine impact categories and four endpoints (human health, social assets, biodiversity, and primary production) are included in this method, as illustrated in Figure 6 (additionally, to facilitate the understanding of our study, a detailed explanation of the parameters included in this method is provided (Tables A4 and A5). The impacts of solid waste and forest resources, however were not considered in our study. As stated previously, the possibility to include a large set of impact categories and provide results using a single indicator were the motivation to use this method. LIME3 also provides damage factors for up to 193 countries in the world, so it was very well-adapted to evaluate the external cost of electricity on a global scale. Finally, another advantage of LIME3 is its consideration of trade between countries, which allows one to adequately estimate the damage caused in mining countries when a resource unit is consumed in the consumer country. A discount rate was also included (3%, 5%, or 7%) to integrate the impact of future cash flows, as this rate represents how much importance is given to current decisions concerning future resource scarcity, a lower rate highlights the higher stress placed on the necessity for resource savings and 5% was chosen in this study.

The external cost (EC) in LIME3 can be viewed as the product of two items: the inventory result and the integration factor (IF), which is itself the product of the damage factor (or endpoint characterization factor) and the G20 population-weighted average economic-value conversion factor specific to each area of protection:

$$EC_{country} = \sum_{Impact\ safe} \sum_X Inv_{country}(X) \times IF_{country}^{impact}(Safe, X) \quad (1)$$

$$IF_{country}^{impact}(Safe, X) = IF_{country}^{impact}(Safe, X) \times EV_{G20\ pop-weighted}(Safe) \quad (2)$$

where:

- Inv(X) is the amount of inventory item X;
- $IF_{country}^{impact}$ is the integration factor associated with “Impact”, which is caused by inventory item X extended to the area of protection “Safe”;
- $DF_{country}^{impact}$ is the damage factor associated with “Impact”, which is caused by inventory item X extended to the area of protection “Safe”;
- EV(Safe) is the economic-value conversion factor based on weighting for the damage of one unit of the area of protection “Safe”.

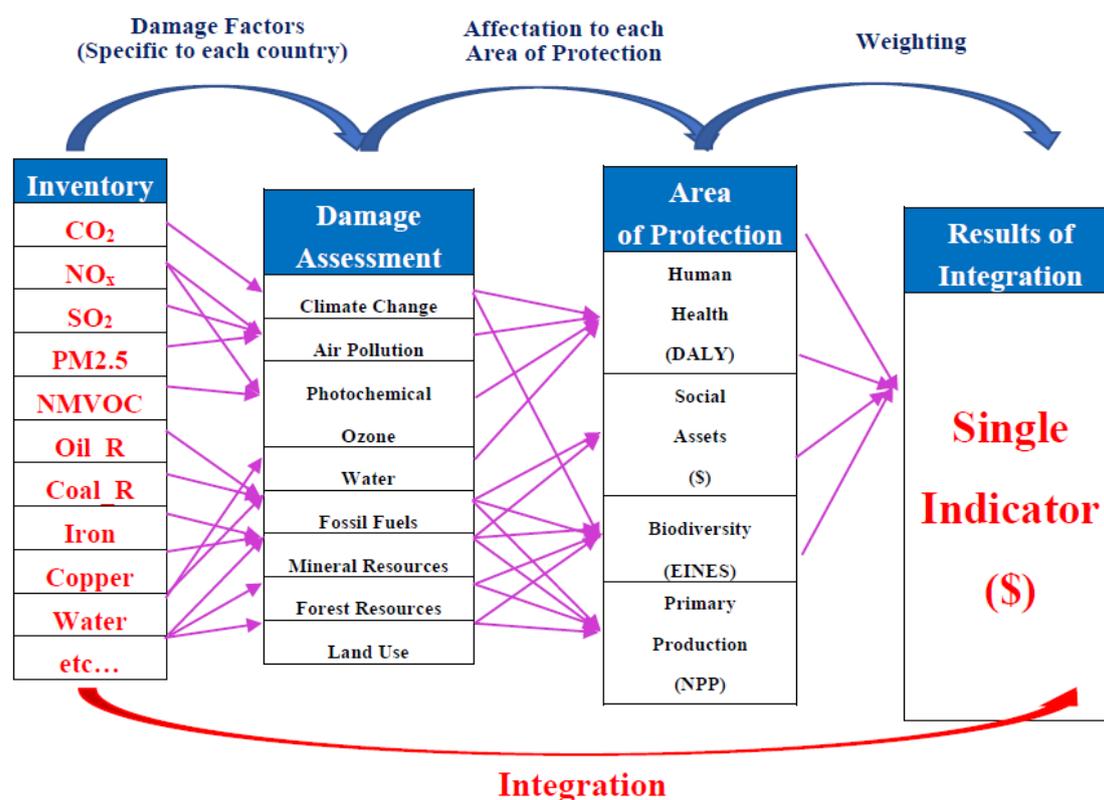


Figure 6. Life cycle impact assessment method based on endpoint modeling (LIME3) framework.

For example, “X” is the total SO₂ emissions, “Impact” is the air pollution, and “Safe” is human health. SO₂ emissions are then expressed in kg, the damage factor in disability-adjusted life years (DALY)/kg_{SO2}, and the economic-value conversion factor in \$/DALY; thus, the integration factor can be directly expressed in \$/kg_{SO2}.

The economic value conversion factors in LIME3 were developed based on the willingness to pay (WTP), following a survey conducted among all G20 members, a total of 6400 responses were obtained. It was determined how much the responders were willing to pay to avoid damages in each area of protection. Based on the answers, it was revealed which areas of protection were prioritized in each G20 country. In this study, economic-value conversion factors for each country were selected to be identical based on the average G20 country weighting factor (Murakami et al. (2018) [46]), as presented in Table 4.

Table 4. Economic value conversion factors for G20 countries (G20 population weighted average).

Human Health (USD/DALY)	Biodiversity (USD/EINES)	Social Assets (USD/USD)	Primary Production (USD/kg)
2.3×10^4	1.10×10^{10}	2.5	5.6×10^{-2}

3. Results

3.1. External Cost Estimation of Each Technology in G20 Countries

To find an explanation for the external cost of electricity for the G20 country power generation mix, it was necessary to evaluate the impact of each technology for each country. A summary of these results is provided in Table 5. The inventory items having influence on the external cost for each system are described in Table A6.

Table 5. External cost for each technology in each G20 country (\$/kWh; from dark green (Low) to dark red (High), the different hydropower systems are left uncoloured).

	HC	Lignite	NG C/CC	Oil	Wind ON/OFF	GEO	Hydro RR/PS/R	Nuclear BW/PW	Solar OG/Roof
ARG	-	-	-/-	-	-/-	-	-/-/-	-/-	-
AUS	0.026	0.026	0.013/0.008	0.096	0.002/-	-	0.000/0.031/-	-/-	0.004/0.003
BRA	0.023	0.047	0.013/0.009	0.081	0.003/-	-	-/-/0.002	-/0.001	-/0.006
CAN	0.034	0.029	0.022/0.014	0.071	0.004/-	-	0.001/0.017/0.002	-/0.004	0.008/0.009
CHN	0.101	-	0.021/0.020	0.146	0.009/0.006	0.009	0.001/0.112/-	-/0.004	0.015/0.014
DEU	0.021	0.027	0.019/0.012	0.083	0.005/0.004	0.005	0.001/0.024/0.004	0.002/0.002	0.011/0.010
FRA	0.037	-	0.017/0.012	0.087	0.003/0.003	0.004	0.001/0.005/0.004	-/0.002	0.009/0.008
GBR	0.064	-	0.017/0.012	0.24	0.004/0.005	0.007	0.001/0.058/-	0.005/0.005	0.014/0.017
IDN	-	0.194	0.020/0.012	0.133	0.002/-	0.006	-/-/0.005	-/-	-/0.010
IND	0.174	0.143	0.021/0.020	0.112	0.006/-	0.009	0.001/0.227/0.068	0.005/0.004	-/0.010
ITA	0.041	0.133	0.019/0.011	0.083	0.005/-	0.005	0.001/0.028/0.006	-/-	0.010/0.009
JPN	0.036	-	0.020/0.013	0.041	0.005/0.005	0.005	0.001/0.038/0.028	0.005/0.005	0.011/0.010
KOR	0.062	0.282	0.020/0.011	0.082	0.004/0.004	-	0.001/0.062/0.042	-/0.007	0.015/0.015
MEX	0.027	0.043	0.022/0.014	0.134	0.003/-	0.004	0.001/-/-	0.003/-	0.009/0.005
RUS	0.033	0.069	0.031/0.008	0.141	0.015/-	0.004	0.000/0.032/0.002	0.001/0.001	-/0.008
SAU	-	-	0.015/0.008	0.046	-/-	-	-/-/-	-/-	-/0.005
TUR	0.048	0.141	0.014/0.009	0.133	0.003/-	0.005	0.001/-/0.009	-/-	-/0.008
USA	0.028	0.055	0.020/0.013	0.138	0.003/-	0.004	0.001/0.029/0.011	0.002/0.002	0.007/0.007
ZAF	0.035	-	-/0.007	0.047	0.006/-	0.004	0.001/0.049/0.013	-/0.002	-/0.009
AVG	0.049	0.099	0.019/0.012	0.105	0.005/0.005	0.005	0.001/0.055/0.015	0.003/0.003	0.011/0.009

Some interesting findings can be highlighted:

For hard coal (HC), the results were between 0.021 (Germany) and 0.174 \$/kWh (India): the emissions of PM_{2.5} for 1 kWh of electricity generated using coal in India were almost seven times higher than the G20 average (2.5 g/kWh). The PM_{2.5} integration factor was also the highest in the G20 with 36 \$/kg due to higher population density. India had a population density of 416 inhabitants/km² compared with the 25 inhabitants/km² in Brazil, resulting in a much smaller integration factor for PM_{2.5} (1.8 \$/kg). In addition, Germany had the lowest emissions of SO₂, NO_x, and PM_{2.5} from coal power-plants among G20 countries due its technological performance.

For lignite, the results were between 0.026 (Australia) and 0.282 \$/kWh (South Korea). For South Korea, the results were mainly explained by the impact of PM_{2.5}: even if the emissions per kWh (0.0088 kg) were close to the G20 emissions average, the integration factor of PM_{2.5} for South Korea was high (25 \$/kg), the third highest among the studied countries (behind India and China). For Australia, the inventory and integration factors for air pollutants (very low population density of 3 inhabitants/km²) had both lower values than those of other countries.

For natural gas (NG), two types of power plants were assessed for this study: conventional and combined-cycle (CC). For the conventional type, results were found between 0.013 (Australia, Brazil) and 0.031 \$/kWh (Russia). For Russia both the CO₂ and natural-gas consumption inventories show the highest amounts among the G20 countries. The CO₂ emissions of conventional plants in Russia are two times higher than the G20 average, but the national reserves of natural gas in the country are the highest in the world. Thus, the impact on this resource was still limited (0.001\$). Indeed, as detailed in Table A5, the damage factors for fossil fuels and resource consumption in LIME3 are based on yearly extraction compared to the actual reserves [57]; the smaller the ratio is, the lower the damage factor is. Global trade was also taken into account in LIME3; as a result, a country that imports resources from another where scarcity was low (e.g., oil from Saudi Arabia) had a smaller damage factor. On the other hand, a country that had limited reserves and mainly used these resources had a higher damage factor

(e.g., oil in Argentina). For Turkey, natural-gas imports were mainly from Russia, and CO₂ emissions were also on the same level of the G20 country average, so impacts were limited. Australia and Brazil both show lower air-pollutant impact due to their small population density. For combined-cycle plants, results were estimated to be lower than conventional ones, with values between 0.007 (South Africa) and 0.020 \$/kWh (China, India). Combined-cycle plants had better efficiency, as they required about 30% fewer resources on average, and CO₂ emissions were also reduced at about the same level. The difference of results between countries for this technology were mainly explained by higher natural-gas consumption and more CO₂ emissions in China and India, while the air pollution damage in South Africa was low due to the population density.

Oil is the resource with the highest external costs (between 0.041 (Japan) and 0.240 \$/kWh (UK)). For Japan, the low cost is explained due to the oil exports from Saudi Arabia, whose reserves are the second highest in the world, with a proven reserve of 266,455 million barrels [58]. For the UK, lower oil reserves coupled with much higher SO₂ emissions (almost two times higher than the G20 average) justify this observation.

For wind power, results were between 0.002 (Australia, Indonesia) and 0.015 \$/kWh (Russia). The difference of impact between onshore (ON) and offshore (OFF) wind turbines was not significant. The impacts mainly come from material consumption (more than 65% of the total impact); in particular, chromium (26%); nickel (24%), as one of the element of stainless steel; and copper (10%), used for cables.

For hydropower (Hydro), several types of systems were evaluated: Run-of-river (RR), reservoir I, and pumped-storage (PS). The highest cost was determined for pumped storage, with 0.227 \$/kWh in India; this impact is due to the use of electricity for pumpage, as more than 1.4 kWh of electricity is necessary on average to generate 1 kWh of electricity. Reservoir technology has the second highest impact, especially in countries where the damage factor for water is high, such as Korea (0.042\$) and Japan (0.028\$). Finally, run-of-river hydropower showed the lowest impact (0.001\$ on average), mainly with an impact on land transformation.

For nuclear power, the results were between 0.001 (Brazil, Russia) and 0.007 \$/kWh (South Korea). The impact is mainly due to the use of water (38%), uranium (12%), and chromium (11%). These findings should be treated with caution, as our method does not include the impact of radioactive leaks/waste or the potential risk of nuclear incidents.

For solar power, the results were between 0.003 (Australia) and 0.017 \$/kWh (UK); the impact were shown to be similar for open ground and roof installations. For roof-top installations, the contribution of metals is mainly from copper (12%), gold (9.3%), and aluminum (5.1%).

Finally, for geothermal power, with emissions of carbon dioxide and air pollutants much lower than those of other technologies, the impacts were shown to be less than that of fossil-based electricity generation. An example to illustrate these results is provided for the UK in Figure 7. This country is a good example of the importance of resource scarcity as even though the inventory for the electricity generation from each type of energy is around in the average of the G20, the importance given to fossil and minerals resources for the UK in LIME3 was the highest among the G20 members in this study.

Figure 7 shows that the electricity generated using oil had the greatest impact, with a value of 0.240 \$/kWh; this value is explained by the integration factor for oil, which is the highest in the G20. The UK has limited country reserves (2564 million barrels), and more than half of its crude oil imports are from Norway, whose oil reserves were also relatively small (6661). It can be also observed that coal has the second highest impact (0.064 \$/kWh) due to CO₂ emissions and coal consumption (the UK has the fourth highest factor in the G20 due to its limited reserves). Solar energy showed a similar impact as natural gas due to the impact of minerals. The impact of geothermal-, hydro- (except for pumped storage for the same reasons as stated previously), nuclear-, and wind-power technologies was found to be low.

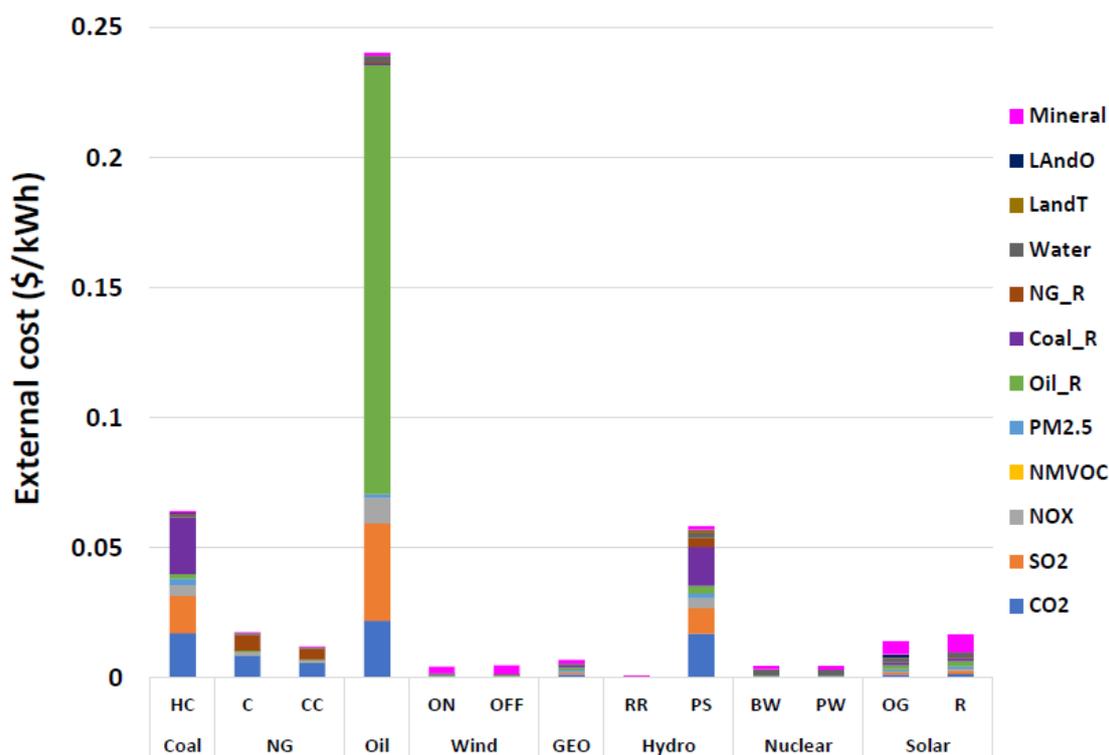


Figure 7. External cost of each technology in the UK for 1 kWh generated by each technology.

3.2. External Cost Estimation of Each Technology in G20 Countries

It is then possible to explain the results for the power generation mix of each country. External cost were determined as detailed in Figure 8. The results were estimated between 0.005 \$/kWh (France) and 0.172 \$/kWh (India). The nonweighted average result for the 19 countries was 0.044 \$/kWh. As suggested by previous studies, the external cost is largely impacted by the dependence of a country on fossil-based energies. The results for each country are detailed in the following subsections.

Table 6 shows a summary of the results for each inventory item. It shows that the average values were the highest for carbon dioxide (0.012\$), PM2.5 (0.013\$), and, to a lesser extent, oil consumption (0.003\$), coal consumption (0.002\$), and land transformation (0.001\$). Standard deviation was found to be the highest for PM2.5 (0.027) and the lowest for NMVOC (0).

Table 6. Range of the external cost (\$) for each inventory item in G20 countries (average; SD).

CO ₂	0.001–0.026 [0.012] [0.006]
SO ₂	0–0.020 [0.005] [0.006]
NO _x	0–0.027 [0.004] [0.006]
NMVOC	0–0 [0] [0]
PM2.5	0–0.089 [0.013] [0.027]
Oil_R	0–0.017 [0.003] [0.006]
Coal_R	0–0.015[0.002] [0.004]
Natural Gas_R	0–0.004 [0.001] [0.001]
Water	0–0.006 [0.001] [0.001]
Land transformation	0–0.003 [0.001] [0.001]
Land Occupation	0–0.001 [0.000] [0]
Mineral	0.001–0.002 [0.002] [0]

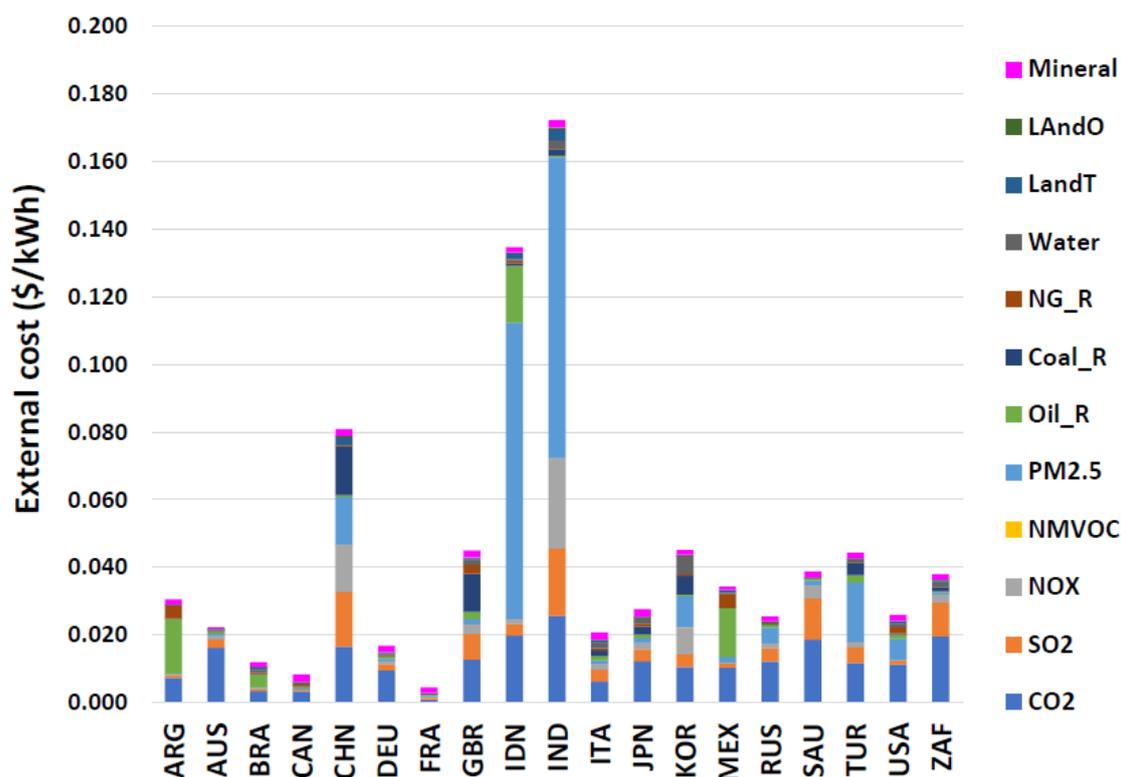


Figure 8. External cost of electricity generation for G20 countries (\$/kWh).

3.2.1. Argentina

The external cost was determined to be 0.031 \$/kWh with the following main-impact distribution: oil (0.016\$), CO₂ (0.007\$), natural gas (0.004\$), mineral (0.001\$), and SO₂ (0.001\$).

The Argentinian mix in 2014 (see Section 2.2) was composed of the following technologies: coal (3%), oil (14%), natural gas (48%), nuclear (4%), hydro (29%), solar/wind (1%), and biofuel (2%). The relatively low dependence on coal explains the lower impact of CO₂ emissions and air pollution. Argentina relies more on oil than most G20 countries, and also produces much of its own oil, as highlighted in Figure 9. This resource being limited (2185 millions of barrels compared to 266,455 in Saudi Arabia or 80,000 in Russia), the social impact is higher than in other countries. The impact of natural gas is clearly explained by the fact that almost half of the electricity is generated using this resource.

3.2.2. Australia

The external cost was determined to be 0.022 \$/kWh with the following main impact distribution: CO₂ (0.016\$), SO₂ (0.002\$), Nox (0.001\$), PM2.5 (0.001\$), and oil (0.001\$).

The Australian mix in 2014 was composed of the following technologies: coal (61%), oil (2%), natural gas (22%), hydro (7%), solar/wind (6%), and biofuel (1%). The relatively high dependence on coal explains the higher impact of CO₂ emissions. Australia has one of the lowest population densities in the world (3 pop/km²), so, despite this dependence on coal, the impact of air pollution on human health in Australia was smaller than elsewhere. As Australian coal reserves are massive (Australia is the largest global coal exporter), the impact on the reserve was not high.

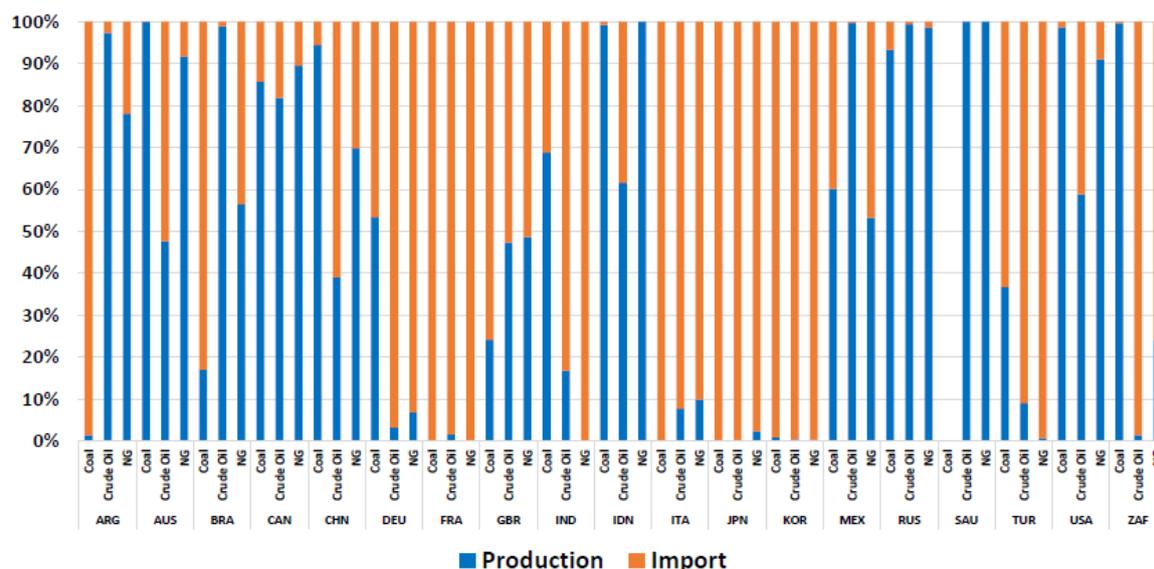


Figure 9. Production vs. importation for coal, oil, and natural gas in G20 countries [2].

3.2.3. Brazil

The external cost was determined to be 0.012 \$/kWh with the following main impact distribution: oil (0.004\$), CO₂ (0.004\$), mineral (0.001\$), land transformation (0.001\$), water (0.001\$), and natural gas (0.001\$).

The Brazilian mix in 2014 was composed of the following technologies: coal (5%), oil (6%), natural gas (14%), nuclear (3%), hydro (63%), solar/wind (2%), and biofuel (8%). The relatively low-dependence on fossil fuels explains the low impact of CO₂ emissions and air pollution. Brazil meets much of its own oil needs and has limited resources (12,999 million barrels), the same as Argentina; therefore, the impact of oil was shown to be slightly higher than that of other countries.

3.2.4. Canada

The external cost was determined to be 0.008 \$/kWh with the following main impact distribution: CO₂ (0.003\$), mineral (0.002\$), water (0.001\$), natural gas (0.001\$), and oil (0.001\$).

The Canadian mix in 2014 was composed of the following technologies: coal (10%), oil (1%), natural gas (9%), nuclear (16%), hydro (58%), solar/wind (4%), and biofuel (1%). The country's relatively low dependence on fossil fuels explains the low impact of its CO₂ emissions and air pollution.

3.2.5. China

The external cost was determined to be 0.081 \$/kWh with the following main impact distribution: CO₂ (0.017\$), SO₂ (0.016\$), coal (0.015\$), PM_{2.5} (0.014\$), Nox (0.014\$), mineral (0.002\$), land transformation (0.002\$), and oil (0.001\$).

The Chinese mix in 2014 was composed of the following technologies: coal (72%), natural gas (2%), nuclear (2%), hydro (19%), solar/wind (3%), and biofuel (1%). The high dependence on coal explains the large impact of CO₂ emissions and air pollution, which is amplified by the country's high population density in urban areas. China is also exploiting its own coal, mainly using it to generate electricity, so the impact on the reserve was quite significant.

3.2.6. France

The external cost was determined to be the lowest at 0.005 \$/kWh with the following main impact distribution: mineral (0.002\$), CO₂ (0.001\$), and SO₂ (0.001\$).

The French mix in 2014 was composed of the following technologies: coal (2%), natural gas (2%), nuclear (78%), hydro (12%), solar/wind (4%), and biofuel (1%). The high dependence on nuclear power explains the absence of damage for all inventory items. However, as highlighted previously, these findings should be interpreted with extreme caution, given that our method does not include the damage caused by radioactive waste or the possible damage risk due to leakages or accidents from nuclear-power plants (as seen, for example, in Japan following the 2011 Tohoku earthquake and tsunami).

3.2.7. Germany

The external cost was determined to be 0.017 \$/kWh with the following main impact distribution: CO₂ (0.010\$), mineral (0.002\$), SO₂ (0.002\$), Nox (0.001\$), oil (0.001\$), and PM2.5 (0.001\$).

The German mix in 2014 was composed of the following technologies: coal (44%), oil (1%), natural gas (10%), nuclear (15%), hydro (4%), solar/wind (15%), and biofuel (9%). The country's high dependence on coal energy explains more than half of the total external cost. However, as stated previously, the impact of coal is the lowest in the G20 due to the low emissions of airborne substances from coal-power plants.

3.2.8. India

The external cost was determined to be the highest at 0.172 \$/kWh with the following main impact distribution: PM2.5 (0.089\$), Nox (0.027\$), CO₂ (0.026\$), SO₂ (0.020\$), land transformation (0.003\$), water (0.003\$), mineral (0.002\$), and coal (0.002\$).

The Indian mix in 2014 was composed of the following technologies: coal (69%), oil (2%), natural gas (5%), nuclear (3%), hydro (10%), solar/wind (1%), and biofuel (1%). Similar to China, the high dependence on coal explains the large impact of CO₂ emissions and air pollution. The higher population density (four times higher on average than other G20 countries) as well as higher emissions of particulate matter are the reasons why the impact of air pollution was much higher in India than in China.

3.2.9. Indonesia

The external cost was determined to be the second highest at 0.135 \$/kWh with the following main impact distribution: PM2.5 (0.088\$), CO₂ (0.020 \$), oil (0.017\$), SO₂ (0.003\$), land transformation (0.002\$), mineral (0.002\$), Nox (0.001\$), natural gas (0.001\$), and coal (0.001\$).

The Indonesian mix in 2014 was composed of the following technologies: coal (53%), oil (10%), natural gas (23%), hydro (7%), and geothermal (4%). Similar to China and India, the high dependence on coal explains the large impact of CO₂ emissions and air pollution. The impact caused by particulate matter was high due to the heavy particulate-matter emissions from the use of lignite: when 1 kWh of electricity was produced in Indonesia, 21 g of PM2.5 were emitted on average (compared to 2.5 g in India and 0.5 g in China).

3.2.10. Italy

The external cost was determined to be 0.021 \$/kWh with the following main-impact distribution: CO₂ (0.006\$), SO₂ (0.004\$), mineral (0.002\$), water (0.002\$), coal (0.002\$), Nox (0.001\$), oil (0.001\$), PM2.5 (0.001\$), land transformation (0.001\$), and natural gas (0.001\$).

External cost was determined at 0.043 \$/kWh. The Italian mix in 2014 was composed of the following technologies: coal (17%), oil (5%), natural gas (33%), hydro (22%), geothermal (2%), solar/wind (14%), and biofuel (8%). The relatively low dependence on coal explained the lower impact of CO₂ emissions and air pollution.

3.2.11. Japan

The external cost was determined to be 0.028 \$/kWh with the following main impact distribution: CO₂ (0.012\$), SO₂ (0.004\$), coal (0.002\$), mineral (0.002\$), water (0.002\$), Nox (0.002\$), PM2.5 (0.001\$), oil (0.001\$), and natural gas (0.001\$).

The Japanese mix in 2014 was composed of the following technologies: coal (34%), oil (11%), natural gas (40%), hydro (8%), solar/wind (3%), and biofuel (3%). The relatively high dependence on fossil fuels explains more than half of the total external cost due to CO₂ emissions and air pollution.

3.2.12. Mexico

The external cost was determined to be 0.034 \$/kWh with the following main impact distribution: oil (0.014\$), CO₂ (0.010\$), natural gas (0.004\$), PM2.5 (0.002\$), SO₂ (0.001\$), mineral (0.001\$), and land transformation (0.001\$).

The Mexican mix in 2014 was composed of the following technologies: coal (11%), oil (11%), natural gas (57%), nuclear (3%), hydro (13%), geothermal (2%), and solar/wind (3%). For the same reason as Argentina and Brazil, the use of oil to generate electricity directly impacted the national reserves and increased the impact compared to other countries (Mexico produced nearly 100% of its own oil). The country's low dependence on coal explained the lower impact caused by carbon dioxide and air pollution. Its higher dependence on natural gas explained the rest of the cost.

3.2.13. Russia

The external cost was determined to be 0.026 \$/kWh with the following main impact distribution: CO₂ (0.012\$), PM2.5 (0.005\$), SO₂ (0.004\$), Nox (0.001\$), mineral (0.001\$), and oil (0.001\$).

The Russian mix in 2014 was composed of the following technologies: coal (15%), oil (1%), natural gas (50%), nuclear (17%), and hydro (17%). The relatively high dependence on fossil fuels explains most of the result, but as Russia has important fossil reserves, the impact was mitigated for resource consumption. The impact related to air pollution was low because of the lower population density.

3.2.14. Saudi Arabia

The external cost was determined to be 0.039 \$/kWh with the following main impact distribution: CO₂ (0.019\$), SO₂ (0.012\$), Nox (0.004\$), mineral (0.002\$), PM2.5 (0.001\$), and oil (0.001\$).

The Saudi Arabian mix in 2014 was composed of the following technologies: oil (49%) and natural gas (51%). The country's sole dependence on oil and natural gas explained most of the result. Despite having large reserves, the country's substantial use of oil still had an impact.

3.2.15. South Africa

The external cost was determined to be 0.038 \$/kWh with the following main impact distribution: CO₂ (0.020\$), SO₂ (0.010\$), Nox (0.002\$), water (0.002\$), mineral (0.002\$), coal (0.001\$), and PM2.5 (0.001\$).

The South African mix in 2014 was composed of the following technologies: coal (92%), nuclear (5%), and hydro (2%). Most of the total external cost was explained by the very high reliance on coal, but as population density was not significant, the potential impact was shown to be less than that in Asian countries.

3.2.16. South Korea

The external cost was determined at 0.045 \$/kWh with the following main-impact distribution: CO₂ (0.011\$), PM2.5 (0.009\$), Nox (0.008\$), water (0.006\$), coal (0.005\$), SO₂ (0.004\$), and mineral (0.001\$).

The South Korean mix in 2014 was composed of the following technologies: coal (42%), oil (3%), natural gas (24%), nuclear (28%), hydro (1%), and solar/wind (1%). The relatively high dependence on fossil fuels explained more than half of the total external cost due to CO₂ emissions and air

pollution. The impact of coal was explained by the fact that Korea mainly relies on coal imports from other countries, and one-third of these imports is from Indonesia [59], a country with extensive coal extraction.

3.2.17. Turkey

The external cost was determined to be 0.044 \$/kWh with the following main impact distribution: PM2.5 (0.018\$), CO₂ (0.012\$), SO₂ (0.005\$), coal (0.004\$), oil (0.002\$), mineral (0.002\$), Nox (0.002\$), and water (0.001\$).

The Turkish mix in 2014 was composed of the following technologies: coal (30%), oil (1%), natural gas (48%), hydro (16%), geothermal (1%), and solar/wind (3%). The high dependence on fossil fuels explained more than half of the total external costs due to CO₂ emissions and air pollution. The impact of coal was explained by the fact that Turkey produces about one-third of its own needs, but the country's reserve decreased every year (its integration factor was the second highest among the G20 countries after Indonesia).

3.2.18. UK

The external cost was determined to be 0.045 \$/kWh with the following impact distribution: CO₂ (0.013\$), coal (0.011\$), SO₂ (0.008\$), Nox (0.003\$), natural gas (0.003\$), oil (0.002\$), mineral (0.002\$), PM2.5 (0.001\$), water (0.001\$), and land transformation (0.001\$).

The UK mix in 2014 was composed of the following technologies: coal (30%), natural gas (30%), nuclear (19%), hydro (3%), solar/wind (11%), and biofuel (8%). The relatively high dependence on fossil fuels explained one-quarter of the total external costs due to CO₂ emissions and air pollution. The impact of coal was explained by the country's lower coal reserves compared to other producers.

3.2.19. USA

The external cost was determined to be 0.026 \$/kWh with the following main impact distribution: CO₂ (0.011\$), PM2.5 (0.006\$), NG (0.002\$), mineral (0.002\$), oil (0.001\$), SO₂ (0.001\$), water (0.001\$), and land transformation (0.001\$).

The USA mix in 2014 was composed of the following technologies: coal (39%), oil (1%), natural gas (27%), nuclear (19%), hydro (6%), solar/wind (5%), and biofuel (2%). The relatively high-dependence on fossil fuels explained more than half of the total external costs due to CO₂ emissions and air pollution.

4. Discussion

4.1. Estimation of the Annual GDP Loss

The product of the annual electricity generated with the external price per kWh (calculated previously) enabled us to estimate the total annual external cost of electricity generation. The data provided annually by Enerdata (Global Energy Statistical Yearbook 2019) [5] were used as presented in Table A7.

The values were found to be between 2.9 billion \$ (France) and 574 billion \$ (China). This clearly indicates that governments should push for the development of renewable energy sources and energy-saving policies.

GDP loss due to electricity generation was then calculated for each country, as detailed in Table 7.

Table 7. Annual external cost and potential GDP loss ratio due to annual electricity generation.

Country	Annual External Cost (Bill USD)	Potential GDP (Nominal) Loss Ratio
Argentina	4.6	0.88%
Australia	5.7	0.40%
Brazil	7.2	0.38%
Canada	5.3	0.31%
China	574	4.22%
France	2.9	0.10%
Germany	11.0	0.28%
India	282	10.37%
Indonesia	36.2	3.47%
Italy	6.1	0.29%
Japan	30.9	0.62%
Mexico	10.9	0.89%
Russia	29.3	1.77%
Saudi Arabia	13.7	1.75%
South Africa	9.7	2.64%
South Korea	26.7	1.65%
Turkey	13.3	1.74%
UK	15.0	0.53%
USA	115	0.56%

Again, the impact in newly industrialized countries was the most important, estimated to be up to 10.4% of India's GDP. The impact was less than 1% in major developed countries except for South Korea (1.65%).

4.2. Comparison of Electricity External Price with Market Price

In this section, the external price of electricity was compared to the market price of electricity [60], and the results are presented in Figure 10.

By comparing these two indicators it was possible to identify which countries could provide cheap electricity while still saving environmental quality. On the other hand, this comparison also highlights the countries that generate a low-cost electricity with a high environmental burden. As expected, a trend could again be delimited between developed and newly industrialized countries. In India and Indonesia, the ratio of external cost and market price was 2.3 and 1.7, respectively. This ratio was also shown to be higher for Turkey and Mexico (0.4–0.5). In contrast, this ratio was less than 0.2 on average for developed countries, partly due to their higher reliance on renewables.

Another conclusion can be made for India, Indonesia, and China: developing countries often rely on fossil energy as it is cheaper to generate electricity with it. However, our comparison showed that it was still possible to produce energy at a lower cost even with renewables as the main energy source. Canada is a very good example: both its market price and external costs are lower than those of other developed countries because of its use of hydropower. The high water scarcity in India, Indonesia, and China likely led to their higher reliance on natural gas. Following the example of Mexico could be their best option to reduce the environmental impact.

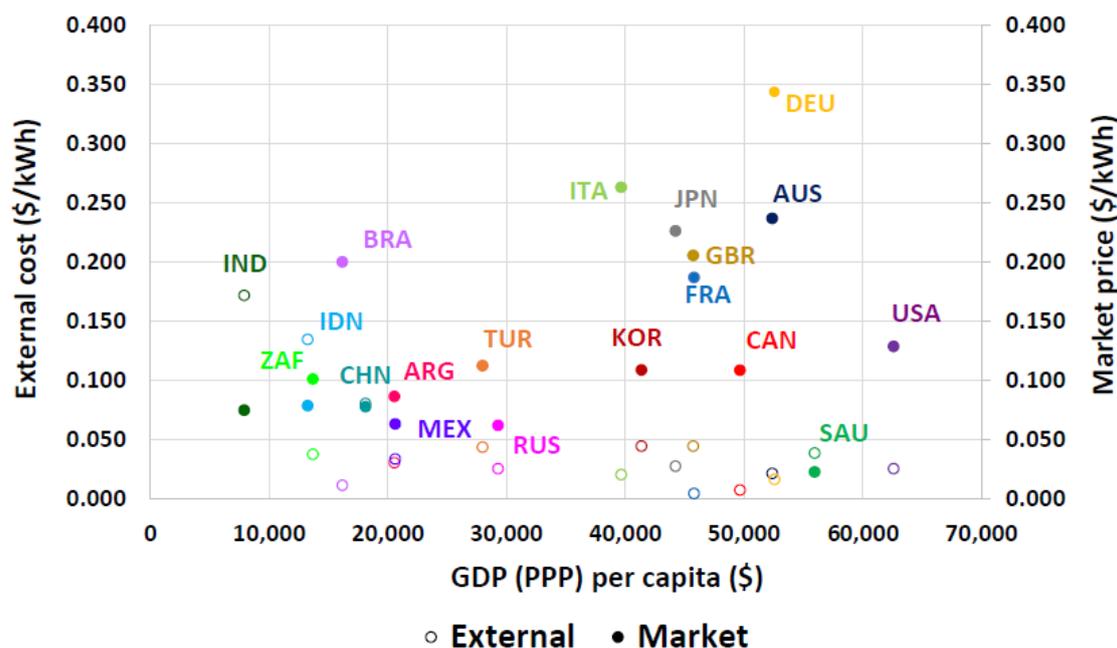


Figure 10. Market price and external cost variation with GDP (PPP) per capita of G20 countries.

4.3. Comparison with Previous Studies

Despite the differences in the method and inventory (Table 8), our results were comparable to those of the study conducted by the EEA for four countries: France, Germany, Italy, and the UK. For France, the external cost for 1 kWh of generated electricity was estimated to be between 0.008 (low estimation) and 0.021\$ (high estimation); for Germany, it was between 0.023 and 0.085\$; for Italy, it was between 0.017 and 0.062\$; and, for the UK, it was between 0.026 and 0.070\$. As described in Section 3.1, in this study, external costs were 0.005, 0.017, 0.021, and 0.045\$ for these countries, respectively. Therefore, the trend observed in both studies is similar.

For France, the power generation mix was almost the same in 2005 and 2014 (with the nuclear share between 75% and 80% of the mix), and the external cost for the electricity generated using nuclear power in our study was also half (0.002 vs. 0.004\$); this could explain why our result for France was two times lower than the EEA's lowest estimation results.

For Germany, the nuclear share was reduced by almost half between 2005 and 2014 for renewables. Moreover, the impact of coal was estimated to be lower in our research (0.021–0.027 vs. 0.050–0.080), likely due to efficiency improvements in the last 10 years. Our results were close to the lowest estimations of the EEA methodology.

For Italy, the share of oil decreased from 15% to 5% between 2005 and 2014 for natural gas. The impact of natural gas was not very different between both studies (0.020–0.030 vs. 0.011–0.019 in our study). Our results were still higher than the lowest estimations in the EEA study due to our consideration of a larger number of impact types.

For the UK, the energy mix has also not drastically changed since 2005. The impact of natural gas was very similar in both studies (0.010–0.020 vs. 0.012–0.017 in our study). This is likely due probably to the impact of coal consumption (0.011\$). Thus, our results agreed with the middle values of the EEA estimations.

It is clear that our study had some similarities with the EEA study, which can be explained by the fact that both studies showed climate change and air pollution to have the greatest important impact. For France, Germany, and Italy, our results were close to the EEA's lowest estimations, but for the UK, the addition of resource scarcity in our method was probably the main reason why our results were two times higher than the lowest estimations of the EEA, which justified the framework and method chosen in our study. Additionally, the EEA study was conducted in 2005, whereas in this study 2014

data were used. Thus, it is possible that, by applying the EEA methodology to more current data, the results might be estimated to be lower than ours. Indeed, EEA research has shown that, between 1990 and 2005, the external cost of the power generation mix in these four countries was reduced by 70% on average. One of the reasons for this reduction is the increasing share of renewables in the power generation mix. In Germany, the share of renewables increased from 4% to about 10% between 1990 and 2005, and from 10% to about 30% in 2016. The thermal efficiency of power plants is another important reason. In the EU28, the maximum efficiency achieved for thermal power plants was around 42% in 1990, 47% in 2005, and approximately 50% in 2015 [61].

Table 8. Comparison of the European Environment Agency (EEA) study and this study.

	EEA	This Study
Main parameters		
Area of interest	EU	G20
Dataset (year)	2005	2014
Currency	Euro	Dollar
Impact categories considered		
Climate change	x	x
Air pollution	x	x
Photochemical ozone	x	x
Water use		x
Fossil fuels		x
Mineral resources		x
Land use		x
Noise	x	
External cost (\$)		
France	0.008–0.021	0.005
Germany	0.023–0.085	0.017
Italy	0.017–0.062	0.021
UK	0.026–0.085	0.045

5. Conclusions

The aim of this research was to evaluate the external cost of electricity generation in G20 countries using the LIME3 global lifecycle impact assessment (LCIA) method. External costs are an interesting indicator that can help decision makers determine which energy sources to prioritize based on the direct emissions from plants alongside the impact of the supply, including the consideration of the trade structure.

It can be confirmed that the share of fossil fuels in the electricity mix of a country is the main parameter that influences the external cost of electricity generation due to climate change and air pollution impacts. Countries such as India (76% of electricity generated through fossil fuels), Indonesia (86%), and China (74%) showed the highest estimated costs at 0.172, 0.135, and 0.081 \$/kWh, respectively. In a similar vein, countries with the highest renewable share had the lowest results: Canada (62%) and Brazil (65%) were 0.008 and 0.012 \$/kWh, respectively.

This study considered the full life-cycle of electricity, as well as a large range of impact categories at a global scale. The results confirmed the suitability of the method, as oil-based electricity, due to oil resource consumption, had the highest external cost on average (0.105 \$/kWh). The external cost of

solar and wind power was also mostly explained by resource consumption, and the external cost of hydropower was high in some locations due to water scarcity (India: 0.068 \$/kWh).

Several indicators were provided for decision makers: to support again the need to switch quickly from fossil energies to renewables, to improve efficiency of power plants, to relocate fossil power plants further from populated areas, and to implement emission control technologies for thermal power plants. However, one additional point should be raised: when switching to renewables, it is necessary to consider the scarcity of resources and, if those resources are imported, the situation at the origin of the imports. Different locations require different strategies.

In the future it would be profitable for LCA researchers to provide an assessment for developing countries, for which studies are still rare. As such information is largely missing at the moment, it is also imperative to collect reliable inventory data concerning the resource consumption and emissions of power-plants in developing countries. A type of LIME3 weighting method based on the willingness to pay among G20 countries could also be developed for developing countries.

Author Contributions: Conceptualization, S.K. and N.I.; methodology, S.K. and N.I.; software, S.K. and Y.I.; formal analysis, S.K. and N.I.; investigation, S.K., A.A. and N.I.; writing—original-draft preparation, S.K.; supervision, N.I. All authors have read and approved the final manuscript.

Funding: This research received no external funding.

Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

Table A1. List of used acronyms.

ARG	Argentina
AUS	Australia
BRA	Brazil
Bio-CCS	Biomass with carbon capture and storage
CAN	Canada
CCS	Carbon capture and storage
CHN	China
Coal_R	Coal Resource
DALY	Disability-adjusted life year
DEU	Germany
DF	Damage factor
EC	External cost
EEA	European Environment Agency
EINES	Expected increase in number of extinction species
EV	Economic-value conversion factor
EU	European Union
FRA	France
GBR	United Kingdom
GDP	Gross Domestic Production
IDN	Indonesia
IEA	International Energy Agency
IND	India

Table A1. Cont.

IF	Integration Factor
ISO	International Organization for Standardization
ITA	Italy
JPN	Japan
KOR	Korea
LandT	Land Transformation
LandO	Land Occupation
LCA	Life-cycle assessment
LCI	Life-cycle inventory
LCIA	Life-cycle impact assessment
LIME	Life-cycle impact-assessment method based on endpoint modeling
MEX	Mexico
NG	Natural Gas
NG_R	Natural Gas Resource
Oil_R	Oil Resource
PPP	Purchasing Power Parity
SAU	Saudi Arabia
SD	Standard Deviation
TUR	Turkey
USA	United States
WTP	Willingness to pay
ZAF	South Africa
\$	US dollars

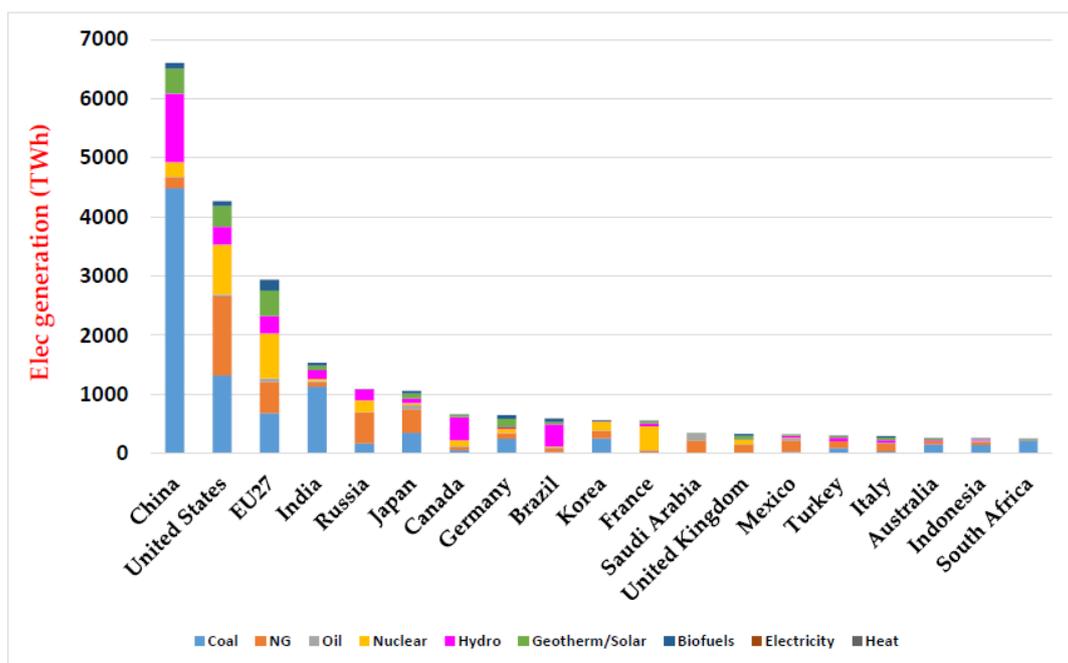


Figure A1. Electricity generation in G20 countries (2017 data).

Table A2. Non-exhaustive findings of the life-cycle assessment (LCA) studies concerning electricity generation published during the period 2019–2020 (up to February 2020).

Coal	-	Zhu et al., 2020 [14]: The water footprint of coal-fired power generation in China was evaluated: 6.60 m ³ /MWh with 24.8% for the blue water footprint and 75.2% for the grey water footprint. Even though Northwest China has water scarcity, it is the main region providing coal-fired power in the country.
	-	Young et al., 2019 [62]: Evaluation of the possible carbon reduction while using amine solvent-based carbon capture systems based on monoethanolamine (MEA) in the USA. The reduction was estimated at 70% for coal power plants (subcritical and super critical coal power plants) in comparison with the systems without CCS however one of the drawbacks is the increase of water consumption (about 60%) due to the cooling load incurred by the carbon capture unit.
	-	Yu et al., 2019 [63]: LCA of transforming (partly or completely) a subcritical power plant into a polygeneration plant. In the complete transformation scenario: the impacts (759.8 kg CO ₂ eq/MWh) were found lower than the best technologies available for coal power plants: ultra-supercritical (USC; 801 kg CO ₂ eq/MWh) and integrated coal gasification combined cycle (IGCC; 813 kg CO ₂ eq/MWh). Compared with the original sub-critical power plant, the complete transformation can reduce greenhouse gas emissions by 36.5%.
Natural gas	-	Young et al., 2019 [62]: Evaluation of the possible carbon reduction while using amine solvent-based carbon capture systems based on monoethanolamine (MEA) in the USA. The reduction was estimated at 63% for natural gas combined cycle (NGCC) power plant in comparison with the systems without CCS however one of the drawbacks is the increase of water consumption (about 60%) due to the cooling load incurred by the carbon capture unit.
	-	Tarannum et al., 2019 [64]: LCA of natural gas combined cycle power plant in Bangladesh: the GWP was 464 g CO ₂ eq/kWh with 71% of the impact due to the electricity generation and 20% due to the transportation of the fuel.
Oil	-	Tarannum et al., 2019 [64]: LCA of heavy fuel oil power plant in Bangladesh: the GWP was 831 g CO ₂ eq/kWh with 88% of the impact due to the electricity generation and 11% due to the transportation of the fuel.
Wind	-	Xie et al., 2020 [65]: Three types of wind turbines were evaluated in China, the average CO ₂ emission was 3.9 g/kWh mainly impacted by manufacturing and decommissioning stages; The average energy input was 0.0625 MJ/kWh.
	-	Kouloumpis et al., 2020 [66]: A real case of small wind turbine is evaluated in Poland. The results were found around 55 g CO ₂ /kWh and 2920 g CO ₂ /kWh depending on whether or not the components are treated after the end of life, the low wind speed affecting the results. If excluding the end-of-life stage, the GWP impact was shared between the foundation (30.9%), the mast (30.9%) and turbine components (29.7%).
	-	Besseau et al., 2019 [67]: A focus on a wind turbine fleet in Denmark. The tool developed (generating more than 10,000 cradle-to-grave life cycle inventories) estimated that the climate change impact will decrease until 2030, projecting a shift from 40 (in 1980) to 13 g CO ₂ eq/kWh by 2030.
Solar	-	Parisi et al., 2020 [68]: The third generation of photovoltaics for the European market was evaluated: raw materials account for 90% of the impact.
	-	Liu et al., 2020 [69]: The differences in CO ₂ emissions of solar PV production were studied in China, the EU, and the USA. It was found that the region of production for the solar panel greatly influences the GWP. The results were found between about 70 (CdTe, EU) and 350 kg CO ₂ /m ² (mono-SI, China) for ground-mounted panels, between about 50 (CdTe, EU) and 330 kg CO ₂ /m ² (mono-SI, China) for roof-integrated panels, due to the sources of electricity used by the production process.
	-	Merida Garcia et al. [70]: A focus was put on-grid and off-grids solar photovoltaics as power source for pumping water in rural irrigation systems in Spain, the on-grid option showed the best results (6 times lower) with 19–29 g CO ₂ eq/kWh, much lower than national grid electricity (200 g CO ₂ eq/kWh) or traditional diesel generator (about 1500 g CO ₂ eq/kWh).

Table A2. Cont.

Biomass	<ul style="list-style-type: none"> - Zang et al., 2020 [71]: Biomass integrated gasification combined cycle (BIGCC) systems were evaluated and compared the mixed electricity grid of EU27, the results were 240 kg CO₂ eq/MWh (which is 43% lower than the intensity of the EU27 electricity mix) and even negative with CCS systems inclusion. Even though the other environmental impacts were higher with than without CCS systems, these impacts were lower than the current EU27 electricity mix. - Masum et al., 2020 [72]: The carbon intensity of electricity generation from bioenergy feedstocks was evaluated in Georgia, USA. Pine chips had the best performance with less than 134 kg CO₂ e/MWh, most of the impact occurred at processing stage. The cost is still a disadvantage (113 \$/MWh vs. 95.1 \$/MWh for the coal-based electricity) however if the processing cost is reduced, it could lower the total cost of biopower. - Beagle et al., 2019 [20]: The study focused on biomass utilization for electricity generation in the EU and in the USA, it was found out that for 1 kWh generated, the GWP could be 76% lower than coal-based electricity (0.28 vs. 1 kg CO₂/kWh), however the results are largely dependent on the biomass heating value, the type of wood (chips or pellets), and the biomass transportation distance. - Sanchez Moore et al., 2019 [73]: A focus on co-generation process operated with sugarcane biomass (bagasse and straw) in Brazil, the lowest environmental impact was found at 688 kg CO₂ eq/MWh with a high boiler operating pressure (100 bar), a straw addition rate of 50% and a low moisture content (10%). - Yan et al., 2019 [74]: A novel biomass fueled power plant with carbon capture and sequestration (BFP-CCS) is analyzed. The life cycle emissions CO₂ was −0.591 kg CO₂/kWh with a leveled cost of electricity of 0.0501 \$/kWh.
Geothermal	<ul style="list-style-type: none"> - Paulillo et al., 2020 [75]: A deep geothermal power plant in the UK was assessed: it was shown that steel and diesel consumption need for the plant construction are mainly the source of environmental impacts. The climate change impact was found slightly lower than solar power but higher than wind and nuclear power. The other impact categories show more or less the same tendency. - Karlsdottir et al., 2020 [76]: Geothermal combined heat and power (CHP) plant was evaluated in Iceland. Again, the construction stage contributed to most of the impacts. The direct emissions of the plant affect the global warming impact (15.9 g CO₂ eq/kWh). - Paulillo et al., 2020 [77]: LCA study on a geothermal power plant in Iceland. The carbon intensity was found in the range of 15–24 g CO₂ eq/kWh depending on the configuration (Single flash or double flash). The construction made of steel and copper has an important role in the different impact categories.
Hydro	<ul style="list-style-type: none"> - Yuguda et al., 2020 [78]: A retrofitting dam to generate hydro-electricity in Nigeria was evaluated. The construction stage is responsible for about 90% of all the different environmental impacts during the life-cycle. The GWP is found between 1.61 and 5.51 kg CO₂ eq/kWh due to the construction composed of steel. - Ueda et al., 2019 [79] focused on 11 micro-hydropower installations in the UK, it was shown that alternative materials such as wood-frame powerhouse instead of concrete construction could lead to a reduction of about 10% of the GWP. The results were found between about 4 and 15 g CO₂ eq/kWh. The authors concluded that the inventories in the different case studies for renewables could significantly influence the environmental assessment. - Parvez Mahmud et al., 2019 [80]: The study focused on hydropower plants comparing alpine and non-alpine regions in Europe, the global warming impact was shown 10 times higher in the latter one (1.41 × 10^{−3} kg CO₂ eq/kWh), it was concluded that studies should focus more on construction materials. - Kaddoura et al., 2020 [81]: A prospective LCA was performed on a 12 MW tidal energy converter array, the GWP was evaluated in the range 18.4–26.3 g CO₂ eq/kWh with operation and maintenance having a major contribution as well as the gravity based foundation (GBF) even though many parts are recycled at the end of life.

Table A3. Life-cycle emission factors for electricity generation (adapted from [8]).

Energy Source	CO ₂ -eq (kg/MWh)	NO _x (kg/MWh)	SO ₂ (kg/MWh)
Hard coal	660–1050	0.3–3.9	0.3–6.7
Lignite	800–1300	0.2–1.7	0.6–7
Natural gas	380–1000	0.2–3.8	0.01–0.32
Oil	530–900	0.5–1.5	0.85–8
Nuclear power	3–35	0.01–0.04	0.003–0.038
Biomass	8.5–130	0.08–1.7	0.03–0.94
Hydropower	2–20	0.004–0.06	0.001–0.003
Solar energy	13–190	0.15–0.40	0.12–0.29
Wind	3–41	0.02–0.11	0.02–0.09

Table A4. Overview of the LIME3 method.

Impact Category	Human Health DALY	Social Asset US\$	Biodiversity EINES	Primary Production NPP	Important Parameters	G20 IF Low	G20 IF High
Climate Change	Malnutrition, diarrhea, cardiovascular disease, malaria, coastal flooding, and inland flooding	-	Terrestrial ecosystem (vascular plants)	-	Diseases Relative Risk against temperature, Average mortality per disease, Future population, Current and Future species distribution, Ratio of Area decrease	Same for all countries	
Air pollution	Chronic death, acute death, respiratory diseases	-	-	-	Total population, Population density, Age distribution, Pollutant dispersion	ARG BRA MEX	IND
Photochemical Oxidant	Chronic death, acute death, respiratory diseases	-	-	-	Total population, Population density, Age distribution, Pollutant dispersion	CAN USA	IND
Water	Waterborne infectious diseases, nutritional deficiency	-	-	-	Water scarcity, Economic adaptation capacity, International trade	ARG	KOR
Land Use	-	-	Terrestrial ecosystem (vascular plants)	Terrestrial ecosystem	National population of threatened species, Species distribution	CAN	IDN
Mineral resources	-	User cost	Terrestrial ecosystem (vascular plants)	Terrestrial ecosystem	Reserve to extraction ratio, International trade	BRA	GBR
Fossil resources	-	User cost	Terrestrial ecosystem (vascular plants)	Terrestrial ecosystem	Reserve to extraction ratio, International trade	SAU	GBR

Table A5. LIME3 integration factors used in this study (Inside each category from dark green (Low integration factor) to dark red (High integration factor)).

	ARG	AUS	BRA	CAN	CHN	DEU	FRA	GBR	IDN	IND	ITA	JPN	KOR	MEX	RUS	SAU	TUR	USA	ZAF
CO ₂ (\$/kg)	1.71×10^{-2}	1.71×10^{-2}	1.71×10^{-2}	1.71×10^{-2}	1.71×10^{-2}	1.71×10^{-2}	1.71×10^{-2}	1.71×10^{-2}	1.71×10^{-2}	1.71×10^{-2}	1.71×10^{-2}	1.71×10^{-2}	1.71×10^{-2}	1.71×10^{-2}	1.71×10^{-2}	1.71×10^{-2}	1.71×10^{-2}	1.71×10^{-2}	1.71×10^{-2}
SO ₂ (\$/kg)	6.18×10^{-1}	1.02	6.18×10^{-1}	7.87×10^{-1}	4.33	2.84	2.84	2.84	1.02	5.11	2.84	1.58	4.33	6.18×10^{-1}	1.85	2.52	1.85	7.87×10^{-1}	1.240
NOX (\$/kg)	3.01×10^{-1}	4.47×10^{-1}	3.01×10^{-1}	4.02×10^{-1}	4.96	2.11	2.11	2.11	4.47×10^{-1}	8.66	2.11	1.37	4.96	3.01×10^{-1}	1.16	1.31	1.16	4.02×10^{-1}	5.23×10^{-1}
NMVOOC (\$/kg)	5.57×10^{-3}	9.41×10^{-3}	5.57×10^{-3}	4.63×10^{-2}	1.28×10^{-1}	8.11×10^{-2}	8.11×10^{-2}	8.11×10^{-2}	9.41×10^{-3}	6.69×10^{-2}	8.11×10^{-2}	4.25×10^{-2}	1.28×10^{-1}	5.57×10^{-3}	4.10×10^{-2}	3.15×10^{-2}	4.10×10^{-2}	4.63×10^{-2}	1.12×10^{-2}
PM2.5 (\$/kg)	1.80	4.14	1.80	3.22	2.51×10^1	1.02×10^1	1.02×10^1	1.02×10^1	4.14	3.64×10^1	1.02×10^1	1.20×10^1	2.51×10^1	1.80	4.21	9.15	4.21	3.22	4.05
Oil_R (\$/kg)	3.63×10^{-1}	1.57×10^{-1}	1.76×10^{-1}	1.32×10^{-1}	2.17×10^{-1}	2.12×10^{-1}	1.43×10^{-1}	4.08×10^{-1}	2.58×10^{-1}	5.50×10^{-2}	1.03×10^{-1}	3.23×10^{-2}	3.72×10^{-2}	3.62×10^{-1}	1.68×10^{-1}	2.49×10^{-3}	3.52×10^{-1}	2.21×10^{-1}	4.84×10^{-2}
Coal_R (\$/kg)	2.12×10^{-3}	1.35×10^{-3}	1.98×10^{-3}	3.98×10^{-3}	2.92×10^{-2}	1.04×10^{-3}	1.76×10^{-3}	3.92×10^{-2}	6.84×10^{-2}	2.03×10^{-3}	1.77×10^{-2}	1.30×10^{-2}	2.42×10^{-2}	1.75×10^{-3}	6.12×10^{-4}	2.12×10^{-2}	3.41×10^{-2}	1.82×10^{-3}	1.78×10^{-3}
NG_R (\$/kg)	4.13×10^{-2}	4.68×10^{-3}	1.75×10^{-2}	3.56×10^{-2}	1.28×10^{-2}	1.80×10^{-2}	3.68×10^{-3}	3.18×10^{-2}	1.02×10^{-2}	1.28×10^{-2}	1.13×10^{-2}	7.65×10^{-3}	7.61×10^{-3}	3.70×10^{-2}	1.98×10^{-3}	5.99×10^{-4}	1.60×10^{-3}	3.40×10^{-2}	8.76×10^{-3}
Water (\$/m3)	1.60×10^{-4}	5.83×10^{-2}	2.95×10^{-2}	2.75×10^{-2}	3.04×10^{-1}	1.15×10^{-1}	9.98×10^{-2}	7.03×10^{-1}	1.02×10^{-1}	5.69×10^{-1}	1.90×10^{-1}	9.34×10^{-1}	1.40	2.43×10^{-1}	3.68×10^{-2}	8.35×10^{-4}	2.69×10^{-1}	3.32×10^{-1}	4.01×10^{-1}
Ag (\$/kg)	5.64×10^2	2.01×10^2	6.40×10^2	8.88×10^2	7.62×10^2	5.04×10^2	6.65×10^2	6.65×10^2	6.47×10^2	5.64×10^2	6.65×10^2	1.19×10^2	5.56×10^2	9.46×10^2	5.10×10^2	5.64×10^2	5.64×10^2	5.95×10^2	5.95×10^2
Al (\$/kg)	3.44×10^{-1}	1.02×10^{-1}	2.28×10^{-2}	2.43×10^{-2}	1.07	4.97×10^{-2}	1.22×10^{-1}	1.14	2.45×10^{-1}	3.74×10^{-1}	1.44	2.25×10^{-1}	2.29×10^{-1}	6.37×10^{-1}	1.03	4.65×10^{-1}	1.67	3.37×10^{-2}	5.49×10^{-1}
Au (\$/kg)	4.13×10^4	2.13×10^4	1.51×10^4	6.43×10^4	7.84×10^4	2.13×10^4	3.91×10^4	3.97×10^4	3.50×10^4	4.01×10^4	3.91×10^4	4.11×10^4	6.32×10^4	2.79×10^4	2.95×10^4	4.37×10^4	3.95×10^4	5.31×10^4	2.43×10^4
Ce (\$/kg)	2.44×10^{-3}	2.43×10^{-3}	3.24×10^{-3}	2.42×10^{-3}	2.40×10^{-3}	2.42×10^{-3}	2.41×10^{-3}	2.43×10^{-3}	2.43×10^{-3}	2.96×10^{-3}	2.42×10^{-3}	2.42×10^{-3}	2.41×10^{-3}	2.42×10^{-3}	2.41×10^{-3}	2.43×10^{-3}	2.41×10^{-3}	2.43×10^{-3}	2.43×10^{-3}
Co (\$/kg)	1.01×10^1	1.05×10^{-2}	3.03	1.94×10^1	4.89	2.62×10^1	2.76×10^{-2}	1.01×10^1	6.34	2.20×10^{-1}	1.01×10^1	1.66×10^1	1.01×10^1	1.01×10^1	1.57×10^1	1.01×10^1	1.01×10^1	6.18×10^1	4.91
Cr (\$/kg)	9.93	9.94	9.95	1.0×10^1	1.02×10^1	1.01×10^1	1.0×10^1	9.96	9.94	1.39×10^1	9.97	1.22×10^1	10^{-1}	9.97	5.48	9.42	9.93	9.93	9.93
Cu (\$/kg)	3.13	1.99×10^{-1}	4.48	8.26	3.39	3.12	3.22	6.74	4.28	3.20	3.19	3.84	3.22	5.85×10^{-1}	2.46	3.62	3.32	4.40	3.97
Eu (\$/kg)	1.30×10^{-1}	1.29×10^{-1}	1.24×10^{-1}	1.48×10^{-1}	1.23×10^{-1}	1.29×10^{-1}	1.26×10^{-1}	1.30×10^{-1}	1.30×10^{-1}	1.53×10^{-1}	1.27×10^{-1}	1.26×10^{-1}	1.25×10^{-1}	1.28×10^{-1}	1.24×10^{-1}	9.87×10^{-2}	1.25×10^{-1}	1.27×10^{-1}	1.30×10^{-1}
Fe (\$/kg)	2.73×10^{-3}	8.87×10^{-3}	2.73×10^{-3}	7.50×10^{-4}	8.69×10^{-2}	5.71×10^{-3}	3.24×10^{-3}	1.57×10^{-2}	1.81×10^{-3}	4.74×10^{-2}	8.27×10^{-3}	1.32×10^{-2}	1.10×10^{-2}	1.10×10^{-2}	2.88×10^{-4}	5.28×10^{-2}	3.50×10^{-3}	1.15×10^{-3}	8.21×10^{-2}
Gd (\$/kg)	4.56×10^{-1}	4.54×10^{-1}	4.42×10^{-1}	5.26×10^{-1}	4.41×10^{-1}	4.52×10^{-1}	4.46×10^{-1}	4.55×10^{-1}	4.54×10^{-1}	4.55×10^{-1}	4.49×10^{-1}	4.47×10^{-1}	4.45×10^{-1}	4.50×10^{-1}	4.43×10^{-1}	3.43×10^{-1}	4.44×10^{-1}	4.49×10^{-1}	4.55×10^{-1}
La (\$/kg)	9.02×10^{-2}	8.96×10^{-2}	1.16×10^{-1}	8.93×10^{-2}	8.89×10^{-2}	8.95×10^{-2}	8.92×10^{-2}	8.97×10^{-2}	8.96×10^{-2}	1.08×10^{-1}	8.93×10^{-2}	8.93×10^{-2}	8.92×10^{-2}	8.94×10^{-2}	8.90×10^{-2}	8.98×10^{-2}	8.91×10^{-2}	8.97×10^{-2}	8.97×10^{-2}
Li (\$/kg)	3.44×10^{-4}	1.15	3.80×10^{-1}	2.24×10^{-14}	1.03×10^{-1}	6.74×10^{-1}	5.16×10^{-1}	5.20×10^{-1}	6.10×10^{-1}	1.62×10^{-1}	2.43×10^{-1}	4.25×10^{-1}	6.10×10^{-1}	1.19×10^{-2}	1.50×10^{-1}	6.10×10^{-1}	6.10×10^{-1}	7.64×10^{-1}	1.32×10^{-1}
Mn (\$/kg)	3.78×10^{-2}	8.86×10^{-1}	1.08×10^{-2}	6.55×10^{-1}	1.62	3.87×10^{-1}	1.07×10^{-1}	3.87×10^{-1}	9.43×10^{-1}	5.11×10^{-1}	4.03×10^{-1}	5.12×10^{-1}	7.07×10^{-1}	2.11	3.52×10^{-1}	4.93×10^{-1}	4.34×10^{-1}	5.48×10^{-1}	3.47×10^{-1}
Mo (\$/kg)	5.22	5.22	7.04	8.54	4.45	5.99	6.38	4.43	5.22	6.38	5.22	8.75	5.86	3.88	3.22	5.22	5.22	6.73	7.91
Nd (\$/kg)	1.05×10^{-1}	1.05×10^{-1}	1.37×10^{-1}	1.04×10^{-1}	1.04×10^{-1}	1.05×10^{-1}	1.04×10^{-1}	1.05×10^{-1}	1.05×10^{-1}	1.27×10^{-1}	1.04×10^{-1}	1.04×10^{-1}	1.04×10^{-1}	1.05×10^{-1}	1.04×10^{-1}	1.05×10^{-1}	1.04×10^{-1}	1.05×10^{-1}	1.05×10^{-1}
Ni (\$/kg)	1.43×10^1	5.80×10^{-2}	8.67×10^{-2}	1.40×10^1	2.13×10^1	1.43×10^1	1.33	1.43×10^1	2.15×10^1	1.33	1.43×10^1	1.78×10^1	1.43×10^1	1.43×10^1	3.16×10^{-1}				
Pb (\$/kg)	3.09	7.33×10^{-1}	2.75	3.21	3.35	2.97	2.75	3.09	2.94	1.89	2.75	1.55	1.46	1.09	3.09	2.75	3.09	2.53	4.34
Pd (\$/kg)	2.66×10^4	2.66×10^4	4.46×10^3	2.47×10^4	1.23×10^4	6.90×10^3	6.07×10^3	1.87×10^4	2.66×10^4	2.66×10^4	1.63×10^4	1.48×10^4	1.24×10^4	2.66×10^4	2.66×10^4	2.66×10^4	2.66×10^4	1.42×10^4	2.66×10^4
Pr (\$/kg)	3.00×10^{-1}	2.98×10^{-1}	3.89×10^{-1}	2.97×10^{-1}	2.95×10^{-1}	2.97×10^{-1}	2.96×10^{-1}	2.98×10^{-1}	2.98×10^{-1}	3.60×10^{-1}	2.97×10^{-1}	2.97×10^{-1}	2.96×10^{-1}	2.97×10^{-1}	2.96×10^{-1}	2.98×10^{-1}	2.96×10^{-1}	2.98×10^{-1}	2.98×10^{-1}
Pt (\$/kg)	2.88×10^4	3.88×10^4	2.25×10^3	2.37×10^4	2.37×10^3	1.21×10^4	3.46×10^3	5.62×10^4	2.88×10^4	2.88×10^4	1.88×10^4	1.52×10^4	1.75×10^4	2.88×10^4	1.19×10^5	2.88×10^4	2.88×10^4	8.72×10^3	2.88×10^4
Re (\$/kg)	8.14×10^2	8.14×10^2	8.14×10^2	2.42×10^3	8.14×10^2	3.75×10^{-1}	8.14×10^2	8.14×10^2	1.90×10^2	8.14×10^2									
Sn (\$/kg)	2.01×10^1	2.01×10^1	6.13	1.25	2.44×10^1	2.01×10^1	1.25	2.01×10^1	2.34×10^1	1.25	2.01×10^1	2.01×10^1	2.01×10^1	1.25	4.08×10^{-1}	2.01×10^1	2.01×10^1	2.01×10^1	1.25
Sr (\$/kg)	3.96×10^{-1}	4.48×10^{-1}	4.48×10^{-1}	4.48×10^{-1}	4.24×10^{-1}	6.00×10^{-1}	4.69×10^{-1}	4.79×10^{-1}	4.48×10^{-1}	4.48×10^{-1}	4.86×10^{-1}	5.49×10^{-1}	5.58×10^{-1}	6.53×10^{-1}	4.48×10^{-1}	4.48×10^{-1}	4.48×10^{-1}	6.28×10^{-1}	4.48×10^{-1}
Ta (\$/kg)	1.07×10^1	1.80×10^{-1}	4.3																

Table A6. Inventory items having an influence on the external cost for each system.

	HC	Lignite	NG C/CC	Oil	Wind ON/OFF	GEO	Hydro RR	Hydro PS	Hydro R	Nuclear BW/PW	Solar OG	Solar Roof
AUS	1-CO ₂ 2-SO ₂	1-CO ₂ 2-SO ₂	1-CO ₂ 2-SO ₂	1-Oil_R 2-CO ₂ 3-SO ₂	Mineral	-	Various	1-CO ₂ 2-SO ₂	-	-	1-LandO 2-Mineral	1-Mineral 2-Oil_R
BRA	1-CO ₂ 2-SO ₂	1-CO ₂ 2-PM2.5 3-SO ₂	1-CO ₂ 2-NG_R	1-Oil_R 2-CO ₂ 3-SO ₂	Mineral	-	-		1-Water 2-LandT	Mineral	1-LandO 2-Mineral	1-Mineral 2-CO ₂ 3-Oil_R
CAN	1-CO ₂ 2-SO ₂	1-CO ₂ 2-PM2.5	1-CO ₂ 2-NG_R	1-Oil_R 2-CO ₂	Mineral	Various	Various	1-CO ₂ 2-Oil_R	1-Water 2-Mineral	Mineral	1-Mineral 2-LandO	Mineral
CHN	1-SO ₂ 2-CO ₂ 3-PM2.5	-	1-CO ₂ 2-NG_R	1-Oil_R 2-SO ₂ 3-NO _x	Mineral	1-PM2.5 2-Mineral	Various	1-SO ₂ 2-CO ₂ 3-PM2.5	-	Mineral	1-Mineral 2-PM2.5	1-Mineral 2-PM2.5
DEU	1-CO ₂ 2-SO ₂ 3-NO _x	1-CO ₂ 2-SO ₂ 3-NO _x	1-CO ₂ 2-NG_R	1-Oil_R 2-CO ₂ 3-SO ₂	Mineral	1-Mineral 2-CO ₂ 3-PM2.5	Mineral	1-CO ₂ 2-SO ₂ 3-Mineral	Water	Mineral	1-Mineral 2-LandO 3-CO ₂	1-Mineral 2-CO ₂ 3-SO ₂
FRA	1-CO ₂ 2-SO ₂ 3-NO _x	-	1-CO ₂ 2-NO _x	1-Oil_R 2-SO ₂ 3-CO ₂	Mineral	1-CO ₂ 2-PM2.5 3-Mineral	Various	1-Mineral 2-CO ₂	Water	Mineral	1-Mineral 2-LandO 3-CO ₂	1-Mineral 2-CO ₂ 3-SO ₂
GBR	1-Coal_R 2-SO ₂ 3-CO ₂	-	1-CO ₂ 2-NG_R	1-Oil_R 2-SO ₂ 3-CO ₂	Mineral	1-Mineral 2-CO ₂	Various	1-Coal_R 2-CO ₂ 3-SO ₂	-	1-Water 2-Mineral	Mineral	Mineral
IDN	-	1-PM2.5 2-CO ₂	CO ₂	1-Oil_R 2-SO ₂ 3-CO ₂	Mineral	1-Coal_R 2-Mineral 3-CO ₂	-	-	1-Land T 2-Mineral	-	-	Mineral
IND	1-PM2.5 2-NO _x 3-CO ₂	1-PM2.5 2-NO _x 3-CO ₂	CO ₂	1-NO _x 2-SO ₂	Mineral	Various	-	1-PM2.5 2-NO _x 3-CO ₂	-	Various	-	1-Mineral 2-PM2.5
ITA	1-CO ₂ 2-SO ₂ 3-NO _x	-	1-CO ₂ 2-NO _x	1-Oil_R 2-SO ₂ 3-CO ₂	Mineral	1-CO ₂ 2-PM2.5 3-Mineral	Various	1-Mineral 2-CO ₂	Water	Mineral	1-Mineral 2-LandO 3-CO ₂	1-Mineral 2-CO ₂ 3-SO ₂

Table A6. Cont.

	HC	Lignite	NG C/CC	Oil	Wind ON/OFF	GEO	Hydro RR	Hydro PS	Hydro R	Nuclear BW/PW	Solar OG	Solar Roof
JPN	1-CO ₂ 2-SO ₂ 3-NO _x	1-PM2.5 2-CO ₂ 3-SO ₂	CO ₂	1-CO ₂ 2-SO ₂ 3-Oil_R	Mineral	1-Mineral 2-CO ₂ 3-PM2.5	Various	1-CO ₂ 2-SO ₂ 3-Coal_R	Water	Water Mineral	-	1-Mineral 2-Water
KOR	1-CO ₂ 2-NO _x 3-CO ₂	1-PM2.5 2-SO ₂ 3-CO ₂	CO ₂	1-SO ₂ 2-NO _x 3-SO ₂	Mineral	-	Various	1-PM2.5 2-CO ₂ 3-NO _x	Water	Water	Water Mineral	Mineral Water
MEX	CO ₂	1-CO ₂ 2-PM2.5	1-CO ₂ 2-NG_R	1-Oil_R 2-CO ₂	Mineral	-	Various	-	-	Mineral	Mineral	Mineral
RUS	1-CO ₂ 2-SO ₂	1-PM2.5 2-CO ₂ 3-SO ₂	CO ₂	1-Oil 2-CO ₂ 3-SO ₂	Mineral	Various	Various	1-CO ₂ 2-PM2.5 3-SO ₂	Various	Mineral	-	Mineral
SAU	-	-	CO ₂	1-CO ₂ 2-SO ₂ 3-NO _x	-	-	-	-	-	-	-	Mineral
TUR	1-Coal_R 2-CO ₂	1-PM2.5 2-CO ₂ 3-SO ₂	CO ₂	1-Oil_R 2-SO ₂ 3-CO ₂	Mineral	Various	Various	-	Water	-	-	Mineral
USA	CO ₂	1-PM2.5 2-CO ₂	1-CO ₂ 2-NG_R	1-Oil_R 2-CO ₂	Mineral	Various	Various	1-CO ₂ 2-PM2.5	Water	Mineral	Mineral	Mineral
ZAF	1-CO ₂ 2-SO ₂	-	CO ₂	1-CO ₂ 2-Oil 3-SO ₂	Mineral	1-Mineral 2-CO ₂	Various	1-CO ₂ 2-SO ₂	Water	Mineral	-	Mineral

Table A7. Electricity generation in 2018 for G20 countries (in TWh).

Argentina	148
Australia	259
Brazil	596
Canada	663
China	7092
France	571
Germany	647
India	1643
Indonesia	268
Italy	291
Japan	1102
Mexico	320
Russia	1128
Saudi Arabia	351
South Africa	256
South Korea	593
Turkey	303
UK	334
USA	4429

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