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The true cost of energy sources: A simplified true cost comparison (EU)

Sustainable Finance Team – December 2022

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1. Introduction

The demand for eco-responsible products skyrocketed in the last decade. According to the Economist Intelligence Unit there has been a 71% rise in online searches for sustainable goods globally in the past five years (“An Eco-wakening,” n.d.). As the matter of fact, consumers are becoming steadily aware of environmental issues and the urgency of climate change, which encourages companies to adhere to this demand. Many countries, institutions and companies have committed to reduce their emissions while the EU has even set the objective of being “climate neutral” by 2050 (“How to reduce my carbon footprint?”, 2021). Moreover, there is a strong willingness from both retail and institutional investors to focus on more environmentally friendly assets and sustainable projects. In 2020, net inflows into ESG (Environmental, Social, and Governance) funds reached 51.1 billion dollars, an all-time high (Ultimus Fund Solutions, 2021). It is safe to claim, that globally investors and consumers are becoming aware of their impact and try to act at their own level. Around 85% of investors value sustainability as an important factor, up from 71% in 2015 according to Morgan Stanley’s 2019 Sustainable Signals survey (Financial Times, n.d.).

With consumers´ and investors´ rising interest in sustainability, organizations are striving to improve their whole ecosystem on a social and environmental level, including their energy usages. A major observation regarding this sustainability trend is the growth in demand for renewable energy (The Politics of a Changing Global Energy Landscape, 2022). In Europe, 75% of greenhouse gas emissions come from the energy sector (Renewable Energy Targets, n.d.). Thus, it is paramount to find an alternative to the traditional energies sources and accelerate the development of renewables energies to protect the climate. With a target to reduce greenhouse gas emissions by 55% by 2030, the European Union needs to develop and increase its renewable energy production until then (Renewable Energy Targets, n.d.).However, with the growth of renewables, there is a multitude of “sustainable” energy sources available. Each of these seemingly have their own positive and negative effects. Furthermore, it is also in question if one should choose to get electricity from renewable energies, or if traditional energies are still preferred. All these uncertainties do not provide companies with clarity on how to make their choices.

2. Research Objective

The aim of this report is to clarify these uncertainties by evaluating different energy options in the EU based on a framework, accounting for financial, economic, social, and environmental value. This allows organizations to make the best choice for society and their own top line. The main research objective of this report can be expressed as follows: What energy sources should companies in the EU choose, considering their financial, social and environmental implications?

3. Literature and Methodology

3.1. Energy Modes

Sustainable energy sources have become increasingly important due to the climate emergency caused by the consumption of traditional energies such as fossil fuels, natural gas, and coal. In particular, the combustion of these energy sources has proved to be the main cause of global pollution (Hood, 2018). Coal-fired power plants alone, represented over 40% of the global CO2 emissions (Hood, 2018)**,** and over 25% of total global greenhouse gas emissions in 2020 (NS Energy, 2015). To prevent these emissions, The UN Secretary General requested governments to cease the construction of new coal plants by 2020 (Lyons, 2019).

Nevertheless, after the peak of coal in 2013 (Executive Summary – Coal 2021 – Analysis, n.d.), another non-renewable, but seemingly less polluting energy source rose in popularity over the past five years, namely nuclear energy (NS Energy, 2015). Despite atomic power plants barely emitting carbon dioxides, or other pollutants during operations (Is Nuclear Energy Renewable or Sustainable? Pros & Cons | Perch Energy, n.d.), there is a large debate about its degree of sustainability, considering the radioactive waste this energy source produces.

To meet the societies' energy needs without compromising the environment, renewable energy sources only exploit natural conditions, such as the sun, wind, seas and rivers, and plants. The most known renewable energy modes are solar panels and wind turbines. The most notorious source in the marine domain is hydraulic energy, using the force of water in rivers. Newer methods efficiently use the force of ocean and see waves and currents. Bioenergy, produced from biomass, although mainly associated with fuel as it is liquifiable, is also becoming more popular energy source.

Application

The above-mentioned energy sources present an opportunity to companies seeking to adhere to the sustainability demand of investors and consumers, as many different options seem to be available. Nonetheless, another challenge is emerging, all these different options present difficulties to companies on choosing the most sustainable source. This report analyses the most commonly known traditional energy sources, coal and natural gas, as well as nuclear energy, next to the most familiar renewable energies: solar, wind (onshore and offshore), and hydraulic energy. Bioenergy and water energy trough ocean/sea forces will not be considered because of the limited amount of online resources and data available on these methods.

3.2 True Cost Methodology

Integrating ESG or sustainability into a companies' process of choosing an energy source remains a challenge. Thus, a systematic approach and methodology is required. A growing trend is to evaluate choices and opportunities on a scale that considers financial as well as social, economic, and environmental implications, "as focusing on the financials alone is no longer enough" (KPMG, n.d.). The KPMG True Value model describes five pillars of a company, starting with the earnings/costs, followed by economic, social, and environmental externalities, finally leading to the so-called "true earnings", which can be seen as the actual "profit/ loss" for our society as an ecosystem. True Cost Accounting (TCA) (a.k.a. True Cost Economics/ True Value) is a method used to identify and evaluate the specific costs of a project, product, or service, considering the direct costs (e.g., raw material, labour, accounts payable) and the impression it leaves on the ecosystem (TRUE COST, 2022). Said secondary effect are identified as negative externalities.

However, the true cost framework in itself, does not identify externalities, thus a closer look at this concept should be taken

Application

The KPMG true value model will be used in this report to aid companies' on choosing an energy source. However, as this general framework was first intended to measure a company's overall true earnings, a slight adjustment is needed to evaluate energy choices. This alteration includes changing the "earnings/costs" part towards the price (cost) on the energy sources, along with changing the "true earnings" to "true costs" as energy sources are analysed. The energy prices (costs) were acquired through the levelized cost of energy (LCOE) (Trinomics et al., 2020). This is an indicator for the price of electricity or heat required for a project, in which revenues would theoretically equal costs, including making a return on the capital invested equal to the discount rate. This study follows the same approach as IRENA (2018) for calculating a simple levelized cost of electricity/heat and applies it to electricity and/or heat generation plants. As a result, the LCOE indicator in this study does not consider taxes, subsidies, or other incentives.

Concluding, the true cost model will be used the following

$$Price + \ Externalities = True\ Cost$$

3.3. Externalities

Negative externalities are unfavourable consequences of processes on a third, not involved party (KPMG, 2014). Furthermore, these affect public resources and thus are inconsequential for companies on a traditional legal scale; organizations cannot be sought out for the consequences their operations have on public resources (KPMG, 2014). Until the recent boom and concern for sustainability, these have not been truly considered in organizational reporting (KPMG, 2014). Accounting for these factors will assure that companies make decisions creating value for direct stakeholders without neglecting its effects on the social and environmental ecosystem. Externalities should be considered throughout the entire supply chain, accounting for upstream and downstream of the company's operations, or the project in consideration. This includes manufacturing of the required hardware of energy sources (e.g. wind turbines) and consideration of the disposal and lifespan of the finished product.

In other words, the entire "life cycle" of the energy source has to be considered, which commonly conducted through a so called "life cycle assessment".

Application

"Economic externalities" do not fall under the traditional umbrella of externalities (KPMG, 2014), thus, this pillar will not be considered in this report. The remaining pillars of the true value model which will be analysed in this report are social and environmental externalities, as well as the energy prices as explained above. It is also important to note that social and environmental externalities are fluent, meaning that e.g., an environmental externality also affects society. The categorization of the analysed externalities is presented in table one.

Concluding, externalities are to be demarcated as environmental and social externalities:

$$Price + Environmental\ Externalities + Social\ Externalities = True\ Cost$$

3.4 Life Cycle Assessment

Life cycle assessment (LCA) is a framework used to elaborate and analyse the total environmental and social externalities during the entire lifespan of a product (FibreNet | Life Cycle Assessment: Benefits and Limitations, n.d.; Smoot, n.d; National Renewable Energy Laboratory, 2021). The UNECE (United Nations Economic Commission for Europe) published an LCA report elaborating on the different electricity sources considered in this analysis (United Nations Economic Commission for Europe, 2021).

However, LCA solely evaluates externalities in their own metric (e.g. tons of CO2 emitted), and not on a financial metric. Considering that true value model requires all externalities to be on a common financial metric, one should consider how to monetize the metrics used in the LCA.

Application

The data from UNECE is used to quantify the externalities (freshwater eutrophication, ionising radiation, land use, dissipated water, minerals and metals) which are elaborated on in table one except for CO_2 emissions, for which further LCA reports were considered and compared (Carbon Dioxide Emissions From Electricity - World Nuclear Association, n.d.; Weber, 2021; National Renewable Energy Laboratory, 2021). The elaborate comparison of the LCA CO_2 emissions of the types of energy sources can be found in Appendix A, the raw results of the LCA analysis by UNECE of the social and environmental externalities, excluding CO_2 can be found in appendix B. For the sake of simplicity, choices on categorizing the externalities have been made based on their description in the report of the United Nations Economic Commission for Europe (2021). Lastly, only externalities for which monetization methods were available, were considered, as the true value model requires all factors to be evaluated on one common financial metric. Table one presents the externalities considered and their categorization.

3.5 Monetization

As the true value model requires externalities to be evaluated on one common financial metric, the LCA metrics will have to be converted (e.g. tons of CO_2 → EURO). Quantifying non-monetary externalities into financial value aids organizations to make decisions based on a commonly known metric. However, this is also a challenge, as monetization of these externalities is not a science but more of an estimation (KPMG, 2014). A report of Arendt et al. did a well elaborated analyses 17 different methods of quantifying energy source externalities financially (2020). Nonetheless, several of these models are applicable to specific regions, and vary vastly in results.

Application

Although, being detailed and explained, the values of (Arendt et al., 2020) could not be directly used for the true costs analysis. Firstly, the metrics were adjusted to the metrics found in the UNEC report and elaborated on in appendix A and B. Secondly the EURO value was adjusted to an inflation of 15.19% from 2019 to 2022 (Value of 2019 Euro Today - Inflation Calculator, n.d.). The adjusted monetization values can be found in appendix D. Moreover, in this report solely the methods applicable to a global and/or European scale have been considered. The elaborated information on the applicability and the different monetization methods for externalities analysed in this report can be found in appendix C.

3.6 Literature and Methods Conclusion

The novelty of this report is the combination of LCA data with different monetization methods on externalities, as most studies have investigated these independently. The combination of LCA and monetization methods presents an opportunity to additionally report on the true costs of these different energy sources as follows:

$$Price + Cost\ of\ Environmental\ Externalities + Cost\ of\ Social\ Externalities = True\ Cost$$

The following table (table one) describes and categorizes the social and environmental externalities used in the analysis of this report:

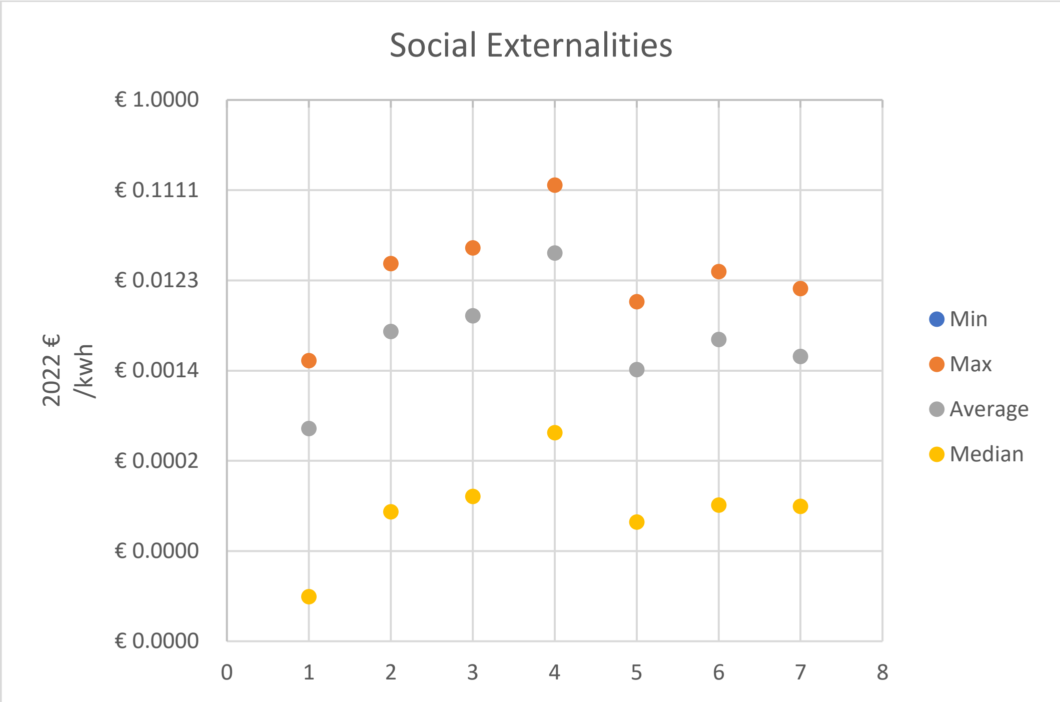
	Description	Type of externality
Minerals and Metals	Scarcity of resource in relation to that of antimony. Scarcity is calculated as « reserve base	Social
Dissipated water	Water use related to local consumption of water. Note: only air emissions are accounted for. In this method, all flows have an identical characterisation factor of 42.95 m3 /m3 – we therefore choose to account for these flows uncharacterised, i.e. 1 m3 /m3.	Social
Land Use	The LANCA model provides five indicators for assessing the impacts due to the use of soil: 1. erosion resistance; 2. mechanical filtration; 3. physicochemical filtration; 4. groundwater regeneration and 5. biotic production.	Environmental
Ionising radiation	Human exposure efficiency relative to 235U radiation. The original model is Dreicer, Tort [18] and follows the linear no-threshold paradigm to account for low dose radiation	Social
Freshwater eutrophication	Expression of the degree to which the emitted nutrients reach the freshwater end compartment. As the limiting nutrient in freshwater aquatic ecosystems, a surplus of phosphorus will lead to eutrophication.	Environmental
Co2 emission	Radiative forcing as global warming potential, integrated over 100 years (GWP100), based on IPCC baseline model	Environmental

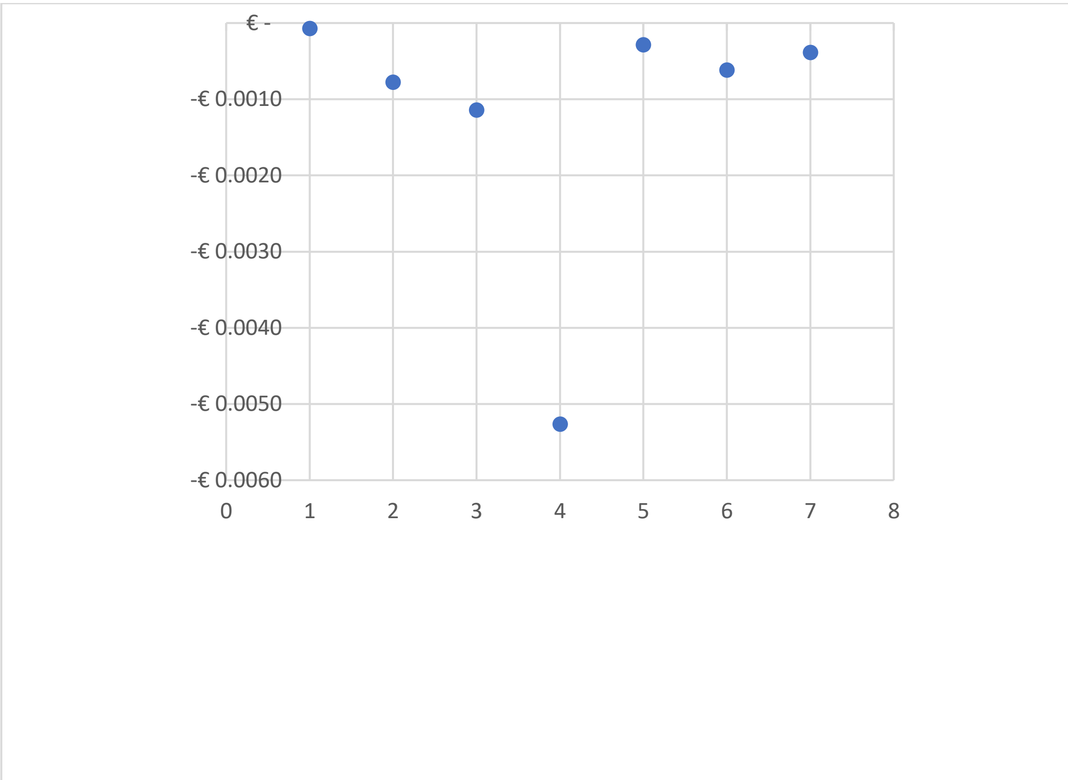
Table 1 - Externalities (United Nations Economic Commission for Europe, 2021)

4. Results

4.1 Social externalities

The average cost of social externalities was found to be relatively low for hydro energy, nuclear energy and natural gas. Wind, solar and coal were found to have not only higher averages, but also a bigger spread. The values found for solar energy were dispersed the most with the lowest minimum and highest maximum value (see figure 1). The exact detail on these values can be read in appendix F.



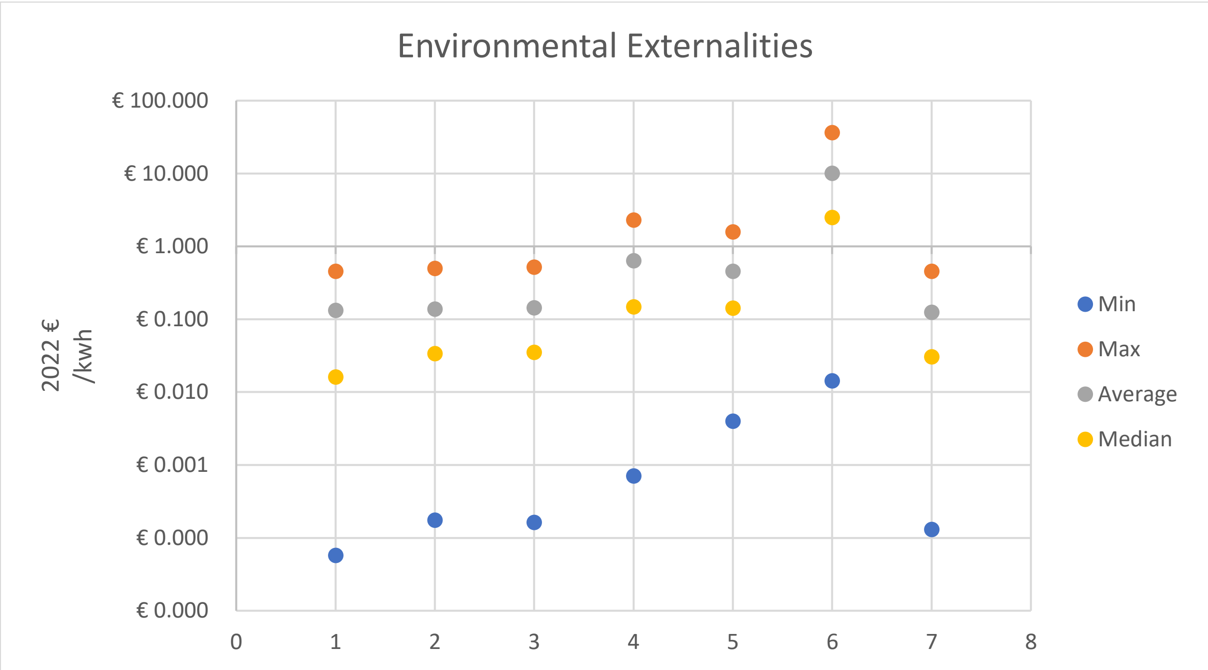


1=Hydro, 2=Wind (onshore), 3=Wind (offshore), 4=Solar, 5=Natural gas, 6=Coal, 7=Nuclear

Figure 1- Social Externalities

4.2 Environmental Externalities

The average cost of environmental externalities for all energy types was found to be around 300 times the average of social externalities, notably resulting from the high mean of coal (see figure 2). Moreover, the maximum value of coal was found to be 36.5 (2022 €/kwh), remarkably the highest value as seen in figure 2. The exact detail on these values can be read in appendix G.



1=Hydro, 2=Wind (onshore), 3=Wind (offshore), 4=Solar, 5=Natural gas, 6=Coal, 7=Nuclear

Figure 2- Environmental externalities

4.3 Price

Data on the cost per MWh was found in a report of the European Commission (2020). For calculation purposes this has been adjusted to 2022 € per kWh (Value of 2019 Euro Today - Inflation Calculator, n.d.). The cost of energy per kWh varies between 6 cents for wind onshore projects and 19 cents for the new nuclear projects. The most cost-effective energy sources were found to be renewable methods, especially wind onshore and hydro energy, in comparison to the most expensive energy mode: nuclear. It is important to note that a future decrease of the price of renewables can be expected, caused by innovation and reduction of traditional energy methods. Table two displays the exact costs per source.

Type of energy	**Electricity Cost per energy in the EU per Kilowatt-Hour (kWh) (in €)**
Wind Onshore	0.06
Wind Offshore	0.085
Solar	0.087
Natural gas	0.095
Coal	0.09
*Hydro energy**	0.08
Nuclear	0.14-0.19

Table 2- Cost per energy in the EU per Kilowatt-hour in euro in 2018 (Trinomics et al., 2020)

**Hydro energy large scale: projects over 10 Megawatt*

4.5 True Costs

For the simplicity of this report, solely the average values of all externalities were considered in the true cost of the energy modes (see figure 3). The true cost is determined as follows:

$$Price + Average\ Cost\ of\ Environmental\ Externalities + Average\ Cost\ of\ Social\ Externalities = True\ Cost$$

For nuclear energy it was found that the true cost is around 32 cents per kWh; most of this cost is resulting from the high selling price of nuclear energy. Moreover, its social cost is under a cent, similar to natural gas, which on the other hand has a hefty true cost of nearly 57 cents per kWh, of which unsurprisingly the environmental cost has over 80% contribution. Solar energy, having a lower initial price than nuclear and gas, remarkably exceeds with its social and environmental cost of externalities. The high social costs result from the excessive amount of materials required to construct solar panels. Furthermore, solar energy also has the highest environmental cost of all renewables, even exceeding natural gas and nuclear, caused by the considerable amounts of water needed for cleaning the reflection panels. In total this results in a true cost of 76 cents per kWh. Wind energy, offshore and onshore were found to have similar true costs, with the onshore variation being slightly more sustainable overall. Lastly, hydro energy was found to have the lowest true cost, resulting from low environmental cost and close to no social cost. Moreover, hydro energy also seems to be the cheapest renewable option from a price perspective.

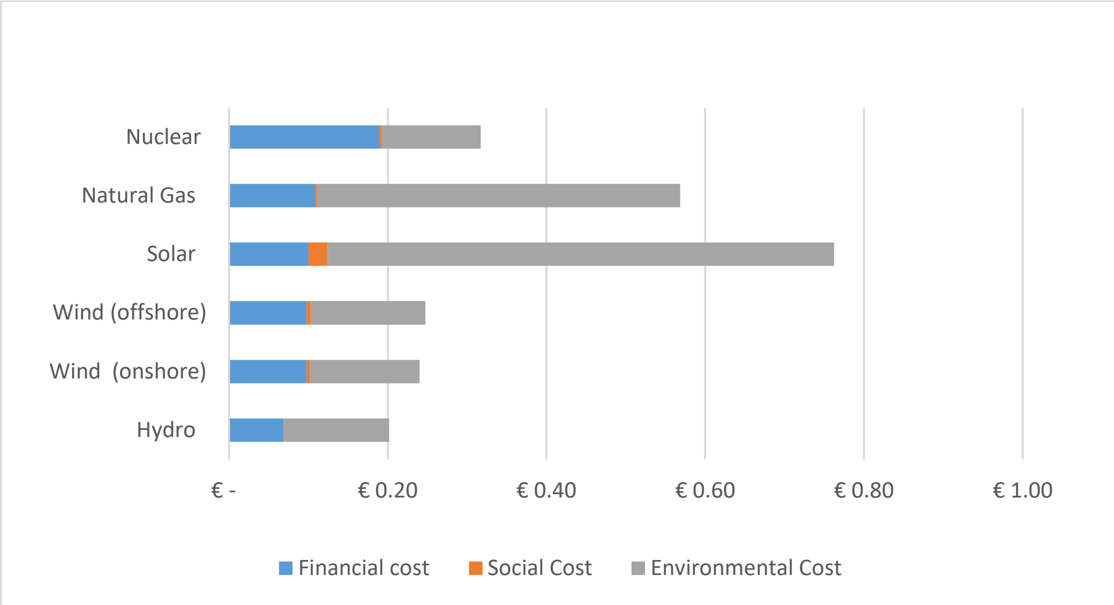
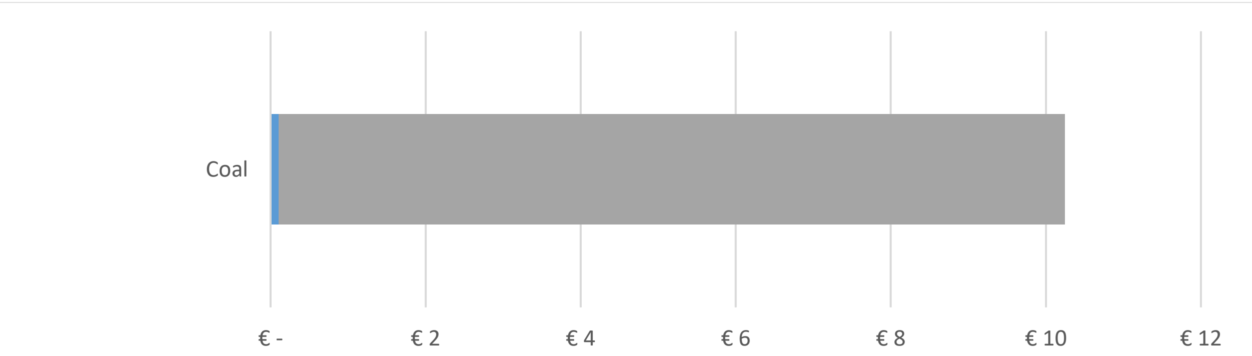


Figure 3- True Cost average (2022 € /kWh)

Lastly, it is unsurprising to see that coal, although have a relatively cheap price, relative to nuclear energy, was found to have true environmental cost out of bounds with the other energy sources. This analysis found that the true cost of coal is over € 10 per kWh, of which 99% are environmental costs (see figure 4)



	Coal
Financial cost	€ 0.10367
Social Cost	€ 0.00294
Environmental Cost	€ 10.13661

Figure 4- True Cost Results of Coal (2022 €/kWh)

5. Limitations

Although the analysis conducted in this report includes several externalities, it is worthwhile mentioning that it does not include all factors. The authors focused on which externalities were monetizable, e.g., the disposal of nuclear waste is not included, which could for example raise the environmental life cycle cost of nuclear energy significantly. Furthermore, it is believed that the true number of externalities is infinite. Next, the analysis of the energy sources in this report is focused on a global /European scale, meaning that the true cost of all modes could vary significantly per location. When a company decides on their choice of electricity, extensive research should be conducted first, therefore this report should serve solely as a guideline. Moreover, it must be acknowledged that a local energy provider might not offer all energy modes, thus, decisions must be based on availability. Lastly, it must be understood that this analysis does not necessarily result in choosing the most sustainable energy source, but the mode with the lowest true cost, based on specific externalities. True cost is in close relation to the concept of sustainability but does not necessarily equal to “most sustainable”; results might differ based on types of analysis and models used.

6. Conclusion

This part of the report aims to answer the objective of the research: “What energy sources should companies in the EU choose, regarding its financial, social and environmental implications?”. Throughout analysis of the available and referenced online resources on LCA and monetization methods, it is concluded that hydro energy has the lowest true cost, considering the settings of this report. As mentioned in the limitations, it is acknowledged that a different result might be found, through small changes in the methods of the study.

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Appendix A – Carbon Footprints

CO2g/kWh	*(Carbon Dioxide Emissions From Electricity - World Nuclear Association, n.d.)*	*(United Nations Economic Commission For Europe, 2021)*	*(Weber, 2021)*	*(National Renewable Energy Laboratory, 2021)*	***Mean***	***Average***	***Min***	***Max***
Hydro	24	10.7	4	7.4	9.05	11.525	4	24
Wind (onshore)	11	12.4	9	13	11.7	11.35	9	13
Wind (offshore)	12	14.2	7	13	12.5	11.55	7	14.2
Solar	48	42	33	43	42.5	41.5	33	48
Natural Gas	490	434	442	486	464	463	434	490
Coal	820	820	949	1001	884.5	897.5	820	1001
Nuclear	12	5.12	117	13	12.5	36.78	5.12	117

Appendix B – Externalities

Energy Modes	Minerals and Metals *mg Sb-Eq*	Dissipated water *Liter*	Land Use *m2/anum*	Ionising radiation *g^235U eq.*	Freshwater eutrophication *mg*
Hydro	0.0606	0.0386	49.94	0.84	1.33
Wind (onshore)	0.6580	0.1750	1.200	1.03	6.62
Wind (offshore)	0.9670	0.1560	1.00	1.18	6.92
Solar	4.4500	0.5790	26.40	9.14	28.40
Natural Gas	0.2430	1.1700	7.00	9.24	19.70
Coal	0.5250	2.8600	38.00	9.07	489.00
Nuclear	0.3310	2.4200	1.02	14.30	5.84

(United Nations Economic Commission For Europe, 2021)

Appendix C – Monetization of Externalities

Monetization models	*Mineral resources* *2019 €/ kg Sb-e*	*Water use* *2019 €/m³*	*Land use* *2019 €/m²/a/MWh*	*Ionizing radiation* *2019 €/ kg kBq U23 5-e*	*Freshwater Eutrophication* *2019 €/PO4- e /MWh*	*Global warming* *2019 €/kgCO2- e*	*Applicable region*
Stepwi se	ND	ND	0.1551	0.0025	1.5510607	0.107281697	Global
LIME3	821.3	0.0015	0.00322	ND	ND	0.00745	Global
Environmental Prices	ND	ND	0.132	0.0483128	0.6432624	0.059316800	Europe
EPS	19063	0.0031	3.7	0.000587	0.0128904	0.137288000	Global
MMG max	6.658209	0.2137	2.5	0.00309	64.1240057	0.106873343	Global
MMG central	1.667224	0.0716	ND	0.001037	21.3746686	0.053436671	ND
MMG min	ND	0.0235	0.0000587	0.000342	7.0536406	0.026718336	ND
Ecotax 2002	ND	ND	ND	ND	2.8258266	0.062312593	Sweden
Ecotax 2002 max	ND	ND	ND	ND	ND	ND	ND
Ecotax 2002 min	ND	ND	ND	ND	ND	ND	ND
Ecovalue14	ND	ND	ND	ND	57.5371384	ND	Sweden

Ecovalue14 max	ND	ND	ND	ND	ND	0.480907426	ND
Ecovalue14 central	ND	ND	ND	ND	ND	0.244747529	ND
Ecovalue14 min	ND	ND	ND	ND	ND	0.008587633	ND
Ligthart 2019	ND	5.428	ND	ND	ND	ND	ND
EVR	8.169192	ND	ND	ND	4.2937316	0.119441934	Europe
EVR max	ND	1.029	6.17	ND	ND	ND	ND
EVR min	ND	-1.029	0	ND	ND	ND	ND

(Arendt et al., 2020)

Appendix D – Monetization of Externalities Adjusted

Monetization method	*Mineral resources 2022€/mg Sb-eq*	*Water Use adjusted 2022€/l*	*Land use adjusted 2022€ /m2/a/kWh*	*Ionizing radiation adjusted 2022 €/ g kBq U23 5-e*	*Fresh water Eutrophication Adjusted 2022 €/g /kWh*	*Global warming adjusted 2022€/gCO2-e*
Stepwise	ND	ND	0.00017866	2.87975E-06	0.001786667	0.000123578
LIME3	0.000946055	1.72785E-06	3.70912E-06	ND	ND	8.58166E-06
Environmental Prices		ND	0.000152051	5.56515E-05	0.000740974	6.8327E-05
EPS	0.02195867	3.57089E-06	0.00426203	6.76165E-07	1.48485E-05	0.000158142
MMG max	7.66959E-06	0.000246161	0.00287975	3.55937E-06	0.073864442	0.000123107
MMG central	1.92048E-06	8.2476E-05	ND	1.19452E-06	0.024621481	6.15537E-05
MMG min	ND	2.70697E-05	6.76165E-08	3.9395E-07	0.008125089	3.07769E-05
Ecotax 2002	ND	ND	ND	ND	0.00325507	7.17779E-05

Ecotax 2002 max	ND	ND	ND	ND	ND	ND
Ecotax 2002 min	ND	ND	ND	ND	ND	ND
Ecovalue14	ND	ND	ND	ND	0.06627703	ND
Ecovalue14 max	ND	ND	ND	ND	ND	0.000553957
Ecovalue14 central	ND	ND	ND	ND	ND	0.000281925
Ecovalue14 min	ND	ND	ND	ND	ND	9.89209E-06
Ligtha rt 2019	ND	0.006252513	ND	ND	ND	ND
EVR	9.41009E-06	ND	ND	ND	0.004945949	0.000137585
EVR max	ND	0.001185305	0.007107223	ND	ND	ND
EVR min	ND	-0.001185305	ND	ND	ND	ND

(Value of 2019 Euro Today - Inflation Calculator, n.d.)

Appendix E – Social Externalities Data

MINERALS AND METALS in €/kWh	Stepwise	LIME3	Environmental Prices	EPS	MMG max	MMG central	MMG min	EVR	EVR max	EVR min	Min	Max	Average	Median	Min Method	Max Method
Hydro		5.73E-05		0.001330695	4.64777E-07	1.16381E-07		5.7E-07			1.16380804731E-07	0.001330695	0.000277836	5.70252E-07	MMG central	EPS
Wind (onshore)		0.000623		0.014448805	5.04659E-06	1.26367E-06		6.19E-06			1.26367276424E-06	0.014448805	0.003016762	6.19184E-06	MMG central	EPS
Wind (offshore)		0.000915		0.021234034	7.41649E-06	1.8571E-06		9.1E-06			1.85709963986E-06	0.021234034	0.004433448	9.09956E-06	MMG central	EPS
Solar		0.00421		0.09771608	3.41297E-05	8.54612E-06		4.19E-05			8.54611519892E-06	0.09771608	0.020402116	4.18749E-05	MMG central	EPS

Natural Gas	0.00023	0.00533957	1.86371E-06	4.66676E-07	2.29E-06	4.66675504121E-07	0.00533957	0.00111409 3	2.28665E-06	MMG central	EPS
Coal	0.000497	0.01152830 2	4.02654E-06	1.00825E-06	4.94E-06	1.00824954594E-06	0.01152830 2	0.00240699 1	4.9403E-06	MMG central	EPS
Nuclear	0.000313	0.00726832	2.53863E-06	6.35677E-07	3.11E-06	6.35677332774E-07	0.00726832	0.00151755 1	3.11474E-06	MMG central	EPS

Dissipated water in € /kWh	**Stepwise**	**LIME3**	**Environmental Prices**	**EPS**	**MMG max**	**MMG central**	**MMG min**	**EVR**	**EVR max**	**EVR min**	**Min**	**Max**	**Average**	**Median**	**Min Method**	**Max Method**
Hydro		1.05E-07		2.16396E-07	1.49174E-05	4.99805E-06	1.64042E-06		7.18E-05	-7.2E-05	-7.182948	0.000378902	5.00974E-05	3.31923E-06	EVR min	Ligthart 2019

								90600E-05				
Wind (onshore)	1.14E-06	2.34965E-06	0.000161974	5.42692E-05	1.78118E-05	0.00078	-0.00078	-7.79930755800E-04	0.004114154	0.000543962	3.60405E-05	EVR min	Ligthart 2019
Wind (offshore)	1.67E-06	3.45305E-06	0.000238038	7.97543E-05	2.61764E-05	0.001146	-0.00115	-1.14619003170E-03	0.00604618	0.000799409	5.29653E-05	EVR min	Ligthart 2019
Solar	7.69E-06	1.58905E-05	0.001095417	0.000367018	0.00012046	0.005275	-0.00527	-5.27460769500E-03	0.027823684	0.00367877	0.000243739	EVR min	Ligthart 2019
Natural Gas	4.2E-07	8.67726E-07	5.98171E-05	2.00417E-05	6.57792E-06	0.000288	-0.00029	-2.880291	0.001519361	0.000200886	1.33098E-05	EVR min	Ligthart 2019

								39300E-04					
Coal	9.07E-07	1.87472E-06	0.000129235	4.32999E-05	1.42116E-05	0.000622	-0.00062	-6.22285177500E-04	0.003282569	0.000434012	2.87557E-05	EVR min	Ligthart 2019
Nuclear	5.72E-07	1.18196E-06	8.14793E-05	2.72996E-05	8.96005E-06	0.000392	-0.00039	-3.92335988100E-04	0.002069582	0.000273634	1.81298E-05	EVR min	Ligthart 2019

Ionizing Radiation €/kWh	**Stepwise**	**LIME3**	**Environmental Prices**	**EPS**	**MMG max**	**MMG central**	**MMG min**	**EVR**	**EVR max**	**EVR min**	**Min**	**Max**	**Average**	**Median**	**Min Method**	**Max Method**
Hydro	2.41899E-06		4.67473E-05	5.67979E-07	2.98987E-06	1.0034E-06	3.30918E-07				3.30917832000E-07	4.67473E-05	9.00974E-06	1.71119E-06	MMG min	Environmental Prices

Wind (onshore)	2.96614E-06	5.73211E-05	6.9645E-07	3.66615E-06	1.23036E-06	4.05768E-07		4.05768294000E-07	5.73211E-05	1.10477E-05	2.09825E-06	MMG min	Environmental Prices
Wind (offshore)	3.39811E-06	6.56688E-05	7.97875E-07	4.20006E-06	1.40953E-06	4.64861E-07		4.64860764000E-07	6.56688E-05	1.26565E-05	2.40382E-06	MMG min	Environmental Prices
Solar	2.63209E-05	0.000508655	6.18015E-06	3.25327E-05	1.09179E-05	3.6007E-06		3.60070117200E-06	0.000508655	9.80345E-05	1.86194E-05	MMG min	Environmental Prices
Natural Gas	2.66089E-05	0.00051422	6.24777E-06	3.28886E-05	1.10374E-05	3.6401E-06		3.64009615200E-06	0.00051422	9.91071E-05	1.88231E-05	MMG min	Environmental Prices
Coal	2.61193E-05	0.000504759	6.13282E-06	3.22835E-05	1.08343E-05	3.57312E-06		3.57312468600E-06	0.000504759	9.72837E-05	1.84768E-05	MMG min	Environmental Prices

Nuclear	4.118 04E-05	0.0007958 17	9.669 16E-06	5.089 9E-05	1.7081 6E-05	5.633 48E-06		5.633482 14000E-06	0.000 79581 7	0.000 1533 8	2.913 1E-05	MMG min	Environm ental Prices

(United Nations Economic Commission For Europe, 2021)

	Min	Max	Average	Median
Hydro	-€ 0.0001	€ 0.0018	€ 0.0003	€ 0.0000
Wind (onshore)	-€ 0.0008	€ 0.0186	€ 0.0036	€ 0.0000
Wind (offshore)	-€ 0.0011	€ 0.0273	€ 0.0052	€ 0.0001
Solar	-€ 0.0053	€ 0.1260	€ 0.0242	€ 0.0003
Natural Gas	-€ 0.0003	€ 0.0074	€ 0.0014	€ 0.0000
Coal	-€ 0.0006	€ 0.0153	€ 0.0029	€ 0.0001
Nuclear	-€ 0.0004	€ 0.0101	€ 0.0019	€ 0.0001

Appendix E – Environmental Externalities Data

land use €/kWh	Stepwise	LIME3	Environmental Prices	EPS	MMG max	MMG central	MMG min	EVR	EVR max	EVR min	Min	Max	Average	Median	Min Method	Max Method
Hydro	0.008922265	0.000185	0.007593417	0.212845778	0.143814715		3.37677E-06		0.354935		3.37676950820E-06	0.354934717	0.104042786	0.008922265	MMG min	EVR max
Wind (onshore)	0.000214392	4.45E-06	0.000182461	0.005114436	0.0034557		8.11398E-08		0.008529		8.11398360000E-08	0.008528668	0.002500027	0.000214392	MMG min	EVR max
Wind (offshore)	0.00017866	3.71E-06	0.000152051	0.00426203	0.00287975		6.76165E-08		0.007107		6.76165300000E-08	0.007107223	0.002083356	0.00017866	MMG min	EVR max
Solar	0.004716616	9.79E-05	0.004014141	0.112517592	0.0760254		1.78508E-06		0.187631		1.78507639200E-06	0.187630687	0.055000592	0.004716616	MMG min	EVR max

Natural Gas	0.001250618	2.6E-05	0.001064356	0.02983421	0.02015825		4.73316E-07		0.049751		4.73315710000E-07	0.049750561	0.01458349	0.001250618	MMG min	EVR max
Coal	0.006789068	0.000141	0.00577793	0.16195714	0.1094305		2.56943E-06		0.270074		2.56942814000E-06	0.270074474	0.079167518	0.006789068	MMG min	EVR max
Nuclear	0.000182233	3.78E-06	0.000155092	0.004347271	0.002937345		6.89689E-08		0.007249		6.89688606000E-08	0.007249367	0.002125023	0.000182233	MMG min	EVR max

Freshwater eutrophication	**Stepwise**	**LIME3**	**Environmental Prices**	**EPS**	**MMG max**	**MMG central**	**MMG min**	**EVR**	**EVR max**	**EVR min**	**Min**	**Max**	**Average**	**Median**	**Min Method**	**Max Method**
Hydro	0.002376267		0.000985495	1.97484E-05	0.098239708	0.032746569	0.010806368	0.006578			1.97484408408E-05	0.098239708	0.027136662	0.006578113	EPS	MMG max

Wind (onshore)	0.011827734	0.004905248	9.82968E-05	0.488982607	0.162994203	0.053788087	0.032742		9.82967506512E-05	0.488982607	0.135071206	0.032742185	EPS	MMG max
Wind (offshore)	0.012363734	0.00512754	0.000102751	0.51114194	0.170380647	0.056225613	0.034226		1.02751286179E-04	0.51114194	0.141192258	0.03422597	EPS	MMG max
Solar	0.050741338	0.02104366	0.000421696	2.097750158	0.699250054	0.230752516	0.140465		4.21696029984E-04	2.097750158	0.579459556	0.140464964	EPS	MMG max
Natural Gas	0.035197336	0.014597187	0.000292514	1.455129511	0.485043171	0.160064246	0.097435		2.92514499672E-04	1.455129511	0.401949059	0.097435204	EPS	MMG max
Coal	0.873680075	0.362336266	0.007260893	36.11971222	12.03990409	3.973168329	2.418569		7.26089291064E-03	36.11971222	9.977314194	2.418569271	EPS	MMG max

Nuclear	0.010434134	0.004327288	8.6715E-05	0.431368342	0.143789448	0.047450517	0.028884		8.67149582784E-05	0.431368342	0.119156472	0.028884345	EPS	MMG max

(United Nations Economic Commission For Europe, 2021)

Environmental externalities total	**Min**	**Max**	**Average**	**Median**
Hydro	€ 0.000	€ 0.457	€ 0.132	€ 0.016
Wind (onshore)	€ 0.000	€ 0.500	€ 0.139	€ 0.034
Wind (offshore)	€ 0.000	€ 0.520	€ 0.144	€ 0.035
Solar	€ 0.001	€ 2.293	€ 0.638	€ 0.149
Natural Gas	€ 0.004	€ 1.582	€ 0.458	€ 0.142
Coal	€ 0.014	€ 36.548	€ 10.137	€ 2.510
Nuclear	€ 0.000	€ 0.457	€ 0.125	€ 0.031

Appendix F – Cost of Social Externalities - Detail

For Hydro energy sources, the analysed values (2022 €/kWh) all lay around the same point (Min=-7.13822E-05, Max=0.001756, Mean= 0.000337, Median= 5.60068E-06), this would indicate that the different methods of monetization of hydro energy externalities giving similar results, which lets one assume that these results are truly accurate. Onshore wind energy similarly has results around the same point (Min= -0.000778261, Max=0.018620279, Mean= 0.003571772, Median= 4.43306E-05), with a higher maximum value, which is assumed to be a result of the Environmental Prices monetization model of the ionizing radiation effect. Wind (offshore) was found to have similar values of social externalities as the onshore methods (Min= -0.001143868, Max= 0.027345883, Mean= 0.005245514, Median= 6.44687E-05). Solar energy on the other hand was found to have the largest spread (Min= -0.005262461, Max=0.126048419, Mean= 0.02417892, Median=0.000304233) caused by the amount of freshwater eutrophication valued by MMG. The non-renewable sources: natural gas (Min= -0.000283922, Max=0.007369537, Mean=0.001414086, Median=3.44196E-05), Coal (Min= -0.000617704, Max= 0.01531563, Mean= 0.002938287, Median= 5.21729E-05) and Nuclear (Min=-0.000386067, Max=0.010133718, Mean=0.001944565, Media=5.03756E-05), were found to have surprisingly comparable value to the renewables with little spread.

Appendix G – Cost of Environmental Externalities - Detail

In similarity with the social externalities, the amount of 2022 €/kWh for the renewable energy sources were found to have little spread: Hydro (Min=5.74518E-05, Max= 0.456969834, Mean= 0.132259713, Median= 0.016224403), onshore wind (Min= 0.000175613, Max= 0.499567121, Mean= 0.138573105, Median= 0.033954686) and offshore turbines (Min= 0.00016289, Max= 0.52049478, Mean= 0.144281934, Median= 0.035274183). Solar energy is standing out for its higher maximum value, resulting from an increased CO2 emission monetized by EPS, with otherwise comparable values (Min= 0.000706676, Max= 2.292971663, Mean= 0.638129602, Median= 0.1488527). Natural gas, not being considered a renewable source, scored very sustainable values (Min=0.004017426, Max= 1.582369675, Mean= 0.457697148, Median= 0.142140249), although with a notably higher average compared to the "green" energy modes. Coal is not surprisingly the most environmentally polluting energy source (Min= 0.014300419, Max= 36.54808688, Mean= 10.13660924, Median= 2.51003005), with an extremely high carbon footprint averaging around 8 cents per kWh, double the value for natural gas, which has the second highest CO2 emission. Although being in discussion for its unsustainable core, nuclear energy seems to have the lowest environmental externalities (Min=0.000130722, Max= 0.457120329, Mean= 0.125093279, Media= 0.03060836).