Exergy Cost and Specific CO_2 Emissions of the Electricity Generation in the Netherlands

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ABSTRACT

In this paper, exergy and environmental analyses are developed to determine the performance of the electricity generation in the Dutch mix. To this end, a comparative assessment of diverse electricity generation routes, including fossil and renewable energy resources, is carried out. An exergoeconomy methodology, successfully applied to other electricity mixes of tropical countries, such as Brazil, allows to properly allocate the renewable and non-renewable exergy costs and specific CO_2 emissions among the various products of a multiple-product energy system. The Dutch electricity mix comprises thermal (*e.g.* petroleum derivatives), nuclear, onshore and offshore wind, and solar electricity generation, as well as an increasing share of biomass-derived resources. By using this methodology, the distribution of exergy destruction throughout the different steps of the energy conversion processes is characterized as it relies on the Second Law of the Thermodynamics for allocating the exergy consumption and partitioning the produced CO_2 emissions to the different exergy flows involved. Accordingly, it proves to be helpful in proposing suitably indicators that may help the Dutch institutes issuing more sustainable energy planning strategies. As a result, a weighted average of renewable and non-renewable unit exergy costs of electricity generated in each route is calculated as c_R=0.8375 kJ/kJ and c_{NR}=1.7180 kJ/kJ, respectively. Regarding the specific CO_2 emissions, about 373.21 g_{CO2}/kWh are emitted in the electricity generation process, leading to a renewable to non-renewable exergy consumption ratio of c_R/c_{NR}=0.49. This fact confirms that the Dutch electricity mix is dominated by fossil fuels resources. Certainly, by using this approach, the electricity generation and its final applications can be better compared to the production and end-use of other energy sources.

KEYWORDS

Exergy analysis, CO_2 emissions, Renewable exergy cost, Non-renewable exergy cost, Dutch electricity mix.

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INTRODUCTION

The share of electricity in the overall final energy consumption could be doubled between 2015 and 2050. Projected trends indicate the reduction of electricity generation via coal power plants and the increase of the renewables participation. For instance, the electricity generated worldwide in 2015 was 23430 TWh and this figure is expected to increase up to 43500 TWh by 2050 [1]. Nevertheless, electricity is not a primary energy source, and its generation efficiency and emissions should be assessed in the conversion process in order to allow comparisons with other kinds of energy resources. In the case of fossil energy-based power plants to produce electricity, direct greenhouse gas emissions (GHG) are inherent to their operation. Alternatively, other technologies such as renewable plants still present CO_2 emissions that, although not necessarily produced in the electricity generation step, take a decisive role in the upstream and downstream steps (***i.e.*** power plant building, obtainment of fuel, plant operation, wastes treatment, and decommissioning) [2]. Hence, it is important to appropriately assess the costs and impacts of the used energy resources in the electricity generation, aiming to identify and pursue the most sustainable energy alternatives.

Different authors have already studied the electricity generation for several countries applying the Life Cycle Analysis (LCA) approach. For instance, Dones et al. [3] applied the LCA in Switzerland and Western Europe of energy systems for heat and electricity generation. The study has found that the trend for modern cogeneration configurations points towards an increasing electricity efficiency with simultaneous preservation of high global performance. Itten et al. [4] reviewed a series of Life Cycle Inventories (LCI) for electricity mixes of selected countries. The inventories are founded on data of the Swiss electricity grid using the Eco-points indicator. Santoyo-Castelazo et al. [5] carried out an LCA of the electricity generation in Mexico, which is dominated by the participation of fossil fuels (similar to the Netherlands), in which the total primary energy contribution was reported as 79%, whereas the renewable energy contribution was 16.2% and the remainder 4.8% reportedly coming from nuclear power. It was identified that 225 TWh of electricity generates around 129 mt_{CO2} per year, of which the majority (87%) is due to the combustion of fossil fuels resources.

A limitation inherent to the previous analyses lies on the issue related to the thermodynamic energy quality, *i.e.*, when the value of the electric energy must be compared with thermal energy [6]. In these studies, all energy forms including electricity are converted into the equivalent primary energy by using conversion factor-based procedures. This approach does not represent a serious inconvenience when only one input and one output, such as fuel and electricity, are considered. However, according to thermoeconomy theory, when more than one product is obtained in the same plant, the use of energy efficiencies, costs, or even mass averaging methods are not adequate to carry out a rational distribution among the different streams and products. In this context, Flórez-Orrego et al. [7] proposed a methodology to calculated the average unit exergy cost of either electricity or substances in terms of their renewable and non-renewable contributions, as well as the CO_2 emissions of the electricity generation routes in the Brazilian energy mix. For the Dutch energy sector, *Ptasinski* et al. [8] evaluated the (*i) exploitation, (ii) transformation, and (iii). distribution of energy sub-sectors* using performance indicators focused on energy, exergy and Cumulative Exergy Consumption (CExC) via the Extended Exergy Accounting (EEA) method.

Accordingly, in this work, the exergy concept is used as a rational base to assess the electricity generation processes through the energy resources involved in the Dutch electricity mix (*namely, natural gas, oil-derived products, coal, nuclear, renewables*). Furthermore, CO_2 emissions comprehend direct and indirect forms, as the latter can be employed to determine the impact of the previous steps of fuel processing (*i.e.*, extraction, transportation or fabrication, as well as construction, operation, and power plant decommissioning).

Although the methodology was based on that performed by Flórez-Orrego et al. [7], this work aimed to analyse the energy mix variation in the Netherlands by using different resources, and subsequently, make a comparison between the Dutch and Brazilian energy demand (two matrices diametrically opposed). The use of exergy as an indicator to compare the extraction, conversion and final consumption of energy resources with different characteristics (substances, fuels, heat, and electricity) was also highlighted. The assessment includes the iterative influence due to electricity and processed fuels utilization on production routes thereof.

Overview of the Dutch energy sector

The Dutch energy strategy aims to ensure the energy supply for the future and reduce emissions from the domestic energy sector. Thus, a mandatory target that encouraged the use of renewable energy and sources to achieve 14 % share of final energy consumption by 2020 was recently introduced in the Netherlands [9]. The goal of the *Dutch Operational Energy Strategy* is to reduce the dependency on fossil fuels (and the associated CO_2 emissions) by 20% in 2030 [10].

Table 1 shows the overall CO_2 emissions from 1990 to 2017. The contribution of renewable energy to the electricity generation is also illustrated [11]. Additionally, the main components of the Dutch energy sector with regard to the total primary energy supply (TPES) is given in Table 2, whereas the percentage of renewable energy contribution is shown in Figure 1. As it can be seen, in 2016, the TPES amounted up to 74.5 million tonnes of oil equivalent (Mtoe) largely dominated by fossil energy resources [9].

Table 1. Comparison between the renewable energy and CO_2 emissions in the Dutch energy mix

CO_2 emissions from fuel combustion (Million metric tons of CO_2)										
	1990	2000	2010	2011	2012	2013	2014	2015	2016	2017
World	20278	22758	29825	30672	31062	31594	31776	31740	31987	32667
Europe	4418	4259	4175	4050	4025	3928	3760	3817	3837	3950
Netherlands	**164**	**181**	**191**	**179**	**176**	**176**	**168**	**174**	**174**	**182**
Share of renewables in electricity production (%)										
World	19.74	18.79	19.93	20.27	21.22	22.01	22.71	23.13	24.08	24.80
Europe	18.08	20.13	25.21	25.23	28.37	30.92	32.28	33.63	34.02	33.58
Netherlands	**1.12**	**3.32**	**9.39**	**10.81**	**12.11**	**11.98**	**11.32**	**12.44**	**12.80**	**13.24**

Table 2. Dutch total primary energy supply in 2016

	%	*PJ*	*TWh*	*Mtoe*
Coal and coal products	13.70	427	118.55	10.19
Crude oil and oil products	37.80	1177	327.10	28.12
Natural gas	40.30	1255	348.73	29.98
Nuclear	1.40	44	12.11	1.04
Waste *(non-renewable)*	1.20	37	10.38	0.89
Electricity *(imported)*	0.60	19	5.19	0.45
Renewable energy	5.10	159	44.13	3.79

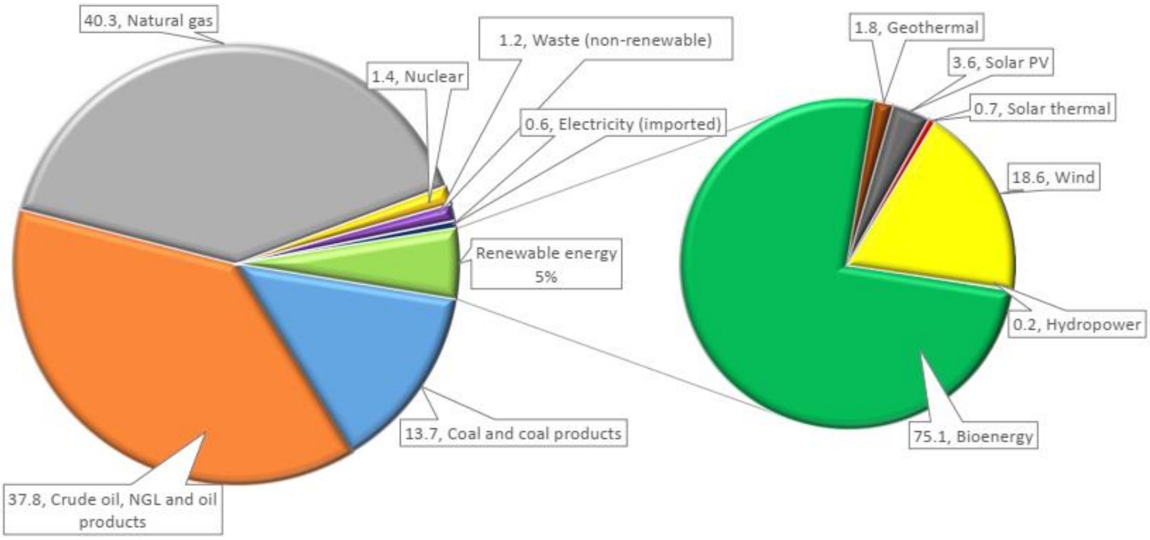

Figure 1. TPES and the renewable energy percentages contribution of the Netherlands in 2016 (adapted from [9]).

COAL

Total supply of coal and coal products was 10.19 Mtoe in 2016, representing 13.70% of TPES. This resource consists mainly of hard coal, with negligible levels of lignite. The main uses of imported coal remain the power and heat generation for steam, as well as iron and steel industry that consumes coking coal. Steam coal is one of the principal energy sources for electricity generation, as all the imported coal is employed in electricity plants and combined heat and power (CHP) generation plants, equivalently to 70% of the total coal supply [12]. All coal imports into the Netherlands came from Colombia (53%), South Africa (21%) and Indonesia (7%), is used for electricity generation [13].

OIL

Oil plays an important role in the Dutch energy mix, accounting for 38% of TPES. In 2016, the total supply of oil (*including crude oil and oil products*) was 28.12 Mtoe. Despite new discoveries being made, particularly offshore fields, oil production has declined 50% since 2002. Notwithstanding, the Netherlands has a strategic position in the European oil supply chain, as a leading importer, exporter of oil products (63%) and refiner of crude oil, also hosting the major oil storage capacity in this region. Actually, Rotterdam has become the energy hub of Europe, with oil refineries and storages, Gas Access to Europe (GATE) terminal of Liquefied natural gas (LNG) and large coal import facilities as well as the major power generation and chemical industries, which use oil and oil products and natural gas as feed materials [12]. Domestic oil production accounts for 2.2% of intake in refineries, rendering the country dependent heavily on crude oil imports. In 2015, according to *Statistics Netherlands*, the main suppliers of crude oil were Russia 29 %, Norway 14%, Saudi Arabia 12%, the United Kingdom (UK) 10% and Nigeria 9%. The Netherlands also exports a small amount of crude oil to Germany, the UK, Sweden and Denmark [14].

NATURAL GAS

The Netherlands remains Europe's second-largest gas producer and is a net exporter of natural gas and refined oil products. This resource dominates the electricity supply, domestic heating, and industry feedstock, such as the petrochemical sector [12]. Natural gas (NG) is the largest source of energy in this country, mainly due to the production of the Groningen basin, which accounted for 40.3% of the total primary energy supply in 2016, when the natural gas energy amounted 30 Mtoe [9].

The first LNG terminal, GATE, came into operation in 2011 at the Maasvlakte facility in Rotterdam with a capacity of 12 billion cubic metres (bcm) of natural gas [12]. In 2017, total production at all Dutch gas fields decreased by 13%, while imports rose. The growing demand for foreign gas was mainly met by Norway (56%) and British gas (44%) [15].

NUCLEAR ENERGY

Nuclear plays a small but steady role in the Dutch energy supply, constituting about 1.7% of the total power generation capacity. In 2016, the only nuclear power plant in operation produced 4 TWh, providing about 3.8% of total electricity and 1.4% of total primary energy supply. Thus, over the period of operation, nuclear power station has generated about 132 TWh of carbon-free baseload electricity [12].

The nuclear power plant is located in Borssele (province of Zeeland) in the south-west part of the country. The pressurised water reactor (PWR), constructed by Siemens, is fuelled with enriched uranium fuel (UOX). In 2006, following an upgrade of the turbine, the net electrical capacity was increased by 7%, to the current level of 482 MW [12].

RENEWABLE ENERGY

According to the IEA, the Netherlands has renewed its ambitions to support the cost-effective deployment of renewable energy sources as a pillar of its '*National Energy Agreement for Sustainable Growth*'. Since its EU target is to achieve a share of 14% of renewable energy share in the final consumption, this country aims to increase renewables to 16% by 2023 [12].

Wind and solar energy

Currently, onshore wind turbines hold a capacity of 2000 MW, providing only 4% of the total Dutch electricity [16]. Meanwhile, the existing offshore wind farms have an installed capacity of approximately 1000 MW. The first two wind farms built in the North Sea off the coast of the Netherlands are the offshore Egmond aan Zee-OWEZ Wind Farm (at 10-18 km), and the Princess Amalia Wind Farm (at 23 km) [16]. In 2016, wind (*onshore+offshore*) and solar (*PV+thermal*) energy sources contributed with 18.6 %t and 4.3 %, respectively, to the TPES.

Biomass

Considering the whole route of the biomass conversion to products (*i.e.* electricity, fuels or chemicals), several processing stages at diverse locations along the route could be defined. For instance, if the large-scale biomass plant station is installed in the Netherlands, the required biomass can be imported as raw matter (*wood logs or chips*) or as intermediate sources (*pellets, pyrolysis slurry, torrefied wood, pellets*) depending on the final product (*methanol, diesel, chemicals, SNG, LNG*) [17]. The biomass production is assumed in the Baltic States and the Rotterdam harbour is considered as the final destination. The harvested biomass is naturally dried in the forest before transport to a pretreatment plant [17]. In 2016, biomass energy contributes with 75 % of the renewable energy in the TPES, which can be further divided among the use of mostly solid biomass by waste incineration plants, industrial boilers and furnaces, co-firing power plants, and the use of liquid biofuels and biogas [9].

Platform BioEnergie reports that the total use of woody biomass increased from 1,210,000 million tonnes (mt) in 2014 to 1,670,000 mt in 2017. This grows consists almost solely of wood chips, supported through increased domestic production of chips and imports, mainly from Germany and Norway. The domestically-sourced chips originate from the management of forests, parks/agricultural land, and the wood processing industry. Another type of biomass imported is sawdust and wood scrap. For instance, in 2018, a volume of about 270,000 mt of sawdust and scrap was imported [18].

The Dutch power generation: Electricity mix summary

Electricity generation in the Netherlands attained 115 TWh in 2016. This represents a decline of 3.3% compared to 2010, one of the largest annual contraction over the past decade. Nevertheless, electricity generation has significantly increased in between 2000 and 2010 [11], as shown in Table 3. Figure 2 presents the Dutch electricity mix, which is as expected dominated by fossil fuels (namely NG and coal) due to the large oil and gas industry.

Table 3. Overview of the Dutch power generation

Electricity production (TWh)										
	1990	2000	2010	2011	2012	2013	2014	2015	2016	2017
World	11894	15524	21557	22253	22750	23424	23910	24317	24918	25592
Europe	2900	3438	3865	3809	3841	3813	3744	3802	3839	3886
Netherlands	72	90	119	114	103	102	103	110	115	117

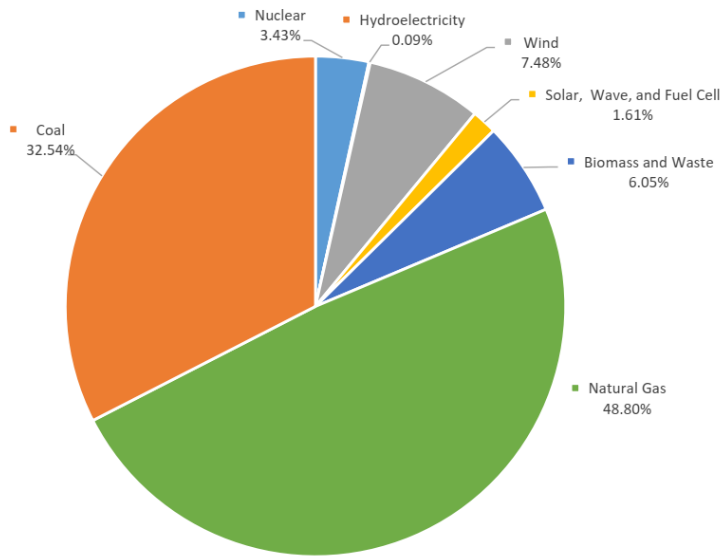

Figure 2. Electricity generation supply by source in the Netherlands (adapted from [19, 20]).

Natural gas accounted for 48.8% of electrical energy generation in 2016, while coal achieved 32.5%. From the former, the electricity generated has experienced only a marginal growth of 0.5% since 2002, while electricity from coal and oil has decreased by 5.9% and 51.5%, respectively [19]. Nuclear energy achieved 3.4% of the generation this year, a share which has reduced slightly from 4.1% in 2002. Over the past decade, there has been a shift towards the use of more renewable energy sources, with a total share of fossil fuels in electricity generation falling from 90.3% in 2002 to 85% in 2016.

In the Netherlands, renewable energy sources are principally from biofuels and waste, alongside with wind, as illustrated in the electricity mix (Fig. 2). Biofuels and waste accounted for 6% of generation, while wind formed an additional 7.4%, whereas solar, wave and fuel cell systems together play a smaller role of 1.6% [20]. Wind power (*onshore and offshore wind turbines*) has experienced the fastest growth over the decade up to 2012 [12]. Electricity from biofuels and waste has more than doubled from 3.1 TWh in 2002 to 6 TWh in 2016. As a share of electricity generation, renewable energy sources have increased from 5.7% to 14.5% over the same period [19].

Table 4 shows the features of power plants and fuels used in the Dutch electricity mix. In addition, Figure 3 presents the different stages/sub-systems of the technological route considered in the electricity mix.

Table 4. Power plants and fuels features used in the Dutch electricity mix

	Power plant efficiency (%)	*LHV (MJ/kg)*	*$\Phi = b^{CH}/LHV$**	*Fuel carbon content – I ($\%C_{mass}$)*	*Emissions (gCO_2/kJ)*
Coal	46.00	30.08†	0.927†	59.50	0.0783
Oil products	40.00	42.00	1.066	86.73	0.0710
Natural gas	46.00	47.34	1.032	75.30	0.0565
Nuclear	32.00	1,016,952	0.950‡		-
Wind	45.00	-	0.927		-
Biomass *(wood)*	30.00	9.30	1.188	22.40	-**

* Φ represents the specific chemical exergy (b^{CH}) and the lower heating value (LHV) ratio of the resource [21].
† Refs. LHV [22], Colombian coal [23].
‡ Ref. [24], Borssele Nuclear Power Plant, 485 MW.
** Release and capture of carbon in direct burning are supposed in a closed natural cycle.

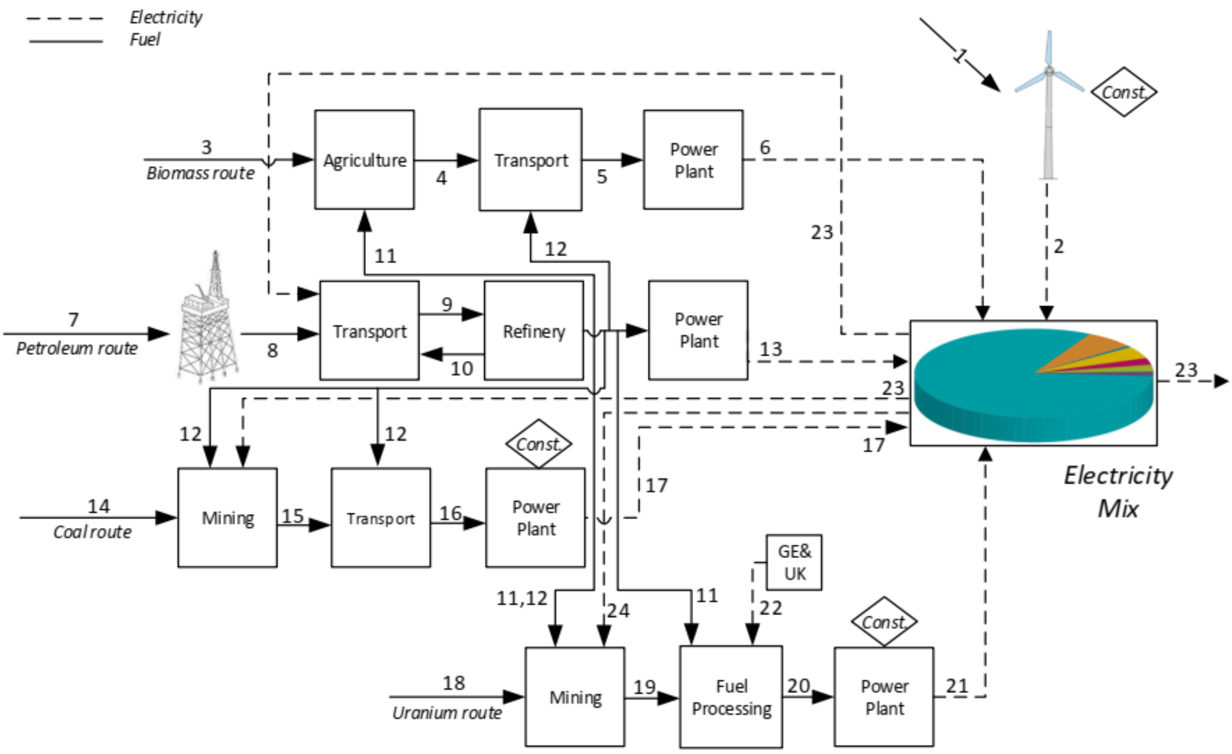

Figure 3. Dutch electricity mix (adapted from [7]).

METHODOLOGY

The methodology is based on the exergoeconomy approach proposed by Flórez-Orrego et al. [7]. Some basic definitions are required: the Non-Renewable Unit Exergy Cost represents non-renewable exergy required to produce one unit of exergy of the analysed substance (*e.g.*, water, wind, biomass, nuclear, NG, coal and oil) or electricity, expressed in kJ/kJ. Moreover, the Total Unit Exergy Cost (c_T) includes the Renewable (c_R) and Non-Renewable Unit Exergy Costs (c_{NR}).

Fuels (*e.g.*, petroleum and gas from wells, coal and uranium ore, biomass, and wind) as present in the environment enter the control volume adopted to assess the technological routes. Next, for each processing stage of a given electrical energy production route such as extraction, mining,

agriculture, transport, and fuel production, the total and non-renewable exergy costs, as well as CO_2 emissions of the processed stream, are accumulated along the route as indicated by [7].
In addition, since exergy consumption in power plant building, operation and decommissioning steps could be amortized along their lifetime; those stages can also be considered as processing steps.
In the case of electricity generation step (*i.e.* the power plant itself), the only input is related to the exergy of the consumed fuel (B^n_F), responsible for the direct CO_2 emissions (M_{CO2}) as long as the examined fuel contains carbon. The desired output is in turn the electricity generated (EE).
As a result, an analysis based on exergy cost balances for each processing and electricity generation step can be carried out. The mathematical representations of the total, renewable, and non-renewable exergy cost accumulation are fully described in [7].
Meanwhile, the CO_2 emission cost (c_{CO2}) is defined as the quantity of CO_2 emitted to obtain one unit of exergy of a given fuel or electricity (g_{CO2}/kJ). The direct CO_2 emission in each step is accounted in the M_{CO2} term (g_{CO2}/s). In addition, m^i_{CO2} denotes the amount of CO_2 directly emitted in the step *i* per unit of exergy of processed fuel (g_{CO2}/kJ) when additional fossil fuel consumptions are required to process it, as given in Equation (1).

$$m^i_{CO_2} = \frac{M^i_{CO_2}}{B^i_{T,F}} \tag{1}$$

Furthermore, m^n_{CO2} represents the CO_2 directly emitted in the power station, when the processed fuel is finally burned in the plant could be calculated by using Equation (2), in g_{CO2}/kJ:

$$m^n_{CO_2} = \frac{M^n_{CO_2}}{B_{EE}} \tag{2}$$

Direct CO_2 emissions, resulting from the burning of fuels containing carbon, depend on the amount of consumed fuel and its carbon content. Thus, those emissions are determinate according to Equation (3):

$$M_{CO_2} = M_C \cdot I \cdot R_m \tag{3}$$

where R_m = 44/12 = 3.7 (kg_{CO2}/kg_{Carbon}) is the ratio between the molecular weight of carbon dioxide and atomic carbon, M_C (kg_{fuel}/s) denotes the fuel consumption rate, and I (kg_{carbon}/kg_{fuel}) is the carbon content of the consumed fuel, founded on the elemental analysis. Thus, the direct CO_2 emissions per unit of exergy of processed fuel in the step *i* can be more explicitly written as shown in Eq. (4):

$$m^i_{CO_2} = \underbrace{\left(\frac{\mathrm{E}^i_{\mathrm{C}}}{\mathrm{E}_{\mathrm{EE}}}\right)}_{I/O} \cdot \underbrace{\left(\frac{\mathrm{E}_{\mathrm{EE}}}{\mathrm{E}^n_{\mathrm{F}}}\right)}_{\eta_{energy}} \cdot \underbrace{\left(\frac{\mathrm{M}^i_{\mathrm{C}}}{\mathrm{E}^i_{\mathrm{C}}}\right)}_{1/LHV^i_{\mathrm{C}}} \cdot I^i_{\mathrm{C}} \cdot R_m \cdot \frac{1}{\varphi^n_{\mathrm{F}}} \cdot 1000 \qquad \left[\frac{gCO_2}{kJ}\right] \tag{4}$$

where I^n_C denote the carbon content of the consumed fuel, fed as an input into step *i*. Analogously, in the case of the power plant, the direct CO_2 emissions per unit of electricity generated could be explicitly obtained by Eq. (5), where I^n_F indicate the carbon content of the processed fuel fed to the power plant.

$$m^n_{CO_2} = \underbrace{\left(\frac{\mathrm{E}^n_\mathrm{F}}{\mathrm{E}_\mathrm{EE}}\right)}_{1/\eta_{en}} \cdot \underbrace{\left(\frac{\mathrm{M}^i_\mathrm{C}}{\mathrm{E}^n_\mathrm{F}}\right)}_{1/LHV^i_\mathrm{C}} \cdot I^n_\mathrm{F} \cdot R_m \cdot 1000 \qquad \left[\frac{gCO_2}{kJ}\right] \tag{5}$$

It is noted that when several products are obtained in the same step of the electricity generation routes (*i.e.* fuel oil, diesel oil, and other petroleum derivatives in the refinery or NG and crude oil in an offshore platform), an exergoeconomy analysis of the specific step is employed for allocating the exergy cost and CO_2 costs among all the products in a rational manner. Furthermore, since the treated streams leaving some processing steps are consumed in other stages, and processing steps consume the electricity from an interconnected network, an iterative calculation approach is applied to figure out the set of linear equations in order to estimate the unit exergy costs and CO_2 costs of the electrical energy generated [7].

RESULTS AND DISCUSSION

The intensity of the renewable and non-renewable energy resources use in the highly integrated Dutch electricity mix is summarized in Tab. 5. In this table, the total, renewable, and non-renewable unit exergy costs and specific CO_2 emissions for the power generated in each technological route presented in Fig. 3 is used to calculate the weighted average of the overall electricity generation. On the other hand, Figure 4 reports the unit exergy cost and CO_2 emissions for the electrical energy generated by mean of the various resources composing the Dutch mix.

Table 5. Unit exergy costs and CO_2 emissions estimated by route

Power plant	***Share (%)***	***c_{NR} (kJ/kJ$_e$)***	***c_R (kJ/kJ$_e$)***	***c_T (kJ/kJ$_e$)***	***Emissions (gCO$_2$/kWh)***	***c_R/c_{NR} ratio***
Coal-fired	23.70	2.0627	0.0106	2.0733	579.11	0.01
Oil-fired	2.54	2.8620	0.0147	2.8767	737.18	0.01
Natural gas-fired	40.72	2.3848	0.0145	2.3994	478.22	0.01
Biomass-Coal	14.54	0.5716	3.3355	3.9071	143.40	5.84
Nuclear power	3.09	3.1389	0.0299	3.1689	38.53	0.01
Wind farms	15.41	0.0344	2.2245	2.2589	3.00	64.70
Dutch mix	*(Weighted Average)*	*1.7180*	*0.8375*	*2.5555*	*373.21*	*0.49*

The renewable to non-renewable c_R/c_{NR} ratio of the exergy invested in the electricity generation routes, which is defined as a 'degree of renewability' of the process (*i.e.* the intensity of renewable exergy over non-renewable exergy necessary to produce one unit of electricity) is also shown in Table 5.

According to Fig. 4, it is important to notice that, among the non-renewable energy resources used as fuel for power generation, the highest unit exergy costs of the electricity generated correspond to the nuclear and oil-fired power stations, mainly due to the average low efficiencies considered (32% and 35%, respectively).

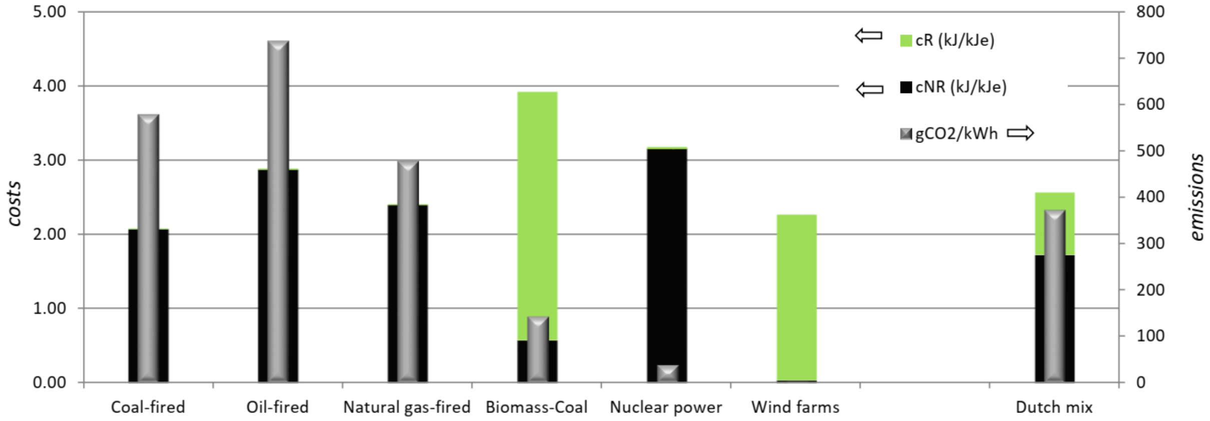

Figure 4. Unit exergy cost and CO_2 emissions of the electricity generation in the Netherlands

As concerns the atmospheric emissions, as expected, the highest CO_2 emitting technologies are the oil-fired, followed by the coal-fired ones. The CO_2 emissions for natural gas-fired power plants are decreased due to a higher H/C ratio of the fuel and the superior efficiency performance related to the combined power plant cycles.

In addition, Table 6 summarizes the total, renewable, and non-renewable unit exergy costs and CO_2 emissions for the streams displayed in Figure 3. As aforementioned, the Dutch electricity mix is dominated by fossil fuels. Hence, the calculated weighted average of the renewable and non-renewable unit exergy costs of the overall electricity generated is c_R=0.8375 kJ/kJ and c_{NR}=1.7180 kJ/kJ, respectively, leading to a renewable to non-renewable cost ratio of c_R/c_{NR} = 0.49, whereas specific CO_2 emissions of 373.21 g_{CO2}/kWh in electricity generation were achieved. These results seem to be consistent with the CO_2 emissions per kWh generated in the Netherlands (351 g_{CO2}/kWh) in 2011 [25]. It must be pointed out that the average CO_2 emission factor for power generation decreased sharply between 1990 and 2011 (around 35%). This reduction in the CO_2 emissions for electricity production was driven by the replacement of coal by NG and the development of renewables, primarily wind and biomass resources.

Table 6. Total, renewable, and non-renewable unit exergy costs and CO_2 emissions for each stream in the Dutch electricity mix represented in Fig. 3

Streams	***1***	***2***	***3***	***4***	***5***	***6***	***7***	***8a***	***8b***
c_{NR} *(kJ/kJ)*	1.0000	0.0344	0.0000	0.0167	0.1715	0.5716	1.0000	1.0060	1.0250
c_T *(kJ/kJ)*	1.0000	2.2589	1.0000	1.0167	1.1721	3.9071	1.0000	1.0060	1.0250
c_{CO2} *(g/kJ$_{prod}$)*	0.0000	0.0008	0.0000	0.0009	0.0120	0.0398	0.0000	0.0006	0.0006
	9a	***9b***	***10***	***11***	***12***	***13a***	***13b***	***14***	***15***
c_{NR} *(kJ/kJ)*	1.0262	1.0550	1.0693	1.0550	1.0568	2.8620	2.3848	1.0000	1.0158
c_T *(kJ/kJ)*	1.0305	1.0550	1.0737	1.0550	1.0612	2.8767	2.3994	1.0000	1.0196
c_{CO2} *(g/kJ$_{prod}$)*	0.0019	0.0023	0.0042	0.0023	0.0048	0.2048	0.1328	0.0000	0.0010
	16	***17***	***18***	***19***	***20***	***21***	***22***	***23***	
c_{NR} *(kJ/kJ)*	1.0167	2.0627	1.0000	1.0380	1.0573	3.1389	2.4026	1.7180	
c_T *(kJ/kJ)*	1.0206	2.0733	1.0000	1.0478	1.0674	3.1689	2.5519	2.5555	
c_{CO2} *(g/kJ$_{prod}$)*	0.0011	0.1609	0.0000	0.0024	0.0036	0.0107	0.1490	0.1037	

In Tab. 6, streams *8a* and *8b* denoted the crude-oil and natural gas produced in offshore platforms, respectively. Stream *9a* is related to transferred crude-oil and *9b* to conveyed natural gas, both up to the refinery, whereas the electrical energy generated in the oil-fired plant and in the natural gas-fired power station corresponds to stream *13a* and *13b*.

For the sake of comparison, this emissions value present six times more than the Brazilian electricity mix (62.09 g_{CO2}/kWh) [7]. According to Flórez-Orrego et al. [7], the renewable and non-renewable unit exergy costs of the electricity generated in the Brazilian scenario achieve c_R=1.4631 kJ/kJ and c_{NR}=0.3329 kJ/kJ, respectively. It is noticed that the electricity mix in Brazil is largely dominated by renewable resources (*e.g.* hydroelectric power plants), leading to a c_R/c_{NR} ratio equal to 4.39 [7].

CONCLUSION

An exergoeconomy assessment accounting for the total and non-renewable unit exergy costs and specific CO_2 emissions of the Dutch electricity mix was carried out focus on representative routes of the electricity generation. The analysis covers the different steps of fuel transportation and processing, as well as the power plant building, operation, and decommissioning, with the electrical energy generated as the final product.
An iterative approach is applied to establish the unit exergy costs of the electricity and intermediate/processed fuels. In addition, the used procedure allowed for the calculation of the direct CO_2 emissions of the technological configurations and their upstream and downstream fuel processing-related indirect emissions, which take a significant role in pathways contrary from fossil-fired power stations. Hence, a rational comparison of the diverse fuels used in the electricity generation was performed in light of the exergy concept and the exergoeconomy analysis. A weighted average of the renewable and non-renewable unit exergy costs of the electricity generated in the Netherlands results in c_R=0.8375 kJ/kJ and c_{NR}=1.7180 kJ/kJ, respectively, whereas the specific CO_2 emissions in the electricity generation achieve 373.21 g_{CO2}/kWh , equivalently to a renewable to non-renewable exergy consumption ratio of c_R/c_{NR} = 0.49.
In a different way from the energy-based analysis, these values could be useful to contrast the electricity commercialisation/destination with another type of exergy sources in a rational manner. Finally, it is pointed out that 67% (weighted average) of the Dutch electricity mix corresponds to non-renewable cost, mainly by reason of the dominance of fossil resources (*nuclear, natural gas, coal, and oil-fired*). Notwithstanding, biomass-fired power plants provide the highest unit exergy cost of electricity generation, 14.6% of such cost equivalent to the non-renewable energy resources.

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NOMENCLATURE

Acronyms/Abbreviations

bcm: Billion Cubic Meters
Const.: Construction Step
CExC: Cumulative Exergy Consumption
CHP: Combined Heat and Power
EEA: Extended Exergy Accounting
LCA: Life Cycle Analysis
LCI: Life Cycle Inventories
LNG: Liquefied Natural Gas
GE&UK: German and English electricity mixes
GHG: Greenhouse Gas Emissions
TPES: Total Primary Energy Supply
$MtCO_2$: Metric Tons of Carbon Dioxide Equivalent
Mtoe: Million Tonnes of Oil-Equivalent
MW: Megawatts
TWh: Terawatt hours

Latin symbols

c: unit exergy cost (kJ/kJ)
B: exergy rate or flow rate (kW)
b: specific exergy (kJ/kg)
E: energy rate or flow rate (kW)
EE: electricity (kWh) or power (kW)
I: fuel carbon content (% weight)
m: specific direct CO_2 emissions (g_{CO2}/kJ)
M: direct CO_2 emissions (g_{CO2}/s)
r: exergy consumption (kJ/kJ)
Rm: molecular weight of CO_2 and elemental carbon ratio (kg/kg)
T: temperature (C, K)

Subscripts and superscripts

C: consumed fuel
CO_2:carbon dioxide emission
en: energy
ex: exergy
F: processed fuel
i: *i*th step
n: *n*th step
NG: natural gas
NR: non-renewable
R: renewable
T: total

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