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The Environmental Footprint of Renewable Energy Transition with Increasing Energy Demand: Eco-Cost

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This study aims to assess the environmental footprint of the increasing share of renewable energy and global energy demand. The considered footprints, including GHG emission, NO_x emission, SO_2 emission and water consumption, are expressed in eco-cost. The assessment indicated that the eco-cost of global energy consumption increased, comparing 2009 (1.66×10^{12} EUR) and 2019 (2.06×10^{12} EUR). This suggests the increasing energy demand (+ 33 %) dominates the positive effect of the renewable energy transition. A significant reduction (≥ ~38 % - 52 %) on the dependency of nonrenewable energy is required to offset the effect of increasing global demand in 2050 without a substantial increase in eco-cost than 2009 and 2019. However, when referring to the European Union case, it was decreased where 2.05×10^{11} EUR in 2009 and 1.65×10^{11} EUR in 2019. It is progressing towards environmental footprint mitigation, provided by the marginal increase in energy demand (+ 0.4 %) and an increase in renewable energy share. The analysis could serve as a guideline for appropriate policy implications towards a sustainable energy system.

1. Introduction

Renewable energy is highly promoted in the effort to minimise the environmental footprint for a sustainable energy system. The contribution to a cleaner energy generation is generally recognised despite still arguments on the end-of-life disposal (Chowdhury et al., 2020) and the utilisation of rare earth products (Arshi et al., 2018). Akram et al. (2020) identified that renewable energy, nuclear energy and energy efficiency improvement have a robust capability to reduce CO_2 emissions. However, it is not necessarily the case for the other emissions and resources consumption as well as with the increase of urbanisation. Misila et al. (2020) suggested that the GHG emission in Thailand can be reduced by 54.5 % and 67.7 % compared to the Business as Usual (BaU) scenario in 2050 through expanding the share of renewable energy and policies related to advanced technology implementation. However, compared to the previous year, e.g. 2010 instead of BaU, the overall GHG emission is still increased. In practice, the relationship between renewable energy and GHG emissions is not indispensable straightforward. For example, (i) the commissioning of a new renewable energy plant enabled the closure of a coal-fired station could lower the domestic coal price, encouraging other consumers to burn it. (ii) the process of harnessing non-fossil fuel energy sources results in extra consumption of fossil fuels, including the construction, maintenance and decommissioning of existing facilities (Jaforullah and King, 2015). It is essential to understand the current progress of renewable energy transition towards environmental footprint reduction and the potential override effect of increasing energy demand. As summarised in Čuček et al. (2012), there has been a wide range of environmental footprints to comprehensively define environmental sustainability and a fair comparison among different alternatives. However, due to the different basis, e.g. high water footprint vs low carbon footprint or air pollution vs climate change, it is challenging to evaluate without transforming to a uniform index. One of the approaches is by expressing the different environmental performance in cost coefficient such as environmental price (CE Delft 2018), taxes (Pintarič et al., 2019), eco-costs (TU Delft, 2020). Zore et al. (2018) suggested that renewable

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energy supply networks are sustainable based on the identified positive metric, sustainability net present value. However, increasing energy demand has not been fully considered in the study by Zore et al. (2018), and the main focus is on a case study for the European Union (EU). Adams and Nsiah (2019) highlighted that a 1 % increase in nonrenewable energy consumption contributes to a 1.07 % increase in CO_2 emissions, while a 1 % increase in GDP (indirectly the demand) could lead to a 1.3 % increase of CO_2 emissions in the short run. This study evaluates the environmental footprint of an increasing share of renewable energy associated with the increasing energy demand. The novel contribution includes (i) the consideration of different emissions (GHG, air pollutants) and water consumption in reflecting environmental footprint with the mean of eco-cost and (ii) the assessment of global and EU performance, progressing towards energy systems with lower environmental footprints by considering the projected demand in 2050. It is intended to highlight the potential loophole in evaluating an energy system's sustainability from a single lens (e.g., share of renewable energy).

2. Methods and case study

The environmental footprint performance is assessed according to the energy mix, contributing to a different GHG level, SO_2, NO_x emissions and water consumption. Table 1 shows the share of nonrenewable and renewable energy globally and the EU energy mix for electricity production (Ember, 2020). The assessed years are 2009 and 2019 to investigate the progress of transition towards renewable energy. Table 2 summarised the average emissions and water consumption of different energy sources. The underlying assumption is the median value based on meta-analysis applied either for 2009 or 2019 for water consumption estimation. The high water consumption of biomass and waste is due to the considered biomass, including woody biomass, herbaceous biomass, aquatic biomass, animal waste etc., and the accounting stages. Water consumption of biomass can be reduced with the increasing share of waste biomass. Other fossil and renewables' emissions and water consumption are assumed by taking the average of the specified fossil and renewables sources. Eco-cost conversion (TU Delft, 2020) is tabulated in Table 3.

Table 1: Energy mix of Global and EU consumption (Ember, 2020)

Energy Mix	World demand (TWh)		EU demand (TWh)	
	2009	2019	2009	2019
Coal	7,679	9,083	807	465
Gas	4,232	6,073	733	700
Other Fossil	980	896	125	89
Wind	277	1,404	133	432
Solar	19	699	14	137
Hydro	3,210	4,271	367	354
Biomass and waste	283	578	122	215
Other renewables	81	102	0	0
Nuclear	2,612	2,716	917	821

Eco-cost is a measure to express the amount of environmental burden based on prevention where the costs are required to reduce the environmental pollution and materials depletion are accounted for (TU Delft, 2020). Eco-costs of water applied in this study is a mid-point value of prevention costs by reverse osmosis of seawater or polluted water (1 EUR/m^3) multiplied by the baseline water stress (BWS) (WRI, 2020) in the respective country. It is about the prevention cost of water extraction from nature rather than water pollution covered by the eco-cost of eco-toxicity. BWS estimates the ratio of total water withdrawals to available renewable water supplies. Eq(1) and Eq(2) show the estimation for absolute eco-cost of emission and resource scarcity, and the total eco-cost for energy consumption. On top of assessing the current progress, the estimation of required increment on the share of renewable energy to meet the global energy demand 2050 without exceeding the eco-cost in 2009 and 2019 are identified. The forecast of global energy demand is based on EIA's (2019) statistics, where 50 % of that in 2008 is predicted. Three 2050 scenarios with 50 % increase in demand are assessed (i) BaU scenario = energy mix remains the same as in 2019, (ii) Scenario 1 = energy mix where eco-cost ≤ 2019, (iii) Scenario 2 = energy mix where eco-cost ≤ 2009. The yearly technology development which improving the conversion efficiency in renewables and nonrenewables are assumed to be proportional. The estimation can be adapted accordingly with the identification of the forecast value.

$$EC_{i,k} = A_{i,k} \cdot CF_k \cdot ECF_k \tag{1}$$

$$TEC = \sum_{i,k} EC_{i,k} \tag{2}$$

Where EC= Absolute eco-cost (EUR), i = type of energy sources (e.g. coal, solar), k = index of the eco-cost type (e.g. GHG, SO_2, NO_x, water), A= energy demand or consumption (MWh), CF = conversion factors of emission released (kg/MWh) or resources consumed (L/MWh) per energy used, ECF = eco-cost of respective emission (EUR/kg) or resources consumed (EUR/L), TEC= the sum of eco cost (EUR)

Table 2: The average emissions (Turconi et al., 2013) and water consumption (Jin et al., 2019).

Energy Mix	GHG (kg/MWh)	NOx (kg/MWh)	SO_2 (kg/MWh)	Water (L/MWh)
Coal	855	2.1	3.365	2,220
Gas	690	2	0.165	598
Other Fossil	915	0.95	4.3	3,220
Wind	22	0.065	0.055	43
Solar	101.5	0.275	0.205	19
Hydro	11	0.032	0.016	4,961
Biomass and waste	69.25	0.89	0.485	85,100
Other renewables	50.938	0.316	0.190	22,531
Nuclear	19	0.025	0.021	2,290

Table 3: The eco-cost of different emissions and resources consumption (TU Delft, 2020).

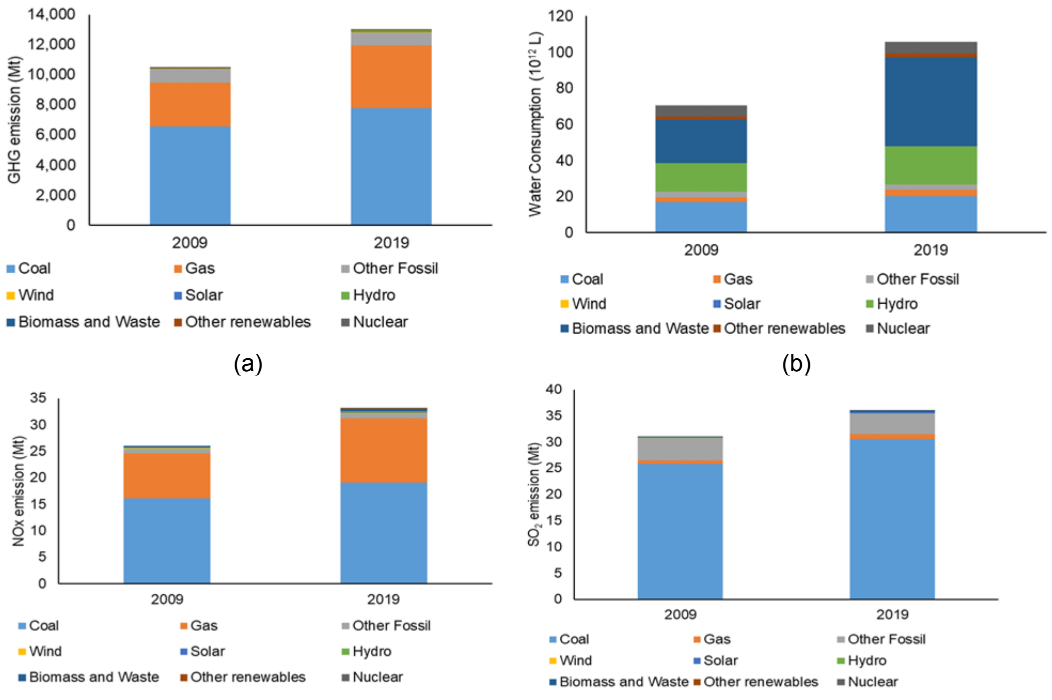
	Eco-cost
GHG	0.116 EUR/kg
Water*	0.5 EUR/m^3, 0.2 EUR/m^3
NO_x	5.35 EUR/kg
SO_2	8.75 EUR/kg

*Note: The same eco-cost is assumed for 2009 and 2019, considering that emission impacts environmental and human health similarly. *0.2 EUR/m^3 is applied for the EU as different in baseline water stress (WRI, 2020).*

3. Results and discussion

Figure 1 shows the emissions and water consumption of the global grid mix in 2009 and 2019. In general, an increasing trend is observed mainly due to the increasing demand. However, considering the emission and water consumed per TWh of electricity produced, it has been decreased. For example, in 2009 is 5.42 x 10^8 kg GHG/TWh (Total Demand = 19,380 TWh) while 2019 is 5.04 x 10^8 kg GHG/TWh (Total Demand = 25,814 TWh). Figure 2 illustrates the total eco-cost to fulfil the global electricity demand in 2009 and 2019 compared to that in the EU. Although the share of renewable energy is increased globally, the eco-cost in 2019 (2.06 x 10^{12} EUR) is still higher than in 2009 (1.66 x 10^{12} EUR). Fatima et al. (2020) highlighted that increased countries' income contributing more the environmental pollution indirectly than nonrenewable energy consumption. This partially explained the increasing trend in Figure 2a, where urbanisation and development contribute to growing demand and hence higher eco-cost. The environmental footprint of global electricity demand is mitigating; however, it is not decreasing compared to the EU performance (Figure 2b). Figure 3 indicates the share of eco-cost. There is a minor change, particularly in the percentage of SO_2 (decrease) and water (increase) for the EU (2009 vs 2019).

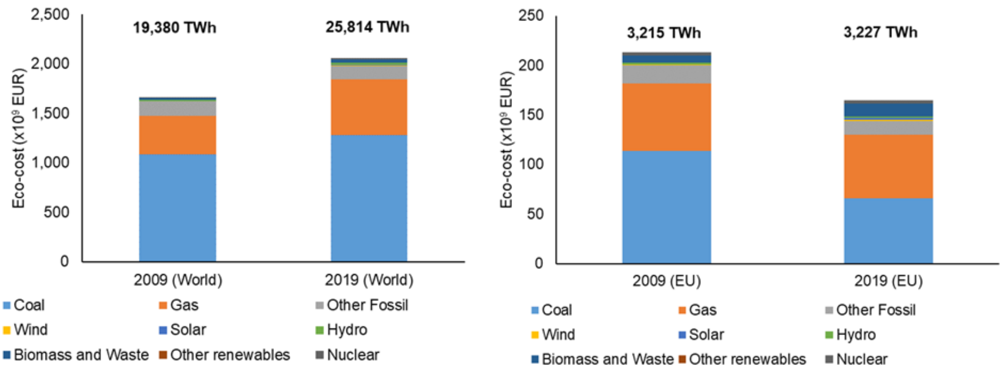
In the EU, the increase in demand is less significant (+ 0.4 %) than the world statistics (+ 33 %), see Table 1. There is a significant decrease in the EU for both the share (25 % to 4.4 %) and absolute amount (- 42.7 %) of coal. It reduced the eco-cost of SO_2, which has a higher prevention cost, serves as the main driver of the decrease in the overall total cost of EU (Figure 3) even with increasing demand. The share of water eco-cost increased in the EU, mainly due to increased electricity generated from biomass and waste. There is a shift of eco-cost from SO_2 to water, leading to a lower total eco-cost (-19.5 %, Figure 2b). Biomass and waste could be a source with lower eco-cost depending on the water stress in a country and the filtration system. Although the global share of electricity generated from coal is decreased (40 % to 35 %), the total consumption is increased (+ 18.3 %), not able to suppress the increase in total eco-cost (1.66 x 10^{12} to 2.06 x 10^{12} EUR, Figure 3). Figure 4 shows the eco-cost performance under three scenarios to fulfil the demand in 2050 (38,863 TWh). Following the energy mix as in 2019 (BaU scenario), the eco-cost in 2050 will reach 3.09 x 10^{12} EUR compared to 2.06 x 10^{12} EUR and 1.66 x 10^{12} EUR in 2019 and 2019. The share of nonrenewable energy in Scenario 1 and 2 has to reduce 38 % and 52 % to have the same eco-cost as in 2019 and 2009 while meeting 2050 demand. It shows both the essential roles of reducing energy demand and nonrenewable energy for an effective solution towards a decrease in environmental footprint. The reduction in energy demand is particularly challenging for developing countries where the population and economy are growing. A significant transition from nonrenewable energy to renewable energy sources is indispensable, especially in Asia (Hanif et al., 2019), to ensure the impact of increasing demand will not override the transition effort. Nguyen and Kakinaka (2019) suggested that renewable energy consumption in low-income countries is positively associated with GHG reduction and negatively associated with economic; however, opposite relationships for high-income countries. The potential effect of renewable energy utilisation inducing a higher energy consumption should also be assessed. It is also important to ensure the relative increase in energy efficiency improvement is not lower than the increase in service demand (Klemeš et al., 2020). Process Integration (Klemeš et al., 2018) and reducing energy consumption at source (e.g. production of different materials/substrate) (Tan et al., 2020) could also contribute to mitigating the impact of increasing energy demand.



(a) (b)

(c) (d)

Figure 1: The (a) GHG emission, (b) Water required, (c) NOx emission and (d) SO_2 emission of global energy consumption in 2009 and 2019



(a) (b)

Figure 2: The share of energy mix and eco-cost for (a) world energy demand and (b) EU energy demand

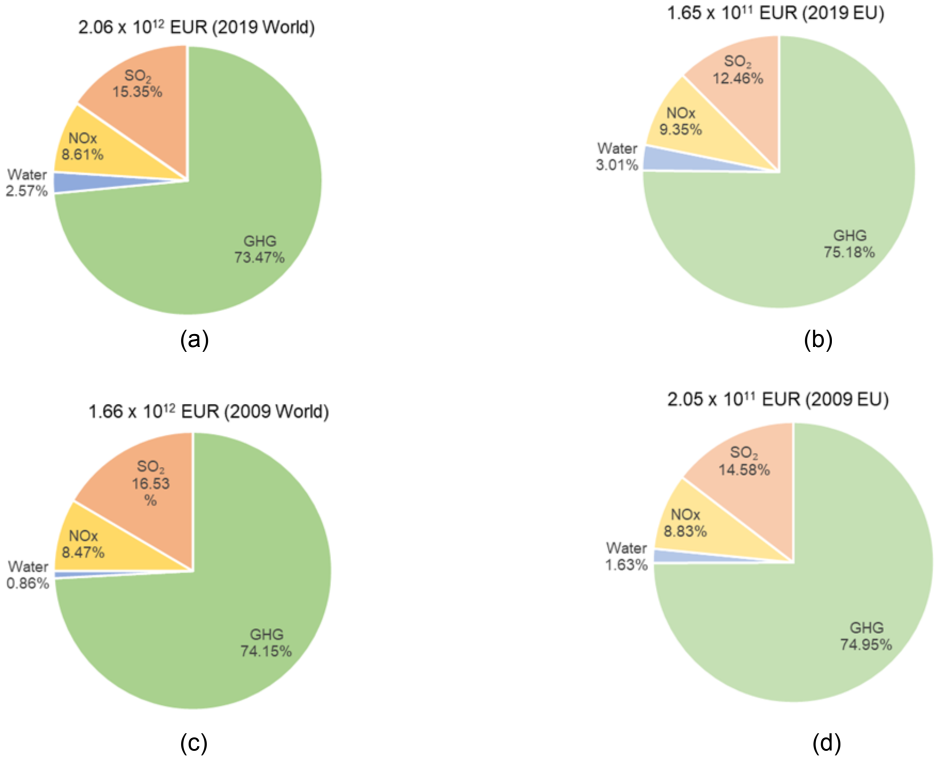


Figure 3: The share of eco-cost by emission/resources consumption for the global and EU energy mix in 2009 and 2019 (a) World – 2019, (b) EU – 2019, (c) World – 2009, (d) EU - 2009

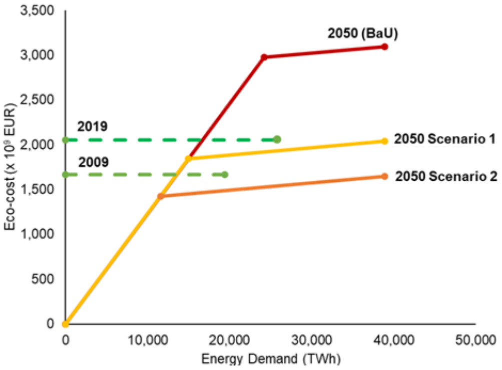


Figure 4: Eco-cost performance versus global energy demand in 2009, 2019 and 2050 under three scenarios (BaU, Scenario 1 and Scenario 2). The red (2050 Bau), yellow (2050 Scenario 1) and orange (2050 Scenario 2) curves can be divided into two portions. The first portion with a higher gradient is the share of average nonrenewable energy. The portion with a lower gradient (end of the curve) represents the average renewable energy share.

4. Conclusions

This study shows that the transition to renewable energy alone would not be sufficient to achieve a sustainable energy system. Improvement of energy efficiency and waste heat recovery to reduce the energy consumption/demand plays a significant role in ensuring the eco-cost is retaining or lower than in the previous years. The total eco-cost in fulfilling the global electricity demand, contributed by the emissions (e.g. GHG, NO_x, SO_2) and resources consumption (e.g. water), is increased from 2009 (1.66 x 10^{12} EUR) to 2019 (2.06 x 10^{12} EUR) even though the share of renewable energy is increased. In contrast, the eco-cost in the EU is reduced by 19.5 %. The policy towards reducing energy consumption should not be overlooked in promoting renewable energy. The focus should be given on a broader range of environmental footprints rather than solely focusing on GHG, contributing to climate change. Net eco-cost could serve as a better mean of interpreting and monitoring the sustainable energy system in different countries than the single indicators such as energy consumption, the share of renewable energy, GHG emission, or Energy Return on Investment and levelised cost, which not covering the environmental aspects.

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