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Estimation of environmental impacts from renewable energy technologies for application in a multi-criteria decision model

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Abstract

The share of electric vehicles and plug-in hybrid electric vehicles in the passenger car stock has been steadily increasing over the last few years. This results in an increasing need for energy hubs and charging facilities along the road network. Addressing some of the required electric power demand by the integration of renewable energy technologies (RETs) to the road electric system could contribute towards a low-carbon transport. The method developed here contributes to a more informed decisions about the type of RETs to be selected by providing an overview on the environmental impact of the renewable energy generation associated with its core technology. By using life cycle assessment, the different RETs can be compared. The information is then intended to be used, along with other criteria, in a multi-criteria decision model to compare the applicable RETs for a given area.

Keywords: renewable energy; life cycle assessment; multi-criteria decision model; EU; decarbonisation; sustainable mobility.

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1. Introduction

Renewable energy is slowly increasing its the market share in the power sector with shares over 40 % in Sweden, Finland, Latvia, Italy, and Spain. Overall, the share of renewable energy, compared to gross final energy consumption in the EU member states combined, was 21.3 % in 2020 (Djunisic, 2021; European Environmental Agency, 2021). Globally, the potential for power generation from renewable sources only is achievable for the current global energy consumption. However, the cost of transition is a challenge as well as the technological connections to electricity and power supplies (Chen et al., 2019). Stable energy supply is essential to maintain national and regional security and increase the resilience of critical infrastructure in Europe (European Commission, 2020). The increasing share of plug-in hybrid electric vehicles (PHEV) and electric vehicles (EV) further increases the energy demand along the road

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network (International Energy Agency, 2021).

The national road authorities recognise that their assets alongside the road network and at service points could offer an opportunity for renewable energy generation. To move in the direction of increased renewable energy production the European National Road Authorities (NRAs), through CEDR (Conference of European Directors of Road), financed a research project ENROAD that aims at providing a GIS-based tool to evaluate the potential for electricity production on/nearby their assets using market-ready technologies. There are many different designs available for roadside renewable energy technologies. Each design has specific objectives and optimal geographical location and climate conditions. The aim of the GIS-tool is to allow the NRAs to select assets they own and get information on the optimal RET, the legal restraints, possibility for connection to grid or energy hubs, and an estimation of the environmental impact of the chosen solution. After initial investigation, roadside RETs, is the technology that is focused on in the project. This is due technological readability of roadside wind power and solar power technologies. The aim of the work was to provide values for the environmental impact of the potential RETs which can be used as one of the criteria in the multi-criteria decision model that the tool developed in the ENROAD project is based on. This is done by identifying representative range of values for the environmental impact of the RETs, which later can be adjusted to the potential electricity generation available in the different areas in Europe. The values must be adjustable to represent both the installation site and the potential power generation at that specific region. To avoid shifting the environmental burden from one aspect of the road network (direct emission from traffic) on to another (energy generation), life cycle assessment is used to estimate the environmental impact from the RETs.

2. Method

A literature review was conducted to attain overview on the availability of information on the environmental impact of RETs from a life cycle assessment (LCA) perspective. LCA evaluates environmental impact of the whole life cycle, from raw material extraction, through processing, production, transport, use and end-of-life (EoL) processing. LCA is based on a functional unit (FU), for the electricity the FU is *environmental impact per kWh* to be able to compare different technologies. For this project, the life-cycle energy will be a variable within the GIS-based tool and therefore the total emissions related to the technology selected is needed. In the GIS-tool the impact will be presented per MWh for comparison purposes. Literature review is used to gain insight into the how the LCA of renewable energy is conducted and finding how, and if, regionality is generally considered.

For the literature review, a search in Scopus was performed for wind energy technologies, solar PV technologies. Biomass power plants are excluded as they are mainly used to provide heat, often for district heating, power for industry, or as a combined heat and power plant (CHP). Mini-hydro are also excluded because of technical variety and lack of environmental information. The search criteria are shown below.

Search criteria 1: "wind power" AND "environmental impact" OR "life cycle assessment" and limited to open access review and research articles not older than 2016.

Search criteria 2 "Solar power" OR "solar energy" AND "environmental impact" OR "life cycle assessment" and limited to review and research articles not older than 2016.

Table 1. Number of returned articles from the search on Scopus and the number of articles that were relevant after evaluation of titles and abstracts.

RET	Initial number of articles returned	Articles after evaluation
Wind power	52	11
Solar PV	61	15

Furthermore, research into available data in the EcoInvent database is used to support the information found in the literature review (Frischknecht et al., 2004; Wernet et al., 2016). The result of the literature review and available data in Ecoinvent is intended to be used for the technologies found to have highest success potential according to the ENROAD project results. This way, the information can be used to evaluate the potential environmental impact of the RETs with the goal of create a site-specific dynamic environmental impact indicators. As the target users of the calculator are CEDR members and other European National Road Authorities (NRAs), a European electric mix is used by default for calculating emissions and for comparison purposes. The final GIS-based application aims at allowing the final users to incorporate their own -more specific- data for example regarding regional information or power source for installation. There are two main reasons for choosing European electricity mix for all locations in the tool. First, the fact that the electricity market in Europe is largely linked physically and second, because the European countries have agreed upon using Guarantees of Origin (GoO) of electricity from renewable energy sources (Association of issuing Bodies, 2021).

The results are presented as a range of values for each region and is to give early indication of the magnitude of the environmental impact and should only be used for comparison purposes within the final ENROAD GIS-based tool. This is because of the high uncertainty in the input data, for example for suppliers, transport distances, construction work needed for installation and removal as well as extraction and processing materials and work needed for maintenance. Here the intension is to allow the user to add own datasets for a more accurate result.

The life-cycle stages included are based on the European standard EN 15804 (European Committee for Standardization, 2013) and focus on A1-A5 (production and installation), and B1 (use, energy production) without excluding the possibility to also include maintenance (B2), End-of-life (C1-C4) and possible reuse (D) where the information is available.

In the project, four wind turbine technologies were investigated, namely HAWT, Savonius, Darrieus and H-rotor (see Fig. 1). As the HAWT is highest on the TRL scale it is the main option considered here for estimation of the environmental impact.

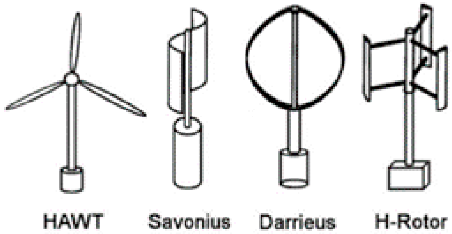

Fig. 1. Wind turbine technologies.

For the environmental estimation for wind turbines two sizes are included from the Ecoinvent database. The 2 MW and 750 kW onshore wind turbines offer a good range of size. This is important as the MCDM tool will have to consider available area and from there find the appropriate number of RETs to be placed at the chosen location. The dataset used represents global market with an adjustment in few of the processes (see Table 2). The adjustments are mostly to represent European situation rather than global.

Table 2. Ecoinvent process for 750kW and 2MW wind turbines and the adjustments made to represent Europe to a larger degree.

Original process	Process used in analysis
Steel, low-alloyed, global	The steel, low-alloyed changed to only include the RER steel production. Transport also adjusted to European average.
Electricity, medium voltage, global	Electricity, medium voltage, Europe without Switzerland
Concrete, normal, rest of world (other than Switzerland)	Concreate, normal, CH at market
Glass fibre reinforced plastic, polyamide, injection moulded, global	Changed to only include European production of glass fiber reinforced plastic
Sheet rolling, steel, global	Values for rest of world changed to the lower, European values and vice versa.

For the environmental estimation for solar power a ground-mounted, multi-silicon crystalline PV-panels technologies was selected because of high technological and market readiness level (TRL and MRL). In the Ecoinvent database "1 p Photovoltaic plant, 570kWp, multi-Si, on open ground" process was selected to represent the PV plant. Again, the size of the plant is important because the MCDM tool will have to consider available area. The process for the PV plant has been adjustment in to represent European situation rather than global (see Table 3).

Table 3. Changes in the Ecoinvent process for PV plant in Europe.

Original process	Process used in analysis
Photovoltaic mounting system, for 570kWp open ground module {Europe}| production	Process adjusted to Europe by using European production for steel, concrete, and other smaller material processes
Electricity, medium voltage, global	Electricity, medium voltage, Europe without Switzerland
Concrete, normal, rest of world (other than Switzerland)	Concreate, normal, CH at market
Inverter, 500kW {GLO}| production	Changed to *Inverter, 500kW {RER}| production*
Photovoltaic panel, multi-Si wafer {Europe}	Process changed from global mix to only European production

3. Results

The literature review revealed that available literature is very site and case specific. Results from the literature review along with values obtained from the EcoInvent database give a range of values for each road-side technology considered. The regional differences are from the power generation potential. The electricity potential is obtained from the ENROAD project through a developed methodology for the estimation of potential energy production based on technology trends but not on single generation device (wind turbine, solar panel etc.) approach. The methodology identifies relevant RET parameters and bring an overview of its trends based on products in the market, so a set of meta-parameters is obtained for each technology. The RET's meta-parameters allow to predict a representative RET generation device as function of main inputs and problem constraints, so the optimal generation device and its associated energy production can be evaluated based on the availability of renewable energy source (eg. wind speed, irradiance), the defined NRA asset location and specific application case. This methodology allows for a more general comparison against the commonly used methods based on single generation device approach.

3.1. Wind power

For the life-cycle environmental impact estimation of wind power the potential energy generation and favourable wind conditions are important. The wind energy generation technologies are divided into large-scale wind (500 - 1500 kW), and small-scale wind (up to 200 kW). Location of the wind turbines is very relevant for the environmental assessment of the technology for other reasons. For example, in relation to the transportation distance, and need for construction work for installation of the infrastructure.

These changes reduced the impact category indicator for global warming about 10 % per each 2 MW wind turbine, which is minimal. These results are then linked to site specific date on the number of turbines that can be placed in the area and their calculated potential electricity production. Thereby it is possible to roughly estimate the impact per kilowatt hour from the installation.

Table 4. Impact category indicator results for 750 kW and 2 MW wind turbine.

Impact category indicator	Unit	750 kW	2 MW
Global warming	kg CO_2 eq	544972	1022289
Ionizing radiation	kBq Co-60 eq	40414	87201
Ozone formation, Human health	kg NOx eq	1902	3140
Fine particulate matter formation	kg PM2.5 eq	1554	2439
Terrestrial ecotoxicity	kg 1,4-DCB	10737824	12320101
Freshwater ecotoxicity	kg 1,4-DCB	449008	481225
Marine ecotoxicity	kg 1,4-DCB	556234	602102
Human carcinogenic toxicity	kg 1,4-DCB	171187	419926
Human non-carcinogenic toxicity	kg 1,4-DCB	2889542	3925579
Land use	m^2a crop eq	75006	85879
Mineral resource scarcity	kg Cu eq	23025	36102
Fossil resource scarcity	kg oil eq	168473	291481
Water consumption	m^3	6271	12710

According to the estimation the main contribution towards most of the impact categories is steel and other metals. Note that these results do not include operation and maintenance, nor the energy for assembly or transport of the wind turbine parts to the site. The connection to the grid is included. Maintenance is negligible as the parts of the turbine have the same lifetime as the turbine (20 years) and therefore should not need shifting. Transport is not included here but is to be included in the final tool as a possible unput from the user. This is because of the variation in transport distance between locations.

3.2. Solar power

Sustainability of large-scale solar power plants have been questioned in the literature where Brunet et al. (2020) found that these types of power plants can result in problem shifting between the different sustainable development goals for instance because of the toxicity in production and waste handling. However, PV plant sites do not, unlike wind power parks, produce noise nor, unlike biowaste plants, bad smell. Furthermore, visual impact did not seem to affect nearby residents.

Photovoltaic power systems transform the solar energy into electrical power by exposing semiconductor materials to solar radiation. The energy harvested depends therefore on solar radiation, which is highly affected by location and angle as well as the efficiency of the solar PV panel. The life-cycle impact per MWh thus varies highly between locations. The capacity of the PV panel used is 570 kWP/unit where Estimated average radiance per year is about 300 W/m2 and the lifetime of the solar panels is 25 years. The efficiency of the solar power panels decreases with time and is estimated to be at 98% in the first year, decreasing to about 87% at year 25.

For use in the MCDM tool the estimated environmental impact is presented per photovoltaic panel. In the tool information on the average radiance per year, available area and thereby the total capacity is provided based on location selected. This would then give impact per MWh produced at the plant. Table 5 shows the estimated environmental impact per PV panel in Europe. The size of the PV plant presented here is 4401,75 m2 and therefore must be adjusted according to available area and the solar radiance.

Table 5. Estimated emissions based on Ecoinvent process photovoltaic plant, 570 kWp, multi-Si, on open ground adjusted for Europe.

Impact category indicator	Unit	PV plant 570 kWp, multi-Si
Global warming	kg CO_2 eq	1285006
Ionizing radiation	kBq Co-60 eq	98316
Ozone formation, Human health	kg NOx eq	3244
Fine particulate matter formation	kg PM2.5 eq	2843
Terrestrial ecotoxicity	kg 1,4-DCB	29294526
Freshwater ecotoxicity	kg 1,4-DCB	209683
Marine ecotoxicity	kg 1,4-DCB	281411
Human carcinogenic toxicity	kg 1,4-DCB	141240
Human non-carcinogenic toxicity	kg 1,4-DCB	2919399
Land use	m^2a crop eq	469424
Mineral resource scarcity	kg Cu eq	14389
Fossil resource scarcity	kg oil eq	321404
Water consumption	m^3	40624

3.3. Solar power

To better visualize the use of environmental impact indicators in the tool and how they can affect decisions the following example is presented. The theoretical, Norwegian area shows how the multi-criteria decision-making tool would include environmental estimation in relations to possible RE technologies and climate in the given area. The area is located near a road and is an NRA asset (see Fig. 2). To be able to estimate the environmental impact from a decision on a RE technology there are some essential terrain and climatic information that need to be included in addition to specific characteristics of the RE technology (here, HAWT wind turbine). For this wind turbine park the available area was 1.8km x 1.5km (eq. Length x eq. Width), the angle between prevalent wind and eq. terrain length is 16°. The mean wind speed in the area (at 50m) is 8 m/s, and the wind speed Weibull shape factor is 2 and the power curve. This is needed to find the possible energy output for the given wind park at this specific site. Generally, the estimated return on energy (break-even point) for this type of wind turbine is 9 months.

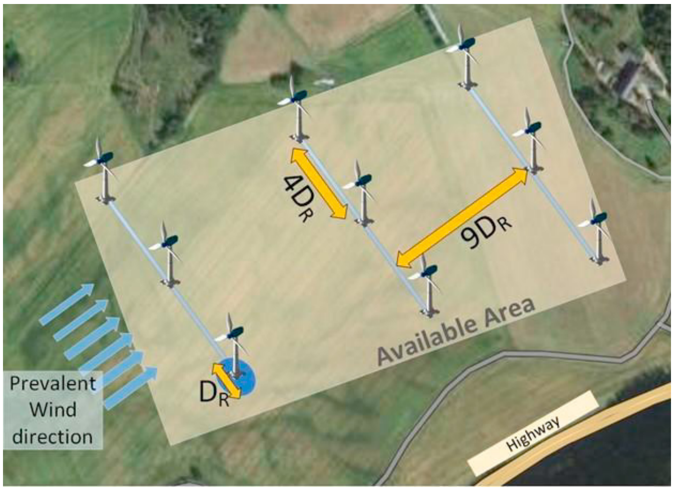

Fig. 2. Example of an area near a road with wind turbine set-up.

For a given wind turbine with provided power curve $P_{eW}(v_w)$, the expected annual energy production (AEP_{WT}) can be calculated by Equation 1.

$$AEP_{WT} = 8760 \cdot k_{AWT} \cdot \sum_{i=1}^{N_{vw}} P_{eW}(v_{wi}) \cdot f_W(v_{wi}) \qquad \text{Equation 1}$$

where the full span of wind speeds from cut-in to cut-out wind speed has been discretized into N_{vw} wind speed bins with equal width, and the total AEP is calculated by summing all contributions of each wind speed bin, v_{wi} is the wind speed of the i-th bin at the wind turbine hub height, and f_W is the wind speed PDF of the area of interest scaled to the wind turbine hub height. k_{AWT} gives the wind turbine annual availability (assumed 95% for both turbines). The total annual energy production of the wind park (AEP_{WP}) is then calculated by Equation 2.

$$AEP_{WP} = N_{PWD} \cdot \eta_{GI} \cdot AEP_{WT} \cdot \frac{1-(k_{PDW})^{N_{AWD}}}{1-k_{PDW}} \qquad \text{Equation 2}$$

N_{PWD}: Number of wind turbines perpendicular to prevalent wind direction.
N_{AWD}: Number of wind turbines along the prevalent wind direction.
η_{GI}: Average efficiency of the grid interface power conversion (for example power converter and transformer)
k_{PDW}: Power ratio of downstream turbines to upstream turbine (assumed 0.9 as best case with 9 turbine diameters as distance between the turbines along the prevalent wind direction)

The example presents the possible energy output per year and from there calculate emissions per unit of energy from the plant (see Table 6).

This example shows the potential GHG emissions from production of electricity in the given area. This can then be compared to other energy sources in the same area, or it can be compared to electricity from the European electricity market. Compared to Norwegian electricity from wind it is considerably lower. The process for Norwegian wind power electricity is estimated to emit approximately 12,7 kg/CO2 eq. per MWh (2MW turbines). There are mainly two explanations for this. First, the ENROAD data is adjusted to European situation with several global processes switched out for processes that emit less. This for example applies to energy use, construction materials and transport technology. This results in about 10% reduction in emissions. The second explanation is the optimalisation of the set up according to very specific local conditions. This results in optimal use of the turbines.

Table 6: Specifications for the possible wind turbine parks and the estimated greenhouse gas emissions per MWh during the lifetime of the wind park.

Wind power	Used Area/ available area	Number of turbines in the area	Potential energy [GWh/year]	Estimated kg GHG/MWh
2 MW wind turbine (Rotor Diameter 90m, Nominal wind speed: 11.5m/s, hub high 80m)	0.693	3x3	131.218	4,09
750 kW wind turbine (Rotor diameter 54m, nominal wind speed 12m/s, hub high 65m)	0.93	4x5	89.785	6,39

The Ecoinvent database contains information on wind power produced electricity for several of the European countries. These processes have been used for support during the modelling. However, the country-based processes are not applicable in the ENROAD MCDM because they already contain possible energy output while the ENROAD project goal is to optimise energy output on selected specific location and the conditions there.

Today, LCA does not include biodiversity loss and issues like land use change for vulnerable natural areas and emissions from those. Land use changes are included to some degree, but it is important for local NRAs to keep in mind use of both crop land and vulnerable natural areas like mires.

4. Conclusion and future works

The results show the importance of carefully evaluate local conditions before selecting, first the technology and then the set-up of selected technology. For the European NRA´s the information on local assets and the climate conditions there can be crucial in the decision about possibly investing in RETs. The MCDM tool will be very useful for the European NRAs in their decision process. This way the NRAs can increase the resilience of their infrastructure and increase national safety with roads and tunnels that can have the possibility to be energy self-sufficient.

As the exact design, producer, transportation distance and actual power conversion are known facts, their values should be evaluated again after a location and technology is selected. Finally, it is important to keep in mind that these values are only to have a range of possible impact for an early phase screening of the RE technologies that should be selected and the locations where they should be implemented. Finally, the MCDM tool needs to be tested on pilots locations to verify the results and usability.

References

Association of issuing Bodies. (2021). Renewable Energy Guarantees of Origin. Retrieved October 18, 2021, from https://www.aib-net.org/certification/certificates-supported/renewable-energy-guarantees-origin

Brunet, Savadogo, Baptiste, Bouchard, Rakotoary, Ravoninjatovo, Cholez, Gendron, and Merveille. (2020). Impacts generated by a large-scale solar photovoltaic power plant can lead to conflicts between sustainable development goals: A review of key lessons learned in Madagascar. Sustainability (Switzerland). https://doi.org/10.3390/SU12187471

Chen, Mcelroy, Wu, Shu, and Xue. (2019). Transition towards higher penetration of renewables: an overview of interlinked technical, environmental and socio-economic challenges. Journal of Modern Power Systems and Clean Energy. https://doi.org/10.1007/s40565-018-0438-9

Djunisic. (2021). Spain generates 43.6% of power from renewables in 2020. Retrieved January 27, 2022, from https://renewablesnow.com/news/spain-generates-436-of-power-from-renewables-in-2020-725418/

European Commission. (2020, April 27). In focus: Energy security in the EU. Retrieved May 14, 2022, from https://ec.europa.eu/info/news/focus-energy-security-eu-2020-avr-27_en

European Committee for Standardization. (2013). EN 15804:2012+A1:2013. Sustainability of Construction Works—Environmental Product Declarations—Core Rules for the Product Category of Construction Products. Brussels, Belgium: EN (European Committee for Standardization).

European Environmental Agency. (2021). Share of energy consumption from renewable sources in Europe. Retrieved from https://www.eea.europa.eu/ims/share-of-energy-consumption-from

Frischknecht, Jungbluth, Althaus, Doka, Dones, Heck, Hellweg, Hischier, Nemecek, Rebitzer, and Spielmann. (2004). The ecoinvent Database: Overview and Methodological Framework (7 pp). The International Journal of Life Cycle Assessment, 10(1), 3–9. https://doi.org/10.1065/lca2004.10.181.1

International Energy Agency. (2021). Global EV Outlook 2021 - Trends and developments in electric vehicle markets. Retrieved October 4, 2021, from https://www.iea.org/reports/global-ev-outlook-2021/trends-and-developments-in-electric-vehicle-markets

Wernet, Bauer, Steubing, Reinhard, Moreno-Ruiz, and Weidema. (2016). The ecoinvent database version 3 (part I): overview and methodology. Retrieved March 11, 2016, from http://link.springer.com/10.1007/s11367-016-1087-8