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Abstract

Electricity supply is frequently cited as a significant hot spot in life cycle assessment (LCA) results. Despite its importance, however, LCA research continues to overuse simplified methodologies regarding electricity supply modeling. This work aims to demonstrate the usefulness of electricity trade analysis (proposed model) for integrating the short-term dynamics of electricity supply and refining LCA results. Distributed generation using renewable energy is applied as a case study to demonstrate how electricity trade analysis provides more refined estimates when environmental impact abatements are assessed compared with the conventional (simplified) approaches in LCA. Grid-connected photovoltaic panel (3 kWp mono- and poly-crystalline) and micro-wind turbine (1, 10 and 30 kW) environmental impact abatements are investigated by determining the displaced marginal electricity production on an hourly basis. The results indicate that environmental impact abatements calculated using the developed short-term time horizon approach can be significantly different (up to 200% difference) from those obtained using a simplified approach. Recommendations are provided to LCA practitioners to address this issue of differing results.

KEYWORDS. Life cycle assessment; Short-term marginal technology; Electricity dynamics; Wind; Solar.

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1. Introduction

LCA researchers agree that there are two main approaches to life cycle assessment (LCA): attributional LCA (ALCA) and consequential LCA (CLCA) [1, 2]. ALCA aims to describe the environmentally relevant physical flows to and from a life cycle and its subsystems [3], whereas CLCA seeks to describe how environmentally relevant physical flows will change as a consequence of the analyzed decisions [4]. The distinction between ALCA and CLCA is more distinct in the process of resolving methodological debates, such as the choice of data [5]. Average data (used for ALCA) represent the average environmental burdens for producing a unit of good or service in the system [5], whereas marginal data (used for CLCA) represent the effects of a small change in the output of goods or services in the environmental burdens of the system [4]. The differences between average and marginal data can be seen in the following example of electricity supply presented below.

1.1. Electricity supply modeling in LCA

a) Electricity supply modeling using attributional approaches

Electricity supply is often highlighted as a significant hot spot in LCA results [6, 7]. LCAs are typically performed using attributional approaches, and thus, electricity production has been modeled using average data, called grid mix data. These data represent all power plants producing electricity at a given period of time and a geographic delimitation such as a country or a region [7]. The major assumption behind modeling these data is that any increase or decrease in electricity demand results in an increase or decrease in supply from all power plants supplying a given geographic delimitation proportional to their averaged contribution. The second assumption is that all power plant supply comes from a given geographic delimitation. Indeed, a common method of modeling electricity supply considers the national grid mix, such as the US average mix, which unrealistically simplifies the complexity of the grid [8-10]. In a comparison of the results of recent studies modeling US state consumption mixes (i.e., state generation mixes including imports) with the results of different commonly used geographic delimitations (i.e., US average mix and state generation mixes), significant variations (more than 100%) were observed for the LCA results (environmental impacts) [9-11].

b) Electricity supply modeling using consequential approaches

From the CLCA perspective, a distinction is made between short- and long-term marginal data for electricity supply. Short-term marginal data represent changes in the use of existing power plant production (i.e., generation changes from the available power plants) [4, 12]. The long-term marginal data represent changes in the production capacity and/or the technology itself. In other words, long-term marginal data are an estimate of the next power plant likely to be built in the case of a growing market with all potential constraints (e.g., economic, political, and resource) [4, 12]. The major assumption behind marginal data modeling is that a power plant that operates at the margin to provide electricity is more likely to respond to a change in electricity demand than the average contribution of all power plants to the grid.

Beyond the distinction between the short- and long-term perspective, marginal data for electricity supply are often considered too complex to model [4, 10]. Therefore, LCA publications often assume one single marginal technology [13, 14], whereas several technologies are at the margin at different periods of time. A stepwise procedure has been proposed to avoid unjustified assumptions [12]. This procedure consists of determining the scale and time horizon of the studied change, the market delimitation and trend, the production constraints and the technologies most responsive to change.

Beyond avoiding unjustified assumptions, this procedure still highlights only one marginal technology [12]. Earlier work has identified long-term marginal electricity production technologies for the Nordic and the German electricity systems as a function of time by using an energy system analysis model in combination with LCA [15, 16]. The obtained results clearly demonstrated how long-term effects include consequences for investments in multiple technologies rather than one marginal technology. From a short-term perspective, the consequences of increased electricity demand are likely to concern a mixture of technologies producing peak load and base-load electricity [4, 10]. As a matter of fact, power plants that turn on to deliver power on the margin use different fuels, which change as a function of the electricity demand [9, 10].

Despite a frequent focus on the short-term perspective [12], LCA studies taking into account the time varying nature when modeling short-term marginal data for electricity supply are surprisingly sparse in the literature. The few identified papers integrating temporal aspects of electricity supply possess different limitations, such as approximating the dispatch order of power plants [17] or not accounting for the energy flows between electricity markets [18, 19].

Price bids from generators, defining the supply curve, and hence the “marginal” power plant, would be ideal for the analysis. However, in a context of increased deregulation, price bids are not always publicly available. In the absence of such data, a procedure for integrating the short-term time variations of marginal technologies is missing. Such a procedure could play an important role in increasing the robustness of LCA studies and refining their estimates of environmental impact abatements, as we will illustrate in this work by using the case study of renewable distributed generation.

1.2. LCA of distributed energy systems

Distributed generation (DG) using renewable energy systems (RES) is often proposed as a sustainable solution to comply with current energy policies such as reducing greenhouse gas emissions and adding supply to meet increasing demand [20]. Recent work modeling DG life cycle environmental impacts using RES and, more precisely, grid-connected photovoltaic panels and micro-wind turbines in the province of Quebec indicated an abatement of environmental impact when oil electricity emissions are avoided[2] in Quebec adjacent markets (i.e.,

[2] By avoided emissions, we refer to the emission increase that would have occurred, given the current generation mix, if renewable DG had not been injected to the grid.

Northeastern American market) from a short-term perspective [21]. However, the latest work did not consider the temporal variations of the short-term marginal electricity production technologies. *As previously introduced, ignoring these variations could reduce the relevance of the study results, and that is the main hypothesis of this work.*

1.3. LCA of distributed energy systems

This paper's objective is to assess the implications of incorporating temporal patterns of electricity supply into LCA. Environmental impact abatements of distributed generation (DG) using renewable energy system (RES) are estimated and compared to conventional LCA approaches. More precisely, temporal variations of electricity supply are modeled, and the results are used to estimate the displaced types and quantity from the short-term marginal electricity production. It is anticipated that the obtained results will help in answering the following questions. What are the potential abatements in terms of environmental impact as a consequence of RES production when a time varying marginal electricity production technology is taking into account? How do these estimates differ from those obtained using the conventional approach, from a short-term perspective[3]?

2. Materials and methods

One of the RES deployment objectives is the reduction of greenhouse gas (GHG) emissions related to electricity production. Given the time-varying output of RES and the diversity of fuel types for electric generators providing electricity at different moment of time, there is significant uncertainty regarding avoided emissions and thus the actual environmental benefits of RES.

Using historical generation information to estimate units that would have reduced their electricity production in response to the variable output from RES provides a good picture of the current grid operation and also good insight into the efficiency of distributed generation as a new energy program for policy makers [22]. Indeed, distributed renewable generation has recently gained support from the province of Quebec, Canada. Therefore, using historical generation information, and hence a short-run time horizon, is particularly well-suited for examining the impact of adding a small quantity of electricity to the electricity-generating system, as is the case for a new energy program such as distributed generation. However, historical generation information is rarely publically available, which consequently justify a procedure development to identify the short-term marginal electricity production.

[3] A short time horizon choice was made in this manuscript to solve a methodological issue in LCA modeling: the identification as a function of time marginal technology and in a context of electricity trade. Beyond this methodological issue, a short-run time horizon perspective is important for policy makers as provides a good picture of the environmental benefits and efficiency of the new energy policy, as is the case with renewable distributed generation.

This procedure is explained in more detail in the following five subsections (steps) below: 1) Estimating RES hourly production, 2) Identifying the short-term marginal electricity production, 3) Matching RES production with the right marginal production for a given hour, 4) Assessing life cycle emissions rates, and 5) Estimating avoided emissions as a consequence of RES generation.

Before going further, it is important to bring to the reader's attention that past performance does not ensure future results, and no forecast should be considered a guarantee either. Because economic and electricity market conditions change frequently, there can be no assurance that the trends described within the assessed short-term period will continue. However, the presented methodology can be easily applied regardless of the electricity market conditions to isolate avoided emissions as a consequence to renewable DG and thus to give a refined estimate to decision makers on the efficiency of such an energy policy.

2.1. Estimation of the RES hourly production

HOMER software[4] is used to generate, for one year, synthetized hourly wind speeds and solar radiations from measured average monthly values [23]. Measured hourly values are not publicly available; therefore, using Homer software is helpful to overcome this difficulty. The average monthly selected values are representative of climatic conditions prevailing in the province of Quebec (Canada) [24]. Annual wind speeds of 7, 5.6 and 3.5 (m/s) and solar radiation values of 1387, 1230 and 1067 (kWh/m2/year) represent the selected above average, average and below average conditions in the province of Quebec, respectively. The compiled monthly values corresponding to each condition, illustrated in Figure 1, refer to the long-term site averages for the province of Quebec [24].

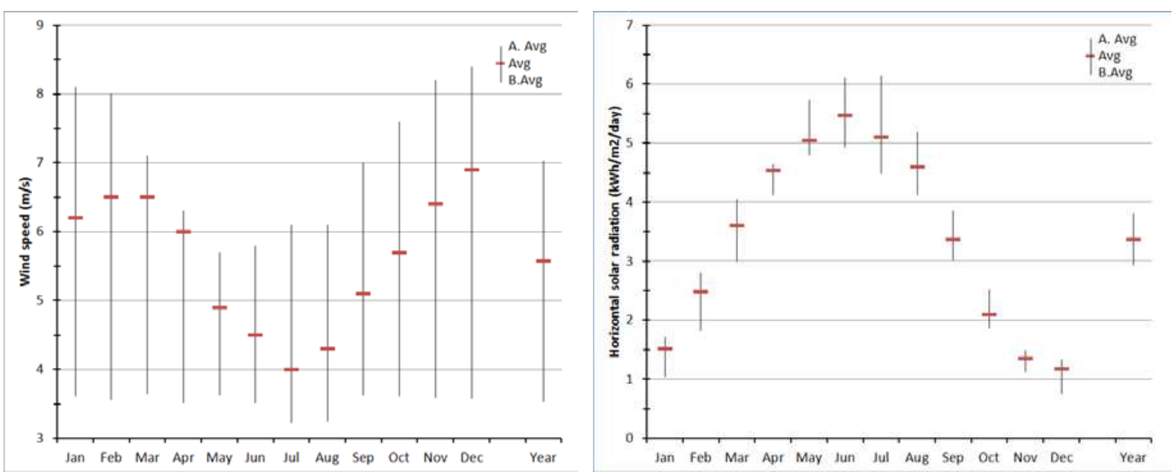

Figure 1. Average monthly wind speed and solar radiation for the Quebec province, measured at 10 m (B. Avg.: below; Avg.: average; A. Avg.: above average condition).

[4] Computer model for evaluating design options for both off-grid and grid-connected power systems for remote, stand-alone, and DG applications.

Mono- and poly-crystalline photovoltaic panels (3 kWp) with slanted roof mounting systems are selected because of their frequent installation, as well as micro-wind turbines (1, 10 and 30 kW), including their commonly used tower heights (10, 22 and 30 m, respectively). The technical specifications of the selected grid-connected RES, including the performance of the inverter and all of the necessary connections are also considered [21]. Table 1 presents the annual energy output as a result of the sum of the hourly energy production of each assessed RES and, thus, considering each RES's intermittency. Once again, the produced energy considers the performance of the inverter, including all the necessary connections and efficiencies (93.5% [25]) and the height of different wind towers. Table 1 also presents the capacity factor (CF) matching each yearly energy output. As a reminder, CF is defined as the ratio of the annual energy output of a given RES and its output if it had operated the entire time at full capacity. Under below average conditions, the shown micro-wind turbine CF values range between 11.5 and 12.4%. This is in agreement with reported values in the literature [26]. For average and above average conditions, micro-wind turbine CF values are comparable with those obtained for a commercial wind farm [26]. The CF values for photovoltaic systems are also in agreement with typical values [27].

Table 1. Annual RES energy output for the considered climatic conditions (W30: micro-wind 30 kW, W10: micro-wind 10 kW, W1: micro-wind 1 kW, PVm: 3 kWp mono-crystalline, PVp: 3 kWp poly-crystalline)

RES	Power curve reference	Below Average		Average		Above Average	
		Output (kWh)	CF([a])	Output (kWh)	CF	Output (kWh)	CF
W30	[28]	32,695	12.4%	71,308	27.1%	91,227	34.7%
W10	[29]	10,032	11.5%	22,137	25.3%	29,031	33.1%
W1	[29]	1,004	11.5%	2,278	26.0%	3,019	34.5%
PVm([b])	[25]	2,727	10.4%	3,154	12.0%	3,559	13.5%
PVp([b])	[25]	2,727	10.4%	3,154	12.0%	3,559	13.5%

[a] CF: Capacity factor is the energy output as a percentage of the theoretical maximum rated output.

[b] 3 kWp mono-crystalline (PVm) and 3 kWp poly-crystalline (PVp) have the same produced energy. The performance is implicitly included in the amount of panel per Wp (i.e., 21.4 m² and 22.8 m² / 3 kWp, respectively [25]).

2.1. Identification of the short-term marginal electricity production

Once hourly energy production for each selected RES is estimated, displaced hourly marginal electricity production as a consequence of RES production is identified in each Quebec adjacent market by adapting previous work methodology [30]. As the province of Quebec is active in electricity trading with its adjacent jurisdictions (i.e., Ontario, New Brunswick, New England, New York), identifying their respective marginal electricity production technology had to be considered. Hourly RES generation can then be matched with the right hourly marginal electricity generation and the consequence of RES generation can be indicated.

Marginal electricity production technology is defined as the last power plant in the merit-order of all power plants needed to meet electricity demand and which has an output that varies with small changes in local market conditions [31]. Readers should note that the short-term marginal electricity production within the province of Quebec is not considered, as more than 95% of Quebec's production comes from hydropower [32]. Given such a particular energy context, DG does not present any environmental benefits in cases where hydropower emissions are avoided (see previous work quantifying the absence of environmental benefits [33]).

Once again, price bids from generators, defining the supply curve, and thus, the "marginal" power plant, would be ideal for the analysis. However, in the context of increased deregulation, price bids are not always publicly available. Therefore, to single out the marginal technology for each of Quebec's bordering jurisdictions, the following steps are proposed:

I. Estimating fuel cost (i.e., marginal production cost) of electricity generation by fuel type;
II. Collecting the day-ahead hourly electricity market prices from the independent system operators in New England, New York and Ontario (ISO NE, ISO NY and IESO);
III. Comparing the fuel cost with the day-ahead hourly electricity market prices and identifying hourly marginal electricity production technology in each Quebec adjacent market.

The 2006-2008 period is selected for data availability, but one has to note that the proposed methodology can easily be extended to other periods of time.

<u>I-Estimating fuel cost (i.e., marginal production cost) of electricity generation by fuel type:</u> Fuel cost estimation is crucial to assessing the plant rank according to merit order [31]. Costs reflect the plant's heat rate (Btu/kWh) and its fuel market price [31]. The fuel market prices (i.e., US$ per short ton of coal, thousand cubic feet of natural gas and barrel of oil) are also collected over the same period from the EIA fuel market price databases [34-36]. In more detail, the Central Appalachian region is the dominant coal production area for the Northeastern region [37, 38], and thus, its coal market price was selected. Finally, the crude oil market price was used as a proxy for the actual diesel or heavy oil market price.

Heat rate (Btu/kWh) is also needed to estimate the fuel cost. Coal, natural gas and oil power plant heat rates were estimated for Quebec adjacent markets as follows.

1. For Ontario and New Brunswick, data were provided by Statistics Canada [39, 40]. As there are no available data for 2008, the 2007 heat rates were used as a proxy. In addition, in the absence of detailed value by prime mover (i.e., steam turbine, gas turbine, internal combustion and combined cycle), an average value was used.
2. For New England and New York, data were provided by the EIA electricity databases [41]. For these jurisdictions, estimating the heat rate as a function of prime mover was feasible. This additional step (disaggregating heat rates by fuel and prime mover) helps in giving detailed fuel cost data as a function of the fuel type and also of the prime mover (e.g., natural gas combined-cycle plants are dispatched at a lower fuel cost than natural gas steam turbine plants).

<u>II-Collecting the day-ahead hourly electricity market prices from the independent system operators in New England, New York and Ontario:</u> The day-ahead hourly electricity market prices are provided, for the US jurisdictions, by the independent system operator ISO NE and NY ISO and, for Ontario, by the Hourly Ontario Energy Price [42-44]. For the New Brunswick

jurisdiction, because of missing data, the New England day-ahead hourly electricity market price at the New Brunswick interconnection is used as a proxy.

<u>III-Comparing the fuel cost with the day-ahead hourly electricity market prices and identifying hourly marginal electricity production technology in each Quebec adjacent market:</u> As previously mentioned, fuel costs and day-ahead hourly electricity market prices are compared to single out the hourly marginal electricity production technology for each of the considered jurisdictions. For example, if, at a given hour, the day-ahead hourly electricity market price is below the lower value at which natural gas production can be profitable and falls within the range of prices where coal production covers its fuel cost, coal is identified, during that hour, as the marginal electricity production technology. In that case, if Quebec electricity imports from a given adjacent jurisdiction occur under such conditions, coal power plants are assumed to be affected by increasing their production to meet the adjacent market increased demand. However, if Quebec electricity exports occur under such conditions, coal power plants are assumed to decrease their production, as lower requirement is needed to meet adjacent market electricity demand.

2.3. Matching RES production with the right marginal production for a given hour

Once the hourly marginal electricity production technology in each Quebec adjacent market is identified, matching the consequence of the estimated RES hourly generation, when it occurs, with the corresponding marginal electricity production technology is straightforward. If one of the selected RES is not producing electricity, no offsets of centralized electricity generation can occur during that time (i.e., hour). On the other hand, during RES generation, the province of Quebec could be importing or exporting electricity from or to adjacent jurisdictions. It is assumed that, during Quebec imports due to its increased electricity demand, the marginal technology in adjacent jurisdictions responding to Quebec imports would decrease its production by the part that RES is able to cover. On the other hand, during Quebec exports, it is assumed that marginal technology in the adjacent jurisdictions will decrease its production, as lower requirement is needed from these technologies, by the part equivalent to the RES production. It is worth to mention that the marginal consequence of RES generation (i.e., decrease in the marginal technology electricity production in the Quebec adjacent markets) is assumed to be proportional to the magnitude of RES generation because of unavailable data on transportation losses. Finally, it is assumed that electricity exchanges are not sufficient to cause a shift from a fuel type to another, and no local network constraints would justify out of merit power plant dispatching.

2.4. Assessing life cycle emissions rates

Before estimating life cycle environmental impact abatements (see section 2.5), the environmental impacts of the assessed RES as well as of the identified marginal electricity production technologies must be assessed.

The emission rates of each investigated RES are based on the life cycle inventory previously modeled [21] and using the annual RES energy output (see Table 1). Readers should note that mission rate estimates cover all the life cycle stages (i.e., from resource extraction, the production of energy including the installation and the decommissioning of the infrastructure).

The list of materials for the selected RES is obtained from manufacturers and completed with the ecoinvent database [25, 28, 45]. The IMPACT 2002+ impact assessment method is selected because midpoint characterization potentials are converted to four damage characterization results: human health (DALY/kWh), ecosystem quality (PDF*m^2*year/kWh), climate change (kg CO_2eq/kWh) and resources (MJ primary/kWh) [46]. The Simapro software is used for modeling [47]. Table 2 presents the final estimates per kWh and takes into account representative climatic conditions prevailing in the province of Quebec (i.e., above average, average and below average conditions-section 2.1).

Table 2. Life cycle RES emission rates and their geographical variations (W30: micro-wind 30 kW, W10: micro-wind 10 kW, W1: micro-wind 1 kW, PVm: 3 kWp mono-crystalline, PVp: 3 kWp poly-crystalline). (B.Avg.: below average conditions; Avg.: average conditions, A.Avg.: above average conditions).

RES	Conditions	Damage category			
		Human Health	Ecosystem Quality	Climate Change	Resources
		DALY/kWh	PDF*m^2*yr/kWh	kg CO_2 eq/kWh	MJ primary/kWh
W30	B.Avg.	9.85E-08	3.25E-02	6.26E-02	9.75E-01
	Avg.	4.57E-08	1.50E-02	2.89E-02	4.51E-01
	A.Avg.	3.56E-08	1.17E-02	2.24E-02	3.50E-01
W10	B.Avg.	2.16E-07	8.61E-02	1.96E-01	2.94E+00
	Avg.	9.60E-08	3.83E-02	8.67E-02	1.30E+00
	A.Avg.	7.42E-08	2.95E-02	6.72E-02	1.01E+00
W1	B.Avg.	5.41E-07	2.53E-01	3.69E-01	6.14E+00
	Avg.	2.38E-07	1.11E-01	1.62E-01	2.70E+00
	A.Avg.	1.83E-07	8.57E-02	1.24E-01	2.07E+00
PVm	B.Avg.	5.75E-08	2.07E-02	7.22E-02	1.24E+00
	Avg.	5.00E-08	1.80E-02	6.27E-02	1.08E+00
	A.Avg.	4.44E-08	1.59E-02	5.57E-02	9.58E-01
PVp	B.Avg.	5.41E-08	2.05E-02	6.53E-02	1.08E+00
	Avg.	4.71E-08	1.78E-02	5.68E-02	9.44E-01
	A.Avg.	4.18E-08	1.58E-02	5.04E-02	8.37E-01

The emission rates of each marginal electricity production technology are assessed for Quebec adjacent markets (i.e., Ontario, New Brunswick, New England, New York). Therefore, the emission rate assessments should take into account consider such spatial variability. To do so, heat rate (Btu/kWh) and GHG emission rates (kg CO_2/Btu, kg CH_4/Btu and kg N_2O/Btu) corresponding to the operation stage of centralized electricity production (i.e., coal, natural gas and oil power plant) are determined from EIA data tables [48] and completed with the eGrid database to include nitrogen oxides and sulfur dioxides emissions rates (kg NO_x/Btu and kg SO_2/Btu) [49]. The mercury emission rates corresponding to the coal power operation stage are also included from the eGrid database. The ecoinvent database is adapted by including the obtained operation stage emission rates and IMPACT 2002+ method is applied, for consistency, for the life cycle environmental impact assessment. Table 3 presents the final results per kWh, considering the four IMPACT 2002+ damage categories: human health (DALY/kWh), ecosystem quality (PDF*m^2*year/kWh), climate change (Kg CO_2eq/kWh) and resources (MJ primary/kWh) [46].

Table 3. Life cycle emission rates by fuel type and prime mover (ST, GT, IC and CC refer to steam turbine, gas turbine, internal combustion and combined cycle).

	Power plant type	New York				New England				Ontario	New Brunswick
		ST	GT	IC	CC	ST	GT	IC	CC		
Human Health (DALY/kWh)	Coal	4.36E-07				4.85E-07				4.43E-07	4.54E-07
	N. gas	1.36E-06	1.30E-06	1.53E-06	6.91E-08	1.81E-06	1.06E-06		6.88E-08	1.13E-06	1.00E-06
	Oil	3.70E-07	4.65E-07	4.69E-07	2.68E-07	4.22E-07	6.06E-07	3.81E-07	2.30E-07	4.83E-07	4.71E-07
	Hydro	4.03E-09				4.03E-09				4.03E-09	4.03E-09
Ecosystem Quality (PDF*m2*yr/kWh)	Coal	1.40E-01				1.56E-01				1.42E-01	1.46E-01
	N. gas	1.55E-02	1.49E-02	1.74E-02	1.13E-02	2.06E-02	1.21E-02		1.13E-02	1.29E-02	1.14E-02
	Oil	1.05E-01	1.32E-01	1.33E-01	6.70E-02	1.19E-01	1.71E-01	1.08E-01	5.75E-02	1.37E-01	1.33E-01
	Hydro	6.73E-04				6.73E-04				6.73E-04	6.73E-04
Climate change (kg CO2 eq/kWh)	Coal	1.04E+00				1.16E+00				1.06E+00	1.09E+00
	N. gas	6.98E-01	6.68E-01	7.84E-01	4.52E-01	9.26E-01	5.43E-01		4.50E-01	5.78E-01	5.13E-01
	Oil	9.80E-01	1.23E+00	1.24E+00	7.84E-01	1.12E+00	1.60E+00	1.01E+00	6.73E-01	1.28E+00	1.25E+00
	Hydro	4.68E-03				4.68E-03				4.68E-03	4.68E-03
Resources (MJ Primary/kWh)	Coal	1.08E+01				1.21E+01				1.10E+01	1.13E+01
	N. gas	1.48E+01	1.34E+01	1.58E+01	9.47E+00	1.86E+01	1.09E+01		9.43E+00	1.16E+01	1.03E+01
	Oil	1.48E+01	1.86E+01	1.88E+01	1.19E+01	1.69E+01	2.42E+01	1.53E+01	1.02E+01	1.93E+01	1.88E+01
	Hydro	4.90E-02				4.90E-02				4.90E-02	4.90E-02

2.5. Estimating avoided emissions as a consequence of RES generation

Once emissions are estimated, emission abatements as a consequence of RES production can be estimated. This can be performed by subtracting the life cycle emissions (not emitted) of the displaced centralized marginal electricity production from the RES life cycle emissions (emitted). This operation is repeated for each hour over the entire 2006-2008 period. Finally, the overall life cycle environmental impact abatements of a given RES generation are simply the summation of all the subtraction results. This step (summation) is applied for each of the assessed RES. For the sake of simplicity, all results are presented as a function of 1 kWh of electricity produced in the province of Quebec and affecting the neighboring electricity market (see sections 3.2 and 3.3).

2.6. Methodological choice implications

The obtained results from the described methodology above will help in answering the first question of the paper: what are the potential abatements in terms of environmental impact as a consequence of RES production when a time varying marginal electricity production technology is taking into account? However, they do not help with the second question: how do these estimates differ from those obtained using the conventional approach?

This section describes how results obtained from the developed approach are compared with those obtained by using the conventional ones. As a reminder, the average approach entails the use of the consumption supply mix data (i.e., production mix including imported electricity), based on different geographic delimitations. In the present case study, various regional mixes could be used. As the assessed RES are located in the province of Quebec (Canada), a first option is to consider regional delimitation. Both Quebec production and consumption mixes could also be taken into account. As electricity is transferred between the province of Quebec and its adjacent jurisdictions with very different mixes, using the production mix could result in incorrect conclusions [11]. Therefore, the Quebec consumption mix has been selected as a first scenario to estimate the life cycle environmental impact abatements as a consequence of RES generation. This first scenario underlines the hypothesis that all power plants composing the Quebec consumption mix are more likely to respond by decreasing their production during RES production and thus their average contributions to the grid.

The national average could also consider the Canadian or the North American grid mixes. However, with a small net electricity importer or a net electricity exporter, using a larger geographic scale is less appropriate. Referring to the total amount of transferred electricity over the 2006-2008 period [30], the province of Quebec is classified as a net electricity exporter, which justifies the choice of using the Quebec consumption mix as a first conventional approach. Table 4 also presents the life cycle emissions rates of the average Quebec consumption mix.

Table 4. Life cycle emission rates of the Quebec consumption mix.

Damage category	Unit	Quebec electricity consumption mix
Human health	DALY/kWh	1.26E-08
Ecosystem quality	PDF*m2*y/kWh	1.58E-03
Climate change	kg CO2 eq/kWh	2.31E-02
Resources	MJ primary/kWh	5.98E-01

In addition to the average electricity consumption mix (average approach), marginal generation technology is also of importance [9, 10]. Thus, in this study, a comparison using the stepwise procedure is also proposed as a second conventional approach [12]. When applied to the Northeastern American context, the stepwise procedure results indicate that oil and natural gas power plants are a short-term marginal electricity production technology and therefore can be chosen to estimate the life cycle environmental impact abatements as a consequence of RES generation [21]. One again, an explicit line of simplification when selecting oil or natural gas as marginal electricity production technology is to ignore the time variations of the electricity market. This means that electricity is modeled as a static system and that, from a short-term perspective, RES generation consequences will unlikely affect a mixture of peak- and base-load electricity production power plants. The emission rates of the short-term marginal electricity production technologies are taken from Table 3.

3. Results and discussion

3.1. Hourly marginal electricity production technology in each Quebec adjacent market

Marginal electricity production technologies differ depending on the moment of the day and they are affected if RES production occurs during that time period. Table 5 shows that when RES production occurs, coal-fired generators are the frequent marginal electricity production technology in the Ontario market in comparison with natural gas units in other jurisdictions. This trend is the same when RES generation consequences are analyzed for above and below Quebec average conditions (i.e., sensitivity analysis). Referring to the results in Table 5, it is worth noting that marginal electricity production is not solely based on one marginal technology but on a complex set able to meet the hourly demand, which is in agreement with recent findings on the complex set using the long-term perspective [15, 50].

Table 5. Marginal technology frequencies (% of hours during 2006-2008) in Quebec adjacent markets (W30, W10, W1, PVm and PVp refer, to micro-wind 30 kW, micro-wind 10 kW, micro-wind 1 kW, 3 kWp mono-crystalline, and 3 kWp poly-crystalline, respectively)

Affected market	RES	Marginal technology				No consequences (a)
		Hydropower	Coal	Natural Gas	Oil	
Ontario	W30	20%	**65%**	11%	0%	4%
	W10	20%	**66%**	11%	0%	2%
	W 1	20%	**65%**	11%	0%	4%
	PVm	8%	**36%**	9%	0%	47%
	PVp	8%	**36%**	9%	0%	47%
New Brunswick	W30	4%	37%	**53%**	2%	4%
	W10	4%	38%	**54%**	2%	2%
	W 1	4%	38%	**53%**	2%	4%
	PVm	1%	15%	**36%**	1%	47%
	PVp	1%	15%	**36%**	1%	47%
New England	W30	4%	37%	**53%**	2%	4%
	W10	4%	38%	**54%**	2%	2%
	W 1	4%	38%	**53%**	2%	4%
	PVm	1%	15%	**36%**	1%	47%
	PVp	1%	15%	**36%**	1%	47%
New York	W30	4%	37%	**53%**	2%	4%
	W10	4%	38%	**54%**	2%	2%
	W 1	4%	38%	**53%**	2%	4%
	PVm	1%	15%	**36%**	1%	47%
	PVp	1%	15%	**36%**	1%	47%

(a) No consequences refer to the percentage of hours when no electricity production is affected (i.e., no marginal technology) because of the absence of RES generation.

* Bold numbers refer to the most frequently used marginal technology that would decrease its production as a consequence to RES generation.

With the intermittency of RES generation, identifying their consequences to the right marginal electricity production technology is worth exploring when assessing their (i.e., RES) environmental impact abatements.

3.2. Life cycle environmental impact abatements as a consequence of RES generation

Life cycle environmental impact abatements are shown in Figure 2. In addition to these abatements, marginal electricity production technologies contributions by source of energy to the total environmental impact abatements are also illustrated. These contributions depend on marginal electricity production technology frequencies (Table 5) and their emission rate intensities (e.g., kg CO2 eq/kWh-see Table 3). As an example, looking at the climate change indicator in Figure 2, the contribution of New Brunswick's coal-fired generators to the total climate change impact abatement is more significant than natural gas units, even if natural gas units represent the most frequent marginal electricity production technology in the New Brunswick market (Table 2). This shift is explained by the high intensity of coal-fired generator emission rates (kg CO2 eq/kWh-see Table 3).

The results presented in Figure 2 are first useful in comparing RES based on their respective life cycle environmental impact abatements (i.e., Consequential LCA). The results in Figure 2 are also of importance as they can be compared to the life cycle environmental impacts obtained using ALCA (i.e., Attributional LCA-without considering any abatement because of avoided centralized electricity production technology). Such comparisons are crucial in highlighting the methodological choice implications on the study conclusions (CLCA and ALCA results). The ALCA environmental impacts are available in Table 2.

In the context of Quebec average climatic conditions, micro-wind 30 kW has less environmental impact than a 3 kWp poly-crystalline photovoltaic panel, using ALCA, for all indicators. However, when applying CLCA using the methodology developed in this article, different results are found. Indeed, as illustrated in Figure 2, no significant differences are noted between the micro-wind 30 kW and the 3 kWp poly-crystalline photovoltaic panel for the ecosystem quality, the climate change and the resources indicators, even if the 3 kWp poly-crystalline photovoltaic panel presents a higher percentage of hours of no electricity generation (see Table 2). From the human health indicator perspective, the ranking between the two systems varies depends on the assessed markets. Resource abatements using micro-wind turbines are slightly higher than those obtained for the photovoltaic panels, up to 5% difference in comparison with the 109% based on ALCA results. The climate change abatement estimates from CLCA results range from 1 to 20% in comparison with 96% based on the ALCA results. Finally, for the human health indicator, the presented ranking between the two systems also changes. In fact, Figure 2 shows that human health abatements obtained for the photovoltaic panels are slightly higher than those for the micro-wind turbines. One exception is noticed for New York electricity market, where micro-wind turbines display a higher abatement in comparison with photovoltaic panels. Below and above average Quebec climatic conditions are also considered to assess the results sensitivity, and the highlighted observations remain the same. Indeed, abatement intensity only decreases or increases when below or above average climatic conditions are respectively considered. These presented observations are in accordance with previous work highlighting how ALCAs and CLCAs yield complementary knowledge on environmental performance (i.e., environmental impact versus abatements) [51, 52].

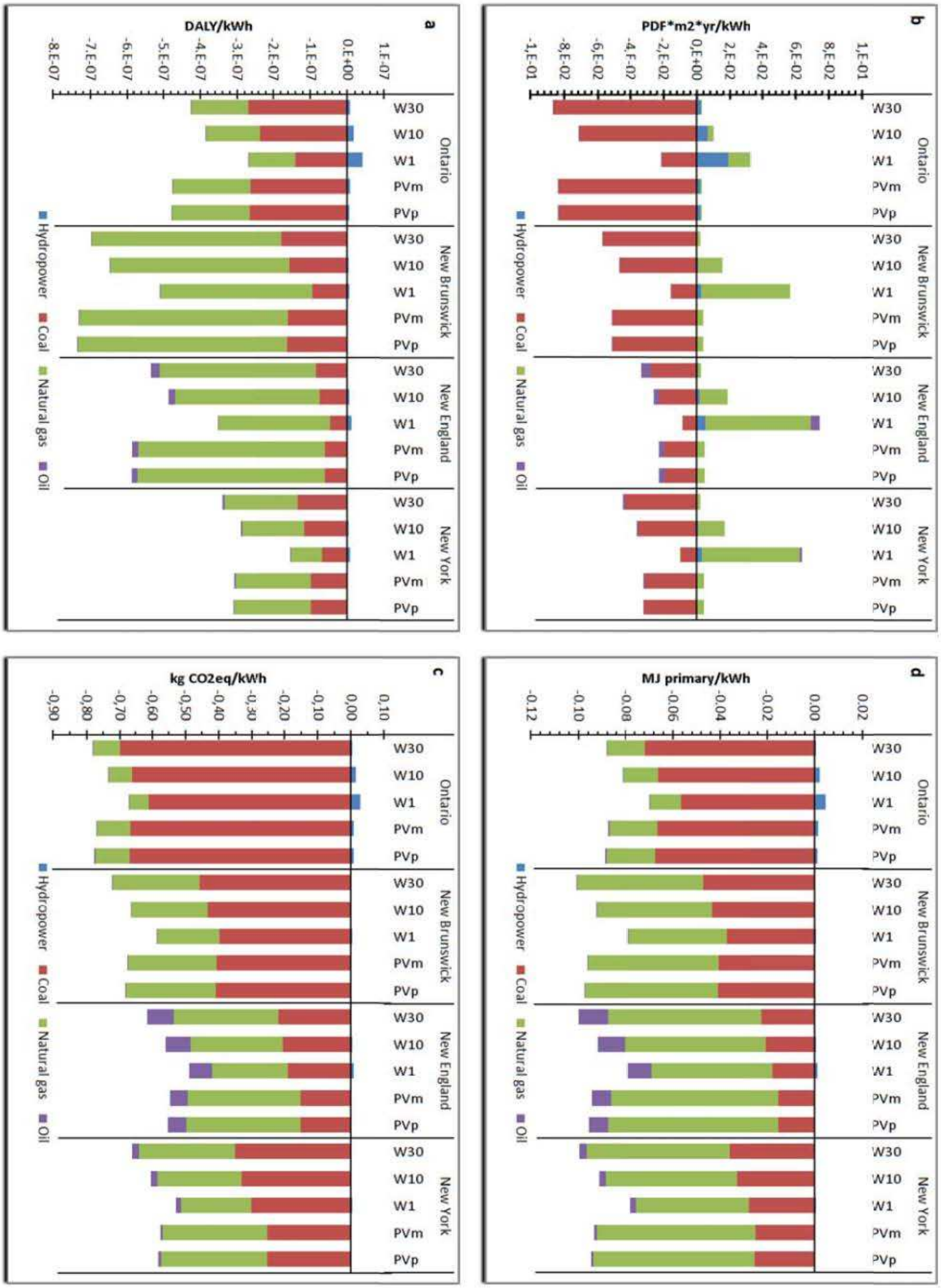

Figure 2. Marginal production contributions to the avoided life cycle environmental impact as a consequence of RES generation in Quebec average climatic conditions (a, b, c and d refer to Human Health, Ecosystem Quality, Climate Change and Resources, respectively; W30, W10, W1, PVm and PVp

refer to micro-wind 30 kW, micro-wind 10 kW, micro-wind 1 kW, 3 kWp mono-crystalline, and 3 kWp polycrystalline, respectively).

3.3. Methodological choice implications and results

The results presented in Figure 2 helped in answering the following question: what are the potential abatements in terms of environmental impact as a consequence of RES production, when time varying marginal electricity production technology is taking into account? They also can help in answering the second question of the paper: how are the obtained estimates, presented in Figure 2, different from those obtained using the conventional approach? To answer the second question, it is possible to compare Figure 2 results to those obtained using conventional approaches: 1) Average production data and 2) the identified static marginal electricity production technologies (oil and natural gas fired plants; both described in section 2.6). All results are shown in Figure 3 and discussed below.

<u>Comparison of the average approach with the developed approach</u>: Quebec's average electricity consumption mix (i.e., Average data) is composed of 95.1% hydropower, 3.2% nuclear, 0.7% coal, 0.5% natural gas and 0.2% of wind power [32]. When using the Quebec consumption mix to estimate life cycle environmental impact abatements due to RES generation, Figure 3 shows the absence of environmental impact abatement in comparison with the proposed approach results. Indeed, for the human health indicator, the values range from 108% to 154% lower than those obtained by applying the proposed approach. A similar trend is observed for the ecosystem quality and climate change indicators (estimate reductions from 116% to 231% and from 100% to 120%, respectively). Finally, for the resources indicator, abatement values are also lower than those obtained with the proposed approach (from 100% to 125% lower). Bearing in mind the large percentage of hydropower in Quebec's average consumption mix (95%), when using average data, there is an assumption that the decrease of the supply from all power plants is proportional to their contribution to the grid. This is in contradiction with the results is Table 5, where it is shown that the hydropower frequency as marginal technology is between 1 and 4[5]%. These percentages are slightly higher in the case of the Ontario jurisdictions (from 8 to 20%). These differences indicate that using the Quebec's average consumption mix overestimates hydropower as being marginal and underestimates the life cycle environmental impact abatement. Such an underestimation could lead to a biased recommendation made regarding RES and consequently could convince a decision maker to avoid deploying DG as an energy policy in the Northeastern American market.

[5] Produced energy from distributed renewable systems can be provisionally stored in reservoirs for inter-temporal arbitrage purposes (water storage allowing the power to be generated when GHG emissions from the marginal source are high). To the best of the author's knowledge, inter-temporal arbitrage is strategic and thus difficult to capture within actual models. Moreover, following the obtained results in Table 5, and keeping in mind that hydropower frequency of being marginal reach a maximum of 4% for 3 jurisdictions over the 4 assessed jurisdictions, taking into account inter-temporal arbitrage will not dramatically influence the obtained results. One potential exception is for the Ontario jurisdiction, where hydropower reaches a maximum of 20% of marginal use during wind generation. Finally, we consider that such mechanisms will not influence the applicability of the developed procedure in assessing avoided emissions as a consequence of renewable distributed generation.

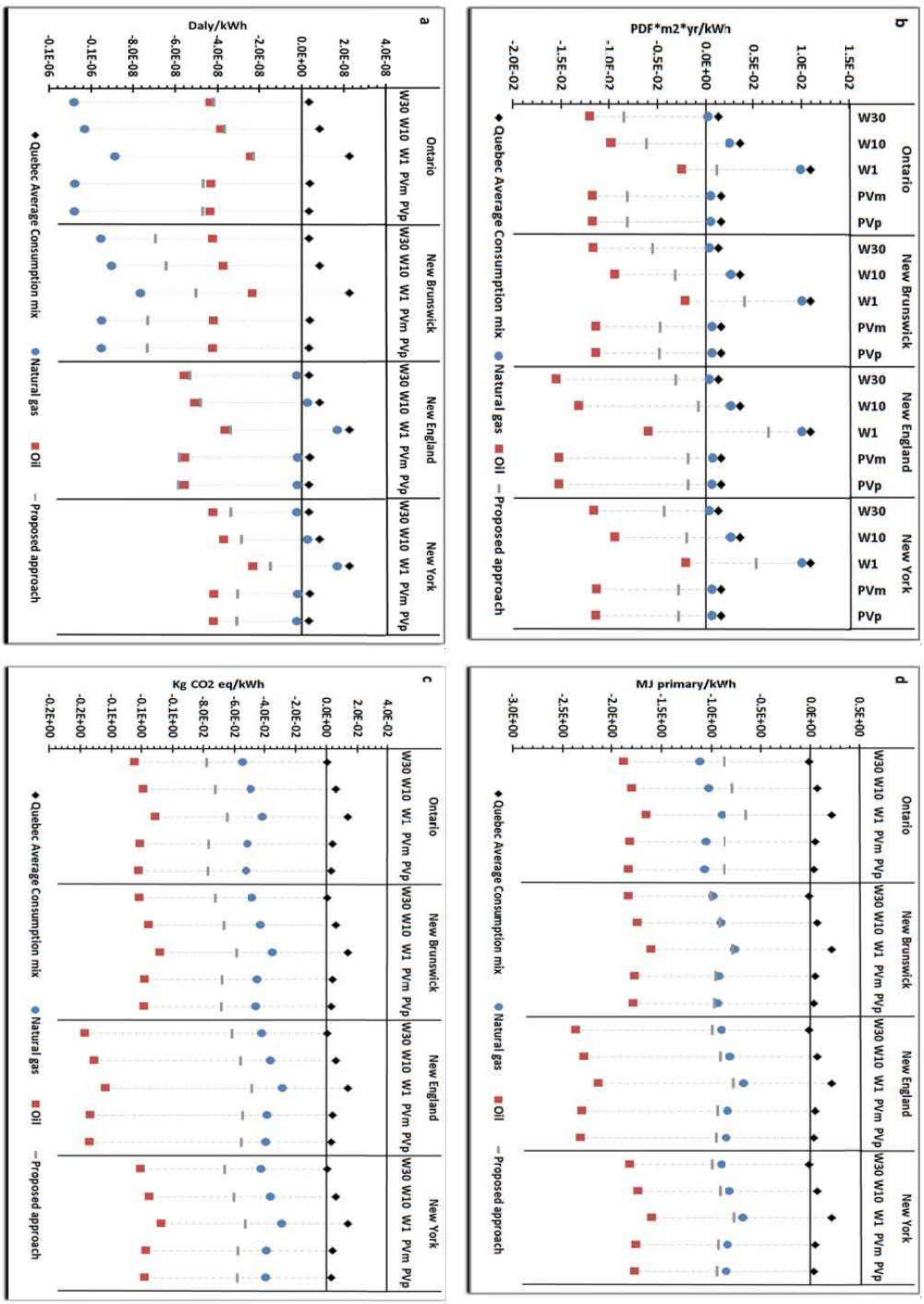

Figure 3. Implications of electricity modeling choices on the avoided emissions as a consequence of renewable DG (a, b, c and d refer to Human Health, Ecosystem Quality, Climate Change and Resources,

respectively; W30, W10, W1, PVm and PVp respectively refer to micro-wind 30 kW, micro-wind 10 kW, micro-wind 1 kW, 3 kWp mono-crystalline, and 3 kWp poly-crystalline. Average Quebec climatic.

Comparison of the marginal approach with the developed approach: Oil- and natural gas-fired plants are identified as marginal technologies when the conventional approach is applied (i.e., the step wise procedure [12]). Figure 3 presents the life cycle environmental impact abatements when these two technologies are considered in comparison with those obtained with the proposed approach. The results, obtained with the proposed approach, fall within the range of the avoided emissions when considering only oil and natural gas as marginal technology. However, no clear trend can be observed if assuming only oil or natural gas as a single marginal technology will systematically give results below or above the ones obtained using the developed approach. Indeed, when only oil power plants are considered as marginal, the results are at most 172% above (for the ecosystem quality indicator value) or 75% below the proposed approach estimate (for resources indicator). In the case of using natural gas power plant as a marginal technology, these percentages are at most 159% above (human health indicator) or 219% below the proposed approach estimates (ecosystem quality indicator).

The observed percentages demonstrate how integrating time into electricity supply when assessing life cycle environmental impact abatements provides more refined estimates in comparison to the conventional approach (i.e., static). These observations still apply for below and above average conditions in the province of Quebec. Moreover, the absence of a clear trend of systematic overestimation or underestimation, when a single marginal technology is applied, makes it difficult to suggest a simplified procedure when a practitioner would not integrate electricity dynamics during the estimation of environmental impact abatements.

4. Conclusion

In a context where LCA is an essential tool used by decision makers, the presented results are particularly relevant in assessing the implication of choosing different electricity supply modeling approaches during decision making. Indeed, we demonstrated when using an average supply mix that renewable DG does not appear to be a sound energy policy, given its abated environmental impacts. On the other hand, renewable DG displayed interesting environmental benefits in cases considering static marginal technologies. In addition to giving contradictory information to decision makers, the results are sensitive to the selected temporal resolution when the short-term marginal perspective is assessed. As a matter of fact, the obtained results using a static perspective displayed a significant difference from those obtained when hourly short-term marginal technologies are integrated: a maximum variation from 172% to -219% (for the ecosystem quality indicator) when static and dynamic approaches are compared.

In cases where it is important to accurately estimate the environmental impacts associated with electricity use, using the proposed methodology is recommended. In other cases, one must keep in mind that expecting an LCA analyst to estimate environmental impact abatements at a high level of detail can be arduous. Therefore, knowing the implications associated with electricity supply modeling choices, it is highly recommended that practitioners exercise caution and sensitivity analyses using different electricity supply scenarios to take into account the complexity of electricity systems.

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