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Wind turbines in Brazil and Germany: an example of geographical variability in life-cycle assessment

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Abstract

A life-cycle assessment of a single product can produce substantially varying results that depend on the location of production. It is the aim of this study to provide an example of this geographical variability by examining the energy and CO_2 embodied in a particular wind-turbine manufactured in Brazil and in Germany. Our results demonstrate the importance of adequately considering the background system of the local economy.

Keywords: Life-cycle assessment; Wind turbines; Brazil; Germany; Energy; CO_2

1. Introduction

A life-cycle assessment (LCA) of a product or process aims at capturing a range of environmental liabilities or impacts that accumulate over the entire cradle-to-grave period. Generally speaking, these impacts occur either directly during the manufacture of the product, or during the process (on site), or are caused indirectly during the provision of inputs into the manufacture, or process (off site). While direct impacts are a unique characteristic of the very product or process, indirect impacts can be expected to vary with the structure and performance of the supplying background system, that is the economy of the location of production (see Ref. [1] for a

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demonstration of the variability of energy inputs and CO_2 emissions in the electricity sectors across a wide range of countries).

It is the aim of this study to obtain an idea about the variability of the indirect contribution to a life-cycle inventory (LCI) for nominally-identical products, caused by geographical variations of the background supply system. We examine the life cycle of a specific wind-turbine model produced in Brazil and Germany. These countries were chosen partly because of data availability, and partly because of striking differences in economic structure and energy-supply characteristics. The analysis is carried out predominantly in energy and CO_2 terms, because energy is a proxy quantity for a wide range of other impacts (for example SO_2, NO_x), and in order to enable comparisons with previous studies to be achieved.

Cumulative energy requirements for wind turbines in different countries have been calculated before for Germany and India by Gürzenich et al. [2], including the transport between the two countries. However, these authors use non-specific process-analysis-based "energy factors", that are "suitably modified for Indian conditions, wherever found necessary". In contrast to their approach, we use generic data sets for both countries, reflecting both the domestic economic and energy-use structures.

This paper is structured as follows. The following section introduces the E-40 wind turbine and describes the structure of the Brazilian and German economies with a focus on the energy-supply systems. Following, we explain the hybrid (process/input–output) LCI approach taken in this work, including estimates of uncertainty and data sources. Results of all calculations are then presented in a comparative manner, discussed, and the paper concluded.

2. The E-40 in Brazil and Germany

The wind turbine model E-40 manufactured by the German company Enercon features a three-blade, pitch-controlled rotor with a nominal power of 500 or 600 kW (depending on the wind class). The rotor diameter and the height of the hub are variable so that it can be efficiently adjusted to the prevailing wind conditions of any location. The turbine does not have a gearbox and the rotor is directly connected to the generator. The rotor blades (diameter 40 or 44 m) are made of fibreglass-reinforced epoxy. The tower can be either of tubular steel or steel–concrete.

In 1996, Enercon founded a subsidiary in Brazil. The E-40 model has since been assembled, initially from locally produced blades, foundations and towers, and imported nacelles and generators. The manufacture of completely Brazilian-made turbines commenced in 2000. At the beginning of 2001, the subsidiary had installed 35 wind turbines in the states of Ceará and Paraná with a total nominal power of 17.5 MW (81% of Brazil's total wind-power capacity) [3].

Since the emphasis of this work is on the background supply systems, we provide the reader with an overview of the economic and energy structure of Brazil and Germany (Figs. 1 and 2). All sectors, except for services, are more important for generating Gross Domestic Product in Brazil. Germany, as an industrialised

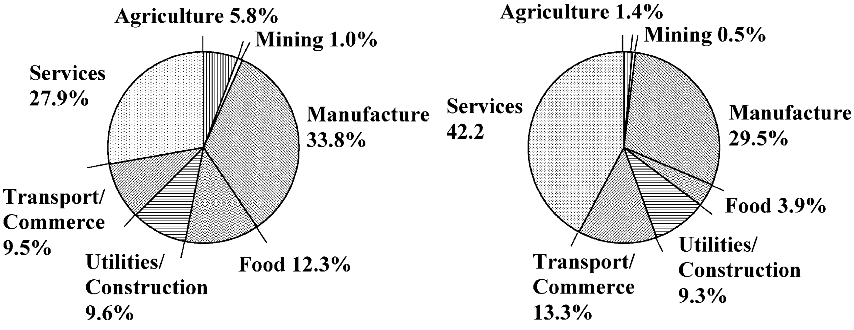

Fig. 1. Breakdown of Gross Domestic Product of Brazil (left pie chart) and Germany (right pie chart) by broad industry class [26,28].

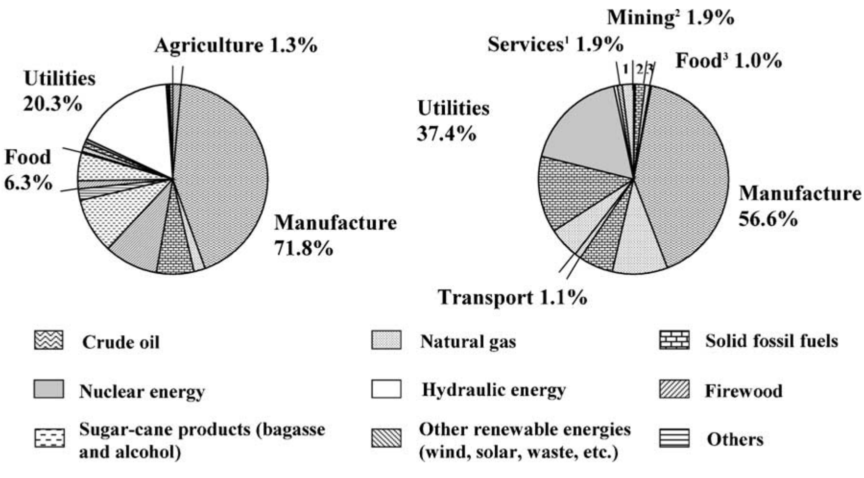

Fig. 2. Breakdown of primary-energy use in Brazil (left pie chart) and Germany (right pie chart) by broad industry class [25,29]. Note: Secondary transport fuels are represented by their primary equivalent (crude oil or sugar-cane alcohol) within manufacturing (refining).

country, naturally relies to a much larger extent on the tertiary sector. The per-capita Gross Domestic Product in 1995 was equivalent to 5928 U$PPP[1] in Brazil and 20,370 U$PPP in Germany.

Both countries feature a large consumption of oil-based liquid fuels. While natural gas and nuclear energy are only important for German industries, hydraulic energy, bagasse and firewood, and sugar-cane-based alcohol are unique to Brazil. Since the latter are all renewable energy sources, the CO_2 balance for Brazilian products can

[1] The World Bank (http://www.worldbank.org/depweb/english/modules/glossary.htm#ppp) defines Puchasingh Power Parties (PPP) as “a method of measuring the relative purchasing power of different countries’ currencies over the same types of goods and services. Because goods and services may cost more in one country than in another, PPP allows one to make more accurate comparisons of standards of living across countries.”

be expected to be considerably lower. Note that the utilities (mainly electricity generation) sector consumes considerably less energy in Brazil, which is due to the conversion efficiency of hydraulic energy being much higher than that of coal.

3. Methodology: hybrid IO-LCA

Triggered by the oil crises of the 1970s, *energy analysis* emerged as a discipline to investigate the total energy required to perform a given task. Initially, this discipline employed *process analysis*, where the energy requirements of the main production processes and some important contributions from suppliers of inputs into the main processes are assessed in detail (e.g. by auditing or using disparate data sources), and the system boundary is usually chosen with the understanding that the addition of successive upstream production stages has a small effect on the total energy embodiment [4]. Process-based energy analyses of wind-energy converters have been carried out by various authors (see for example Refs. [5–9], and [10] for a review).

A drawback of the setting of system boundaries and, as a consequence, the omission of processes outside these boundaries, is the introduction of a systematic *truncation error*. The magnitude of this error varies with the type of product or process considered, but can be of the order of 50% [11]. More importantly, it is not significantly reducible by extending the system boundary [12, 21]. One way to avoid such significant errors is to complement a conventional process analysis with an input–output analysis, resulting in a hybrid life-cycle assessment method. In this work we employ a *tiered hybrid energy analysis*, where the direct and downstream energy requirements (for construction, use, and end-of-life), and some important lower order upstream requirements of the functional unit are assessed in a detailed process analysis. System completeness is achieved by covering the remaining higher-order requirements (for materials extraction and manufacturing) using input–output analysis. Input–output-based energy analyses of wind-energy converters can be found in Refs. [13,14].

Input–output analysis is a top-down economic technique, which uses sectoral monetary transactions data to account for the complex interdependencies of industries in modern economies. The result of generalised input–output analyses is a $1 \times n$ *factor multiplier*, that is embodiments of production factors (such as water, labour, energy, resources and pollutants) per unit of final consumption of commodities produced by n industry sectors. A multiplier $\boldsymbol{m}$ can be calculated from a $1 \times n$ vector $\boldsymbol{f}$ containing sectoral production factor usage, and from a $n \times n$ *direct requirements* matrix $\mathbf{A}$ according to

$$\boldsymbol{m} = \boldsymbol{f}(\boldsymbol{I} - \boldsymbol{A})^{-1}, \tag{1}$$

where $\mathbf{I}$ is the $n \times n$ unity matrix. In this work, $\boldsymbol{m}$ is expressed in producers' prices, containing margins, but no sales tax (see Ref. [15]). The *factor inventory* Φ (scalar) of a given product or process represented by a $n \times 1$ commodity inputs vector $\boldsymbol{y}$ and a scalar Φ_d of direct factor usages is then simply

$$\Phi = \boldsymbol{my} + \Phi_d. \tag{2}$$

my represents the indirect usage of factors embodied in all inputs into the product and process.

An introduction into the input–output method and its application to environmental problems can be found in Refs. [16–18]. A more elaborate treatment of the theory underlying hybrid LCA is provided by Suh and Huppes [19]. For further details on input–output-based LCA techniques, see Refs. [20–22].

4. Data sources

This work is based on a life-cycle study of the E-40 wind turbine by Pick and Wagner [23,24]. We adopt all technical details, site conditions and cost from the German example, and translate these into the Brazilian context. This means that we examine a wind turbine identical to the one operating in Germany, but (partly or fully) produced and operating in the Brazilian economy.

Considering Eqs. (1) and (2), this study requires three types of data: (1) factor use statistics ***f*** on energy and CO_2, (2) direct requirements matrices **A**, and (3) a common commodity input vector ***y***, preferably expressed in a common currency (here: US$).

For Brazil, data on industrial and residential energy usage for 24 primary and secondary fuels are regularly published by the National Department for Energy Development [25]. Hydroelectricity was valued as hydro-potential and not converted into a thermal equivalent. The direct requirements matrix is part of the input–output tables published by the Instituto Brasileiro de Geografia e Estatística [26], detailing 80 commodities and 43 industries. Finally, CO_2 contents of fuels were taken from Ref. [27].

For Germany, data on energy and CO_2 are contained in the input–output tables published by the Statistisches Bundesamt [28,29]. The latter distinguishes 59 commodities and industries.

All freight transport was examined on the basis of distances between and within the countries, using energy and greenhouse-gas intensities calculated for Australia [30]. The impact of the disposal of the turbine was assumed to be negligible (cf. [31] and [32]). Finally, input cost ***y*** for the E-40 turbine in 1995 DM could be derived from data documented by Pick and Wagner [24]. These costs were converted into 1995 US$ using an exchange rate of 1.5 1995DM/1995US$ [33]. Costs for Brazilian production were obtained by adjusting the German cost data with the lower percentage of primary inputs (such as wages and capital) in Brazil.[2] In 1995, the Brazilian Real (R$) was pegged to the US$.

5. Uncertainties

Input–output analysis suffers from uncertainties arising from various sources, the most important of which are *source data errors* due to unreliable sampling, reporting and imputation, the *aggregatio*n of input–output data over different producers, and

[2] Primary inputs in Brazil and Germany represent 40 and 60% of total input, respectively [26,28].

the aggregation of input–output data over different products supplied by one industry sector (*allocation error*) [12].

The Brazilian statistical bureau (IBGE) does not keep comprehensive standard error estimates on the direct requirement coefficients. However, since these coefficients arise from industry surveys that are similar to those conducted in Australia, we apply Australian error terms for source data and aggregation errors. Allocation errors for the Brazilian input–output model were estimated by comparing the energy multipliers of similar commodity groups (construction materials and metal products; chemicals and plastic products; food products; services) with their aggregate value. The estimation of standard errors for multipliers as in Eq. (1) is not so straightforward, because standard errors of the *Leontief inverse* $\mathbf{L}=(\mathbf{I}-\mathbf{A})^{-1}$ cannot be calculated analytically, but by using a Monte-Carlo technique to simulate the propagation of uncertainties [34]. In this work, errors for Brazilian energy and CO_2 multipliers were calculated from 24,000 energy multipliers generated from 3000 simulation runs.

Given the resulting standard errors Δm_j, and the standard errors Δy_i and $\Delta\Phi_d$ of $\boldsymbol{y}$ and Φ_d, the total standard error $\Delta\Phi$ of the factor inventory Φ is then

$$\Delta\Phi = \sqrt{\sum_{k=1}^{n}(y_k\Delta m_k)^2+\sum_{k=1}^{n}(m_k\Delta y_k)^2+\Delta\Phi_{\mathrm{d}}^2}. \quad (3)$$

If the standard errors Δm_k, Δy_k, and $\Delta\Phi_d$ are assumed to be stochastic, the total standard error $\Delta\Phi$ decreases with increasing number of non-zero entries in $\boldsymbol{y}$, that is, with increasing detail of the breakdown of the inputs for the product or process. In order to minimise the relative standard error of the factor inventory, it is therefore important to (1) obtain a breakdown of the inputs that is as detailed as possible, and (2) obtain important direct factor inputs with low relative standard errors $\Delta\Phi_d/\Phi_d$. In a process-type LCA, strategy (1) is not applicable, because of systematic errors due to the truncation of the system. For these non-stochastic errors, a decrease of the overall error with increasing detail does not occur. For further details on the uncertainty calculus, see Ref. [12].

6. Results

We examine five scenarios:

1. production and operation in Germany;
2. production (except foundation) in Germany, operation in Brazil;[3]
3. 1999: production of generator and nacelle in Germany, remaining parts and operation in Brazil;[3,4]

[3] Operation in Brazil occurs either in Paraná—a southern interior state of Brazil, or Ceará—a northern coastal state of Brazil.

[4] Production in Brazil occurs in Sorocaba in the state of São Paulo, about 500 km from Paraná and about 3000 km from Ceará.

4. production and operation in Brazil;[3,4]
5. production and operation in Brazil,[3,4] but assuming a high proportion of recycled steel.

For each scenario, we consider five installation options featuring different locations (with different tower heights and foundation masses, see Table 1). The annual output in Brazil was calculated based on German data in Pick and Wagner's report, but using an average wind speed of 7 m/s (instead of 5 m/s for German sites [35]). Further technical details can be found in Pick and Wagner's report [24].

For the hypothetical scenario 5, we have assumed that 75% of Brazil's steel production is from scrap steel via the Electric Arc Furnace (EAF) route, and 25% from primary ore via the Basic Oxygen Furnace (BOF) route (as opposed to 24%/74% in 1995 [36]). The EAF route is more energy efficient than the BOF route, and in the case of Brazil's hydroelectric capacity cause substantially less CO_2 emissions. This scenario was calculated by adjusting the Brazilian energy matrix using input data provided by Worrell et al. [36], and subsequently calculating a revised Leontief inverse.

The differences in the primary-energy embodiment of wind turbines produced in Germany and Brazil are considerable (Table 2).[5] The main reason for these differences is the higher conversion efficiency of the Brazilian electricity generation system (above 90%). An evaluation of all scenarios using a fossil-fuel equivalent of Brazil's hydraulic energy yielded energy embodiments that were similar to those of German-produced turbines (around 12,000 GJ). It is remarkable that the energy

Table 1
Technical characteristics of the examined wind turbine and site options (after Ref. [24]).

	Coastal 44	Coastal 55	Near-coastal	Inland 55	Inland 65
Tower height (m)	44	55	55	55	65
Foundation mass (t)	132.7	163.8	163.8	150.2	185.8
Transport distance, land[a] (km)	3000/100	3000/100	3000/200	500/800	500/800
Transport distance, sea[b] (km)	8000/10130	8000/10130	8000/10130	8000/10130	8000/10130
Annual output (kWh) Brazil	3,558,926	3,748,666	2,910,409	2,196,404	2,420,131
Annual output (kWh) Germany	1,296,985	1,366,132	1,060,645	800,439	881,972

Coastal = state of Ceará, inland = state of Paraná

[a] The two numbers represent the distances from the place of production/delivery to the place of installation (first number—land transport within Brazil from the place of the production in Sorocaba either to Paraná (500 km; I-55, I-65) or to Ceará (3000 km; C-44, C-55, NC-55); second number—land transport from the nearest seaport to Paraná (800 km; I-55, I-65) or Ceará (100 km, C-44, C-55; 200 km, NC-55).

[b] These two numbers represent the distances between Germany and the seaport in Ceará (8000 km; C-44, C-55, NC-55) or the seaport Santos (10,130 km; I-55, I-65).

[5] Note that the cumulative energy requirement for German production obtained in this work is almost twice as high as Pick and Wagner's estimate (6000–7000 GJ). This discrepancy is due to the remarkable low energy intensities used in the latter study (around 5 MJ/DM). A back-of-the-envelope calculation of an average German energy intensity by dividing total primary energy consumption by GDP yields about 8.9 MJ/DM. This shows that Pick and Wagner's values are probably too low.

Table 2
Total and specific energy requirements (GJ and MJ/kWh_{el}) for the production and operation of the E-40 under different scenarios in Brazil and Germany

Scenario	C-44	C-55	NC-55	I-55	I-65	C-44	C-55	NC-55	I-55	I-65
	(GJ)					(MJ/kWh_{el})				
P&O in Germany	11,263	12,568	12,326	12,330	12,938	0.43	0.46	0.58	0.77	0.73
P Germany O Brazil	11,627	13,029	12,835	13,055	13,797	0.16	0.17	0.22	0.30	0.29
P Germany and Brazil, O Brazil	9525	10,607	10,326	10,147	10,733	0.13	0.14	0.18	0.23	0.22
P&O in Brazil	8094	8827	8547	8486	9214	0.11	0.12	0.15	0.19	0.19
P&O in Brazil, recycled steel	6289	6667	6368	6322	6834	0.09	0.09	0.11	0.14	0.14

C = coastal (Ceará); I = inland (Paraná); NC = near coastal; O = operation; P = production.

embodiments vary stronger with the production scenario than with site conditions (tower high, foundation, mass) and transport distances. Looking at the specific energy requirements (see the right-hand block of Table 2), the differences become even more pronounced: the best and the worst option differ by a factor of more than 8. This is because the total output is higher on average for Brazilian sites (see Table 1).

In general, the largest amount of energy is consumed for the tower (approximately 30–40% of the total), followed by the generator (25–30%) and the nacelle (10–15%). Transport energy is consistently below 5% of the total energy requirement (Fig. 3, left diagram). The shares of the components vary only slightly with the installation option and country of production, except for scenario 5, where steel components (tower and nacelle) consume relatively small shares due to the assumed efficient steel-industry.

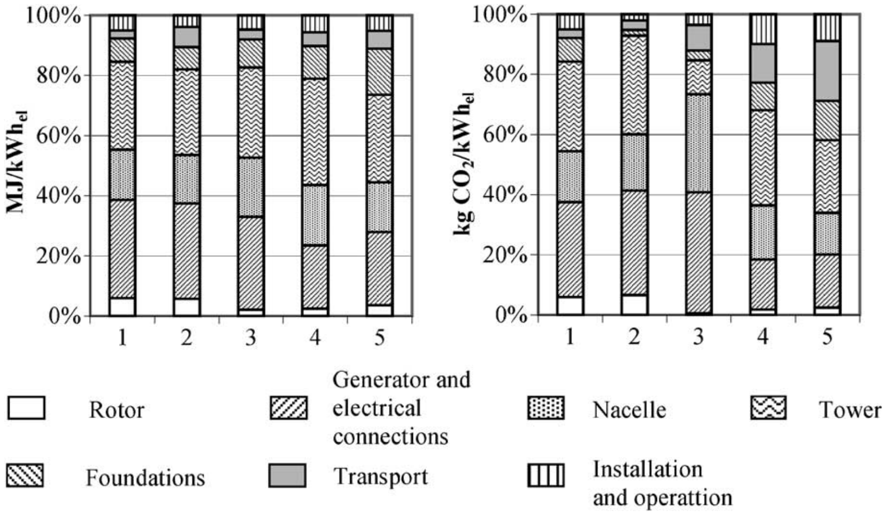

Fig. 3. Shares of components in the specific energy and CO_2 requirements; installation option C-44 (1—P and O in Germany; 2—P Germany, O Brazil; 3—Real case; 4—P and O in Brazil; 5—P and O in Brazil, recycled steel).

While the transport energy requirement seems surprisingly low, our finding is supported by Wenzel [37] and Gürzenich et al. [2]. The latter authors arrive at transportation between Germany and India representing between 4 and 5.4% of the cumulative energy requirement of wind turbines. Examining the effect of explicitly considering imports and foreign emissions on the life-cycle CO_2 emissions on the German production of passenger cars, computers and food items, Wenzel [37] finds that in spite of long distances, CO_2 emissions from transport form a relatively minor part of total emissions ($+1\rightarrow 2\%$ for cars and computers, and around $+6\%$ for food items). If, however, foreign energy production (especially electricity) was explicitly taken into account, CO_2 requirements changed significantly (−9% for cars and computers; food was not examined). Wenzel concludes that within effects of trade on CO_2 emissions, and within reduction potentials, differences in production structure are more important than increased transport requirements.

CO_2 embodiments vary substantially with the location of production (Table 3): the more components are produced in Brazil, the more favourable the score on emissions. CO_2 emissions for production and operation of wind turbines in Brazil under present conditions are a factor of 5 lower than those for Germany. This remarkable difference is entirely due to the differences between the energy-supply systems of the respective economies, as depicted in Fig. 2. Once again, these differences become even more pronounced in terms of the specific CO_2 requirement. Even if the wind speed conditions were reversed, the better sites in Germany would not be able to compensate for the advantages of the Brazilian production-system.

The shares of components in the specific CO_2 requirements vary significantly with the production scenario. Shifting production of components from Germany (1, 2) to Brazil (3) reduces every share except that of the nacelle and the generator, which in 1999 were still produced in Germany. Once production is fully transferred to Brazil (4), transport, installation and operation assume a larger share, because these tasks still rely on fossil fuels only. Their share even increases if the steel sector becomes more efficient (5).

Table 3
Total and specific CO_2 requirements (t and kg/kWh_{el}) for the productions and operation of the E-40 under different scenarios in Brazil and Germany

Scenario	C-44	C-55	NC-55	I-55	I-65	C-44	C-55	NC-55	I-55	I-65
	(tons of CO_2)					(kg of CO_2/kWh_{el})				
P and O in Germany	1176	1315	1290	1291	1358	0.045	0.048	0.061	0.081	0.077
P Germany O Brazil	1053	1183	1178	1186	1244	0.015	0.016	0.020	0.027	0.026
P Germany and Brazil, O Brazil	599	628	588	580	564	0.008	0.008	0.010	0.013	0.012
P and O in Brazil	204	202	196	195	212	0.003	0.003	0.003	0.004	0.004
P and O in Brazil, recycled steel	134	119	114	113	123	0.002	0.002	0.002	0.003	0.003

C = coastal (Ceará); I = inland (Paraná); NC = near-coastal; O = operation; P = production.

Table 4
Standard errors of energy and CO_2 embodiments in Tables 2 and 3 [after Eq. (3), in %]

Scenario	C-44	C-55	NC-55	I-55	I-65
P and O in Brazil	26.1	28.1	29.1	29.1	30.1
P and O in Brazil, recycled steel	23.9	25.4	25.8	26.9	28.8

C = coastal (Ceará); I = inland (Paraná); NC = near-coastal; O = operation; P = production.

Given standard errors for multipliers m_k and input costs y_k

$$\frac{\overline{\Delta m_k}}{m_k} \approx 20\%, \quad \frac{\overline{\Delta y_k}}{y_k} \approx \sqrt{\mathrm{Var}(C) + \mathrm{Var}(L)} = \sqrt{(5\%)^2 + (16\%)^2} \approx 17\%\,, \tag{4}$$

with C and L representing component and labour costs, respectively, and further assuming an additional standard error of 50% for mis-allocation of wind-turbine components to input–output categories, and considering $n \approx 3$ significant components (tower, generator, nacelle) standard errors of total energy and CO_2 requirements can be estimated to be about

$$\frac{\Delta \Phi}{\Phi} \approx \sqrt{\left(\frac{\overline{\Delta m_k}}{m_k}\right)^2 + \left(\frac{\overline{\Delta y_k}}{y_k}\right)^2 + 50\%^2} \quad \sqrt{n}^{-1} \approx 28\% \cdot \tag{5}$$

Table 4 contains results from a more detailed calculation of standard errors for all installation options in Brazil.

7. Conclusions

Over the past 20 years, electricity demand in Brazil grew much faster than GDP and overall energy demand. Especially the residential sector features a substantial potential for further growth, due to unsatisfied demand. At the same time, hydropower plants—currently supplying more than 90% of Brazil's electricity—are increasingly perceived by investors as expensive, controversial and risky [38].

With this in mind, Schaeffer and Szklo [38] conclude that a future electricity mix that meets both least-cost and environmental protection criteria will feature a significant proportion of wind turbines. The indirect energy requirements for a potential transition to this mix can potentially form a substantial part of the national energy consumption [10]. The results of this work can be used to determine to what extent projected levels of available power during such a transition are being overestimated if energy embodied in power plants is not taken into account.

On a more hypothetical note, differences in specific CO_2 embodiments may cause the production of wind turbines (or other commodities) to move to CO_2-efficient economies such as Brazil, if CO_2 emissions were to be penalised sufficiently, and accounted for in a life-cycle context ("positive leakage"). Geographical variability of the embodied CO_2 emissions is at least comparable to the variability across wind turbine designs, so that a production shift abroad would be a serious alternative to design improvements within "dirty" economies in order to achieve emission reductions.

In any case, we have demonstrated that an identical product such as the E-40 can exhibit quite different resource and pollutant embodiments, due to upstream supply chain effects. These can only be comprehensively assessed when the background supply-system is adequately accounted for, such as in the present study.

References

[1] Wenzel P, Wenzel B, Wagner H-J. Länderspezifische Strombereitstellungs- und CO_2-Emissionsfaktoren. Energiewirtschaftliche Tagesfragen 1999;49(7):432–7.

[2] Gürzenich D, Methur J, Bansal NK, Wagner H-J. Cumulative energy demand for selected renewable energy technologies. International Journal of Life-Cycle Assessment 1999;4(3):143–9.

[3] Spencer P. Brazil: enough wind for everyone. REFOCUS 2001;January/February:20–2.

[4] International Federation of Institutes for Advanced Studies. IFIAS Workshop Report Energy Analysis and Economics. Resources and Energy 1978;1:151–204.

[5] Devine WD. An energy analysis of a wind-energy conversion system for fuel displacement. Report No. ORAU/IEA(M)-77-2. Oak Ridge (TN, USA): Institute for Energy Analysis, Oak Ridge Associated Universities; 1977.

[6] Haack BN. Net energy analysis of small wind-energy conversion systems. Applied Energy 1981;9: 193–200.

[7] Hagedorn G, Ilmberger F. Kumulierter Energieverbrauch und Erntefaktoren von Windkraftanlagen. Energiewirtschaftliche Tagesfragen 1992;42(1/2):42–51.

[8] Roberts F. Energy accounting of alternative energy sources. Applied Energy 1980;6:1–20.

[9] Voorspools KR, Brouwers EA, D'haeseleer WD. Energy content and indirect greenhouse-gas emissions embedded in 'emission-free' plants: results from the Low Countries. Applied Energy 2000;67: 307–30.

[10] Lenzen M, Munksgaard J. Energy and CO_2 analyses of wind turbines—review and applications. Renewable Energy 2001;26(3):339–62.

[11] Lenzen M, Dey CJ. Truncation error in embodied energy analyses of basic iron and steel products. Energy 2000;25:577–85.

[12] Lenzen M. Errors in conventional and input–output-based life-cycle inventories. Journal of Industrial Ecology 2001;4(4):127–48.

[13] Krohn S. The energy balance of modern wind turbines. Wind Power Note 1997;16:1–16.

[14] Schleisner L. Life-cycle assessment of a wind farm and related externalities. Renewable Energy 2000; 20:279–88.

[15] Lenzen M. A generalised input-output multiplier calculus for Australia. Economic Systems Research 2001;13(1):65–92.

[16] Leontief W, Ford D. Environmental repercussions and the economic structure: an input-output approach. Review of Economics and Statistics 1970;52(3):262–71.

[17] Bullard CW, Penner PS, Pilati DA. Net energy analysis—handbook for combining process and input–output analysis. Resources and Energy 1978;1:267–313.

[18] Proops JLR. Input-output analysis and energy intensities: a comparison of methodologies. Applied Mathematical Modelling 1977;1(March):181–6.

[19] Suh S, Huppes G. Techniques for life-cycle inventory of a product. Journal of Cleaner Production [accepted for publication].

[20] Lave LB, Cobas-Flores E, Hendrickson CT, McMichael FC. Using input-output analysis to estimate economy-wide discharges. Environmental Science and Technology 1995;29(9):420 A-426A.

[21] Treloar G. Extracting embodied energy paths from input-output tables: towards an input-output-based hybrid energy analysis method. Economic Systems Research 1997;9(4):375–91.

[22] Suh S, Lenzen M, Treloar GJ, Hondo H, Horvath A, Huppes G, et al. System boundary selection in life-cycle inventories. Environmental Science and Technology [submitted for publication].
[23] Pick E, Wagner H-J, Bunk O. Kumulierter Energieaufwand von Windkraftanlagen. Brennstoff-Wärme-Kraft 1998;11/12:52–5.
[24] Pick E, Wagner H-J. Beitrag zum kumulierten Energieaufwand ausgewählter Windenergiekonverter. Arbeitsbericht Juli 1998. Essen, Germany: Fachgebiet Ökologisch verträgliche Energiewirtschaft, Universität GH; 1998.
[25] National Department for Energy Development. Brazilian energy balance 2000. Brasília (Brazil): Ministry of Mines and Energy; 1999.
[26] Instituto Brasileiro de Geografia e Estatística. Matriz de Insumo-Produto Brasil 1995. Rio de Janeiro (Brazil): Ministério de Planejamento e Orçamento; 1997.
[27] Schechtman R, Szklo A, Sala J. Determinação das emissões de carbono derivadas do sistema energético brasileiro-abordagem bottom-up. Technical report, Projeto BRA/95/G31. Rio de Janeiro (Brazil): MCT/COPPE/Universidade Federal do Rio de Janeiro; 1999.
[28] Statistisches Bundesamt. Volkswirtschaftliche Gesamtrechnung: Input-Output-Rechnung 1997. Fachserie 18, Reihe 2. Stuttgart (Germany): Metzler-Poeschel; 2002.
[29] Statistisches Bundesamt. Umweltökonomische Gesamtrechnung: Material- und Energieflussrechnung 2001. Fachserie 19, Reihe 5. Stuttgart, Germany: Metzler-Poeschel; 2002.
[30] Lenzen M. Total energy and greenhouse-gas requirements for Australian transport. Transportation Research Part D 1999;4:265–90.
[31] Hinsch C. The disposal of wind-energy converters and its influence on the life-cycle phases. European Union Wind Energy Conference. Bedford (UK): Stephens & Assoc; 1996.
[32] Kehrbaum R. Perspektiven eines Recycling von Windkraftanalagen. DEWI Magazin 1995;7:35–8.
[33] Development Data Center. World development indicators. Washington (DC, USA): The World Bank; 1998.
[34] Bullard CW, Sebald AV. Monte-Carlo sensitivity analysis of input-output models. The Review of Economics and Statistics 1988;LXX(4):708–12.
[35] Trøn I, Petersen EL. Europäischer windatlas. Roskilde (Denmark): Risø National Laboratory; 1990.
[36] Worrell E, Price L, Martin N, Farla J, Schaeffer R. Energy intensity in the iron and steel industry: a comparison of physical end economic indicators. Energy Policy 1997;25(7–9):727–44.
[37] Wenzel B. Der Einfluß internationaler Arbeitsteilung auf den Energiebedarf und die CO_2-Emission bei der Herstellung ausgewählter Konsumgüter. VDI-Fortschrittsberichte 1999;16(103).
[38] Schaeffer R, Szklo AS. Future electric power technology choices of Brazil: a possible conflict between local pollution and global climate change. Energy Policy 2001;29(5):355–69.