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Net Emergy Assessment of Wind-Electricity Generation in the Brazilian Northeast Region

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ABSTRACT

The search for energy alternatives to fossil fuel is increasing along years, in which wind energy receives an important role in a global future scenario mostly dependent on renewable energy. Specifically for Brazil, federal government is promoting wind-electricity production in its territory, mainly in the Northeast region with the best natural conditions. However, although assuming this kind of electricity as renewable, it still demands high investments in material, energy, labor and information for components manufacturing, transportation, installation and maintenance. This claims for studies to verify its real effectiveness in providing net emergy (with an "m") to support societal development. This work aims to assess the net emergy of wind-electricity generated at "Chapada do Araripe", Piaui State, Brazil. The wind-electricity energy complex has 195MW through its 115 wind-turbines that occupies about 2,600 ha of land. Results show that wind-electricity generated has higher global efficiency (59,600 seJ/J) compared to other usual sources for electricity production (i.e. hydropower, fossil oil, natural gas, nuclear and biomass; ranging from 104,664 to 391,440 seJ/J); this reinforces its usage in a world with reduced resources availability. Regarding net emergy, the values of 1.21 and 2.99 seJ/seJ obtained for the emergy yield ratio (EYR) calculated from two different approaches indicate that wind-electricity energy complex evaluated is providing a net emergy of 0.21 and 1.99 seJ, respectively, to society per 1 seJ invested from economy. These numbers indicate that wind-electricity energy complex should be supported to collaborate towards the Brazilian societal development.

INTRODUCTION

The worldwide wind electricity production was equivalent to zero in 1980, but in 2013 it reached 2.7% of total electricity consumed. The USA was the largest wind electricity producer in 2013 with 27% of total production in the world. Brazil occupied the 15th position of that ranking, but it has the 1st place for the capacity factor with 36%, a value superior to Turkey (33%), Australia, and USA (32%); this means that Brazil has the highest worldwide potential capacity to produce electricity from wind energy (N3E, 2014). Although considering all this potential, the installed power in Brazil was 12TW in 2014, which corresponds to less than 2% of total electricity produced from all summed sources (including hydro, fossil based, biomass and wind) (BEN, 2015). This indicates a huge potential for increase in this field.

Brazilian government has a long term strategic planning to keep with the current importance level of about 43% for the so-called renewable sources (mainly including firewood, sugarcane bagasse, wind, and hydraulic) in its national energy matrix until 2023 (BRASIL, 2014). For this, an important political action was presented aiming to promote the usage of alternative energy sources: the PROINFA program. Among all renewable energy sources cogitated, the wind energy received special attention by PROINFA.

According to BRASIL (2007), it is expected an increase of about 3,300 MW of wind-electricity between 2015-2030 period, which will result in a total of 4,682 MW for 2030. It is worth to say that wind-electricity generation has been benefited by the reduction of its market price as established by public auctions, from 110 USD/MWh in 2004 to 41 USD/MWh in 2014 (N3E, 2014) – using the current ratio of 3.3 BRZ/USD for Brazilian to American dollar currency.

More than be renewable, the ability of energy sources in providing a positive net energy to society deserves equal attention. A renewable energy source can support a sustainable development, but when considering the growing phase of society – divided into growth, climax and degrowth phases (Odum and Odum, 2001) –, the positive net emergy allows its real development independently of energy source renewability. This claims for efforts in evaluating the net emergy obtained from alternative energy sources to fossil fuels.

When well structured, political efforts in replacing fossil-based energy sources as the Brazilian PROINFA program can be viewed as a good strategy towards a sustainable development. Additionally, the energy generation and consumption at the same region is other positive aspect, because it reduces the amount of material and energy that would be demanded to convert and transport that generated energy to other regions. On the other hand, important issues must be carefully considered before stating that such energy source will return in net benefits to society. Although there are technical studies evaluating the most appropriate regions in Brazil where wind farms must be installed (i.e. intermittent wind availability with high speed), the used technology by wind turbines production is still foreign, which results in high costs related to payment of legal rights– i.e. information – in using such technology. Notwithstanding, the wind turbine components are usually produced far from the regions where they will be actually installed in Brazil, which increase the transportation costs; lets remind that wind turbine components are large and heavy. These aspects raise doubts about the net energy provided to Brazilian society by the wind electricity produced and its performance compared to hydropower that currently provides about 80% of total Brazilian electricity.

The widely used methodological approach in calculating the net energy of fuels is the embodied energy analysis through its main indicator named energy return on investment (EROI). However, the results obtained by this approach could be considered as underestimated because it does not account for important input resources recognized as essential for system functioning. For example, natural resources and human labor are usually disregarded from traditional EROI calculation due to its reduced scale of analysis (Agostinho and Siche, 2014). In this sense, emergy accounting (Odum, 1996) appears to be a powerful alternative in estimating the net energy of fuels, in which its main indicator for this purpose is the emergy yield ratio (EYR). This indicator shows how much emergy from nature (considered free of market) has become available for societal development by investing emergy from economy. According to Odum (1996), when an energy source delivers more emergy than is used to obtain it, then societal economy is abundant with high standards of living. Specifically for this work, EYR evaluates if the emergy invested with human labor, information, steel, concrete, diesel and several other necessary inputs to generate electricity by the assessed wind-turbines results in a positive net emergy for Brazilian societal development.

The objective of this work is to use emergy accounting to assess the net emergy of wind electricity generated by the ongoing project of wind farms supported by Brazilian government in the Piaui State.

METHODOLOGY

Case Study and Data Source

This work evaluates the wind-electricity energy complex called *"Chapada do Araripe"*, located at Piaui State, Brazil (Figure1). This region is identified by Brazilian governmental reports as the most appropriated place to install wind farms in Piaui State, due to landscape (accessibility and availability) and wind conditions. Seven wind farms are being implemented and will generate 504 GWh/yr of wind electricity (Table 1).

Regarding scale of analysis, the system boundaries of this work include (i) wind-turbine components manufactured by different suppliers, (ii) components transport from industries to wind- farms (gate to gate), (iii) wind-turbines installation, (iv) operation and maintenance (Figure 2). Decommissioning step was not included at this time due to lack of available information. Transportation is a special subsystem because each component is manufactured in industries located at different regions within Brazilian territory. For instance, some components of wind-turbine are produced at 2,000 km far away from the studied wind farms, while others are produced regionally. Regarding temporal analysis, it is considered the lifespan of 20 years for wind-turbines (as considered by Yang and Chen (2013) and Dolan (2007)), thus all resources needed in operating and maintaining the wind-turbines during this time are included.

A single reference for all primary data used in this work was not found. The wind farms studied depend on different industries that are focused on specific aspects regarding wind-turbine production (rotor, nacelle, and tower) by demanding different materials and technological levels for their production. Thus, primary data were obtained from a number of different sources (including Yang and Chen (2013) and *in situ*) and validated by engineers that work in the wind-turbine industry suppliers in Brazil including for the energy complex evaluated.

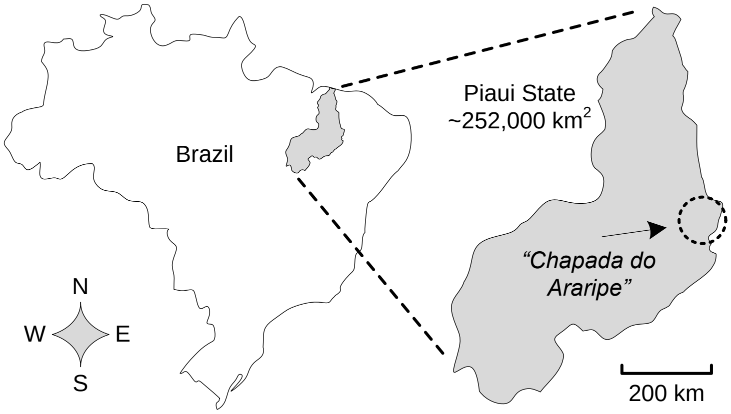

Figure 1. *Geographical position of "Chapada do Araripe" wind-electricity energy complex in the Piaui State, Brazil.*

Table 1. Main characteristics of the "*Chapada do Araripe*" wind-electricity energy complex evaluated (195MW).

Wind farms	Land occupation (ha)	Wind-turbines [a] (units)	Electricity generated [b] (GWh/yr)
Ventos de Santa Joana IX	278	16	70.08
Ventos de Santa Joana X	353	16	70.08
Ventos de Santa Joana XI	187	16	70.08
Ventos de Santa Joana XII	593	17	74.46
Ventos de Santa Joana XIII	245	16	70.08
Ventos de Santa Joana XV	489	17	74.46
Ventos de Santa Joana XVI	443	17	74.46
Total:	2588	115	503.70

[a] Model GE 1.7-100MW hh80m with 1.7MW of nominal power.

[b] Average of generated electricity per each wind-turbine = 1 MWh/h or 8.76 GWh/yr. Considering 50% for conversion efficiency, each turbine provides about 4.38 GWh/yr of electricity.

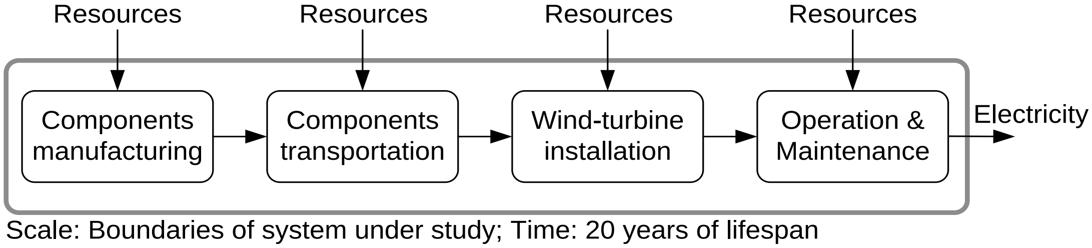

Figure 2. *Process considered within wind-electricity generation as evaluated in this work.*

All unit emergy values (UEVs) used in this work were updated on the emergy baseline of 15.83E24 seJ/yr (Odum, 2000) and do not account for labor and services. UEVs were taken from scientific literature and referenced accordingly. All calculation procedures are provided when assumptions and corrections were judged necessary to better represent the evaluated system or the Brazilian regional specificities. Appendix A contains primary calculations and the UEVs used in this work.

Uncertainty analysis was not addressed in this study at this time, but further effort will be considered in this direction through a Monte Carlo analysis for the parameters source of uncertainty regarding primary data and UEVs used. Similar approach was considered by Agostinho et al. (2014) to evaluate parameters uncertainty on the energetic-environmental performance of enzyme industrial production. Additionally, the renewability fraction of each input used by the studied wind-electricity complex will be considered to assess its sustainability and help in the discussion about considering it as an alternative in replacing totally or partially the hydro-electricity as currently used in Brazil.

Emergy Yield Ratio (EYR)

Emergy is defined as the available energy of one kind of previously used up directly and indirectly to make a service or product (Odum, 1996). Its broader scale of analysis accounts for all resources from a larger economic system and from the natural environment which is usually disregarded by other methodological approaches because no monetary flow circulates on them (Agostinho and Pereira, 2013). Additionally, emergy approach recognizes the energy hierarchy in the universe, which implies in different quality for resources and could reflects more appropriately the effort done by the biosphere in providing a resource for the human economy (i.e. a donor side perspective is considered rather than a receiver one in valuing resources.)

The traditional emergy performance indices provided by Odum (1996) and other emergy analysts along with the last two decades of emergy publications are available to be used in emergy synthesis. However, according to Odum (1996), the Emergy Yield Ratio (EYR) could be considered as the most appropriated when assessing net emergy for fuels and electricity. EYR is a measure of its net contribution to the economy beyond its own operation. H.T. Odum states that if the sources of these goods deliver much more emergy than is required to obtain them, then the economy is abundant and the standards of living are high; this is because prosperity of society depends on the net emergy of its primary sources.

According to Tilley (2015), what differentiates the choice of a method rather than other in calculating the EYR (and also for transformities) is related to objectives of study and mainly to understand if system is maximizing empower (i.e. if the output emergy flow per time is maximized). According do Elliot Campbell (personal communication), maximum empower is relative: (i) no human system (or most natural systems) are functioning at maximum empower because systems are constantly being subjected to pulses and changing; (ii) a counter-argument could be made that all systems are functioning at maximum empower when considering a large enough spatial and temporal scale. Tilley (2015) also identified the difficult in identifying if the system is working at maximum empower, however, the author emphasizes that since EYR is usually calculated to analyze if system is delivering more emergy to economy than divert from it, “it is crucial that proper yield be estimated”. Recognizing that main goal of this study is to verify the net emergy contribution of wind-electricity to the current electricity grid in Brazil, both approaches were here considered in calculating EYR:

(a) Assuming that complex analyzed is at maximum empower. The justification is that system is operating at large geographical scale at multiple places in the world, it has multiple generations of innovation, and it is economically connected to society. In this case, the system yield (Y) is calculated by summing all indigenous and feedback from economy emergy resources demanded by system, Y=R+N+F (Figure 3).

(b) Assuming that complex is not working at maximum empower, thus the yield (Y*) is estimated by multiplying the energy generated by system (electricity output) by an equivalent unit emergy value ($UEV_{eq.}$) representative of the Brazilian electricity matrix, $Y^*=E_{out}*UEV_{eq.}$ (Figure 3). The used $UEV_{eq.}$ was previously estimated by Giannetti et al. (2015) as 1.47 E5 seJ/J considering the different sources for Brazilian electricity matrix (77% hydraulic, 8% natural gas, 7% biomass, 3% fossil oil, 3% nuclear 1% coal, and 1% wind). This second approach could be considered most representative for this work because it is relating the efficiency of current Brazilian electricity matrix in demanding emergy to generate electricity against the wind-electricity energy complex evaluated. In other words, it indicates how far is the efficiency of wind-electricity energy complex compared to the current Brazilian electricity mix.

RESULTS AND DISCUSSION

The energy diagram of Figure 4 shows the main input and output flows, as well as internal relationship of the evaluated wind-electricity energy complex. The external energy sources include wind as the renewable natural resource used by the system. Other external sources come from the larger economy, including materials (i.e. steel, cooper, glass, concrete, etc.), energy (diesel), labor, and services. All of them are necessary resources for the system implementation and operation during its 20 yrs of lifespan. Internal subsystems include components manufacturing and transportation until wind farms, concrete-based foundation to support wind turbines at farm, and energy demanded for maintenance. The output is the electricity available to the Brazilian national grid. The wind-electricity generated has a market cost agreed between the wind energy company with the government through previous public auction. The different layers in the energy diagram represent the seven existing wind farms that belong to the wind-electricity energy complex evaluated. Monetary flow of electricity sold to market goes into the system boundaries, then it charges the money storage, and finally it is used to pay external sources of labor & services. The approach described in Ulgiati and Brown (2014) to accounted for services is considered here, in which services associated with materials and energy inputs to a process (i.e. background, indirect labor) are accounted for by their monetary market costs.

The present study disregarded the non-renewable resources from nature (N), however, as identified and considered by Riposo (2008) and Dolan (2007), the wildlife impact (i.e. birds, bats, and bugs killed by wind-turbines) and land appropriation could be accounted for better representation of emergy performance for the generated wind electricity. Although potentially reducing the renewability (%R) and sustainability (ESI) emergy indices, the inclusion of those N resources would result in better performance for the emergy yield index (EYR=(R+N+F)/F); for the second approach in calculating EYR*, including N resources will have no influence on final numbers. The propositions of new emergy indices as suggested by Ortega and Bastianoni (2015) could be useful to assess, critically, different aspects of system under study as its sustainability. The EYR issue is also discussed by Ulgiati et al. (2005) and Raugei et al. (2005), in which authors argue, “short-term competitiveness may turn into medium or long-term self-destructiveness”. In short, high EYR should not be the goal when natural non-renewable resources are considered in its calculation algebra, if not, the system will be at the same time a good supplier of net emergy to society and unsustainable at medium to long terms.

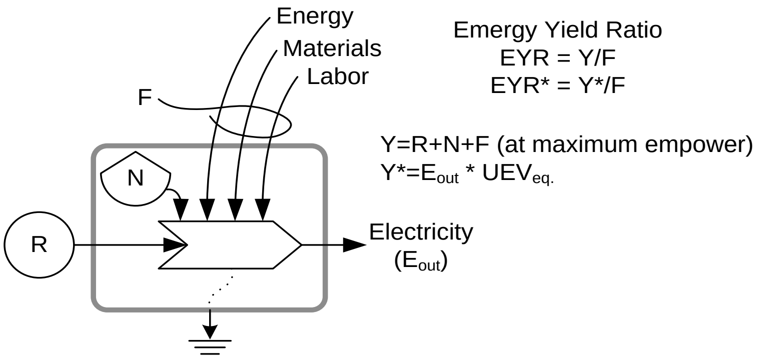

Figure 3. *Generic energy diagram showing two methods in calculating emergy yield ratio (EYR). Legend: R = renewable resources from nature; N = non-renewable resources from nature; F = feedback from economy; Y = yield; Eout = energy output; UEVeq. = Equivalent unit emergy value.*

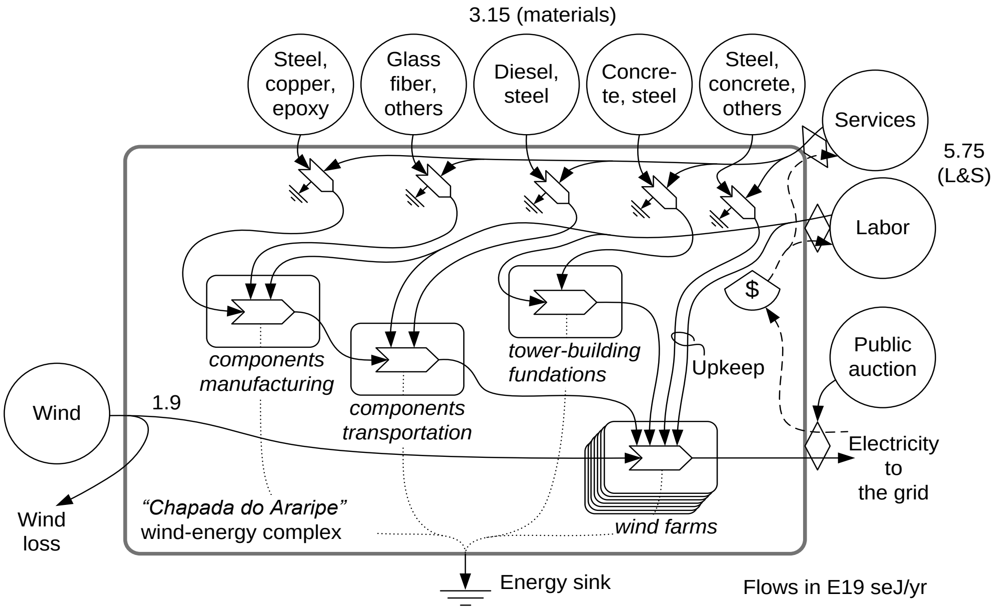

Figure 4. *Energy diagram of "Chapada do Araripe" wind-electricity energy complex. It comprises seven similar and independent wind-farms. Numbers come from Table 2.*

According to Odum and Odum (2001), indicators have different meanings and importance in the different stages of a production-consumption pulse (growth, climax, descent, and restoration), thus the policies that are good in times of abundant resources (renewable or non-renewable) may not be good in times of or scarce resources. Assuming that emergy related to N resources in the wind-electricity energy complex is smaller to the renewable emergy obtained from wind (i.e. R>>N), then the EYR index becomes R+F/F. In this case, it can be said that higher EYR means better performance because the system is increasing its dependence on natural renewable resources that results in higher net emergy provided to society through a renewable way. Maybe, a system who does not use non-renewable resources could not be considered competitive during the society's growth phase, but in accordance with current availability reduction of cheap fossil-based energy, tendencies indicates that society is facing climax or descent phase; this means that both are important, net emergy and renewability.

Table 2 shows those items that have higher influence on total emergy demanded by system. Labor & services related to wind-turbine manufacturing correspond to 48% of total emergy, followed by wind (17%), concrete used to make foundations (13%), total steel (9%) and copper (4%) used in the wind-turbines; all other items correspond to 9%. The high influence of Labor & Services can be explained by the high market cost of wind-turbine, because it was accounted for in currency units in the emergy evaluation, which includes not only the subjective willingness-to-pay for that good, but also, it includes indirectly all research and development applied to provide such high-tech good for society.

Table 2. Emergy evaluation table of wind electricity generated by "*Chapada do Araripe*" wind-electricity energy complex, Piaui State, Brazil.

#	Description	Amount[a]	Unit/yr	UEV[b] (seJ/Unit)	Emergy (seJ/yr)	Emergy (%)
NATURAL RESOURCES (I)						
1	Wind (R)	7.55E+15	J	2.51E+03	1.90E+19	17.5
2	Birds loss (N)	-	-	-	-	-
3	Bats loss (N)	-	-	-	-	-
4	Bugs loss (N)	-	-	-	-	-
5	Aesthet. value loss (N)	-	-	-	-	-
6	Noise (N)	-	-	-	-	-
RESOURCES FROM ECONOMY (F)						
Components manufacturing						
7	Steel (F)	1.05E+03	ton	7.81E+15	8.20E+18	7.6
8	Fiber glass (F)	1.29E+02	ton	1.32E+16	1.70E+18	1.6
9	Epoxy (F)	1.50E+01	ton	5.51E+15	8.27E+16	0.1
10	Copper (F)	4.97E+01	ton	9.80E+16	4.87E+18	4.5
11	Aluminum (F)	2.88E+00	ton	2.13E+16	6.13E+16	0.1
12	Glass (F)	2.01E+00	ton	1.29E+16	2.59E+16	<0.0
13	Polyester (F)	1.73E+00	ton	5.51E+15	9.53E+15	<0.0
14	Lab.&Serv. (F)	1.22E+07	USD	4.24E+12	5.17E+19	47.8
Components transportation						
15	Diesel (F)	4.37E+11	J	1.81E+05	7.91E+16	0.1
16	Steel (F)	3.67E-02	ton	7.81E+15	2.87E+14	<0.0
17	Lab.&Serv. (F)	1.24E+06	USD	4.24E+12	5.26E+18	4.9
Wind-turbine installation &maintenance						
18	Concrete (F)	5.98E+03	ton	2.42E+15	1.45E+19	13.4
19	Steel (F)	2.19E+02	ton	7.81E+15	1.71E+18	1.6
20	Diesel (F)	3.32E+11	J	1.81E+05	6.01E+16	0.1
21	Water (F)	1.74E+03	ton	3.27E+11	5.69E+14	<0.0
22	Electricity (F)	1.04E+12	J	1.47E+05	1.53E+17	0.1
23	Gasoline (F)	1.01E+12	J	1.87E+05	1.89E+17	0.2
24	Lab.&Serv. (F)	1.24E+05	USD	4.24E+12	5.26E+17	0.5
Emergy without Lab.&Serv.		-	-	-	5.06E+19	-
Emergy with Lab.&Serv.		-	-	-	1.08E+20	-
Electric. without Lab.&Serv.		1.81E+15	J	2.79E+04	-	-
Electric. with Lab.&Serv.		1.81E+15	J	5.96E+04	-	-

(R) = renewable resource from nature; (N) = non-renewable resource from nature; (F) = feedback from economy; Aesthet. Loss = aesthetic loss; Lab.&Serv. = Labor & Services; All UEVs are updated to baseline of 15.83 E24 seJ/yr (Odum, 2000) and do not include labor & services.

[a] Calculation details in Appendix A.

[b] References for UEV are presented in Appendix A.

The influence of all other items in Table 2 was previously expected, mainly for steel, which correspond to a huge part of structural weight of wind-turbines, and because there is not such a "special material" with high UEV being used. Fiberglass, copper, aluminum, and glass materials have the highest UEVs and could change this interpretation, but they are used in small amounts and do not have influence on final numbers.

The UEV for wind-electricity obtained for the wind-electricity energy complex correspond to 59,600 seJ/J (including Labor & Services; Table 2). For comparison, this value correspond to a higher efficiency in generating electricity than other energy sources published by several authors and summarized in Giannetti et al. (2015): hydraulic (104,664 seJ/J), sugarcane biomass (231,000 seJ/J), natural gas (290,640 seJ/J), nuclear (320,000 seJ/J), coal (342,720 seJ/J), and fossil oil (391,440 seJ/J). The obtained UEV for wind-electricity in this work has also higher efficiency compared to other studies that assessed wind-electricity generation, for instance, the works of Ulgiati and Brown (2002; 104,328 seJ/J) and Riposo (2008; 159,000 seJ/J). On the other hand, Dolan (2007; 10,300 seJ/J) and Yang et al. (2013; 17,400 seJ/J) have found better efficiency for wind-electricity than this present work.

Regarding the net emergy, the EYR and EYR* emergy indices obtained for the evaluated wind-electricity energy complex are 1.21 and 2.99 respectively (Table 3). Although recognizing the existence of differences among methodological approaches considered by referenced authors, Table 3 provides EYRs for different energy sources for a rough comparison. According to previously defined meaning of EYR as used in this work, the 1.21 value means that for each emergy unit from economy demanded by the complex evaluated, the resultant emergy net value of 0.21 is being provided for societal development. This value is considered as a positive aspect, mainly because 100% of those 0.21 seJ/seJ comes from renewable energy source – exclusively from wind. Focusing now on the EYR*, a value of 2.99 seJ/seJ indicates better performance than EYR, which means that higher amount of net emergy is being provided to societal development by the wind-electricity energy complex. This number indicates that, when comparing it with the average current electricity mix in Brazil, the wind-electricity energy complex evaluated can provide 2.99 emergy to society per each emergy invested. Disregarding other variables that must be considered for a decision about what kind of electricity source should be used to allow the Brazilian societal development (for instance, economic costs, socio cultural issues, climatic conditions, systems stability and resilience, etc.), the evaluated wind-electricio energy complex appears as a good alternative since it provides net emergy to society.

Although reaching a positive net emergy value, Table 3 shows that both EYRs for the evaluated wind-electricity energy complex are lower than other electricity energy sources. This can be interpreted under two different perspectives:

> (i) The better performance values of EYR for wind-electricity found by Dolan (2007; EYR=11.6) and Brown and Ulgiati (2004; EYR=5.59) – disregarding Riposo (2008) because it is an offshore wind-energy system –, could be useful as a target in guiding a strategic planning aiming to reach those high performance values.
>
> (ii) The EYR value of 5.41 for hydroelectricity found by Brown and Ulgiati (2004) – Odum (1996) also estimated a EYR of 10 for hydroelectricity – indicates that using electricity from this source results in higher benefits to society than using wind-electricity as evaluated. This is especially true considering the growing phase of societal development under a pulsing paradigm view, in which higher yields could be considered as more beneficial than sustainability.

Table 3. EYR comparison of electricity generation from solar radiation, wind, hydro and oil energy sources.

EYR[a]	Energy Source	Reference	Observations
1	Solar	Brown et al., 2012	$1m^2$ ground-mounted CdTe PV; EYR updated
1.21 [b]	Wind	This work	195MW wind farm in Brazilian Northeast region
1.25	Wind	Yang et al., 2013	30MW wind farm in Guagxi Zhuang region, China
2.99 [c]	Wind	This work	195MW wind farm in Brazilian Northeast region
5.41	Hydro	Brown & Ulgiati, 2004	85MW plant in southern Italy
5.59	Wind	Brown & Ulgiati, 2004	2.5MW plant in southern Italy
6.3	Oil	Brown et al., 2012	500MW oil fired plant; EYR updated
10.34	Wind	Riposo, 2008	322MW offshore Maple Ridge Facility, NY, USA
11.6	Wind	Dolan, 2007	180MW theoretical offshore in Jacksonville, USA

[a] EYR' digits for referenced values were kept in their original form as found in literature; [b] EYR = (1.08E20 seJ/yr) / (8.9E19 seJ/yr); [c] EYR* = (1.81E15 J/yr) * (1.47E5 seJ/J) / (8.9E19 seJ/yr).

It is worth to say that EYR values considered as reference in this work still demands a deeper assessment to verify its usefulness and compatibility with the methodological approach used here. The present work includes the preliminary results found by a larger project under development, thus authors recognize that more efforts towards its improvement is needed, for instance: (i) the inclusion of potential non-renewable natural resources contributing for wind-electricity generation (see Table 2); (ii) the inclusion of an uncertainty analysis on parameters (primary data and UEVs); (iii) the inclusion of decommissioning stage after materials lifetime; (iv) a study of the electricity transmission stage (this is important especially due to largeness of Brazilian territory); (v) the inclusion for other emergy indices to support a better-based discussion about the sustainability of wind-electricity.

CONCLUSIONS

(a) The unit emergy value (UEV) for the electricity generated by the wind-electricity energy complex evaluated (59,600 seJ/J) indicates better efficiency compared to other usual electricity sources as hydropower, fossil oil, coal, natural gas, nuclear and biomass (from 104,664 seJ/J to 391,440 seJ/J). This means that wind-electricity has higher global efficiency in converting resources into electricity, which is strengthened by other published values on wind-electricity generation (10,300 seJ/J and 17,400 seJ/J).

(b) The EYRs indices of 1.21 and 2.99 seJ/seJ show that evaluated wind-electricity energy system is able to explore and make available to society a net emergy of 0.21 and 1.99 seJ, respectively, per 1 seJ invested from economy. Specifically for the EYR* of 2.99 seJ/seJ, it indicates that wind-electricity energy complex evaluated provides net emergy to the Brazilian society when compared to the current average of Brazilian electricity energy matrix, thus wind-energy should be supported in strategic political decisions concerning energy.

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REFERENCES

Agostinho, F., Pereira, L., 2013. Support area as an indicator of environmental load: comparison between embodied energy, ecological footprint, and emergy accounting methods. Ecological Indicators, 24, 494-503.

Agostinho, F., Bertaglia, A.B.B., Almeida, C.M.V.B., Giannetti, B.F., 2014. Influence of cellulase enzyme production on the energetic-environmental performance of lignocellulosic ethanol. Ecological Modelling (2014), http://dx.doi.org/10.1016/j.ecolmodel.2014.09.005.

Agostinho, F., Siche, R., 2014. Hidden costs of a typical embodied energy analysis: Brazilian sugarcane ethanol as case study. Biomass and Bioenergy 71, 69-83.

BEN, 2015. Brazilian Energy Balance 2015, year 2014. Empresa de Pesquisa Energética (EPE), Rio de Janeiro. Available at <https://ben.epe.gov.br/downloads/Relatorio_Final_BEN_2015.pdf>. Accessed on August 25th 2015.

BRASIL, 2007. Matriz Energética Nacional 2030, Ministério de Minas e Energia (MME), Empresa de Pesquisa Energética (EPE), Brasília. Available at <http://www.mme.gov.br/web/guest/publicacoes-e-indicadores/matriz-energetica-nacional-2030>. Accessed on August 25th 2015.

BRASIL, 2014. Plano decenal de expansão de energia 2023, Ministério de Minas e Energia (MME), Empresa de Pesquisa Energética (EPE), Brasília. Available at <http://www.epe.gov.br/Estudos/Documents/PDE2023.pdf>. Accessed on August 27th 2015.

Brown, M.T., Raugei, M., Ulgiati, S., 2012. On boundaries and investments in emergy synthesis and LCA: A case study on thermal vs. photovoltaic electricity. Ecological Indicators 15, 227-235.

Brown, M.T., Protano, G., Ulgiati, S., 2011. Assessing geobiosphere work of generating global reserves of coal, crude oil, and natural gas. Ecological Modelling 222, 879-887.

Brown, M.T., Ulgiati, S., 2004. Emergy analysis and environmental accounting. Encyclopedia of Energy 2, 329-353.

Buenfil, A.A., 2001. Emergy evaluation of water. PhD Thesis, University of Florida, USA, Gainesville.

Buranakarn, V., 1998. Evaluation of recycling and reuse of building materials using the emergy analysis method. PhD. thesis, University of Florida, Gainesville, USA.

Campbell, E.T., 2014. Emergy analysis of emerging methods of fossil fuel production. Ecological Modelling (2014), http://dx.doi.org/10.1016/j.ecolmodel.2014.10.036.

Cohen, M.J., Sweeney, S., Brown, M.T., 2007. Computing the unit emergy value of crustal elements. In: Emergy syntheis 4, theory and applications of the emergy methodology. Proceedings of the 4th Biennial Emergy Research Conference, Gainesville, University of Florida. Available at <http://www.cep.ees.ufl.edu/emergy/conferences/index.shtml>. Accessed on August 24th 2015.

Dolan, S., 2007. Life cycle assessment and emergy synthesis of a theoretical offshore wind farm for Jacksonville, Florida. M.Sc. thesis, University of Florida. Available at <http://www.cep.ees.ufl.edu/emergy/documents/dissertations_theses/Dolan_2007_LCAandEmergySynthWindFarmJax_FL_Thesis-UF.pdf>. Accessed on June 19th 2015.

Giannetti, B.F., Agostinho, F., Moraes, L.C., Almeida, C.M.V.B., Ulgiati, S., 2015. Multicriteria cost-benefit assessment of tannery production: the need for breakthrough process alternatives beyond conventional technology optimization. Environmental Impact Assessment Review 54, 22-38.

N3E, 2014. Energia eólica no Brasil e no mundo. Núcleo de Estudos Estratégicos de Energia, SPE/MME, edição 22/12/2014. Available at <www.mme.gov.br>. Accessed on August 26th 2015.

Ortega, E., Bastianoni, S., 2015. Open issues in emergy methodology. In: Brown et al. (editors), Emergy Synthesis 8: Theory and Applications of the Emergy Methodology. Proceedings of the 8th Biennial Emergy Conference. Center for Environmental Policy, University of Florida, Gainesville.

Odum, H.T. 1996. Environmental Accounting: Emergy and Environmental Decision Making John Wiley and Sons. New York.

Odum, H.T. 2000. Folio #2: Emergy of Global Processes. Handbook of Emergy Evaluation. Center for Environmental Policy, University of Florida, Gainesville, FL. Available at <http://www.emergysystems.org/folios.php>. Accessed on 6th August 2015.

Odum, H.T., Odum, E.C., 2001. A prosperous way down: principles and policies. Boulder, University Press of Colorado, 326pp.

Raugei, M., Bargigli, S., Ulgiati, S., 2005. Emergy "yield" ratio: Problems and misapplications. In: Brown et al. (editors), Proceedings from the 3rd Biennial Emergy Conference, Gainesville, University of Florida, USA.

Riposo, D., 2008. Integrated energy and environmental analysis of utility-scale wind power production. M.Sc. thesis, University of Maryland. Available at <http://drum.lib.umd.edu/bitstream/1903/8598/1/umi-umd-5707.pdf>. Accessed on June 19th 2015.

Tilley, D., 2015. Transformity dynamics related to maximum power for improved emergy yield estimations. Ecological Modelling 315, 96-107.

Ulgiati, S., Brown, M.T., 2002. Quantifying the environmental support for dilution and abatement of process emissions: the case of electricity production. Journal of Cleaner Production 10, 335-348.

Ulgiati, S., Bargigli, S., Raugei, M., 2005. Dotting the I's and crossing the T's emergy synthesis: Material flows, information and memory aspects, and performance indicators. In: Brown et al. (editors), Proceedings from the 3rd Biennial Emergy Conference, Gainesville, University of Florida, USA.

Ulgiati, S., Brown, M.T., 2014. Labor and services as information carriers in emergy-LCA accounting. Journal of Environmental Accounting and Management 2, 160-167.

Yang, J., Chen, B., 2013. Integrated evaluation of embodied energy, greenhouse gas emission and economic performance of a typical wind farm in China. Renewable and Sustainable Energy Reviews 27, 559-568.

Yang, Q., Chen, G.Q., Liao, S., Zhao, Y.H., Peng, H.W., Chen, H.P., 2013. Environmental sustainability of wind power: An emergy analysis of a Chinese wind farm. Renewable and Sustainable Energy Reviews 25, 229-239.

APPENDIX

Appendix A. Calculation procedure for primary data and UEVs

"I" - NATURAL RESOURCES

#1 Wind – average of annual wind power available = 250 W/m^2 (http://www.cresesb.cepel.br/index.php?section=atlas_eolico&); effective diameter for each wind turbine = 103 m (https://renewables.gepower.com/wind-energy/turbines/1-7-100-103.html); amount of wind turbines = 115 units; Conversion = (W/m^2) ($\pi*(103)^2/4$) (115 turbines) (31,536,000 s/yr); Flow = 7.55E15 J/yr; UEV = 2.51E3 seJ/J (Odum, 1996).

#2 Bird loss – not considered

#3 Bat loss – not considered

#4 Bug loss – not considered

#5 Aesthetic landscape value loss – not considered

#6 Noise – not considered

"F" - RESOURCES FROM ECONOMY

Components manufacturing

#7 Steel – rotor 6.2 ton/turbine, nacelle 48.06 ton/turbine, tower 129 ton/turbine (Yang & Chen, 2013) = 183.26 ton/turbine; total of 115 turbines; 20 yrs of lifespan; Conversion = (ton/turbine) (turbines) / (yrs); Flow = 1.05E3 ton/yr; UEV = 7.81E9 seJ/g (Brown and Ulgiati, 2004).

#8 Fiber glass – 3.9 ton/turbine (Yang & Chen, 2013); total of 115 turbines; 20 yrs of lifespan; Conversion = (ton/turbine) (turbines) / (yrs); Flow = 1.29E2 ton/yr; UEV = 1.32E10 seJ/g (Buranakarn, 1998).

#9 Epoxy – 2.6 ton/turbine (Yang & Chen, 2013); total of 115 turbines; 20 yrs of lifespan; Conversion = (ton/turbine) (turbines) / (yrs); Flow = 1.50E1 ton/yr; UEV = 5.51E9 seJ/g (Buranakarn, 1998; considered as plastic).

#10 Copper – 8.64 ton/turbine (Yang & Chen, 2013); total of 115 turbines; 20 yrs of lifespan; Conversion = (ton/turbine) (turbines) / (yrs); Flow = 4.97E1 ton/yr; UEV = 9.80E10 seJ/g (Cohen et al., 2007).

#11 Aluminum – 0.5 ton/turbine (Yang & Chen, 2013); total of 115 turbines; 20 yrs of lifespan; Conversion = (ton/turbine) (turbines) / (yrs); Flow = 2.88E0 ton/yr; UEV = 2.13E10 seJ/g (Buranakarn, 1998; conventional aluminum sheet production).

#12 Glass – 0.35 ton/turbine (Yang & Chen, 2013); total of 115 turbines; 20 yrs of lifespan; Conversion = (ton/turbine) (turbines) / (yrs); Flow = 2.01E0 ton/yr; UEV = 1.29E10 seJ/g (Buranakarn, 1998; float glass production).

#13 Polyester – 0.3 ton/turbine (Yang & Chen, 2013); total of 115 turbines; 20 yrs of lifespan; Conversion = (ton/turbine) (turbines) / (yrs); Flow = 1.73E0 ton/yr; UEV = 5.51E9 seJ/g (Buranakarn, 1998; considered as plastic).

#14 Labor & Services – 7,000,000 R$/turbine; total of 115 turbines; 20 yrs of lifespan; 3.3 R$/USD; Conversion = (R$/turbine) (turbines) / (R$/USD) (yrs); Flow = 1.22E7 USD/yr; UEV = 4.24E12 seJ/USD (Giannetti et al., 2015).

Components transportation

#15 Diesel – sum of #15.1, #15.2, and #15.3; Flow = 4.37E11 J/yr; UEV = 1.81E5 seJ/J (Brown et al., 2011).

#16 Steel – sum of #16.1, #16.2, and #16.3; Flow = 3.67E-2 ton/yr; UEV = 7.81E9 seJ/g (Brown and Ulgiati, 2004).

#17 Labor & Services – About 10% of generated electricity cost is due to transport; Cost for the wind-complex evaluated is estimated as 4,200,000 R$/MW or 1,273,000 USD/MW of power capacity (considering a ratio of 3.3 R$/USD); the evaluated wind-energy complex has 195 MW of power capacity; 20 yrs of lifespan; Conversion = (10%) (USD/MW) (MW) / (yrs); Flow = 1.24E6 USD/yr; UEV = 4.24E12 seJ/USD (Giannetti et al., 2015).

*** Rotor ***

#15.1 Diesel – Rotor is currently produced at Sorocaba city (São Paulo state) located about 2530 km far away from the wind-energy complex in Piauí state; Wind-blades are produced 582 km away at Fortaleza city (Ceará state); Distance of 3112 km/rotor; 1 wind turbine contain 1 rotor; total of 115 turbines; 20yrs of lifespan; average for diesel consumption of 3 km/L; Conversion = (km/turbine) (turbines) (0.85 kg/L) (10,000 kcal/kg) (4,186 J/kcal) / (km/L) (yrs); Flow = 2.12E11 J/yr.

#16.1 Steel – Truck weight for Rotor transporting = 23.5 ton; 42h/rotor demanded to transport each rotor + 10h/wind-propeller; total of 115 turbines; 1 wind turbine contain 1 rotor and 1 wind-propeller; 52h is equivalent to 0.0197% of 30 yrs, then 115 turbines are equivalent to 2.27% of 30 yrs truck lifetime; Conversion = (ton) (2.27%) / (30yrs); Flow = 1.78E-2 ton/yr; UEV = 7.81E9 seJ/g (Brown and Ulgiati, 2004).

*** Nacelle ***

#15.2 Diesel – Nacelle is currently produced at Camaçari city (Bahia state) located about 798 km far away from the wind-energy complex in Piauí state; Distance of 798 km/nacelle; 1 wind turbine contain 1 nacelle; total of 115 turbines; 20yrs of lifespan; average for diesel consumption of 3 km/L; Conversion = (km/turbine) (turbines) (0.85 kg/L) (10,000 kcal/kg) (4,186 J/kcal) / (km/L) (yrs); Flow = 5.44E10 J/yr; UEV = 1.81E5 seJ/J (Brown et al., 2011).

#16.2 Steel – Truck weight for Nacelle transporting = 23.5 ton; 13h/nacelle demanded to transport each nacelle; total of 115 turbines; 1 wind turbine contain 1 nacelle; 13h is equivalent to 0.005% of 30 yrs, then 115 turbines are equivalent to 0.57% of 30 yrs truck lifetime; Conversion = (ton) (0.57%) / (30yrs); Flow = 4.46E-3 ton/yr; UEV = 7.81E9 seJ/g (Brown and Ulgiati, 2004).

*** Tower ***

#15.3 Diesel – Tower is currently produced at Cubatão city (São Paulo state) located about 2503 km far away from the wind-energy complex in Piauí state; Distance of 2503 km/rotor; 1 wind turbine contain 1 rotor; total of 115 turbines; 20yrs of lifespan; average for diesel consumption of 3 km/L; Conversion = (km/turbine) (turbines) (0.85 kg/L) (10,000 kcal/kg) (4,186 J/kcal) / (km/L) (yrs); Flow = 1.71E11 J/yr; UEV = 1.81E5 seJ/J (Brown et al., 2011).

#16.3 Steel – Truck weight for Rotor transporting = 23.5 ton; 42h/rotor demanded to transport each rotor; total of 115 turbines; 1 wind turbine contain 1 rotor; 42h is equivalent to 0.016% of 30 yrs, then 115 turbines are equivalent to 1.84% of 30 yrs truck lifetime; Conversion = (ton) (1.84%) / (30yrs); Flow = 1.44E-2 ton/yr; UEV = 7.81E9 seJ/g (Brown and Ulgiati, 2004).

Wind-turbine installation & maintenance

#18 Concrete – 433 m^3/turbine (Yang & Chen, 2013); 2.4 ton/m^3; total of 115 turbines; 20 yrs of lifespan; Conversion = (m^3/turbine) (ton/m^3) (turbines) / (yrs); Flow = 5.98E3 ton/yr; UEV = 2.42E9 seJ/g (Buranakarn, 1998).

#19 Steel – 38.1 ton/turbine (Yang & Chen, 2013); total of 115 turbines; 20 yrs of lifespan; Conversion = (ton/turbine) (turbines) / (yrs); Flow = 2.19E2 ton/yr; UEV = 7.81E9 seJ/g (Brown and Ulgiati, 2004).

#20 Diesel – 16,242L/turbine (Yang & Chen, 2013); total of 115 turbines; 20 yrs of lifespan; Conversion = (L/turbine) (turbines) (0.85 kg/L) (1,000 kcal/kg) (4186 J/kcal) / (yrs); Flow = 3.32E11 J/yr; UEV = 1.81E5 seJ/J (Brown et al., 2011).

#21 Water – 303.03ton/turbine (Yang & Chen, 2013); total of 115 turbines; 20 yrs of lifespan; Conversion = (ton/turbine) (turbines) / (yrs); Flow = 1.74E3ton/yr; UEV = 3.27E5 seJ/g (Buenfil, 2001).

#22 Electricity – 50,000kWh/turbine (Yang & Chen, 2013); total of 115 turbines; 20 yrs of lifespan; Conversion = (kWh/turbine) (turbines) (3.6E6 J/kWh) / (yrs); Flow = 1.04E12J/yr; UEV = 1.47E5 seJ/J (Giannetti et al., 2015).

#23 Gasoline – 5,061L/turbine (Yang & Chen, 2013); total of 115 turbines; 20 yrs of lifespan; Conversion = (L/turbine) (turbines) (8,325 kcal/L) (4186 J/kcal) / (yrs); Flow = 1.01E12 J/yr; UEV = 1.87E5 seJ/J (Brown et al., 2011).

#24 Labor & Services – About 1% of generated electricity cost is due to installation and maintenance; Cost for the wind-complex evaluated is estimated as 4,200,000 R$/MW or 1,273,000 USD/MW of power capacity (considering a ratio of 3.3 R$/USD); the evaluated wind-energy complex has 195 MW of power capacity; 20 yrs of lifespan; Conversion = (1%) (USD/MW) (MW) / (yrs); Flow = 1.24E5 USD/yr; UEV = 4.24E12 seJ/USD (Giannetti et al., 2015).