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ECOLOGICAL ASPECTS OF ELECTROLYTIC HYDROGEN: COMPARING RENEWABLE AND NON-RENEWABLE SOURCES

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Abstract.
The environmental problems arising from the use fossil fuel, as the global warming, have promoted the increased use of renewable energy sources. However, solar, wind and hydroelectric hydrogen energy, almost always are labeled as perfectly clean sources, but it is not true. Thereby, this paper aims to clarify how clear can be the hydrogen production via electrolysis, considering renewable and non-renewable sources. Our work highlights the negative environmental impacts coming from wind, photovoltaic and hydroelectric energy, analyzing their life cycle assessment (LCA) studies. The data compilation of global warming potential (GWP) of several energy sources allows comparing the ecological energy efficiency (EEE) of each source for hydrogen production by electrolysis. The results show that hydrogen from hydroelectric and wind energy have high EEE and due to the low energy efficiency of the photovoltaic panel, hydrogen from solar energy has an intermediate position, behind the hydrogen from biomass sources.

Keywords: *energy ecological efficiency, global warming potential, hydrogen, life cycle assesment*

1. INTRODUCTION

Actually, the efforts to change the electric matrix including renewable energy is a trend to avoid the effects of the global warming. Several sources are possible candidates and also there is an interaction between them. In this way, the hydrogen produced by electrolysis from solar, wind and hydroelectric energy, appears as an important energy vector with a clean label in literature (Dincer and Zamfirescu, 2012). However, through the life cycle assessment (LCA) is noticed that even renewable energy presents environmental impacts. The LCA concerns a standard methodology defined by ISO 14040 and ISO 14044 that analyzes the product's life, since the extraction of raw materials, passing through manufacturing and operation phases, until the disposal at the end-of-life. The results are categories of environmental impacts, as the global warming potential (GWP), in $CO_{2_{(eq)}}$, that means the equivalent in mass of CO_2, which has the same impact of release 1 kg of another green house gas(GHG) (Klöpffer and Grahl, 2014). GWP indicator provides a useful tool to compare a different kind of energy sources, but does not include any aspect related to energy efficiency in the process.

In this way, this paper intends to generalize the concept of "energy ecologic efficiency" developed by (Cardu and Baica, 1997) and (Cardu and Baica, 1999), applied to thermopower plants, to perform a global comparison between several electricity sources, renewable and non-renewable, to hydrogen electrolysis production. Then, a review of the most important points of the LCA of solar, wind and hydroelectric energy is done. After, the GWP data is collected from the available literature to support proposed methodology. Three scenarios are discussed emphasizing solar, wind and hydroelectric hydrogen. Additionally a global comparison is proceeded including renewable and non-renewable sources.

2. ENVIRONMENTAL IMPACTS FOR RENEWABLE ENERGY

2.1 LCA of wind, solar and hydroeletric energy

Altough the operation phase of wind energy has a low environmental impact, the manufacturing phase deserves special attention due to the manufacture of the wind turbine components like: the tower, rotor, and nacelle, as well as the building of the foundation (Demir and Taşkin, 2013). The tower is the most critical component, because its impact is intrinsically related to a large amount of steel used (Pereg and de la Hoz, 2013). Also, the foundation requires a large amount of steel and concrete in order to support the wind turbine structure. Regarding rotor, the critical component is the manufacturing of blades, wich uses fiberglass and epoxy resin (Oebels and Pacca, 2013). The steel and copper are extensively used in

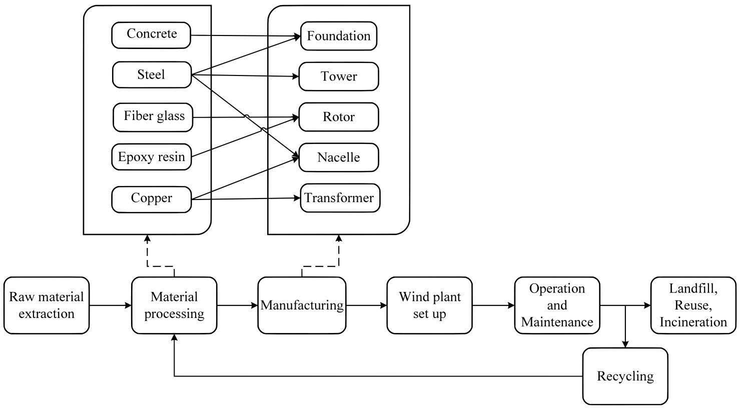

Figure 1. Life cycle assessment scheme for wind turbine.

Nacelle and represents the main sources of environmental impact for this component. A detailed LCA flowchat of the wind turbine is shown in Fig. 1.

Considering the solar energy, the material processing and the manufacturing of PV panels phases are highly criticals. The relantionship between the main materials and the main components are highlighted in Fig. 2. The silicon is obtained from silica through an energy-intensive purification process. Posteriorly, the metallurgical-grade silicon, with 98% purity is transformed into the solar-grade silicon, with 99,999% purity, by Siemens process. This solar-grade silicon is converted in mono-Si or poly-Si to produce the wafers. After this steps, the solar cell is tested, connected physically and electrically to assembly the modules. Generally, cells are encapsulated between two ethylene vinyl acetate sheets. A Tedlar film (polyvinylfluoride) is used in posterior part and a glass sheet in anterior part. Finally, an aluminium frame is added. The glass sheet and the aluminium frame are very energy-intensive materials and their consumption is significant in PV panels (Stoppato, 2008). To reduce the environmental impact, an important alternative to be considered at the end-of-life is the recycling. Nowadays is possible recovering broken wafers, recycling glass and metals from crystalline solar modules.

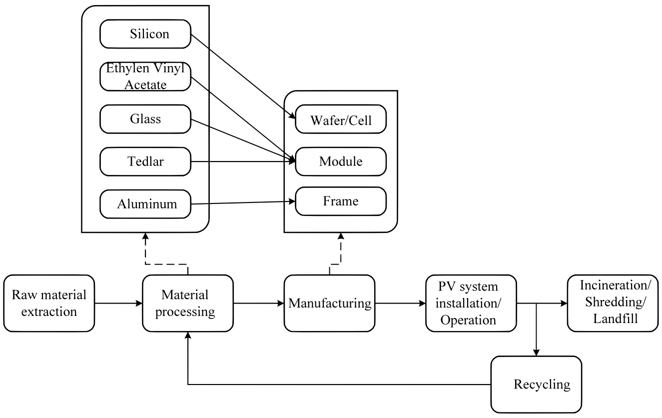

Figure 2. Important stages to be considered by LCA for PV panels.

Concerning the hydroelectric energy, the main environmental impacts are originating in the construction phase and in the GHG emissions from the reservoir. To build the hydroelectric power station, cement and gravel are the most used materials in terms of mass. These materials are presented in dams, equalising the reservoir, buildings in general, transport infrastructure etc. The steel is used as reinforcement and bulkhead, besides its use in equipment, as well as copper, for instance, in generators, transformers, turbines etc. The explosives are used for the excavation of the dam, removing big rocks, to do deviation of the river (Flury and Frischknecht, 2012). Other basic materials in the process are diesel oil, lubricant oil, and oil for the transformer. The two first are necessary because transport is an important phase in a hydroelectric LCA, both for workers transportation, as equipment and operation transportation (Ribeiro, 2003). GHG emissions from reservoirs, mainly CO_2 and CH_4, occur due to the decomposition of the flooded organic matter and depends on several aspects, e.g. the location of the reservoir. In general, the emissions in tropical regions are much higher than in boreal regions, because the decomposition of organic matter is favoured to the high water temperature and a great amount of organic carbon (Yang *et al.*, 2014). Figure 3 shows the LCA flowchart for a hydroelectric power plant.

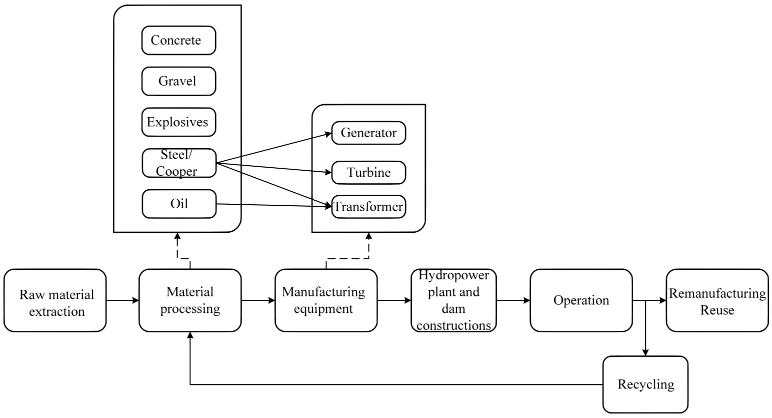

Figure 3. Key processes to be considered in LCA for hydroelectric power.

2.2 GWP data of wind, solar and hydroelectric energy

The GWP data is gathered from several sources, like academic papers, government and agency reports, and companies' environmental product declarations. Turconi *et al.* (2013) presents a complete review about electricity LCA and many references are extracted from them. For solar and hydroelectric energy, there are two main references: Peng *et al.* (2013) and IEA (2000), respectively. Table 1 presents the GWP data for wind energy specifying the plant location.

Table 1. GWP data of wind energy.

Reference	$kgCO_{2_{(eq)}}/MWh$	Location	Reference	$kgCO_{2_{(eq)}}/MWh$	Location
(Voorspools *et al.*, 2000)	9.0	coast	(Guezuraga *et al.*, 2012)	17.4	on land
(Voorspools *et al.*, 2000)	28.0	inland	(Guezuraga *et al.*, 2012)	23.3	
(Khan *et al.*, 2005)	10.5		(Guezuraga *et al.*, 2012)	38.3	
(Khan *et al.*, 2005)	7.1	on land	(Demir and Taşkin, 2013)	16.3	on land
(Khan *et al.*, 2005)	3.7		(Demir and Taşkin, 2013)	40.4	
(Gagnon *et al.*, 2002)	9.0	on land	(Pereg and de la Hoz, 2013)	8.0	on land
(Schleisner, 2000)	9.7	on land	(Tremeac and Meunier, 2009)	15.8	on land
(Schleisner, 2000)	16.5	offshore	(Ardente *et al.*, 2008)	14.8	on land
(Dones *et al.*, 2005)	13.4	offshore	(D'Souza *et al.*, 2011)	7.0	on land
(Dones *et al.*, 2005)	10.5	on land	(Garrett and Rønde, 2014)	8.2	on land
(Vestas, 2006)	5.2	offshore	(Fischer and Bill, 2010)	10.9	on land
(Vestas, 2006)	4.6	on land	(Hondo, 2005)	20.3	on land
(Vattenfall, 2010)	15.0	on/offshore	(Atilgan and Azapagic, 2016)	7.3	on land
(Enel, 2004)	27.9	on land	(Gamesa, 2013)	9.8	on land
(Pehnt, 2006)	11.0	on land	(Vattenfall, 2014)	17.0	on/offshore
(Pehnt, 2006)	9.0	offshore	(Gamesa, 2014)	9.3	on land
(Hondo, 2005)	29.5	on land	(Gamesa, 2015)	9.6	on land
(Rule *et al.*, 2009)	3.0	on land	(Iberdrola, 2015a)	10.2	on land
(White and Kulcinski, 2000)	15.0	on land	(Iberdrola, 2015b)	13.7	on land
(Oebels and Pacca, 2013)	7.1	coast	(Vattenfall, 2013)	16,2	on/offshore

It is possible to observe that the values are not uniform and encompass a wide range, because the boundaries adopted are different by each author, as well as the location and the database consulted. Thus, in order to establish an average value for the GWP, the following steps are done: (1) the average and the standard deviation is calculated including all values; (2) a new table is done excluding the values one standard deviation above or below of the average; (3) the new average is calculated including the remaining values. It is important to keep in mind that is nothing wrong about the data, the variability encountered is normal, but the idea introduced intend to achieve a better average. Thereby, the average obtained for wind energy is 11.8 $kgCO_{2_{(eq)}}/MWh$. Hereafter, Tab. 2 shows the GWP data of solar energy including panels of single crystalline (sc-Si) and multicrystalline silicon (mc-Si). Both silicon-based technologies have similar manufacture process, then they are analysed together in this work. So, the average GWP achievied for solar energy is 51.7 $kgCO_{2_{(eq)}}/MWh$.

Table 3 introduces the GWP data of hydroelectric energy, considering studies that account the contribution of reservoir

Table 2. GWP data of solar energy.

Reference	$kgCO_{2_{(eq)}}/MWh$	Technology	Reference	$kgCO_{2_{(eq)}}/MWh$	Technology
(Voorspools *et al.*, 2000)	130.0	sc-Si	(Jungbluth *et al.*, 2008)	84.0	sc/mc-Si[1]
(Voorspools *et al.*, 2000)	60.0	sc-Si	(Jungbluth *et al.*, 2008)	50.0	sc/mc-Si[1]
(Pehnt, 2006)	104.0	mc-Si	(Jungbluth *et al.*, 2008)	87.0	sc/mc-Si[1]
(Hondo, 2005)	53.4	mc-Si	(Jungbluth *et al.*, 2008)	72.0	sc/mc-Si[1]
(Dones *et al.*, 2005)	53.8	sc-Si	(Jungbluth *et al.*, 2008)	79.0	sc/mc-Si[1]
(Dones *et al.*, 2005)	53.4	sc-Si	(Jungbluth *et al.*, 2008)	46.0	sc/mc-Si[1]
(Dones *et al.*, 2005)	34.1	sc-Si	(Fthenakis *et al.*, 2011)	37.0	sc-Si
(Alsema, 2000)	60.0	mc-Si	(Fthenakis *et al.*, 2011)	35.0	mc-Si
(Raugei *et al.*, 2007)	167.0	mc-Si	(Fthenakis *et al.*, 2011)	29.0	sc-Si
(Raugei *et al.*, 2007)	72.0	mc-Si	(Fthenakis *et al.*, 2011)	28.0	mc-Si
(Alsema and Wild-Scholten, 2005)	31.0	mc-Si	(Alsema, 2000)	30.0	mc-Si
(Alsema and Wild-Scholten, 2005)	41.0	sc-Si	(Alsema, 2000)	20.0	mc-Si
(Kato *et al.*, 1998)	61.0	sc-Si	(Alsema *et al.*, 2006)	15.0	mc-Si
(Kato *et al.*, 1998)	20.0	mc-Si	(Alsema *et al.*, 2006)	35.0	sc-Si
(Alsema *et al.*, 2006)	32.0	mc-Si	(Kato *et al.*, 1998)	83.0	sc-Si
(Pacca *et al.*, 2007)	72.4	mc-Si	(Kato *et al.*, 1998)	25.0	sc-Si
(Pacca *et al.*, 2007)	54.6	mc-Si	(Kato *et al.*, 1998)	18.0	mc-Si
(Ito *et al.*, 2010)	43.0	mc-Si	(Kato *et al.*, 1998)	13.0	mc-Si
(Ito *et al.*, 2010)	50.0	sc-Si	(Stoppato, 2008)	80.0	mc-Si
(Jungbluth *et al.*, 2008)	73.0	sc/mc-Si[1]	(Hondo, 2005)	43.9	mc-Si

(1) Inclued a small amount of ribbon-silicon, thin-film cells with a-Si, CdTe and CIS (less than 10%).

emission and not. In general, when authors are studying run-of-river or small plants, emissions are not considered. The average of GWP is calculated covering all data, without distinguish the presence or not of the reservoir emissions. Then, the value obtained is 6.8 $kgCO_{2_{(eq)}}/MWh$.

Table 3. GWP data of hydroelectric energy.

Reference	$kgCO_{2_{(eq)}}/MWh$	Resevoir	Reference	$kgCO_{2_{(eq)}}/MWh$	Resevoir
(Gagnon *et al.*, 2002)	15.0		(Gagnon *et al.*, 2002)	2.0	
(Dones *et al.*, 2005)	3.7		(Pehnt, 2006)	10.0	
(Axpo, 2010)	3.2		(Pehnt, 2006)	13.0	
(Axpo, 2011)	5.2		(Hondo, 2005)	11.3	
(IEA, 1998)	4.0		(Rule *et al.*, 2009)	4.6	
(IEA, 1998)	15.0		(Uchiyama, 1996)	18.0	
(SECDA, 1994)	48.0		(SECDA, 1994)	1.0	NO
(Fritsche, 1992)	2.0		(Flury and Frischknecht, 2012)	3.6	
(Vattenfall, 2015)	10.2		(Flury and Frischknecht, 2012)	3.8	
(Vattenfall, 2005)	4.4		(Flury and Frischknecht, 2012)	4.9	
(Vattenfall, 2011)	9.9		(Flury and Frischknecht, 2012)	1.9	
(Ribeiro and Silva, 2010)	4.3		(Arnøy and Modahl, 2013a)	2.2	
(Flury and Frischknecht, 2012)	10.8	YES	(Atilgan and Azapagic, 2016)	4.1	
(Flury and Frischknecht, 2012)	5.1				
(Flury and Frischknecht, 2012)	5.9				
(Flury and Frischknecht, 2012)	16.6				
(Arnøy and Modahl, 2013b)	1.9				
(Atilgan and Azapagic, 2016)	8.3				
(Atilgan and Azapagic, 2016)	4.2				
(Skone, 2012)	43.8				
(Skone, 2012)	29.0				
(Skone, 2012)	28.3				
(Skone, 2012)	27.7				

2.3 GWP of other electricity sources

In order to support the methodology proposed and the boundaries assumed, is necessary evaluate the GWP of other electricity sources, including non-renewable energy, assuming a scenario when these electricity source could be used to supply an electrolyser. Turconi *et al.* (2013) provide data for the others sources not detailed until now and similar statistical approach as aforementined, eliminate the peak values. Figure 4 shows the significant difference between the GWP of renewables and GWP of non-renewables sources.

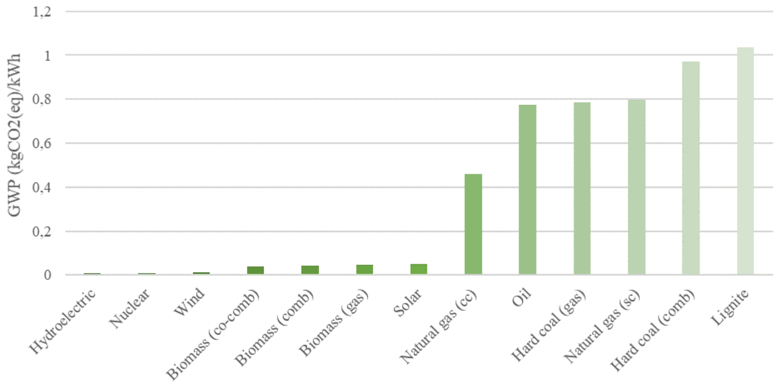

Figure 4. GWP data for several electricity sources.

Hydroelectric energy has the lowest GWP indicator wheres lignite coal has the largest. Natural gas (combined cycle) appears between the transition of renewables (except nuclear) to non-renewables sources, and has an intermediate GWP. Nuclear source, which shows a very small GWP, should have special attention because this indicator does not take into account the potential risk of handling with radioactive fuel.

3. HYDROGEN ENERGY-ECOLOGICAL EFFICIENCY

Cardu and Baica (1997) and Cardu and Baica (1999) proposes an indicator called "energy-ecological efficienc" (EEE) for thermal power plants. In this work, an adaptation of this indicator is presented in order to fit the analysis of hydrogen production by electrolysis with energy from the renewable sources previously detailed (wind, solar and hydroelectric) and comparing with all sources shown in Fig 4. Assuming that the EEE has the form given by Eq. (1).

$$\varepsilon = [c \cdot \varphi(\eta, GWP) \cdot \psi(GWP)]^n \tag{1}$$

Where:
ϵ - energy-ecological efficiency [-];
c - constant to be determined [-];
η - overall energy efficiency [-];
GWP - global warming potential [$kgCO_{2_{(eq)}}/kgH_2$];
n - exponent to be determined [-];

The values of c and n are found defining boundary conditions. Thereby, three scenarios are developed with different boundaries to be analyzed.

3.1 Scenario I

To determine hydrogen energy-ecological efficiency, $kgCO_{2_{(eq)}}/kWh$ GWP was converted to $kgCO_{2_{(eq)}}/kgH_2$, considering that for the production of 1 kg of hydrogen is necessary 59.0 kWh. The electrolyser contribution to the total GWP is assumed 5% (Spath and Mann, 2004) and this value is used in all scenarios. Then, the following conditions in the scenario I are established: (1) considering GWP = 0 $kgCO_{2_{(eq)}}/kgH_2$, $\epsilon = 1$ for any η; (2) considering GWP = 70 $kgCO_{2_{(eq)}}/kgH_2$ (10 % above lignite), $\epsilon = 0$ for any η; (3) considering GWP = 28 $kgCO_{2_{(eq)}}/kgH_2$ (natural gas - combined cycle) and η = 0.405 (product of natural gas in combined cycle thermal power plant efficiency of 54 % (Villela, 2007) for the electrolyser efficiency of 75% Ursua *et al.* (2012)), ϵ = 0.55 - 0.65.

Condition 1 imposes a 100% efficient process if there is not GWP, regardless process efficiency. This condition expresses the upper limit for the EEE and can be considered as the ideal case. Condition 2 states that the process is totally inefficient if the GWP is 10 % higher than the lignite coal. Thus, a GWP slightly above the worst real case is considered the limit of inefficiency, independently of the process efficiency, making possible include the energy-ecological efficiency of lignite. Then, the condition 2 states that is not feasible to have electrical efficiency at the expense of environmental impact. Additionally, condition 3 provides an intermediate level for the EEE, establishing that the energy from the natural gas burned in combined cycle would be between 55 % - 65 %. This efficiency range is justified both by the GWP level of this source, which is slightly less than half of lignite GWP (as shown in Fig. 4), and by the fact that natural gas is a transition technology between renewable sources and fossil fuels.

The overall energy efficiency of the process is calculated as presented in Eq. (2).

$$\eta = \eta_{source} \cdot \eta_{electrolyzer} \tag{2}$$

Where:
η_{source} - efficiency of the electricity source [-];
$\eta_{electrolyzer}$ - electrolyzer efficiency [-];

Assuming that $\varphi(\eta, GWP)$ has the form given by Eq. (3).

$$\varphi = \frac{\eta}{(\eta + GWP)} \tag{3}$$

Where:
φ - function η and GWP dependent.

It is observed that $\varphi(\eta, GWP)$ considers both the energy efficiency of the process (η), as well as the ecological efficiency, with the inclusion of GWP. The natural logarithm is chosen to cover the wide range of GWP values to convert it in a range of $\epsilon = 0 - 1$, as given by the Eq. (4).

$$\psi = \ln(K - GWP) \tag{4}$$

Where:
ψ - function GWP-dependent;
K - constant to be determined [$kgCO_{2_{(eq)}}/kgH_2$];

Thus, EEE equation can be expressed as shown in Eq. (5)

$$\varepsilon = \left[c \cdot \frac{\eta}{(\eta + GWP)} \cdot \ln(K - GWP)\right]^n \tag{5}$$

Using the boundary condition 2, for $\epsilon = 0$, $ln(K - GWP) = 0$, then $K = 71kgCO_{2_{(eq)}}/kgH_2$. From de condition 1, if GWP = 0 $kgCO_{2_{(eq)}}/kgH_2$, thus $c = 1/ln(71) = 0.234$. Through the condition 3, replacing the constants K and c in the Eq. (5) for the limit values of ϵ adopted, $n = 0.137 - 0.0984$. Using the average value $n = 0.117$, the function to determine the ecological-energy efficiency is obtained according Eq. (6).

$$\varepsilon = \left[0.234 \cdot \frac{\eta}{(\eta + GWP)} \cdot \ln(71 - GWP)\right]^{0.117} \tag{6}$$

Figure 5 compares the EEE of wind, solar and hydroelectric hydrogen related to η_{source}.

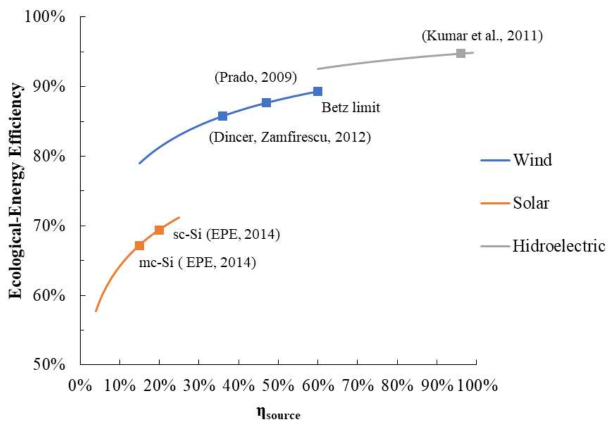

Figure 5. EEE versus the efficiency of the electricity source for the scenario I.

Although the analysis of the GWP for solar energy do not be particularized for each available technology, both η_{source} are highlighted in Fig. 5. So, sc-Si and mc-Si, have 19 and 15% of η_{source}, respectively, resulting in an EEE of 69.0%, 67.0%. For a wind turbine, the Betz limit represents the maximum theoretical efficiency that a turbine reaches. In practice, this values does not exceed 46.0%. At this point, the EEE is 88.0%. A more realistic value for the average η_{source}, 35.0%, results in an EEE of 86.0%. Hydroelectric power has high η_{source} value, around 90.0% allowing an EEE of 95.0%. The combination of a small GWP and a high η_{source} gives the best results for hydroelectric hydrogen.

3.2 Scenario II

The diference between the scenarios is the boundaries adopted to solve the Eq. 5. For the scenario II the following conditions are established: conditions (1) and (2) same as Scenario I; (3) considering GWP = 50 $kgCO_{2_{(eq)}}/kgH_2$ (natural gas-single cycle) and $\eta = 0.225$ (product of natural gas in single cycle with efficiency of 30% (Turconi *et al.*, 2013) for the electrolyzer efficiency of 75%), $\eta = 0.55 - 0.65$. The same hypothesis of Scenario I, considering natural gas as a source of transition between renewable and non-renewable sources is adopted. However, the comparison takes into account burned natural gas in the simple cycle, which has lower efficiency comparing with the combined cycle. The same procedure conducted in the scenario I is used, resulting in the Eq. (7).

$$\varepsilon = \left[0.235 \cdot \frac{\eta}{(\eta + GWP)} \cdot \ln\left(71 - GWP\right)\right]^{0.089} \tag{7}$$

Figure 6 presents the results obtained for the scenario II.

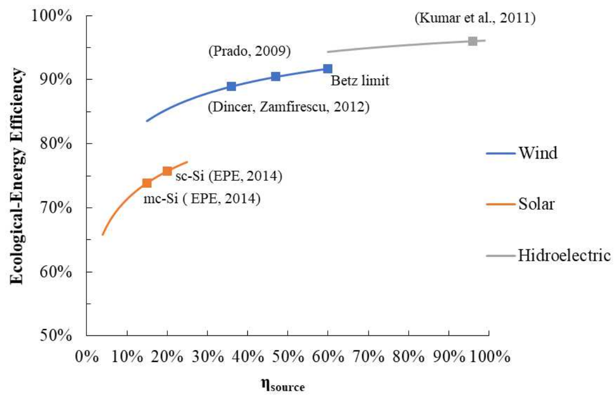

Figure 6. EEE versus the efficiency of electricity source for the scenario II.

It is possible to notice that the three curves shift up due to the greater GWP and lower η_{source} of natural gas in the simple cycle compared with combined cycle. For the solar hydrogen, at the point mc-Si, the EEE is 74.0% and for sc-Si is 75.0%. In the case of wind hydrogen, at $\eta_{source} = 36\%$, EEE is 89.0%, and for $\eta_{source} = 47\%$, EEE is 90.0%. Additionally, for hydroelectric hydrogen at $\eta_{source} = 96\%$, EEE is 96.0%. Even though the difference to scenario I is not so large, is observed that the same source could provide different results due to the difference in the electricity generation process.

3.3 Scenario III

Again, the boundaries are established according some assumptions: conditions (1) and (2) are identical to the scenarios I and II; (3) considering GWP = 0.416 $kgCO_{2_{(eq)}}/kgH_2$ (hydroelectric) and $\eta = 0.675$ (product of hydroelectric power plant efficiency of 90% Kumar *et al.* (2011) for the electrolyzer efficiency of 75%), $\epsilon = 0.95 - 0.99$. It is possible to verify through Fig 4 and the results of the previous scenarios, that EEE of hydroelectric hydrogen is always higher than any other type of technology. Thus, it is appropriate to adopt hydroelectric energy as a reference for optimal performance, analyzing the behavior of the other sources. One more time, the same procedure conducted in the scenarios I and II is used, resulting in Eq. (7) and Fig. 7 show the results.

$$\varepsilon = \left[0.234 \cdot \frac{\eta}{(\eta + GWP)} \cdot \ln\left(71 - GWP\right)\right]^{0.064} \tag{8}$$

The condition 3 pulls up the EEE for all sources evaluated. For solar hydrogen, at mc-Si point, EEE is 81.0% and for sc-Si point is 82.0%. Wind hydrogen with $\eta_{source} = 36\%$ achieves EEE equals 92.0%, and with $\eta_{source} = 47\%$, EEE is 93.0 %. Finally, for hydroelectric hydrogen, for $\eta_{source} = 96\%$, EEE obtained is 97.0 %.

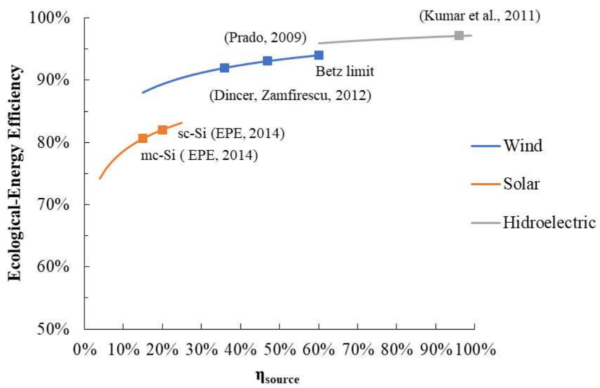

Figure 7. EEE versus the efficiency of electricity source for the scenario III.

3.4 Comparison among different scenarios and sources

To compare the effectiveness of the proposed methodology, Tab. 4 summarizes the EEE of several electricity sources including non-renewables, considering the boundaries of the three previous scenarios.

Table 4. EEE for renewable and non-renewable sources considering the boundaries of the three scenarios presented.

Source	GWP ($kgCO_{2_{(eq)}}$ $/kgH_2$)	η_{source} [%]	Ref.	EEE-I [%]	EEE-II [%]	EEE-III [%]
Hydroelectric	0.416	90	(Kumar *et al.*, 2011)	95	96	97
Nuclear	0.646	45	(Ozbilen *et al.*, 2013)	88	91	93
Wind	0.725	35	(Dincer and Zamfirescu, 2012)	86	89	92
Biomass (co-comb)	2.339	33	(Heller *et al.*, 2004)	76	81	86
Biomass (gas)	2.960	36	(Heller *et al.*, 2004)	75	80	85
Biomass (comb)	2.556	33	(Heller *et al.*, 2004)	75	80	86
Solar	3.170	14	(EPE, 2014)	67	73	80
Natural gas (cc)	28.314	54	(Villela, 2007)	60	68	76
Hard coal (gasification)	48.115	52	(Briem *et al.*, 2004)	55	63	72
Oil	47,471	44	(Villela, 2007)	54	62	71
Natural gas (simple cycle)	48.956	30	(Turconi *et al.*, 2013)	51	60	70
Hard coal (combustion)	59.566	44	(Villela, 2007)	51	60	69
Lignite	63.539	44	(Villela, 2007)	49	58	68

It is observed that hydroelectric hydrogen is the technology with the largest EEE in any scenario. Immediately after the hydroelectric hydrogen, comes nuclear hydrogen, however as GWP does not consider the risks of handling with radioactive fuels, the result deserves special attention. Wind energy has not an expressive η_{source} as hydroelectric energy, but corroborates that is environmentally efficient. Biomass hydrogen reveling a good performance, even though the small η_{source}. Solar hydrogen gets an intermediate position in the EEE indicator, due to low η_{source} of solar panels. Solar hydrogen has the largest GWP among the renewable sources, as shown in Tab. 4, but this value is still much lower than the impact araising from fossil fuels, demonstrating the importance of η_{source} in EEE calculation and its continuous improvement by manufactures. This fact illustrates the EEE indicator behavior that, weight the environmental aspect likewise the energy aspect. Among fossil fuels, natural gas (combined cycle) hydrogen gets the highest EEE, both for its better efficiency, as for its relatively low GWP. In the natural gas, the proper choice of thermal power plant technology (combined or single cycle) should also be considered. The other fossil fuels, oil, coal (combustion, gasification) and lignite have similar EEE, since their GWP and η_{source} are close.

4. CONCLUSIONS

The evaluation of the environmental impact from an electrolytic hydrogen production with renewable (mainly solar, wind and hydroelectric energy) and non-renewable sources was realized. The scenarios considered and the adoption of different boundaries conditions were quite useful for checking the behaviour of the results. In all scenarios, solar generation is less efficient among the other renewables, and the hydroelectric generation always shows the best performance, followed by wind power. Even with small GWP levels, the major drawback for solar energy is the very low energy efficiency thats push down the EEE. However, the impacts due to non-renewable energy are greater, and this work clarify that, instead electrolytic hydrogen from solar wind and hydroelectric energy are not perfectly clear, they provide a cleaner solution.

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