International Journal of Energy and Environmental Engineering
ISSN: 2008-9163
Vol.2 / No.3 (pp.63-78) / Summer 2011

Life cycle assessment of different hypotheses of hydrogen production for vehicle fuel cells fuelling

Lidia Lombardi[*1], Ennio Carnevale[2], Andrea Corti[3]

[1,2] Dipartimento di Energetica "Sergio Stecco" - Università degli Studi di Firenze
[3] Dipartimento di Ingegneria dell'Informazione - Università degli Studi di Siena

Received Date: 1 May.; 2011 Accepted: 30 May.; 2011

ABSTRACT

The aim of this study is to compare the environmental effects, through Life Cycle Assessment Approach, of three hydrogen production methods: methane steam reforming, water electrolysis fed by photovoltaic electricity, water electrolysis fed by mini-hydroelectric electricity. The assumptions are based on a project proposal of introducing some mini-buses in the city centre of Florence (Italy), equipped with fuel cells fuelled with hydrogen. The inventory of the compared productive cycles has been performed using the literature and direct data obtained from device manufactures. The impact analysis has been carried out using two methods, the Ecoindicator'95 and the Ecoindicator'99 also with the intention of qualitatively comparing the results. Besides the "basic option" an improvement has been proposed focusing on the weak points of the productive cycles. In particular concerning photovoltaic and mini-hydroelectric, the construction phase showed a high contribution to the environmental load, so some improvements were proposed. The results of the basic option and the improved one have been compared. According to the initial assumptions and the proposed changes, the best option for hydrogen production has been highlighted.

Keywords

Hydrogen production, LCA, photovoltaic, methane reforming, mini-hydroelectric

1. Introduction

The primary aim of the study is to compare, by means of Life Cycle Assessment (LCA), the environmental load of three methods of hydrogen (H_2) production: methane steam reforming, water electrolysis fed by a photovoltaic (PV) plant, water electrolysis fed by mini-hydroelectric plants. The second aim is to analyse the weak points for the three production methods.

In literature, other LCA studies have been carried out to investigate the environmental aspects of hydrogen production, considering production by natural gas steam reforming and production upon renewable energy sources such as wind, hydropower and solar thermal energy [1]. Besides the devoted studies about LCA of renewable energy for electricity generation systems were performed [2]. Two of the most promising water splitting thermochemical cycles (the Westinghouse cycle and the SulphureIodine cycle) were analysed by LCA and compared with two different processes for hydrogen production (coal gasification and coal pyrolysis) in [3].

Thermal and autocatalytic decomposition of methane were studied and compared with the

[*] Corresponding author: Lidia Lombardi (e-mail: lidia.lombardi@unifi.it)
Tel. +39 055 4796349; Fax +39 055 4796342

steam reforming with and without CO_2 capture and storage from an environmental point of view, using LCA [4]. Also, exergetic life cycle assessment of hydrogen production from renewables, using wind and solar energy, was performed [5]. Steam methane reforming process for hydrogen production was analysed, also, by means of exergoenvironmental analysis [6]

The idea of this work was originated by the a project proposal of introducing some mini-buses in the city centre of Florence (Italy), equipped with fuel cells fuelled with hydrogen [7]. The mini-buses traction system is "hybrid" with fuel cells and brake energy recovery.

The engine power is fed by a battery pack charged by the fuel cells. The required fuel cells power was estimated in about 16,5 kW. Hydrogen is compressed and stored on board.

The mini-bus autonomous path is 150 km, corresponding to a whole average daily trip (with reference to the conventional minibuses that are presently circulating in the Florence city centre) and avoiding to go back to the bus depot during the day for refuelling.

The corresponding storage volume of H_2 on board – in order to assure the autonomous path - is about 111 Nm^3 of H_2 (about 10 kg) [7].

2. Lca: Goal and Scope Definition

According to ISO 14041 [8] the first phase of a LCA consists of defining the aims of the study, the system boundaries and the functional unit. The aim of this study is to supply a tool for choosing from among the available options for fuelling the above-mentioned mini-buses.

All the productive cycles are built up from the daily consumptions of the buses and are analysed considering two different scenarios: scenario 1 and scenario 2, that respectively consider 4 and 24 circulating mini-buses. The H_2 consumptions are summarised in table 1.

Table 1. H_2 consumptions.

	Bus	H_2 [kg/h]	H_2 [kg/day]	H_2 [kg in 20 years]
	1	0,42	9,98	72.829
Scenario 1	4	1,66	39,91	291.318
Scenario 2	24	9,98	239,44	1.747.906

The aim of this study is to supply a source of consultation for decision makers to select the H_2 production method, which allows the minimisation of environmental load, following a sustainable path. This work aims to clarify the environmental aspects related to the production of H_2 in order to investigate the benefits of its use. The two considered scenarios are also compared.

2.1. System Boundary and Functional Unit Definition

The analysis includes the extraction and manufacturing of materials and fuels, the construction phases of plants and devices and it considers the H_2 production. The following H_2 compression step, required to supply hydrogen at the bus storage pressure (about 350 bar) was not considered, since the delivery pressures of both the electrolyser and the reformer are similar (about 9 bar), hence the energetic expense for compression would be the same in both cases, having no influence on the comparison.

The power production from hydroelectric and PV plants and the extraction of methane are not geographically located, while the H_2 production should be located at the storing and distribution site (bus fuelling station). The period of the analysis is 20 years

The selected Functional Unit (FU) for data collection is: 1 kg of produced H_2.

The following paragraphs will describe the studied systems:

2.2. Methane steam reforming

The flow diagram for the methane steam reforming system is reported fig. 1. With reference to an existing reforming device [9], a proportional scaling was considered in order to adapt the plant dimension - and the whole productive cycle - to the requirements of the considered scenarios.

2.3. Photovoltaic

The flow diagram for the photovoltaic production cycle is reported in fig. 2. Also in this case, with reference to an existing PV modular panel, produced by an Italian company [10], a proportional scaling was considered in order to adapt the plant dimension - and the whole productive

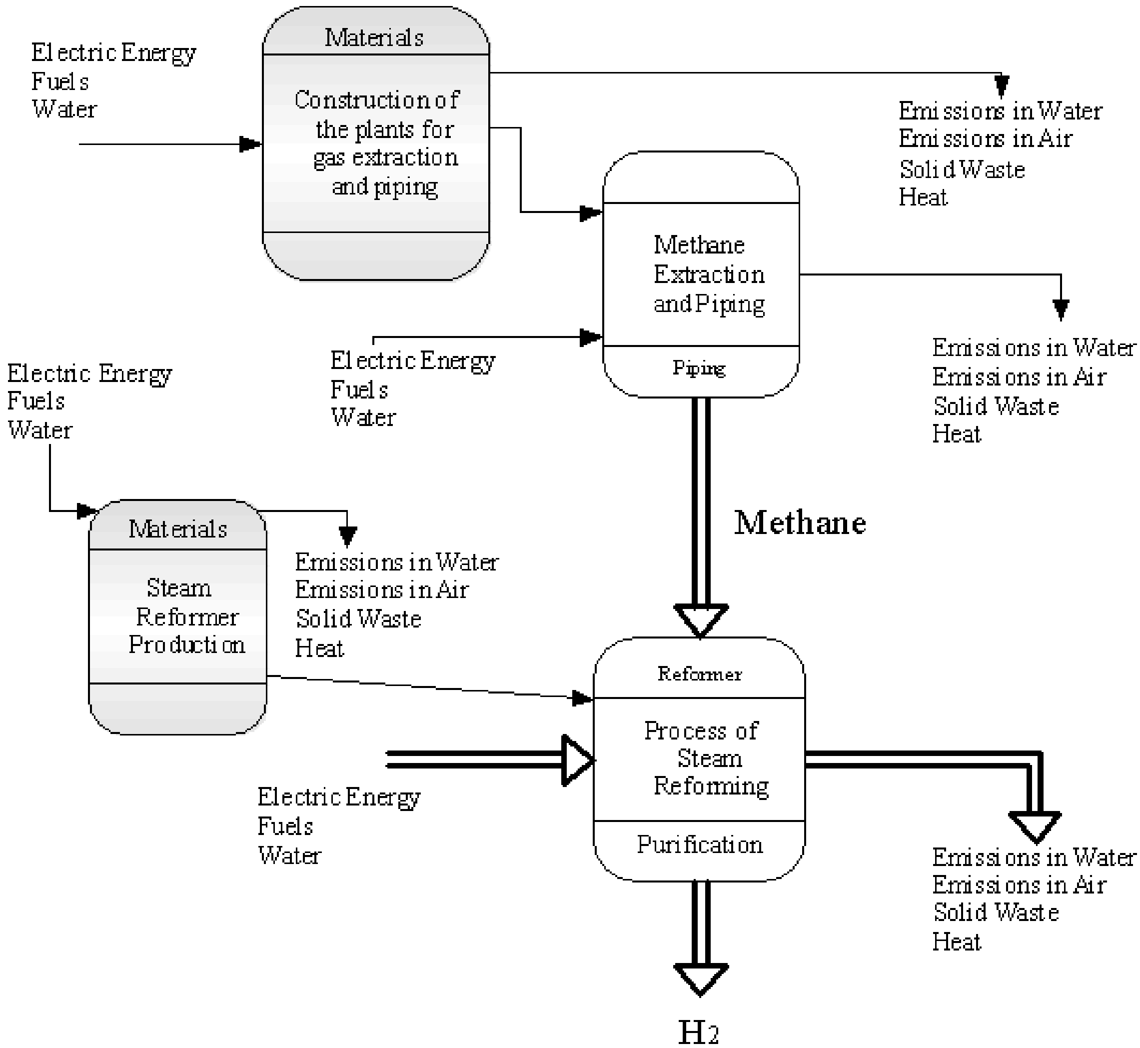


Fig. 1: Flow diagram and system boundaries for the methane steam reforming productive cycle.

cycle - to the requirements of the considered scenarios.

Since the PV plant is connected to the national grid, no hypothesis about its geographical location was made, with the exception of the latitude, which was assumed at Florence's one, to calculate the PV electricity output.

Concerning the electrolysers, two different models were considered, respectively for the two scenarios, both produced by an Italian company [11].

2.4. Mini-hydroelectric

The flow diagram of the mini-hydroelectric system is shown in fig. 3. Concerning the electrolysers, the production process and the use phase are exactly the same of the PV system. The data scaling for the mini-hydroelectric plants was made on the power production basis.

The dimension of the plants was adapted to the two scenarios considering the available Francis turbine models, produced by an Italian company [12].

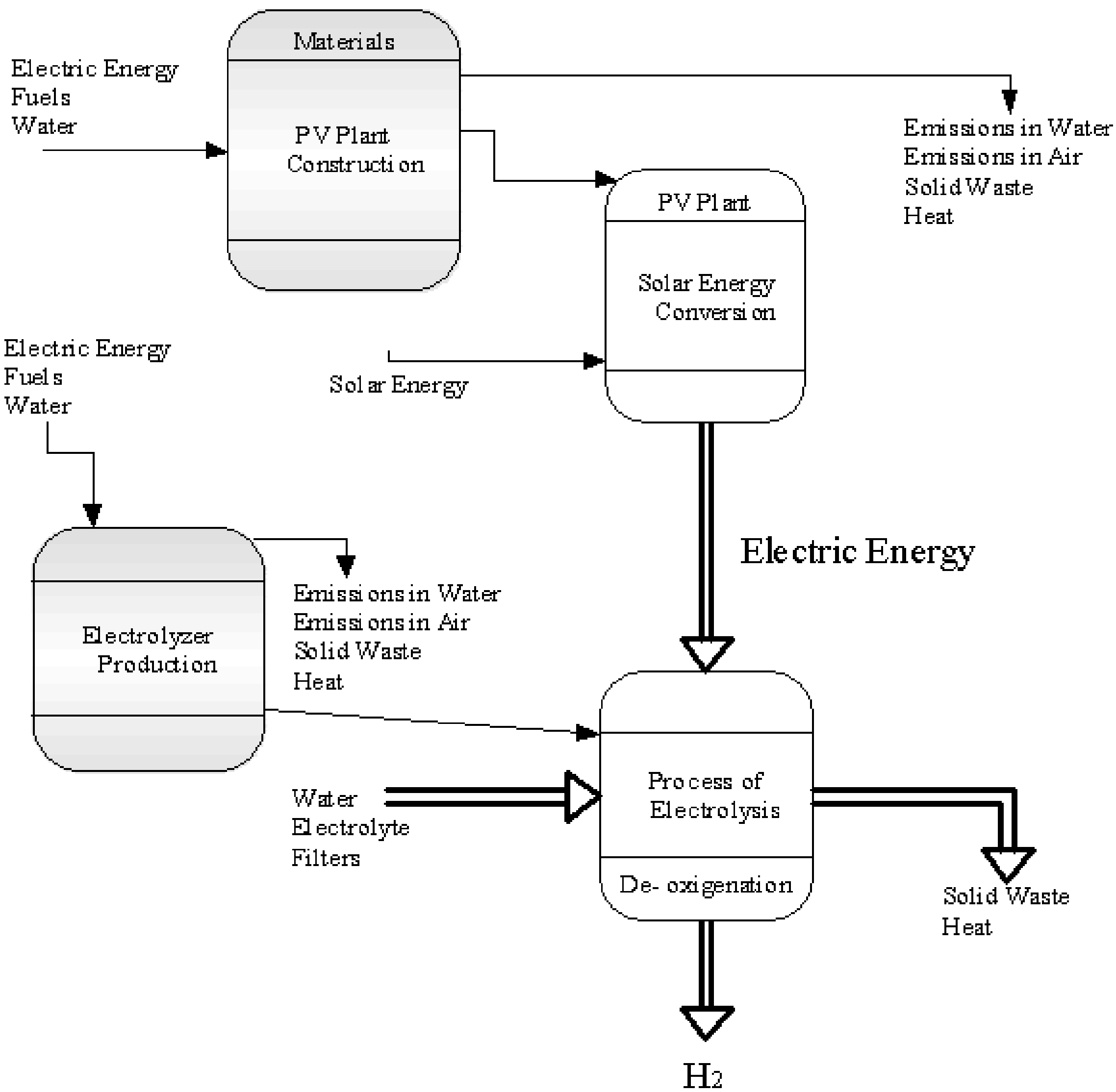


Fig. 2: Flow diagram and system boundaries of Photovoltaic productive cycle.

3. LCA: Inventory Analysis

The inventory analysis phase consists of energy and material flows quantification for each sub-system [8]. The amounts of the materials used for the main devices manufacturing and the fuels used for their production and use were considered.

When primary data were not available, literature data were used. The data source and elaboration are specified in each case.

Waste treatments was not included, except for the treatments already included in the used records from SimaPro database [13]. All the recycling processes or resources re-utilization are also excluded in order to keep the comparability.

Italian electric mix from I-LCA database [14] was used, for production processes electric consumption. The following paragraphs will report the inventory for the studied systems:

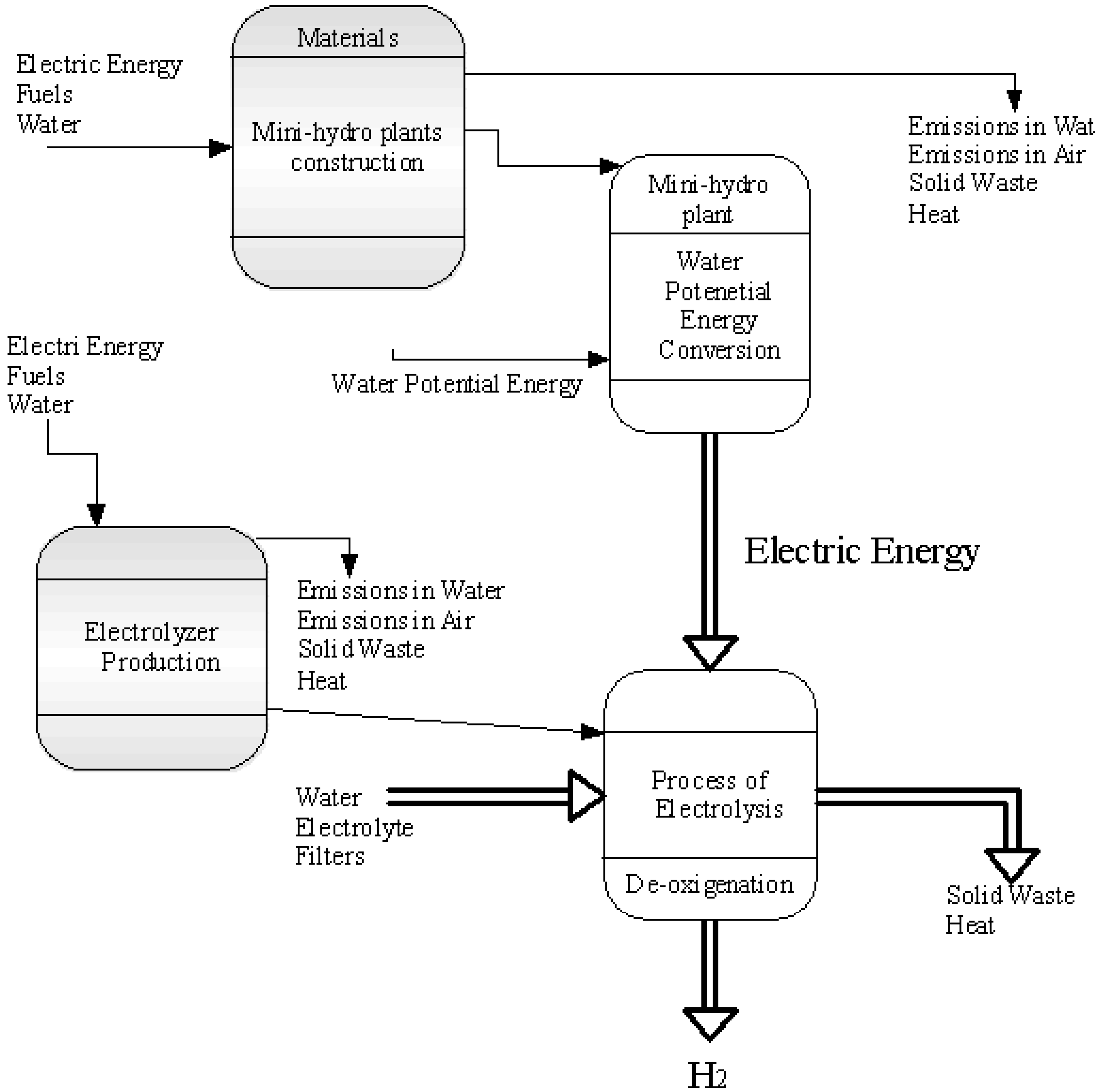


Fig. 3: Flow diagram and system boundaries of Mini-hydroelectric productive cycle.

Table 2. H_2GEN reformer technical features [9].

	Units	Values
Life time	Years	10
Thermal Efficiency	%	66
H_2 Production	Nm^3/h	52,8
Weight	kg	3.175
Load Variation	%	35-100
H_2 delivery pressure	atm	9-15
H_2 Purity	%	99,9995

3.1. Methane Steam Reforming

Data for extraction, production and transport of methane (referred to 1 Nm^3) are retrieved from I-LCA Database [14]. Concerning the reformer, methane, water and electric power consumption data, and also the amounts of construction materials were supplied directly by the manufacturing companies [9]. Data concerned with energy for plant construction (including civil works) come from the literature [15] and have been scaled on the basis of H_2 production rate. Table 2 reports the technical features of the considered reformer. Since the lifetime of this device is 10 years, while the period considered for the analysis is 20 years, all the data referred to the construction were accounted twice. The reformer model H_2GEN does not include water demineralizer but it incorporates a pressure swing absorption unit (PSA). Tables 3 and 4 show, respectively, the reformer consumptions and emissions. Table 5 summarises the construction data (material and energy use) for the reformer. Production processes for the materials that have weight percentage lower than 1% are excluded. Materials above 1% in weight of the total are: steel, iron and cement. However, also aluminium was included, because of its high energy intensive production process. For each material, only one of the main production processes was considered: the most expensive or the most complete across the whole productive cycle. Table 6 reports the reformer data in reference to two scenarios (assuming a 24 hours running for the reformers).

Table 3. H_2GEN reformer consumptions [9].

	Units	Values
Methane	Nm^3/h	24,55
Pure Water	m^3/h	0,0908
Cooling Water	m^3/h	1,14
Dry N	Nm^3/h	2,4
Drain	m^3/h	0,045
Electric Power	kW	15

Table 4. H_2GEN reformer emissions (use) [9].

Emissions during use phase (20 years)	kg
CO_2	6.938.008
CO	59,71
NO_x	671,89
Particulate matter	16,46
Drain (water)	7.884.000

Table 5. Construction data for one reformer.

Material	Units	Amount	Data type
Aluminium	kg	26	Primary [9]
Steel	kg	3.111	Primary [9]
Iron	kg	38	Primary [9]
Concrete	kg	2.394	Secondary [15]
Steel (in concrete)	kg	120	Secondary [15]
Energy (plant construction)	MWh	118	Secondary [15]

3.2. Photovoltaic

For the PV system associated to electrolysis, it is necessary to consider the construction – and hence the materials, their extraction and processing – of both the photovoltaic and the electrolyser plant. The consumption of water to produce H_2 was considered, too. The O_2 produced by the electrolyser is not used, stored or sent for the other purposes.

3.2.1. Inventory of the electrolyser.

The chosen electrolysers are equipped with a water demineraliser, a deoxygenator and a dryer. Table 7 reports the technical features of the considered electrolyser model. Also in this case, being the lifetime of the electrolyser 10 years and the analysis period of 20 years, the data for the construction were considered twice. Table 8 reports the type and amount of the construction materials for the electrolysers. According to the previously settled criteria, the materials for which the main production processes were included are steel, copper and PVC. In scenario 1, three electrolysers will be used, while in scenario 2 eight electrolysers will be required.

3.2.2. Inventory of PV plant.

Table 9 reports the technical data of the PV panels [10]. The materials data for the PV plant were retrieved from a literature analysis [16]

Table 6. Reformer requirements in the two scenarios.

	Bus	H_2 [kg/day]	Reformer	Load [%]	CH_4 [kg/day]
Scenario 1	4	39,91	1	35	422,36
Scenario 2	24	239,44	3	70	1267,09

Table 7. Electrolyser technical features [11].

	Units	Piel MP G10.2 (Scenario 1)	Piel MP 22.5 (Scenario 2)
H_2 production	l/h	7.600	15.000
H_2 delivery pressure	bar	up to 9	up to 9
O_2 production	l/h	3.800	7.500
H_2 purity	%	99,9995	99,9995
Maximum load power	kW	41	73
Electric consumption	kWh/day	912	1.752
Pure water consumption	l/h	6,3	12,8
Power supply type	V – Hz	380 – 50	380 – 50
Load variation	%	25-100	25-100
Size	cm	93x123x170	108x191x170
Weight	kg	640	1.560
Life time	years	10	10

Table 8. Construction materials and consumptions of the electrolysers [11].

Material	Units	Piel MP G10.2 Scenario 1	Piel MP 22.5 Scenario 2
Steel	kg	564,2	1.419,6
PVC	kg	24,8	62,4
Copper	kg	24,8	62,4
Nickel	kg	6,2	15,6
Total Weight	kg	640	1.560
Total consumptions	(in 20 years)		
Electric Power	kWh	6.657.600	12.789.600
NaOH	kg	300	600
Activated carbon	kg	180	360

[17]. The silicon used for the PV cell is the same as what was used for the electronic industry (high purity silicon for microchips) [17].

Type and level of refinement required by electronic industry is very high and useless at all for the PV industry [17]. Table 10 summarises the main materials that constitute the PV plant. The criteria for the inclusion/exclusion of materials flows are the same mentioned above. Data for silicon processing appear in the literature [17] while those of extraction are retrieved from SimaPro database [13].

Table 11 reports the PV+electrolyser system data in reference to the two scenarios (assuming a 24 hour operation for the electrolyser). The required total PV panel surface, in the two scenarios, was calculated on the basis of the electrolyser power request (daily) and the panels output.

3.3. Mini-hydroelectric

Mini-hydroelectric system is basically composed by the mini-hydroelectric plant and the electrolyser, which is exactly the same as the previous system: hence all the above reported data are used also in this case.

Table 9. Technical data of PV panel, Mod. ES80 [10]

	Units	Value
Module Power	Wp	80
Module Area	m^2	0,6286
Cell Area	m^2	0,0156
Cells Number		36
Module Weight	kg	7,5
Specific Power	Wp/ m^2	127,6
Length	m	1,175
Width	m	0,535
Cell kind		Polycrystalline
Efficiency	%	12,73
Direct Current	A	4,9
Voltage	V	21,70
Life time	Years	> 20

Table 10. PV Plant construction material data.

Material	kg/m^2 of module	Weight %	Reference
Steel	131,7129	54,726	[16]
Aluminium	2,4360	1,012	[17]
$CaCO_3$ (Limestone)	1,8069	0,751	[17]
Coal	1,1692	0,486	[17]
Cement	6,3629	2,644	[16]
H_2SO_4 (Sulphuric Acid)	0,7076	0,294	[17]
HCl	58,0339	24,113	[17]
NH_3 (Ammonia)	0,0104	0,004	[17]
Plastics	11,8351	4,917	[16]
Copper	13,7440	5,711	[16]
SiC (Silicon Carbide)	0,9976	0,415	[17]
Silicon (high purity)	1,0629	0,442	[17]
Soda + potash (NaOH+KOH)	1,7168	0,713	[17]
Glass	9,0790	3,772	[17]

Table 11. PV system requirements in the two scenarios.

	Unit	Scenario 1	Scenario 2	% load
N° Bus		4	24	
H_2 Requirement	kg/d	39,9	239,4	
Mod G10.2 MP	n°	3	--	90,7
Mod 22.5 MP	n°	--	8	92,5
Electric Consumption	kWh/d	2736	14016	
Water Consumption	l/d	151,2	307,2	
PV Area	m^2	3583	18356	

3.3.1. Inventory of Mini-hydroelectric plants.

Inventory data are referred to a single 86 kW plant (table 12) produced by an Italian company [12] used as reference for the modular adaptation to the two scenarios. The inventory also includes data for the required additional civil works retrieved from the literature [18].

The system includes an upstream water storage, a steel closed pipe (adduction pipe) 1 km long, a small decanting tank, a segment of pipe leading to the turbine. An electric generator is connected to the turbine.

Table 13 reports the inventory of the construction materials for a single mini-hydro plant.

The criteria for the inclusion/exclusion of the device materials production are the same as what was mentioned for reforming and PV systems. Table 14 reports the mini-hydro+electrolyser system data in reference to the two scenarios.

Table 12. Technical features of the mini-hydroelectric turbine [12].

	Units	Value
Power	kW	86
Flow rate	m^3/sec	0,68
Fall	m	16,36
Speed	rpm	1.020
Weight	kg	700
Operation	hours/year	6.000
Energy Production	kWh/year	412.800

4. LCA: Impact Analysis

From the inventory data, it is possible, according to different methodologies, to carry out a quantification of the environmental load caused by the natural resource depletion and the emissions accounted for in the inventory itself: this is called the impact analysis phase of LCA [19].

In this work two different impact analysis methods have been used: Ecoindicator'95 [20] and Ecoindicator'99 [21].

Ecoindicator'95 method uses nine environmental effect indicators (GWP – Greenhouse Effect in kg of equivalent CO_2; ODP – Ozone Depletion Potential in kg of equivalent CFC; AP – Acidification Potential in kg of equivalent SO_2; NP- Nitrification Potential in kg of equivalent phosphate; HM - Heavy Metals in kg of equivalent Pb.; Carcinoges in kg of equivalent benzo[a]pyrene; WS – Winter smog in kg of equivalent SO_2; SS – Summer Smog in kg of equivalent ethane; Pesticides in kg of active substance [20]).

Ecoindicator'99 method defines three damage categories: human health (unit: Disability Adjusted Life Years - DALY), ecosystem (Potentially Disappeared Fraction of vegetable species per m^2 per year - PDF*m^2*year) and resources depletion (MJ) [21].

The main difference with respect to the Ecoindicator'95 is that the defined categories are damage categories instead of simple effects.

The cultural perspective used, for Ecoindicator'99, is the Hierarchist-H and the set of weights the Average-Á (H,A) (these are the default ones) [21]. A comparison between the results obtained from the two methods can be only qualitative

Table 13. Materials for a single mini-hydro plant construction [12] [18]

Material	Weight %	Total Weight [kg]	Water storage and adduction[kg]	Tank [kg]	Plant housing [kg]	Turbine [kg]	Electric generator [kg]
Concrete	86,89	759.598		450.000	173.687		
Steel	9,11	79.621	79.355			266	
Iron	3,54	30.939		18.000	6.947	406	150
Paints	0,34	2.928	2.591	330		7	
Bitumen	0,09	760			760		
Copper	0,03	300					300
Insulating	0,01	50					50
Bronze	0,002	14				14	
Teflon	0,0008	7				7	

Table 14. Mini-hydro plant requirements in the two scenarios.

	Units	Scenario 1	Scenario 2
N° Bus		4	24
H_2 requirements	kg/day	39,9	239,4
N° Electr. Mod G10.2		3	--
N° Electr. Mod 22.5		--	8
Electric Consumption	kWh/day	2.736	14.016
N° 86 kW Turbines		3	13

4.1. Results for Ecoindicator '95

Fig. 4 shows the comparison of the Ecoindicator'95 effects, per kg of produced H_2, for the three systems with reference to scenario 2.

In this case none of the three systems corresponds to the minimisation of all the indicator values, so the indication of a best choice is not supplied.

4.1.1. Cumulative Curve for Ecoindicator'95.

Some interesting considerations can be drawn by the analysis of the 20 years cumulative curves for some critical effects.

As an example, fig. 5 shows the cumulative Greenhouse Effect production for the three systems with reference to scenario 2.

The trends correspondent to PV and Mini-hydro systems are almost parallel, starting from an initial relatively high value (construction) with a small annual increase (operation), due mainly to the electrolysis consumptions. On the contrary, the methane reforming system trend starts from a relatively low value, correspondent to the effects associated to the plant construction, and grows up consistently during the years, due to operation loads. This kind of result presentation allows the estimation of the lifetime after which one system has a lower environmental impact with respect to another: in this case, in reference to Greenhouse Effect, after about 11 years of operation, the PV systems starts to be better than methane reforming system, while mini-hydro will be better after about 19 years of operation.

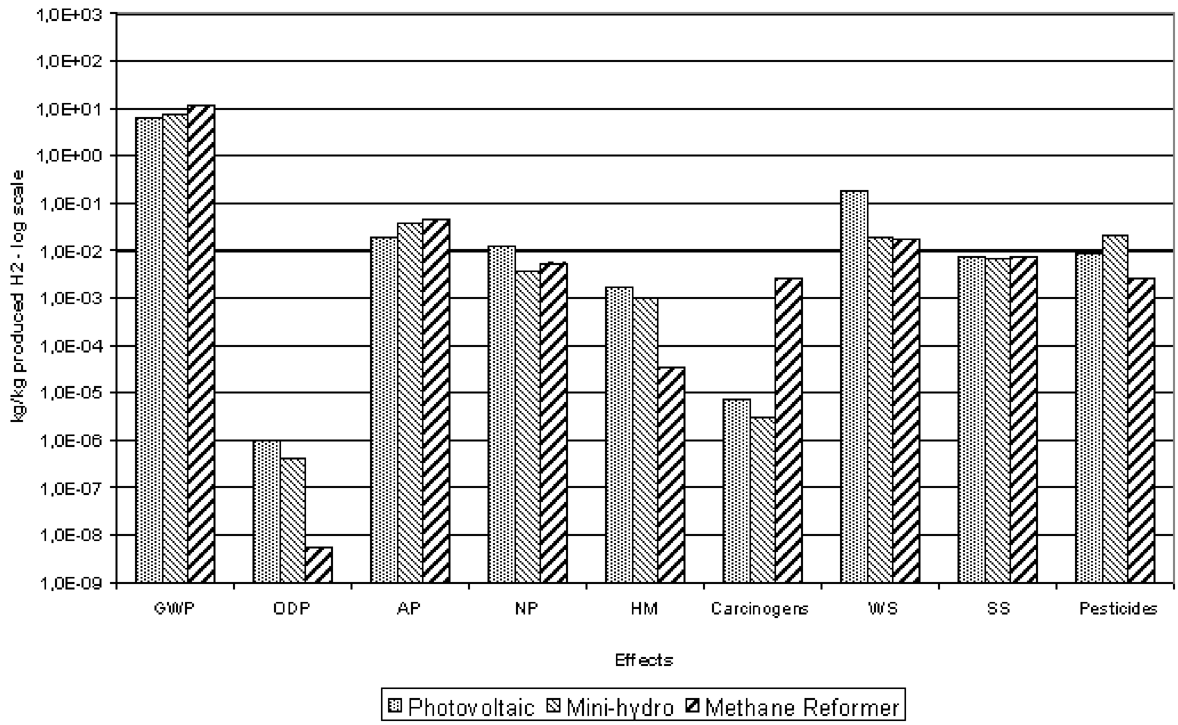


Fig. 4: comparison of the three systems, scenario 2 – Ecoindicator'95 effects.

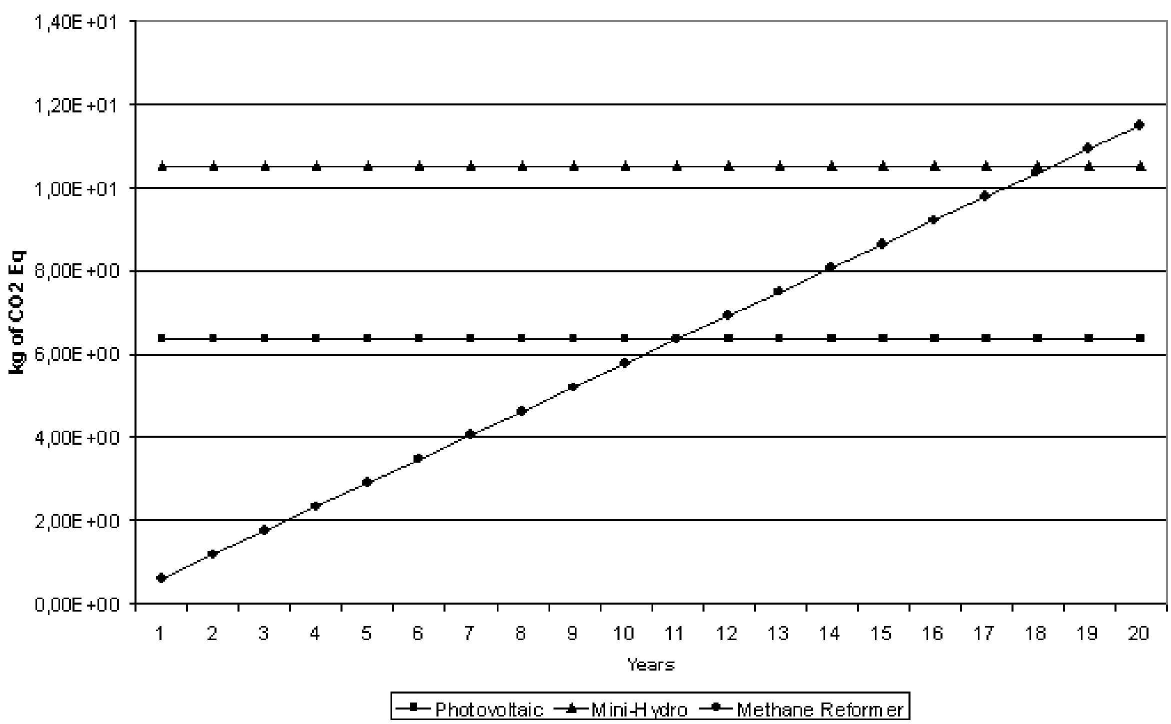


Fig. 5: Greenhouse Effect production cumulative trends – Scenario 2

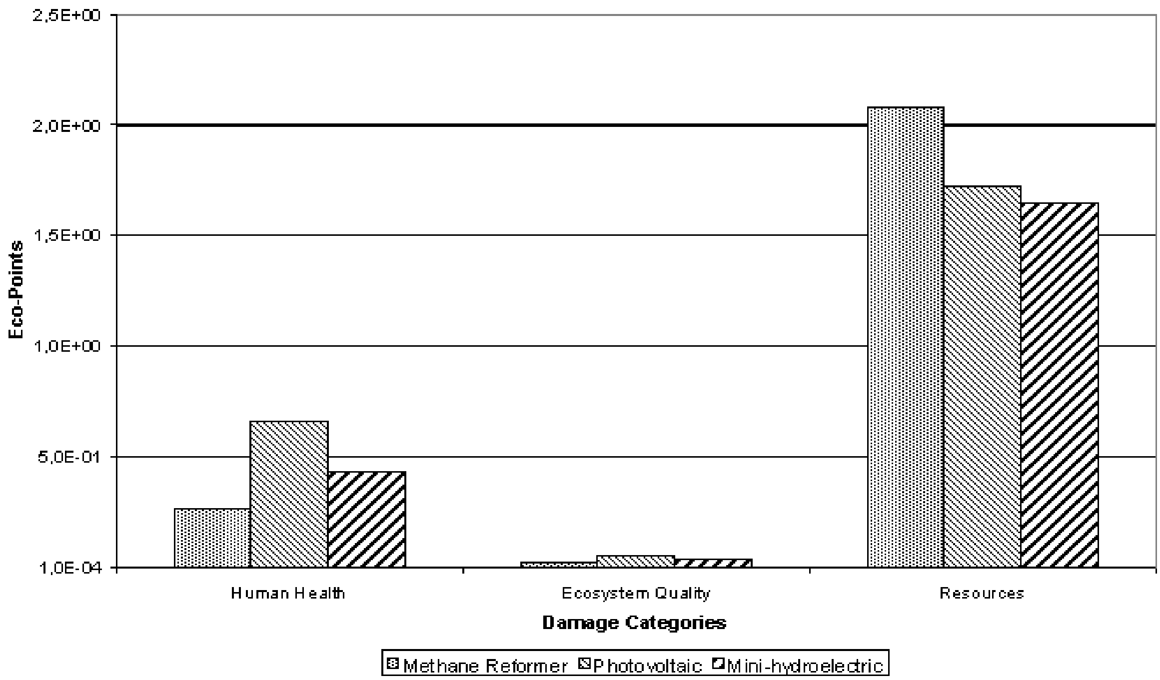


Fig. 6: Comparison of Ecoindicator'99 damage categories for the three systems - Results per kg of produced H_2 (H,A) – scenario 2.

4.2. Results for Econdicator'99

Fig. 6 shows the comparison among the three H_2 production systems – scenario 2- considering the three damage categories of Ecoindicator'99. As already highlighted in the case of Ecoindicator'95, none of the three systems shows a minimisation of all the damage categories. In this case, a single Ecoindicator was calculated, according to the normalisation and weighting steps proposed by Ecoindicator'99 method [21].

These steps are again based on subjective choices of the specific method, but these choices are more easily to be shown, with the aim of transparency, since we are dealing with only three indicators to be added together (instead of the nine effects in Ecoindicator'95), also with the help of particular graphical representations [21]. Fig. 7 shows the final single score for the Ecoindicator'99 methods for both scenarios, highlighting the mini-hydroelectric as the best choice in both cases.

5. Lca: interpretation and improvement

In this phase of LCA some improvements to the studied systems are proposed with respect to the main highlighted weak points [22].

Analysing the contributions to environmental load of the different phases of the construction for the PV and mini-hydro, systems some processes appeared to supply relatively high contributions.

In particular, the PV system shows critical point in the silicon production that is generally manufactured for the use in the electronic industry [17] which requires a high pure silicon, that, on the contrary, is not necessary for PV panel manufacture [17].

So a simplified silicon production process was considered [16] [23] [24] [25].

Concerning the Mini-hydro system, an improvement was identified in the steel adduction pipe substitution with a concrete adduction pipe.

5.1. PV System Improvement.

Table 15 reports the used data for manufacturing the PV panels considering only, in relation to silicon production, the ingot production (simplified silicon production process excluding the refining phases) [17].

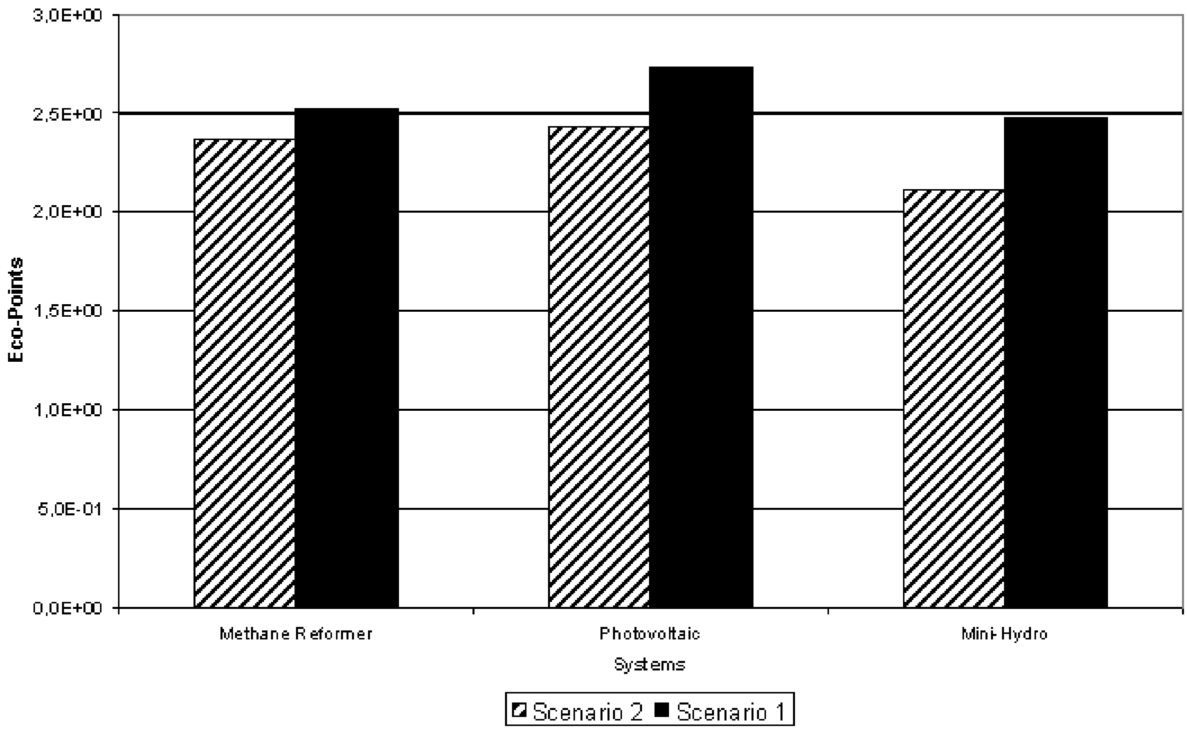


Fig. 7: Comparison of Ecoindicator'99 final score for the three systems - Results per kg of produced H_2 (H,A) –Scenario 1 and 2.

Table 15. Materials for the PV panel construction – improved option.

Material	Quantity (kg/m^2 of module)	Reference
Steel	5,97	[23]
Concrete	63,63	[18]
Copper	0,028	[24]
Aluminium	1,60	[23]
Silicon	1,063	[17]
Glass	6,49	[25]
EVA	0,79	[24]
Tedlar	0,22	[24]

5.2. Mini-Hydroelectric System Improvement

The substitution of the steel adduction pipe (1 km) with a concrete adduction pipe (1 km), in the mini-hydro system, leads to the modified construction data with respect to table 13. In particular in the fourth column (Water storage and adduction) of table 13, additional concrete is considered (increasing from zero to 124.877 kg), while steel is reduced (decreasing from 79.355 kg to 9372 kg).

5.3. Improvement Results.

As shown in fig. 8, for scenario 2 referred to Ecoindicator'95 results, the obtained improvement is consistent. The environmental impact of the PV decreases significantly lowering all the Ecoindicator'95 effects.

The substitution of the steel with concrete, for the Mini-Hydro adduction pipe, also improves the environmental performances for this option.

The improvement is also confirmed by the application of the Ecoindicator'99 method, reported in fig. 9 for scenario 2. In particular, according to this method, the best option for H_2 production is the PV systems.

6. Conclusions

Three different possibilities for H_2 production were studied and compared by means of LCA: methane steam reforming, water electrolysis fed

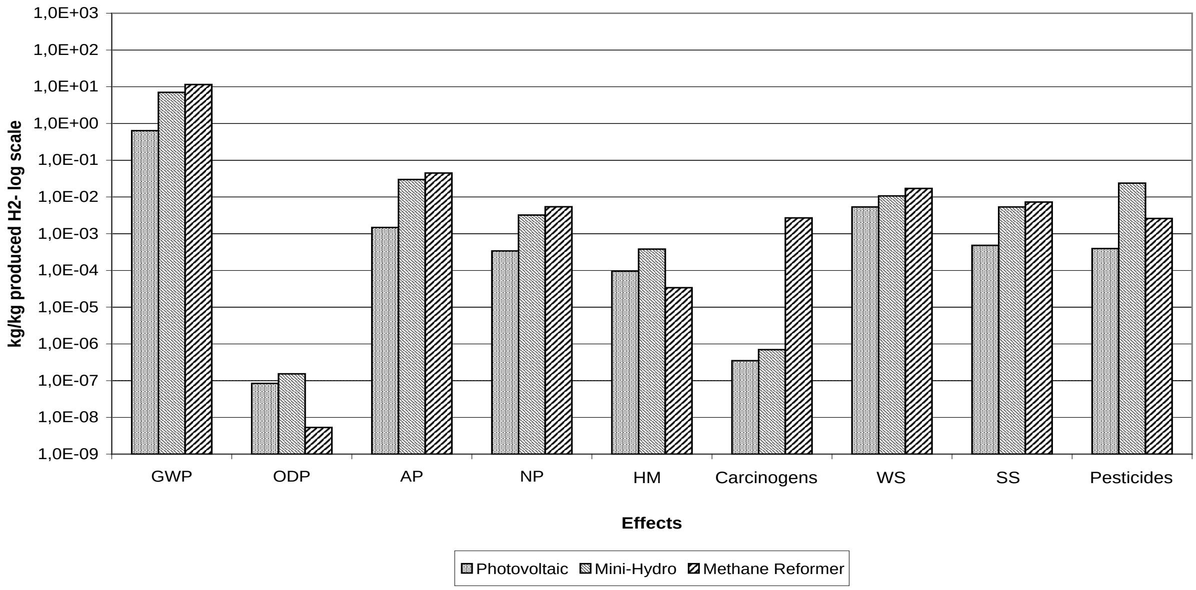


Fig. 8: Comparison of the three systems, scenario 2 – Ecoindicator'95 effects – improved options.

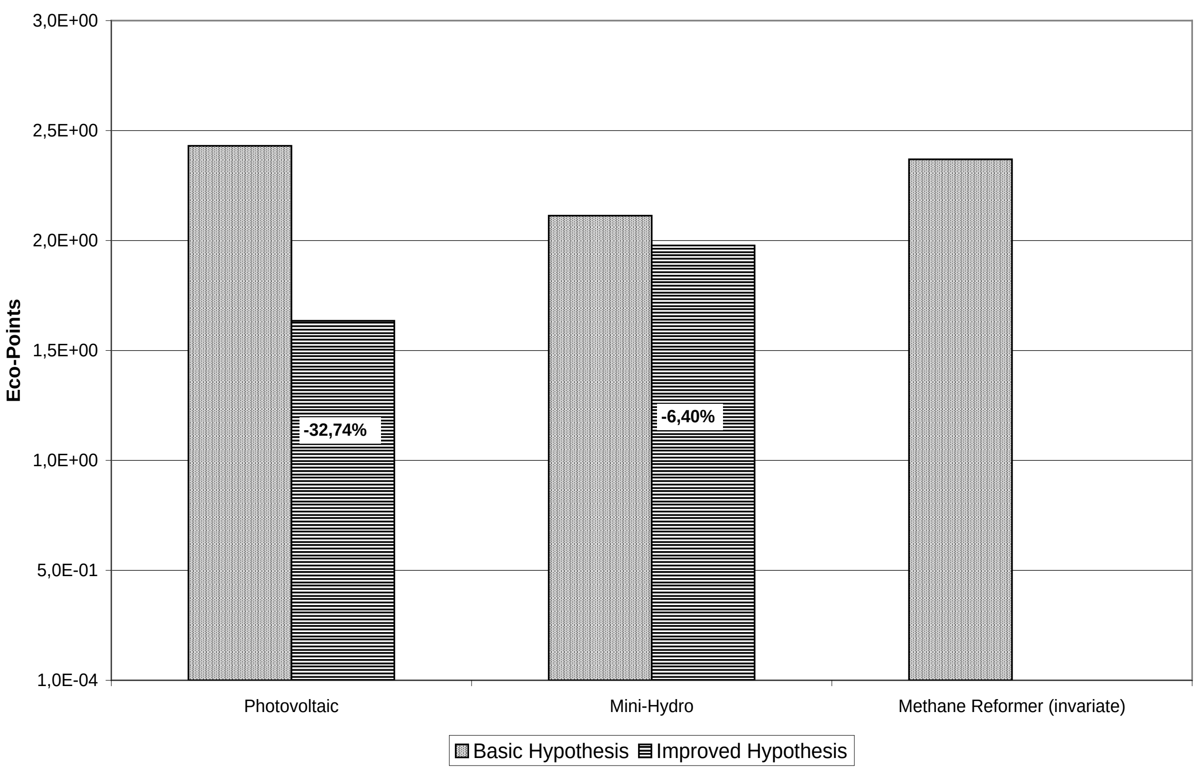


Fig. 9: Comparison of Ecoindicator'99 final score for the three systems - Results per kg of produced H_2 (H,A) – scenario 2 – improved option.

by a photovoltaic (PV) plant, water electrolysis fed by mini-hydroelectric plants.

The results of the study can be summarised as follows:

- the Ecoindicator’95 method does not supply the best choice for H_2 production;
- the Ecoindicator’99, applied with a standard set of weighting, indicates as the best choice the Mini-hydro option. The PV system, according to this method, shows the worst performance;
- in the PV construction the silicon production is a key factor. The use of low purity silicon leads the PV system to be the best choice for H_2 production. Improvement results are confirmed by both impact assessment methods;
- in Mini-hydro the substitution of steel adduction pipe with concrete adduction pipe leads to an improvement, with a significant environmental load reduction.

7. Nomenclature

LCA	Life Cycle Assessment
PV	Photovoltaic
FU	Functional Unit
PSA:	Pressure Swing Absorption
GWP	Global Warming Potential
ODP	Ozone Depletion Potential
CFC	Chlorofluorocarbon
AP	Acidification Potential
NP	Nitrification Potential
HM	Heavy Metals
WS	Winter Smog
SS	Summer Smog
DALY	Disability Adjusted Life Years
PDF	Potentially Disappeared Fraction

References

[1] Koroneos C., Dompros A., Roumbas G. and Moussiopoulos N.. Life cycle assessment of hydrogen fuel production processes. International Journal of Hydrogen Energy 29 (2004) 1443 – 1450.

[2] Varun, Bhat I.K., Prakash R.. LCA of renewable energy for electricity generation systems—A review. Renewable and Sustainable Energy Reviews 13 (2009) 1067–1073.

[3] Smitkova M., Janıcek F., Riccardi J.. Life cycle analysis of processes for hydrogen production. International Journal of Hydrogen Energy 36 (2011) 7844-7851

[4] Dufour J., Serrano D.P., Galvez J.L., Moreno J., Garcıa C.. Life cycle assessment of processes for hydrogen production. Environmental feasibility and reduction of greenhouse gases emissions. . International Journal of Hydrogen Energy 34 (2009) 1370 – 1376.

[5] Granovskii M., Dincer I., Rosen M.A.. Exergetic life cycle assessment of hydrogen production from renewables. Journal of Power Sources 167 (2007) 461–471.

[6] Boyano A., Blanco-Marigorta A.M., Morosuk T., Tsatsaronis G.. Exergoenvironmental analysis of a steam methane reforming process for hydrogen production. Energy 36 (2011) 2202-2214.

[7] Gallori M., Melloni E., Pede G., Brocco M., Stefanoni M., Di Mario. F., Iacobazzi A. Definizione di una base conoscitiva sulla realizzabilità di un bus urbano a zero emissioni per i centri storici. Firenze: I2T3, ENEA, Progetto Idrocomb, 2002 (In Italian)

[8] ISO 14041: Environmental management – Life Cycle Assessment – Goal and Scope Definition and Life Cycle Inventory Analysis – 1998.

[9] H_2GEN Innovation – Alexandria. Virginia (VA), USA.

[10] Elettro Sannio - Pietrelcina (BN, Italy) – Personal communication

[11] PIEL - Pontedera (PI, Italy). Web site: www.piel.it. Personal communication

[12] Verdelli – Firenze (FI, Italy). Personal communication

[13] Software SimaPro v.4.0, PRé Consultants B.V., 1998, NL.

[14] I-LCA. Banca dati italiana a supporto della valutazione del ciclo di vita. Italia: ANPA, 2000. (In Italian)

[15] Spath P.L., Mann M.K. Life Cycle Assessment of Hydrogen Production Via Natural Gas Steam Reforming. NREL Report, Golden, Colorado, USA, 2001.

[16] Tahara K, Kojima T., Inaba A. Evaluation of CO_2 payback time of power plants by LCA. Seikei University. Tokio, Japan, 1997.

[17] Alsema E.A., Phylipsen G.J.M. Environmental life cycle assessment of multicrystalline silicon solar cell modules. Netherlands Agency for Energy and the Environmental, Utretch University, NL, 1995.

[18] Bennett K. Small hydro in Canada: an overview. Industry, Science and Technology Canada Aboriginal Economic Programs, Canada, 1990.

[19] ISO 14042: Environmental management – Life Cycle Assessment – Life Cycle Impact Assessment – 2000.

[20] Goedkoop M. The Ecoindicator 95 – Final Report, Prè. Publikatiereeks produktenbeleid, Amersfoort, NL, 1996.

[21] Goedkoop M., Spriensma R. Ecoindicator 99, a damage oriented method for Life Cycle Impact Assessment – Manual for Designers. III Edition, Prè. Publikatiereeks produktenbeleid, Amersfoort, NL, 2001.

[22] ISO 14043: Environmental management – Life Cycle Assessment – Life Cycle Interpretation – 2000.

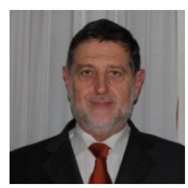
[23] Battisti R., Corrado A. Evaluation of technical improvements of photovoltaic systems through life cycle assessment methodology. Energy, Volume 30, Issue 7, June 2005, Pages 952-967

[24] Boyd S., Buonassisi T., Dillavou T., Sathaye N., Williams T.. Parametric Life-Cycle Assessment: Modern Silicon-Based Photovoltaic Technologies and Applications. University of California, Berkeley USA, 2004.

[25] Kato K., Murata A., Sakuta K. An evaluation on the life cycle of photovoltaic energy system considering production energy of off-grade silicon. Solar Energy Materials and Solar Cell 47, Japan, 1997.

Biographies

Lidia Lombardi engineer, researcher at Dipartimento di tica “Sergio Stecco” dell'Università di Firenze and teacher of the “Waste management and treatment” class. She obtained the PhD in Energy in 2001 with a thesis titled "LCA parison of technical solutions for CO2 emissions duction in power generation".
Her main scientific interests are concerned with waste treatments, in particular with energy recovery, both by thermal and biological processes; carbon dioxide removal and biogas upgrading to biomethane; life cycle assessment (LCA) applied to waste management and energy conversion processes.



Ennio A. Carnevale, is a full professor of Mechanical Engineering at the University of Florence (Italy) since 1980. Dean of Engineering faculty at Florence University from 1995 to 2001. His research ests include: optimization of energy use, cogeneration and renewable energy sources, energy recovery from waste, environmental impact of energy systems. He is the author and co-author of more than 70 papers.

Andrea Corti is an associate professor of Energy and Environment at the University of Siena (Italy). His search interests include: conventional and innovative energy systems and renewables, energy recovery from waste, environmental impact of energy systems, atmospheric diffusion of pollutants. Also he has a large experience in the field of waste management, collection, treatment and disposal. He is the author and co-author of more than 120 papers.