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RES (Renewable Energy Sources) availability assessments for Eco-fuels production at local scale: carbon avoidance costs associated to a hybrid biomass/H_2NG-based energy scenario

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Abstract

Eco-fuels are a sustainable solution to face increasing global energy consumptions and GHG emissions. This work was firstly focused on available renewables assessment linked to a local dimension. Furthermore, identifying the potential Eco-fuels capability, it was discussed how the capital expenditure for infrastructures is associated with carbon avoidance costs.
A coastal municipality and an inland one, located in Central Italy, are selected as case studies.
In order to assess PV and agro-forestry residues availability, a GIS-based analysis was performed. In this framework, a new energy scenario, based on H_2NG blends use and ligneous biomass conversion, was presented. Specifically, the hydrogen for NG enrichment was produced by renewable electricity, while biomass energy content was evaluated considering gasification process. Finally, the governmental incentive schemes incidence (in force for bioenergy and hypothesized for hydrogen) on investments economic sustainability and on infrastructure deployment was compared in terms of carbon avoidance costs.

Keywords: Eco-fuels; RES; GIS analysis; Biomass residues; Renewable hydrogen; H_2NG; Hydrogen-natural gas blends; Hybrid System; Carbon Avoidance; Smart Grid.

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1. Main text

The most critical issues of effective energy management deal with the necessary interconnection of still expensive energy storage systems (electrical and thermal) due to the integration of traditional thermal cycles with non-programmable renewable sources. Another approach, based on a recent achieved economic sustainability [1] (i.e. grid parity for PV array), consists of Eco-fuels production, such as Hydro-methane (H2NG), by direct renewable sources exploitation. In order to cope with increasing global energy consumption and GHG emissions as well [2], European Union has promoted several strategies in energy field [3]. One of them is to switch energy supply chain from fossil fuels to renewable energy sources such as solar, wind and biomass. This strategy is encouraged with EU 20-20-20 initiative, setting an EU-wide target of providing 20% of final energy consumption from renewables by 2020. The target is then broken down by member state: Italy, for instance, has agreed to increase its renewable energy mix from 5.9% in 2005 to 17% by 2020 [4]. In this framework, Eco-fuels play an important role to achieve sustainability goals [5], also in accordance with the Kyoto Protocol. Eco-fuels definition includes gaseous (biogas from anaerobic digestion, syngas from gasification and pyrolysis, hydrogen from reforming and hydrolysis) and liquid (vegetable oil, bio-diesel, ethanol from alcoholic fermentation) pure fuels and their mixtures with fossil ones as well. Adopted policy measures and incentive schemes aim to encourage only commercial deployment of bioenergy at large scale [6]. Nevertheless, several studies state that H2NG blend [7] with different H2 fractions [8] is a promising solution to avoid carbon emissions [9]. This latter can be reduced directly due to higher H/C ratio of the fuel and also indirectly due to a lower energy consumption, having improved the engine thermal efficiency [10]. In this paper, we explore how local renewable sources availability linked to Eco-fuels production can feed the municipal energy supply in two case-studies towards the creation of sustainable communities [11].

Nomenclature

CHP	Combined Heat and Power	GIS	Geographical Information System
CLC	Corine Land Cover	H_2NG	Hydrogen and Natural Gas
EU	European Union	PR	Production rate
GHG	Greenhouse gas	PV	Photovoltaics
H_2	Hydrogen	RES	Renewable Energy Sources

2. Methodology

Renewable energy resources are spatially distributed, and their potential to contribute to societal energy supplies is dependent on local geographic nuances [12]. Hence, spatial analysis represent the optimal tool for mapping and evaluating renewables potential. Then, it is possible to plan sustainable energy scenarios and design the most suitable strategies. Thus, as Figure 1 shows, the 1st step of the study is supported by GIS software use to estimate local biomass and solar sources availability.

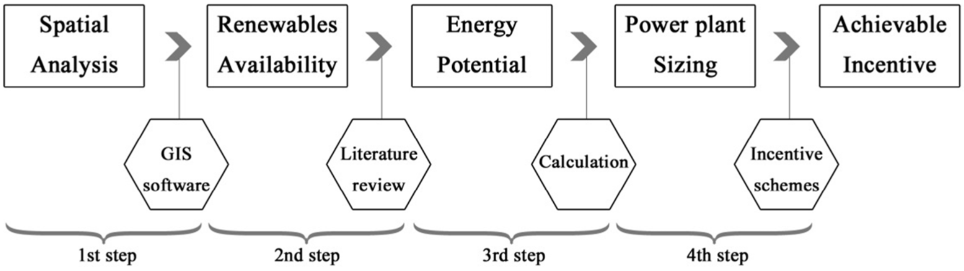

Fig. 1. Methodology flow chart.

These data have been multiplied for energy potential from scientific literature and the gross energy potential is obtained. Assuming the CHP plant operation time for 4,000 hours/year, its optimal size was identified. Finally, taking into account power plant features in terms of technology, size and efficiency, the amount of incomes from governmental incentives in force for bioenergy and hypothesized for renewable hydrogen (produced by PV installation) [8] has been calculated.

3. Data sources

Research project has analysed biomass resources and solar energy due to their tight link to the territory, in terms of availability dependence on territorial features such as morphology, climatic characteristics, accessibility level and infrastructures [13]. In details, the considered spatial analysis was previously carried out as shown below:

1. solar energy: having evaluated the specific solar radiation on the horizontal plan (kWh/m^2) of the analysed areas, all suitable surfaces to install photovoltaic plants were assessed, considering preferentially the ones integrated in the top of the buildings, gathering for each roof the approximate angle of slope and solar exposure information. This calculation has not included shaded areas and surfaces on the top of the buildings characterized by particular constraints or conditions which make infeasible any photovoltaic cells installation (i.e. roofs of churches and other historical buildings);
2. biomass energy: having analysed the CLC (Corine Land Cover) map and the relative land use of each area, taking into account established agro-forestry ecosystems, the potential areas for biomass residues production were highlighted and their bioenergy availability was calculated without considering dedicated crops.

In particular, only following categories were considered:

- Herbaceous: crop residues generated by agricultural production (i.e. wheat, barley, maize, rye, rapeseed, sunflower, etc.);
- Arboreal: wood residues generated by management of perennial crop plantations such as pruning and replanting of trees (i.e. vineyards, olive groves, fruit trees, etc.);
- Forests: cutting or lopping trees purely for fuel wood, collecting deadwood.

All operations were performed and recorded using GIS software and elaborating satellite images. In order to estimate the local renewable resources distribution and availability, in the two case-studies, to build scenarios for biogas (derived from biomass gasification) and hydrogen production (derived from hydrolysis feed with PV), the SoURCE project outcomes [14-16] were used. This project was carried out by Sapienza University of Rome, jointly with KTH - Royal Institute of Technology of Stockholm and its main aim was to assess how local renewable sources can contribute to meet municipal energy needs. Table 1 reports data obtained by SoURCE project (spatial analysis outcomes), and relative elaborations concerning 2nd methodology step to quantify the available amount of biomass and solar sources.

Table 1. Biomass and solar sources availability in the case studies

Municipality	Biomass typology	Available Surface (ha)	Available Residue (t/ha)	Annual Availability (t)	Direct Normal Irradiation (kWh/m^2)	PV Available Surface (m^2)	Annual Gross Solar Radiation (kWh)
Trevignano	Herbaceous Arboreal Forest	416.64 702.52 96.65	2.51 [17] 1.97 [17] 2.14 [18]	1045.77 1383.97 206.83	1,507 [19]	58,290	87,843,030
Sabaudia	Herbaceous Arboreal Forest	3,859.44 553.16 994.72	2.51 [17] 1.97 [17] 2.14 [18]	9687.19 1089.73 2128.70	1,519 [19]	55,960	85,003,240

Furthermore, the total gross energy potential for each municipality has been calculated by multiplying renewables (solar and biomass) annual availability, suitably by a factor related to feasible energy deployment, for their gross energy content (2nd step). These data are reported in Table 2.

Table 2. Renewable gaseous sources (syngas and hydrogen) in the case studies

Municipality	Gross Energy from Biomass (kWh)	Bio Syngas Production Rate (Nm^3/kWh)	Syngas Volume (Nm^3)	Gross Energy from Solar (kWh)	PV Hydrogen Production Rate (Nm^3/kWh)	Hydrogen Volume (Nm^3)
Trevignano	9,746,200	0.45	4,331,640	12,534,679	0.024	300,832
Sabaudia	51,978,360		23,101,491	12,129,458		291,107

Within 3th methodology step (Energy potential) biomass and solar gross energy have been converted respectively in syngas by gasification process and hydrogen by hydrolysis. Syngas PR from biomass has been estimated considering biomass thermal pre-treatment and purification process, while hydrogen PR has been assessed taking into account PV electrical efficiency and hydrolysis process.

Finally, according to 4th methodology step, it is possible to identify power plant size based on previous resources availability analysis. Both bioenergy CHP plant configurations have an electrical efficiency equal to 0.2, whereas H_2NG configurations have respectively 0.32 (4%H_2) and 0.335 (20%H_2).

Bioenergy optimal sizing is described in Equation 1:

$$P_B = \sum \frac{\dot{m} \times LHV \times \eta_g \times \eta_{CHP}}{t_o} \tag{1}$$

Where:

- P_B is the electrical size of the bioenergy power plant;
- $\dot{m}$ is the available biomass amount;
- LHV is the biomass lower heating value;
- η_G is the gasification process efficiency;
- η_{CHP} is the cogeneration electrical efficiency;
- t_o is the operation hours amount.

Bioenergy plant sizing is based on 4,000 operation hours. In Trevignano Romano, total energy potential of bioenergy CHP is 300 kW_{el}, whereas in Sabaudia it is 1,500 kW_{el}.

According to Distributed Generation model, a 300 kW_{el} size was chosen: in Trevignano Romano with one CHP plant and in Sabaudia with five ones. This feature allows a comparison between the two CHP plant of the same size, in terms of economic analysis, owing to different primary energy mixes.

Then, optimal sizing of CHP fuelled with H_2NG blend is identified by Equation 2.

$$P_{H_2NG} = \frac{1}{1 - f_{H_2}} \times \sum \frac{E_S \cdot \eta_{pv} \cdot \eta_{hy} \cdot \eta_{CHP}}{t_o} \tag{2}$$

Where:

- P_{H2NG} is the electrical size of the hydro-methane power plant;
- f_{H2} is the hydrogen volume fraction in H_2NG blend;
- E_s is the available solar energy;
- η_{pv} is the PV conversion efficiency considering operational time of 1,250 hours;
- η_{hy} is the hydrolysis process efficiency;
- η_{BCHP} is the cogeneration electrical efficiency of H_2NG blend;
- t_o is the operation hours amount.

Having identified the optimal size for bioenergy supply chain, the suitable renewable hydrogen ratio for H_2NG blend in the two case studies was calculated. Thus, through the last methodology phase, it is possible to evaluate the most profitable solution, in terms of carbon avoidance cost, for a sustainable energy supply fuelled with local renewables.

4. Results and Discussion

In this section, an economic analysis organized in two hybrid system scenarios is developed. As shown in Figure 2, two different local bioenergy mixes have been considered.

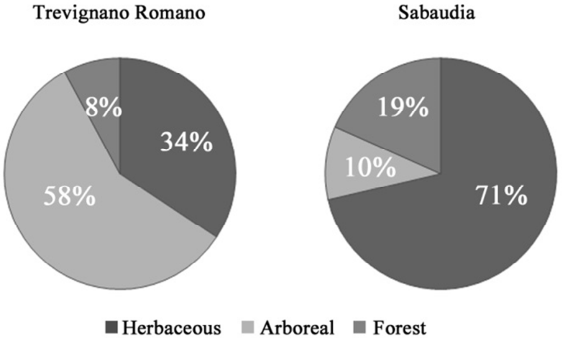

Fig. 2. Different biomass fractions in the two case studies.

In addition, two Renewable Hydrogen, from local PV, mixtures with Natural Gas have been elaborated: a H_2 volume fraction of 20% in Trevignano Romano and another one of 4% in Sabaudia.

In details, PV surface dedicated to H_2 production in H_2NG blend (20% H_2) in the first case study is about 3,160 m^2 out of 58,290 m^2. While it is about 475 m^2 out of 55,960 m^2 in the second one (4% H_2). Excess electricity, derived from not H_2-dedicated PV panels was sold to the grid. Thus, power production costs are related to all technological appliances of the two CHP plant configurations. The costs related to the four energy supply chain are reported in Table 3 (bioenergy mixes) and in Table 4 (H_2NG blends).

Table 3. Power production costs in the Bioenergy scenarios

Municipality	Biomass supply chain (€) [20]			Gasification (€)	Purification (€)	CHP (€)	O & M (€)	Total Costs (€) (20 years)
	Herbaceous	Arboreal	Forest					
Trevignano (Biomass)	49,150	53,980	6,330	1,350,000	115,000	360,000	75,000	5,514,200
Sabaudia (Biomass)	91,050	8,500	13,050	1,350,000	95,000	360,000	75,000	5,557,000

Table 4. Power production costs in the H_2NG scenarios

Municipality	PV panels (€)	Electrolyser (€)	Mixer (€)	CHP (€)	Natural Gas (€)	O & M (€)	Total Costs (€) (20years)
Trevignano (20% H_2)	948,000	591,290	284,500	360,000	228,500	25,000	7,253,790
Sabaudia (4% H_2)	142,500	100,300	45,000	360,000	231,910	25,000	5,786,000

Two hybrid scenarios consist of two 300 kW_{el} CHP plants, one fuelled with bioenergy and one with H_2NG. Furthermore, the difference between total costs in the operational period (20 years) and total incomes derived from governmental incentive schemes in force [21] (bioenergy) and hypothesized, derived from PV energy production [8] (H_2NG), has been calculated, as reported in Table 5.

Table 5. Incentives and Net Value in the case studies

Municipality	Incentive (€/kWh_{el})	Annual Incentive (€)	Total Incentive (€) (20 years)	Total Net Value (€)
Trevignano (Biomass)	0.236	283,200	5,644,000	+129,800
Sabaudia (Biomass)	0.236	283,200	5,644,000	+87,000
Trevignano (20% H_2)	0.105	126,554	2,531,080	-4,722,710
Sabaudia (4% H_2)	0.018	21,408	428,160	-5,357,840
Trevignano (Biomass+20%H_2)				**-4,592,910**
Sabaudia (Biomass+4%H_2)				**-5,270,840**

CO_2 emissions associated to 1 kWh_{el} are reported in Table 6, not accounting biogenic CO_2 for as a GHG emission [22]. Current Italian scenario is based on a CO_2 emission rate of 406 g/kWh_{el} [23].

Table 6. Emissions and Associated Carbon Avoidance in the case studies

Municipality	Emission (g/kWh_{el})	Corrected Emission [24] (g/kWh_{el})	Annual Emission (t)	PV Annual Emission avoided (t)	Total Emission (t) (20 years)	Total Emission (t) BAU Italy	Carbon Avoidance (t) (20 years)
Trevignano (Biomass)	14.40		17.28	-	345.6	9,648	9,302.64
Sabaudia (Biomass)	21.60		25.92	-	518.4		9,129.60
Trevignano (20% H_2)	549.29	109.29	131.148	-178.41	-945.24		10,593.24
Sabaudia (4% H_2)	630.09	190.09	228.108	-30.18	3,958.56		5,689.44
Trevignano (Biomass+20%H_2)							**19,895.88**
Sabaudia (Biomass+4%H_2)							**14,819.04**

Finally, carbon avoidance cost has been used to compare the two hybrid solutions and to identify the most sustainable one. As reported in Table 7, the best scenario is Trevignano. Its carbon avoidance cost is 0.23085 €/kg_{CO2}.

Table 7. Carbon Avoidance cost in the case studies

Municipality	Carbon Avoidance Cost (€/kg_{CO2})
Trevignano (Biomass+20%H_2)	0.23085
Sabaudia (Biomass+4%H_2)	0.35568

5. Conclusion

Based on the study results, it is clear that accounting Carbon biogenic emission as neutral is crucial to consider environmental-friendly the bioenergy production. Building a hybrid scenario allows to exploit different renewables at the same time to obtain the most convenient carbon avoidance cost. All the obtained results can be implemented in a GIS database to elaborate queried maps [25,26], pinpointing areas where renewables availability is suitable. In conclusion, Eco-fuels represent a sustainable energy pathway at local scale.

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