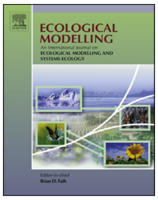
Ecological Modelling xxx (2014) xxx–xxx

Contents lists available at ScienceDirect

Ecological Modelling

journal homepage: www.elsevier.com/locate/ecolmodel



An exergy-based approach to the joint economic and environmental impact assessment of possible photovoltaic scenarios: A case study at a regional level in Italy

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ARTICLE INFO

Article history:
Available online xxx

Keywords:
Exergy
Thermoeconomics
Extended exergy accounting
Thermo-Ecological Cost
Off-design
Photovoltaic

ABSTRACT

Most energy conversion systems, and especially electricity generation plants, do not operate at nominal conditions throughout their useful life: periodic, semi-periodic and stochastic changes in the availability of the resource affect solar (thermal and PV), wind, hydraulic, and geothermal plants, which in reality operate at off-design conditions for most of their life. To a smaller extent, fossil-fuelled plants may also be plagued by fuel availability problems and no longer easily predictable demand oscillation. In spite of the ever growing net connectivity, since the demand curve in even larger geographic regions displays a typical quasi-sinusoidal shape, fleet load modulation is unavoidable. Naturally, off-design operation and load cycling affect the cost of the generated kWh.

This paper presents a general thermoeconomic method to evaluate the economic and environmental effects of energy system integration, taking into account life cycle concerns (supply chains) and the effect of inefficiencies due to off-design operation of the systems. The method here is applied to a realistic case study of an Italian regional utility: an analysis of the implications of the variation of the productive mix between a photovoltaic power plant (PV) and a standard commercial, non-cogenerating gas turbine plant (GT) on the final cost of the electrical kWh. The demand curve is prescribed, and the effect of different mixes is assessed, both on the monetary and on the exergy cost of the electricity.

The economic cost assessment is performed by standard thermoeconomic techniques, whereas the exergy costs are evaluated using both the Extended Exergy Accounting (EEA) and the Thermo-Ecological Cost (TEC) methods. The results show that a purely monetary cash flow accounting and thermoeconomics lead to contrasting results, and also that the EEA and TEC cost indicators generate different rankings among the studied alternative GT/PV mixes.

1. Introduction: impact assessment of energy conversion systems

In modern industrial societies, engineers, system analysts and policy makers are required to deal not only with the economics of the design and operation of energy systems, but also with issues of natural resource scarcity and with the need for an evaluation of the global impact of the conversion system on human society and environment.

The hitherto "virtuous" design goal of reducing the exploitation of natural energy resource while maximizing first and second law efficiencies on a life-time basis is undergoing a radical re-evaluation, in response to the acknowledged interdependency of the energy sector with both the environment and the society at large (Rocco et al., 2014a). The impact of an energy conversion system (ECS), evaluated with a life-cycle approach, must include the effects at local and global scales on the surrounding environment and on the society in which the system is called to operate. Such a "holistic" design approach requires that, from the analyst's perspective, the total (embodied) consumption of natural resources (that includes the effects of non-energetic externalities such as human labor and capital expenses) must be taken into account. To achieve this, it is necessary a) to identify an adequate quantitative measure of the real consumption of natural resources on the part of the system, and b) to apply the selected numeraire to

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http://dx.doi.org/10.1016/j.ecolmodel.2014.11.006
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Nomenclature

A	area (m^2)
c	cost per exergy unit (€/J–J/J)
$\dot{C}$	cost of a flow (€/S–J/S)
CExC	cumulative exergy consumption (J/J)
EE	extended exergy (J)
eec	specific extended exergy cost (J/J)
ee_K	exergy equivalent of the monetary unit (J/€)
ee_L	exergy equivalent of labor (J/h)
$\dot{E}x$	exergy (W)
LCOE	levelized cost of energy
M	mass flow rate (kg/s)
$M2$	total monetary circulation within a society (€)
n	rotating speed (rpm)
N	number, amount of
N_{wh}	cumulative number of work-hours generated by a society
P	pressure (kPa)
P	power (W)
T	temperature (K)
t	time (s)
tec	specific Thermo-Ecological Cost (J/J)
TEC	Thermo-Ecological Cost (J)
$\dot{Z}$	cost of a system (€/S–J/S)
α, β	1st and 2nd econometric factor

Subscript/Superscript

CO_2	carbon dioxide
D	destruction
eco	economic
Env	environment
ex	exergetic
fuel	fuel
gen	generated
l	loss
i, j, l, k	-th material or energy flux
in	inflow
K	monetary capitals
L	labor
om	operating & maintenance
P	product
R	resource
tot	total

a scenario that includes the whole system's life cycle and the effect of the non-energetic externalities on resources consumption.

1.1. Assessment of the economic and environmental impact of an ECS

Exergy is the real "value" of energy exchanges, so much that a paradigm has been proposed called Exergy Cost Theory in which "cost" is defined as the amount of exergy embodied in a unit of material or immaterial goods. Such a perspective constitutes the theoretical foundation of Thermo-economics (TA) (Valero et al., 1993), whose scope is to allocate the production cost among products in multi-product chains, cost being defined in a broad sense as "any effort that has to be made in order to obtain the considered useful effect".

Thermoeconomic analysis evolved into two main categories, which differ for the cost paradigm they adopt:

1. economic cost: indicates the cost of any system product, in terms of € for exergetic Joule; (Tsatsaronis, 1993)
2. exergetic cost: indicates the cost as the amount of energy and materials (expressed by means of their exergy equivalents) involved in the production of any system products and it is expressed in J_{ex}/J_{ex}.

TA is a monetary costing technique that combines second law principles with traditional cost accounting methods and it is considered a standard tool in both academic studies and industrial applications (Lee et al., 2014; Petrakopoulou et al., 2013). When used in the second acceptance, TA constitutes a proper framework to evaluate the global (i.e., life cycle) consumption of natural resources: if an exergy cost, rather than a monetary one, is attributed to all resources involved in the energy system production, the cost of the final product turns out to be evaluated in the same units (J per kg or per unit). The results of the literature review and a thorough discussion about the standard and advanced exergy based techniques can be found in (Rocco et al., 2014a).

1.2. The Italian electric generation system and the growing role of photovoltaics

In the last two decades, the installed power of photovoltaic systems has increased exponentially in the Italian electric system (Association, 2010; GSE, 2011). By the end of 2012, the installed photovoltaic peak power in the Italian grid amounted to 16,450 MWe, producing 18,862 GWh electric energy per year, about 3% of the national electricity consumption. More than 95% of the total installed PV capacity consists of grid-connected PV plants (Programe, 2010). Fig. 1 shows the growth of installed PV peak power from 2007 up to 2012 (solid line). Due to the severe reduction of the Feed In Tariff (FIT), it is unlikely that Italy will maintain this rising trend in the near future (Barnham et al., 2012; Meneghello, 2012). However, the current Italian energy strategy requires that the installed capacity continue to grow by 1 GWe per year (dotted line in Fig. 1), reaching almost 25 GWe of installed capacity by 2020 (GSE, 2011), more than 30% of the 2020 expected total installed capacity. A current open issue is the quantification of the economic and environmental impact of such a large integration of photovoltaic peak power with the Italian power system. In this perspective, thermoeconomic help in evaluating the effects of different future scenarios on both the economic and environmental costs of the generated electricity. It is important to emphasize that the environmental cost is evaluated in TE in terms of natural resources consumption, and that other possible impacts on environment, such as toxicity and effects of pollutants in terms of global warming or biodiversity, are not taken into account.

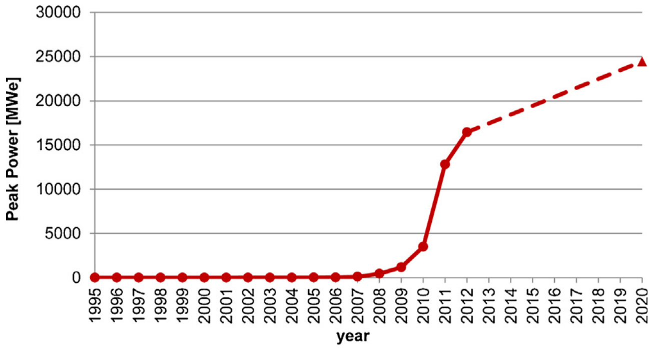

Fig. 1. Cumulative installed photovoltaic peak power from 1995 to 2020. IEA data (Programe, 2010).

Please cite this article in press as: Colombo, E., et al., An exergy-based approach to the joint economic and environmental impact assessment of possible photovoltaic scenarios: A case study at a regional level in Italy. Ecol. Model. (2014), http://dx.doi.org/10.1016/j.ecolmodel.2014.11.006