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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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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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
I	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.

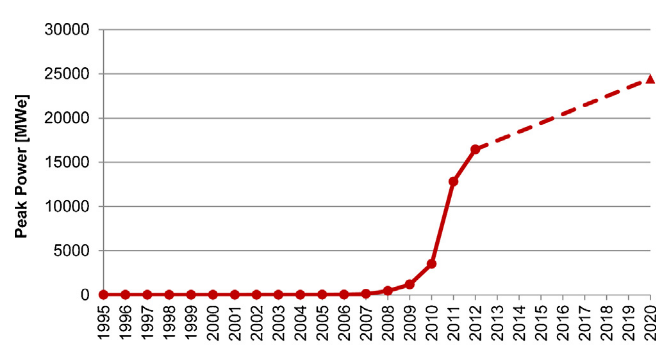

Fig. 1. Cumulative installed photovoltaic peak power from 1995 to 2020. IEA data (Programe, 2010).

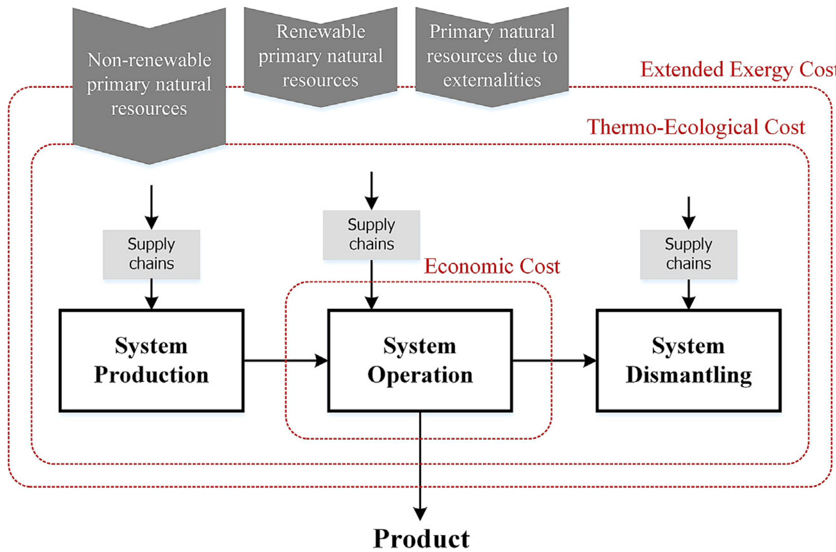

Fig. 2. The different System boundaries for the calculation of the economic, thermo-ecological, and extended exergy cost.

2. Proposed approach

The novel approach proposed here provides a more consistent evaluation of both the monetary and primary resource impact of the integration of renewable peak power capacity with a pre-existing energy conversion system. With reference to Fig. 2, for every given scenario the main steps of the proposed approach are:

1 data collection and thermodynamic modeling of the energy conversion system;
2 thermoeconomic analysis:

a economic cost analysis: investment and operative costs, Feed In Tariff, effects of off-design operation, etc;
b total environmental cost analysis: calculation of the total embodied exergy costs of the system product considering both renewable and non-renewable contributions. These costs include direct resource consumption, plant equipment production, operating and maintenance and externalities, according to the extended exergy cost (EE) paradigm;
c partial environmental cost analysis: calculation of the embodied exergy costs of the kWh related to the non-renewable primary natural resources according to the Thermo-Ecological Cost (TE) paradigm;

3 determination of the main cost indexes:

a monetary cost of system products;
b embodied exergy costs of system products, exergy pay back time (ExPBT), exergy return factor (ExRF);

4 comparison of each scenario based on the calculated indicators;

Considering a system operating at steady state as shown in Fig. 2, once its energy and material flow diagrams have been properly quantified, the general thermoeconomic mathematical system can be written as follows:

$$\sum_i \dot{\text{E}}\text{x}_{\text{R},i} = \sum_j \dot{\text{E}}\text{x}_{\text{P},j} + \sum_l \dot{\text{E}}\text{x}_{l,1} + \dot{\text{E}}\text{x}_{D,\text{tot}} \tag{1}$$

$$\sum_i \dot{C}_{\text{R},i} + \dot{Z}_{\text{tot}} = \sum_j \dot{C}_{\text{P},j} + \sum_l \dot{C}_{l,1} \tag{2}$$

$$\dot{C}_k = c_k \times \dot{\text{E}}\text{x}_k \tag{3}$$

Eq. (1) is the exergy budget, written according to the resource/product/waste (R/P/I) criterion and expressed in terms of exergy rates (J/s) assuming the system operates at steady state: a generic system has i resource inputs, j product outputs, l waste streams and it is affected by a total amount of irreversibility represented by the exergy destruction rate term. Eq. (2) is the cost balance of the system: it is also written according to R/P/I criterion in terms of cost (J_{ex}/s, €/s), and it includes the fixed costs term $\dot{Z}_{tot}$, which represents all costs that are not directly associated to an exergy flow, such as the costs of the system operation and maintenance, of the externalities, etc. The conceptual link between the exergy budget (1) and the cost balance (2) is given by the constitutive relation (3), that expresses the cost of a generic flow k as the product of its associated exergy rate $\dot{\text{E}}\text{x}_k$(J/s) times its cost per exergy unit c_k (J/J, €/J). The application of this generic thermoeconomic mathematical formulation to a complex energy system with different components and multiple inputs and outputs requires the introduction of a number of auxiliary costing relations. A detailed mathematical treatment of the numerical approach to thermoeconomics for industrial processes, based on input-output techniques and can be found in (Querol et al., 2012; Usón et al., 2012).

Table 1
Reference gas turbine operative parameters.

Parameter	u.m.	Value
Nominal power	MW	70
Gas turbine adiabatic efficiency	%	87.7
Compressor adiabatic efficiency	%	88.0
Pressure ratio	–	12.7:1
Thermal efficiency	%	32.7
Turbine speed	rpm	3600

Table 2
Reference PV operative parameters.

Parameter	u.m.	Value
Nominal power	kW	250
Module efficiency	%	15.37
Maximum power voltage V_{mpr}	V	30.02
Maximum power current I_{mpr}	A	8.33
Temperature coefficient of P_{max}	%/°C	−0.46
Module size	mm	1640 × 992 × 40

Table 3
Scenario's main parameters.

Symbol	Units	0 (REF)	1 (GTopt)	2 (PV 10)	3 (PV 30)	4 (PV 60)
P_{TG}	MW_e	70	52.4	70	70	70
P_{PV}	MW_e	0	0	10	30	60
A_{PV}	m^2	–	–	58 406	175 219	350 438
$N_{md,pv}$	n	–	–	40 000	120 000	240 000

In the following paragraphs, the cost balance (2) is rewritten to account respectively for the economic and the embodied exergy costs of the system product.

2.1. Economic cost evaluation: standard thermoeconomic analysis

In standard TA, the cost balance (2) and the constitutive relations (3) are written replacing the generic costs with their respective monetary costs:

$$\sum_i \dot{C}_{€,R,i} + \dot{Z}_{€,tot} = \sum_j \dot{C}_{€,P,j} + \sum_l \dot{C}_{€,l,l} \tag{4}$$

$$\dot{C}_{€,k} = c_{€,k} \times \dot{E}x_k \tag{5}$$

where $\dot{C}_€$represents the cost of the generic exergy flow (€/s), $c_€$ is the specific cost of the considered exergy flow (€/J), and $\dot{Z}_{eco}$is the cost not directly associated to an exergy flow (€/s), such as fixed investments, operating and maintenance, feed in tariff, taxes, etc.

$$c_{€,P} = \frac{\dot{C}_{€,P}}{\dot{E}x_P} \tag{6}$$

The objective of the analysis is to calculate the monetary cost of the system product, as expressed by (6), for each given scenario. As expected, it will be shown below that in the case study discussed here, where there is only one product, namely electricity, the TA cost of the system product is the same as the levelized cost of electricity (LCOE).

2.2. Embodied exergy cost evaluation: EEA and TEC analyses

The cost balance (2) and the constitutive relations (3) are here rewritten by replacing the generic costs with their respective exergetic costs:

$$\sum_i \dot{C}_{ex,R,i} + \dot{Z}_{ex,tot} = \sum_j \dot{C}_{ex,P,j} + \sum_l \dot{C}_{ex,l,l} \tag{7}$$

$$\dot{C}_{ex,k} = c_{ex,k} \times \dot{E}x_k \tag{8}$$

where $\dot{C}_{ex}$ represents the embodied exergy cost of the generic stream (J/s), c_{ex} its specific counterpart (J/J) and $\dot{Z}_{ex}$ is the embodied exergy cost not directly associated to an exergy flow (J/s). In this study, two different cost paradigms were compared: the extended exergy (EE) (Sciubba, 2013; Chen and Chen, 2009; Dai et al., 2012) and the Thermo-Ecological Cost (TEC) (Szargut and Stanek, 2007; Szargut et al., 2002). Without entering details, embodied exergy costs are computed on the basis of validated numerical procedures and databases developed in the field of Industrial Ecology (Suh 2009; UNI, 2001).

2.2.1. The extended exergy cost

Extended exergy (EE) is defined as the total amount of equivalent primary exergy (expressed in J) needed to generate a product. It measures the primary resource consumption by means of a systematic and reproducible thermodynamic procedure that allows for the formulation of an exergy budget for the so-called externalities, i.e., labor, capital, and environmental remediation cost.

The application of the EE costing techniques is called extended exergy accounting (EEA), and its details are described in (Dai et al., 2014; Rocco et al., 2014b; Sciubba, 2013). With reference to Fig. 2, the EE of a product is computed as the sum of the primary exergy consumption of each one of the cost factors in common use among industrial economists: materials, energy (all forms), capital, human labor, environmental remediation. The cumulative consumption of primary exergy involved in the production of an energy or material flux is known as Cumulative Exergy Consumption (CExC) (Bösch et al., 2007; Feng et al., 2004). For the remaining three cost factors, EE proposes a specific paradigm, see below.

Therefore, the EE of a generic "product" p (be it a material or immaterial commodity, a process or the entire production chain) results from the life-cycle integral:

$$EE_p = \int_{LC} (CExC_p + EE_{L,p} + EE_{K,p} + EE_{Env,p})\,dt \tag{9}$$

From its very definition, it follows that the "control volume" considered by an EE analysis must be ideally expanded to

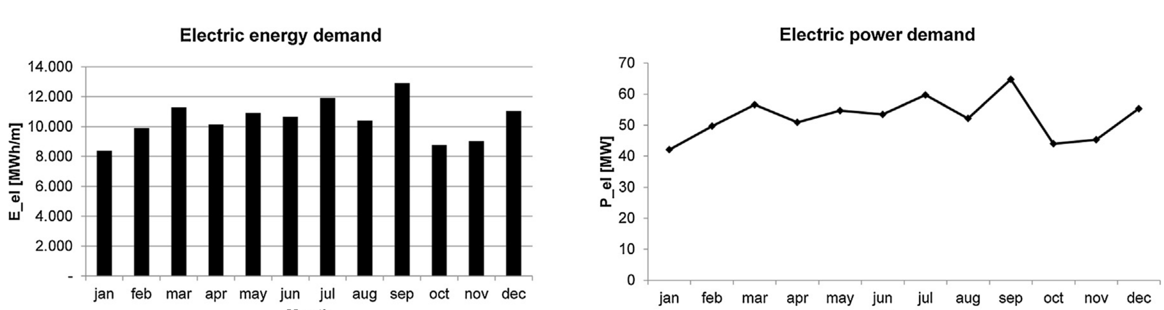

Fig. 3. Monthly distributions of the electric energy and of the peak power demands.

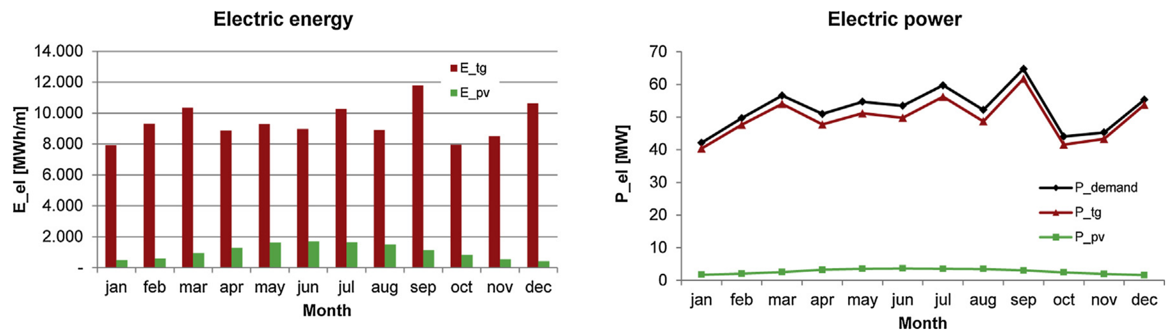

Fig. 4. Monthly distribution of electrical energy and power for Scenario 2.

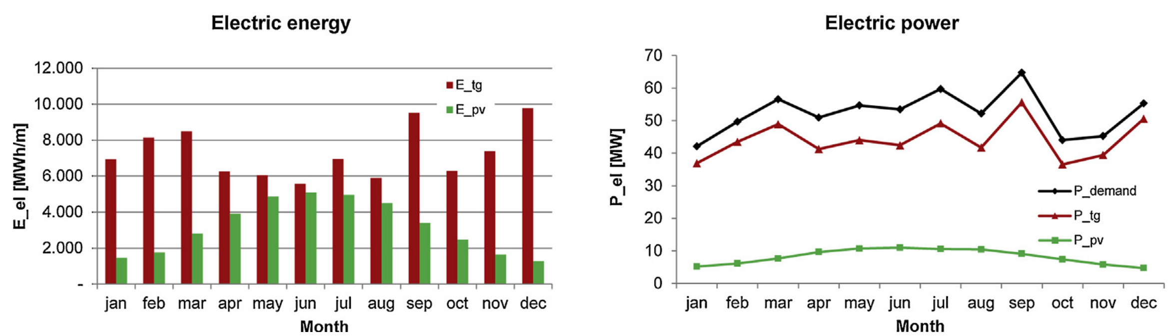

Fig. 5. Monthly distribution of electrical energy and power for Scenario 3.

encompass the mines, wells, quarries, etc., on the one end, and the recycling plant or the landfill on the opposite end.

EEA has been successfully applied to analyze and optimize individual components as electrical wires (Rocco et al., 2014b), energy systems as traditional gas turbines and biogas plants (Dai et al., 2014; Sciubba, 2004), complex processes and supply chains (Talens Peiró et al., 2010), societal sectors, and complex systems (Chen et al., 2014; Chen and Chen, 2009; Dai et al., 2012; Sciubba et al., 2008). Its objective is to determine for each given scenario the specific extended exergy cost of the system product, as expressed by (10), where $\dot{C}_{\mathrm{ee,P}}$ is the total EE cost in J/s and $c_{\mathrm{ee,P}}$ specific EE cost of the system product, both in J/J.

$$c_{ee,\mathrm{P}} = \frac{\dot{C}_{ee,\mathrm{P}}}{\dot{\mathrm{E}}\mathrm{x}_{\mathrm{P}}} \tag{10}$$

The EEA method is based on two fundamental postulates, needed to compute the extended exergy equivalents of labor and monetary capital.

- 1st postulate: in any society, a portion of the global influx of exergy resources Ex_{in} is "used" to directly or indirectly sustain the workers who generate labor. In exergy terms:

$$\mathrm{Ex_L} = a \times \mathrm{Ex_{in}} \tag{11}$$

- 2nd postulate: the exergy flux needed to generate the monetary circulation within a society is proportional to the loabor exergy. In exergy terms:

$$\mathrm{Ex}_k = \beta \times \mathrm{Ex_L} \tag{12}$$

where both α and β are numerical factors that depend on the type of societal organization, the historical period, the technological level, and the geographic location of the society. Their value is not assigned by the theory, and must be calculated from econometric data: this "anchors" an EE analysis to the location and the instant of

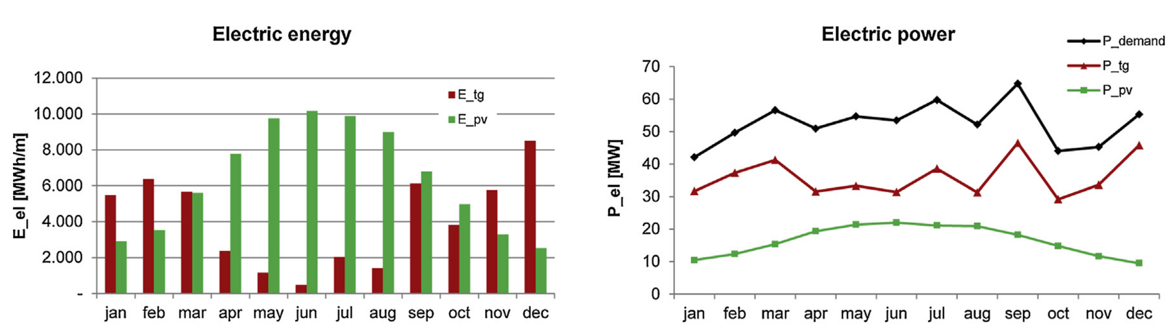

Fig. 6. Monthly distribution of electrical energy and power for Scenario 4.

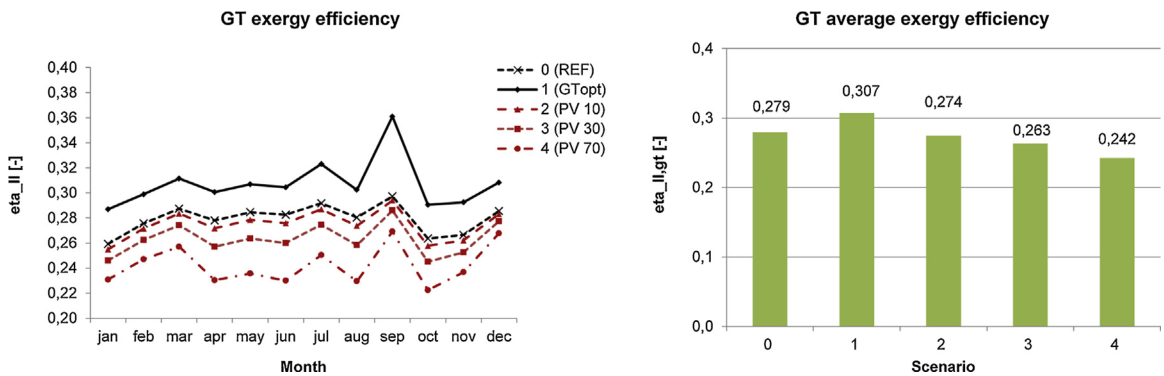

Fig. 7. GT exergy efficiency for every scenarios.

Table 4
Values of the system operative parameters assumed for the simulations.

Symbol	Units	Value	Description
T_0	K	298.15	Reference environment temperature
p_0	kPa	101.3	Reference environment pressure
η_{PV}	%	14	PV module nominal efficiency
η_{inv}	%	90	Inverter efficiency
η_s	%	90	PV Auxiliares efficiency

time in which it was performed, and also constitutes its explicit validation, because if α and β assume values such that the cost balances in which Eqs. (11) and (12) are used do not close or lead to unphysical results, this would falsify the theory.

The primary exergy equivalent of one work-hour is obtained by dividing the net total exergy flux that goes into labor by the cumulative number of work-hours generated in a given period of time:

$$ee_L = \frac{\alpha \times Ex_{in}}{N_{wh}} [J/workhour] \quad (13)$$

Similarly, to compute the primary exergy equivalent of one monetary unit, the total exergy flux allocated to capital by the second postulate is divided by the cumulative monetary circulation maintained for that period of time (expressed by the monetary aggregate M2):

$$ee_K = \frac{\alpha \times \beta \times Ex_{in}}{M2} [J/€] \quad (14)$$

A detailed discussion about these exergy equivalents is provided in (Sciubba, 2011), while their values calculated for the Italian society in 2010 can be found in (Rocco et al., 2014b; Sciubba, 2011).

Finally, the EEA evaluates the environmental externality with a remediation approach: the exergy equivalent amount of all the primary resources needed to eliminate the effects of all system effluents on the environment, denoted EE_{Env}, is calculated as the additional EE of the (real or virtual) processes needed to treat the effluents so that the exergy of each one of them is equal to 0 at the discharge site.

2.2.2. The Thermo-Ecological Cost

According to Szargut (Szargut, 2005; Szargut et al., 1988), the future existence of the human species is endangered by our excessive consumption of non-renewable natural resources; therefore, a minimization of such exploitment would constitute an essential step toward the conservation of both the society and the natural environment. The Thermo-Ecological Cost (TEC) is the cumulative consumption of non-renewable primary natural resources over the life cycle of the considered system or process. In this perspective, with reference to Fig. 2, TEC takes into account only a subset of the EE cost factors, namely the non-renewable

Table 5
Main data for economic cost analysis.

Symbol	Units	GT plant	PV plant	Description
C_{equity}	%	20	Share on equity	Share on equity
C_{debt}	%	80	Share on debt	Share on debt
i	%	6	Interest rate on debt	Interest rate on debt
r	–	0.01	Escalation of O&M costs	Escalation of O&M costs
$op_{life,GT}$	y	25	Economic operative life GT	Economic operative life GT
$op_{life,PV}$	y	25	Economic operative life PV	Economic operative life PV
Z_{inv}	€/kWe	200	1.000	Investment cost
$Z_{om,fixed}$	€/(kW*y)	6	35	Fixed o&m cost
$Z_{om,variable}$	€/MWh	9	–	Variable o&m cost
c_{fuel}	€/Nm^3	0.3	–	Fuel cost
c_{CO_2}	€/t	6	–	Cost of CO_2 emissions
TO	€/MWh		113	Tariffa omnicomprensiva
ee_{MP}	€/MWh		60	Electric energy average price
FIT	€/MWh	–	53	Feed in tariff

Table 6
Total economic cost of the system product, in M€/y.

Symbol	Units	0 REF	1 GTopt	2 PV 10	3 PV 30	4 PV 60	Description
$C_{inv,GT}$	M€	14.00	10.48	14.00	14.00	14.00	Investment cost, GT
$C_{om,GT}$	M€/y	1.55	1.44	1.43	1.21	0.86	o&m cost, GT
$C_{fuel,GT}$	M€/y	13.06	11.88	11.95	9.66	5.91	Fuel cost, GT
$_{,GT}$	M€/y	0.51	0.47	0.47	0.38	0.23	CO_2 emissions cost, GT
$C_{P,GT}$	M€/y	16.39	14.76	15.10	12.47	8.19	Total cost of electricity, GT
$C_{inv,PV}$	M€	–	–	10.00	30.00	60.00	Investment cost, PV
$C_{om,PV}$	M€/y	–	–	0.35	1.05	2.10	o&m cost, PV
FIT	M€/y	–	–	0.66	1.98	3.96	Feed in tariff, PV
$C_{P,PV}$	M€/y	–	–	1.34	4.01	8.01	Total cost, PV
$C_{P,PV,FIT}$	M€/y	–	–	0.67	2.02	4.05	Total cost with FIT, PV
$C_{P,GT+PV}$	M€/y	16.39	14.76	16.44	16.47	16.20	Total cost, GT + PV
$C_{P,GT+PV,FIT}$	M€/y	16.39	14.76	15.78	14.49	12.24	Total cost w FIT, GT + PV

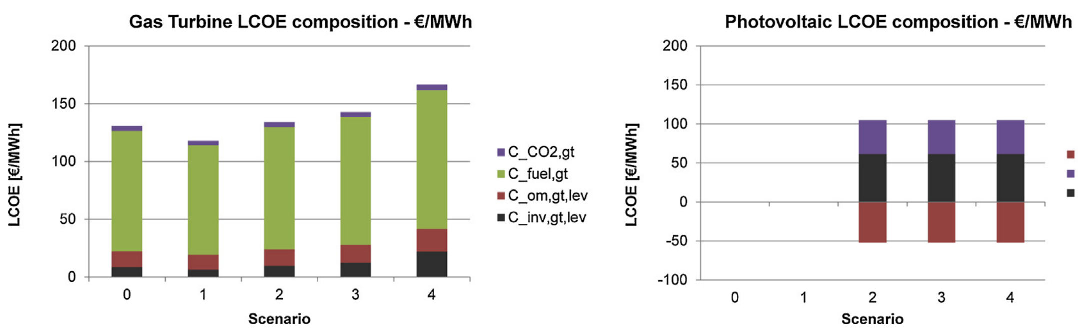

Fig. 8. Levelized cost of energy for the single GT and PV plants.

part. In a way completely analogous to EE, the TEC results from a double integration (in space and time) of the above mentioned cost factors.

The idea underlying the present study is to compare the results of the application of EE and TE costs to the same system, trying to gain some additional insight about the quantitative assessment of the appropriateness of the integration of renewables into a fossil-fuelled electricity generation network. While EEA relies only on its "extended exergy cost" c_{EE} as a measuring stick, TEC proposes two indicators.

- Exergy pay back time (ExPBT) (Font de Mora et al., 2012), measured in years, is defined as the ratio of the total TEC of the product to the yearly primary exergy savings due to electricity generated by renewables:

$$\text{ExPBT} = \frac{\text{Ex}_{\text{input}}}{\text{Ex}_{\text{gen}}}[\text{years}] \tag{15}$$

- Exergy return factor (ExRF): in complete analogy with the energy return factor (ERF) proposed in (Alsema, 1997), an ExRF can be formulated as the ratio of the total exergy generated by the renewable system divided the total primary non-renewable exergy embodied in its life cycle (i.e., its TEC):

$$\text{ExRF}_i = \frac{\text{Ex}_{gen,i,tot}}{TEC_i}[\text{J/J}] \tag{16}$$

3. Description of the case study

The system taken as a case study in this paper consists of a simple cycle gas turbine power plant operating under variable load conditions. Several scenarios have been analyzed that differ from each other with respect to the generation mix: to more loosely reflect the actual state of affairs, each scenario considers a different PV installed power while the GT plant keeps the same fixed installed nominal power operating as a peaking power plant. The GE 7EA (GE, 2009) heavy duty simple-cycle gas turbine operating data have been used, and are shown in Table 1. The PV array parameters (ET-P66250) used for the study are summarized in Table 2 (ET-Solar, 2011). The city of Trapani (Italy) was taken as the designated user: its global annual energy demand (125 GWh/y) is considered as the reference in all scenarios, while the monthly load distribution and the corresponding electric power demand were

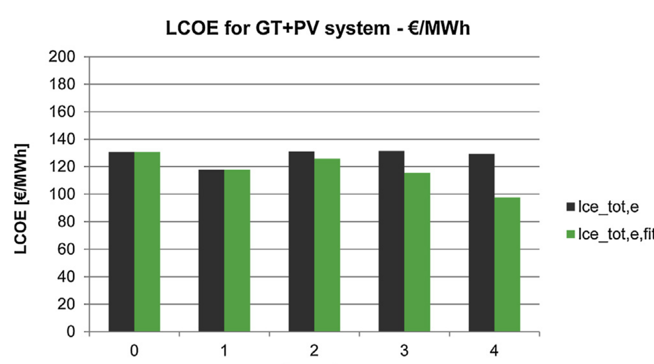

Fig. 9. Levelized cost of energy for the integrated GT + PV system.

Table 7
Levelized cost of energy, €/MWh.

Symbol	Units	0 REF	1 GTopt	2 PV 10	3 PV 30	4 PV 60	Description
$LCOE_{GT}$	€/MWh	130.7	117.7	134.0	142.8	166.6	LCOE, GT
$LCOE_{PV}$	€/MWh	–	–	105.1	105.1	105.1	LCOE, PV
$LCOE_{PV,FIT}$	€/MWh	–	–	53.1	53.1	53.1	LCOE with FIT, PV
$LCOE_{GT+PV}$	€/MWh	130.7	117.7	131.1	131.4	129.2	LCOE, GT + PV
$LCOE_{GT+PV,FIT}$	€/MWh	130.7	117.7	125.9	115.6	97.6	LCOE with FIT, GT + PV

Table 8
Main data for embodied exergy analysis.

Symbol	Units	EE	TEC	Description
Natural gas	MJ_{ex}/MJ_{ex}	1.07	1.07	Natural gas, high pressure, at consumer/RER U
GT plant	MJ_{ex}/MWe	608.000	518.000	Gas turbine, 10 MWe, at production plant/RER/I U
PV panel	MJ_{ex}/m^2	4.990	3.360	Photovoltaic panel, single-Si, at plant/RER/I U
BoS	MJ_{ex}/m^2	1.470	1.001	Open ground construction, on ground
Inverter	MJ/kWe	5.260	5.020	Inverter, 500 W, at plant/p/RER/I
ee_L	MJ/h	85.33	–	Exergy equivalent of labor
ee_K	MJ_{ex}/€	4.58	–	Exergy equivalent of the monetary unit

calculated considering 2393 h/y of operation that correspond to a plant factor of about 0.27 (Fig. 3).

This energy demand is satisfied considering the following five scenarios:

- scenario 0: REF 70 MW GT power plant;
- scenario 1: GT_{opt} 52 MW GT power plant;
- scenario 2: PV 10 70 MW GT power and 10 MW PV power plant;
- scenario 3: PV 30 70 MW GT power and 30 MW PV power plant;
- scenario 4: PV 60 70 MW GT power and 60 MW PV power plant;

Scenario 0 is the current situation (reference scenario), whereas Scenario 1 represents the optimized GT size for the required energy demand, whose nominal power has been calculated defining the GT size in order to satisfy the demand at full load, with the currently available average plant efficiency. Scenarios 2–4 model the effects of an increasing integration of the PV power plant. Table 3 summarizes the main parameters of the five scenarios.

The resulting distribution of the electric power and energy production between PV and GT for each scenario is shown in Figs. 4–6.

Under the strong simplifying assumption that both the hourly distribution and the intensity of the electrical demand remains the same as in the reference scenario of Fig. 3, it is apparent from Fig. 4–6 that every increase in the PV installed power forces the GT plant to operate farther from its nominal condition, thus reducing its efficiency.

Since the aim of this study is to calculate the effect of the off-design on the monetary, extended exergy and Thermo-Ecological Cost of electricity, the five scenarios have been simulated and the respective installation and operation costs have been separately calculated for each scenario. Simulations have been performed by the CAMEL-Pro™ (Sapienza, 2008), a C#, object-oriented, modular process simulator equipped with a user-friendly graphical interface. The system is represented as a network of components connected by material and energy streams; each component is characterized by its own (local) set of equations describing the thermodynamic changes imposed on the streams. The CAMEL-Pro GT components models used in our simulations are discussed in Appendix A, details of PV component in CAMEL-Pro are presented in (Esposto et al., 2010).

Power production of PV plants, and thus their effects on GT operation, have been computed on a monthly based average, neglecting the effects of the daily variation in solar irradiation. Since the main purpose of the paper is to apply the evaluation framework rather than to perform GT and PV systems detailed simulations, the simplification made above can be considered more than acceptable.

All simulations were performed assuming that the prescribed energy demand was to be satisfied only by the two plants working in an ideally isolated environment. Such an assumption is not too far from reality, because in actual cases the PV is operated at its maximum capacity during peak insolation hours (from 10 a.m. to 2 p.m.) while the GT covers the remaining portion of the demand (Barnham et al., 2012).

What explained above is evidently shown in Fig. 7, where it appears clear how the increase of the installed PV power affects negatively GT efficiency.

In Table 4 the main operative parameters for the simulated scenarios are reported. In all simulations of the present work the PV module selected as a benchmark is the “ET Solar ET-P660220 220Wp” [17] and a yearly performance loss of 0.2% in terms of produced energy. The climate data, such as global irradiance (in

Table 9
Results of the EE analysis.

Symbol	Units	0 REF	1 GTopt	2 PV 10	3 PV 30	4 PV 60	Description
$C_{ee,GT}$	GWh/y	0.47	0.35	0.47	0.47	0.47	Plant cost, GT
$C_{ee,PV}$	GWh/y	–	–	19.30	57.91	115.82	Plant cost, PV
$C_{ee,NG}$	GWh/y	480.58	436.96	439.62	355.21	217.39	Natural gas cost, GT
$C_{ee,S}$	GWh/y	–	–	103.03	309.09	618.18	Solar radiation, PV
$C_{ee,K}$	GWh/y	2.07	1.88	2.74	4.05	5.98	Capitals costs, GT + PV
$C_{ee,L}$	GWh/y	0.51	0.51	0.68	0.68	0.68	Labor costs, GT + PV
$C_{ee,P}$	GWh/y	483.63	439.71	565.85	727.42	958.53	Product cost, GT + PV
$c_{ee,P}$	–	3.86	3.51	4.51	5.80	7.64	sp. product cost, GT + PV

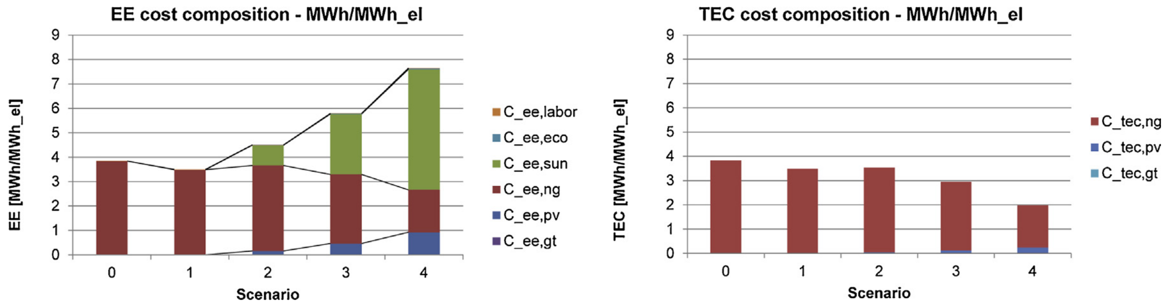

Fig. 10. Embodied exergy costs for the single GT and PV plants.

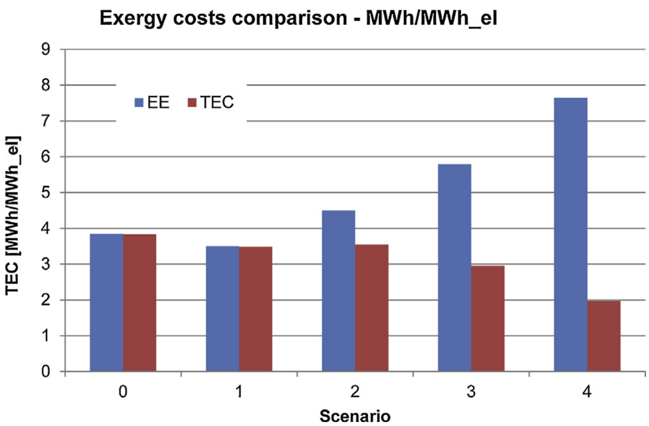

Fig. 11. Embodied exergy costs comparison for the integrated GT + PV system.

kW/m^2), ambient temperature and wind speed, for the city of Trapani are obtained from (UNI, 1994). In the following paragraphs the impact of the integration of PV and GT and the related decrease of GT efficiency on electricity economic and exergetic cost will be discussed in details.

4. Economic and embodied exergy cost analysis

In this paragraph the economic and embodied exergy costs of the exergy unit produced by the whole system is computed, according to the thermodynamic models developed for every single scenario.

4.1. Evaluation of the levelized (economic) cost of energy (LCOE)

The LCOE is an evaluation of the life-cycle energy cost and life-cycle energy production: it is expressed in terms of €/MWh and provides a common way to compare the cost of energy across technologies because it takes into account the installed system price and associated costs such as financing, land, insurance, transmission, operation and maintenance and depreciation, among other expenses. Other factors that affects the costs like carbon emission tax, Feed In Tariff or solar panel efficiency can also be taken into account (Campbell et al., 2008). Note that the method is not suitable for determining the cost efficiency of a specific power plant: in order to do that, a financing calculation must be completed taking into account all revenues and expenditures on the basis of a cash-flow model.

LCOE allows alternative technologies to be compared when different scales of operation, investment or operating time periods exist: in this paper, it is adopted to compare the economic performances of different integrated GT and PV power systems. The calculation of the LCOE for a generic power system consists in the ratio between the total economic expenditures divided by the total energy produced in the operative life of the plant. For a generic energy system with an economic operational lifetime of N years, LCOE can be computed according to the following relation (Branker et al., 2011):

$$LCOE = \frac{I_0 + \sum_{t=1}^{N} A_t/(1+i)^t - D - S}{\sum_{t=1}^{N} E_{t,el}/(1+i)^t} \tag{17}$$

where I_0 is the initial investment expenditure in €, $E_{t,el}$ is the total amount of energy produced in MWh, i is the real interest rate in % and A_t is the total costs at the year t-th, computed as the sum of fixed and variable costs for the operation of the plant, maintenance, service, repairs, taxes, and insurance payments. For sake of simplicity, the depreciation tax shield D and the savage value of any physical assets at the end of the operative life S are here neglected. Relation (17) is adopted here to compute the LCOE of both the GT and the PV plant; the global LCOE of the compound system results by a weighted average with respect to the energy produced by each plant. The LCOE has been computed also taking into account the effect of the current Italian Feed In Tariff: for the considered PV plant, the FIT results as the difference between the so-called Tariffa Onnicomprensiva of 113 €/MWh and the local electric energy market price. In Table 5 the main data for LCOE evaluation are resumed.

Table 10
Results of the TEC analysis.

Symbol	Units	0 REF	1 GTopt	2 PV 10	3 PV 30	4 PV 60	Description
$C_{tec,GT}$	MWh/y	0.40	0.30	0.40	0.40	0.40	Plant cost, GT
$C_{tec,PV}$	MWh/y	0.00	0.00	4.94	14.82	29.64	Plant cost, PV
$C_{tec,NG}$	MWh/y	480.58	436.96	439.62	355.21	217.39	Natural gas cost, GT
$C_{tec,P}$	MWh/y	480.98	437.26	444.97	370.43	247.44	Product cost, GT + PV
$c_{tec,P}$	–	3.84	3.49	3.55	2.95	1.97	sp. product cost, GT + PV
ExPBT	Y	–	–	2.49	2.39	2.20	Exergy pay back time
ExRF	–	–	–	2.57	2.57	2.57	Exergy return factor

As we can appreciate from Tables 5 and 6 from Figs. 8 and 9 $LCOE_{GT+PV}$ doesn't undergo to substantial variations because the reduction of the fuel cost ($C_{fuel,GT}$) is balanced by the growing PV investment cost ($C_{inv,PV}$). Nevertheless, the lowest $LCOE_{GT+PV}$ corresponds to the Scenario 1 (GT_{opt}).

Analyzing the LCOE with the effect of the FIT trend, named $LCOE_{GT+PV,FIT}$, we spot a different behavior and its minimum is located in correspondence of Scenario 4: the effects of FIT overcome the ones related to increase of the global PV + GT investment cost.

Note that LCOE for the considered PV technology results as 0053 €/kWh, as shown in Fig. 8 and Table 7. This value results lower with respect to the average LCOE of PV technology in European context of 0.06–0.08 €/kWh and this is mainly due to the effect of the Italian FIT. (PVPS, 2012)

4.2. Extended exergy and Thermo-Ecological Cost of electricity

Primary and secondary data and assumptions on materials and processes needed to evaluate the embodied exergy costs were collected from recent published studies, manufacturer's data sheets on the relevant processes involved in the production of the systems and from the ecoinvent database published by the Swiss Center for Life Cycle Inventories (http://www.ecoinvent.org) (Battisti and Corrado, 2005; Dones et al., 2007; Halasah et al., 2012; Jungbluth, 2005; Jungbluth et al., 2012; Raugei et al., 2007; Stoppato, 2008).

All the electric energy inputs in the processes involved in the final electricity production were converted to primary energy units based on the average European energy production mix (with an UCTE average efficiency value for electricity production of 32% (Dones et al., 2007)). The exergetic cost of ecological remediation for the extended exergy analysis has been calculated converting CO_2 emissions cost in its equivalent exergy by means of exergy equivalent of capitals in Eq. (14). Table 8 presents all the main aggregated processes and input data adopted for the embodied exergy analysis; Appendix B reports all the details about the balance of system (BoS) for the photovoltaic system. On the other hand, the Thermo-Ecological Cost analysis reported in Table 10 shows an opposite trend: the scenario with the lowest Thermo-Ecological Cost is the one with the highest PV integration, that results also in the lowest ExPBT in terms of years.

The results obtained by the extended exergy analysis for the five scenarios are collected in Table 9 and the global result is shown in Fig. 10. The exergetic capital cost, $C_{ee,K}$ includes only those costs which are not obtained from the ecoinvent database, such as the portion of costs related to taxes and incentives converted in exergy considering the ee_K coefficient reported in Table 8. The $C_{ee,P}$ strongly increases with the integration of PV mainly because of the high exergy content of solar irradiation. Embodied exergy costs comparison for the integrated GT + PV system is presented in Fig. 11.

As showed in Table 10, exergy return factor (ExRF) of the considered photovoltaic plant results in a constant value of 2.57 for scenarios 2, 3, and 4. This result is in line with results obtained by Weißbach et al. in (Weißbach et al., 2013) and resulting in 1.6 (small differences between energy and exergy values for primary resources are not considered here for simplicity). Weißbach et al. computed such value assuming that PV operates in Germany with same average characteristics of the analyzed photovoltaic cell, and suggest that for locations in south Europe, the EROI could be about 1.7 times higher due to the higher solar irradiation.

5. Conclusions

This paper presents a comparative evaluation of the impact of the progressive integration of a PV plant with a gas-fuelled gas turbine power plant in terms of economic cost and global resource consumption.

The results are – not surprisingly – completely different for the adopted cost functions: a monetary approach that includes the CO_2-saving incentives indicates Scenario 4 (high- PV generation mix) as the optimum. An extended exergy analysis, that seems to represent the best approach from a "resource-saving" point of view, identifies Scenario 1 (optimal design of GT system with no PV contribution) as the optimum, while the minimum Thermo-Ecological Cost (that privileges the lowest consumption of non-renewable primary resources) indicates Scenario 4 (maximum PV contribution) as the optimal one.

It is interesting to notice the innovative approach of extended exergy accounting in including the effects of externalities in terms of primary natural resources consumption, and it would be interesting to include non-renewable resources consumption due to such externalities also in the traditional TEC approach in a future work.

Appendix A.

The off-design gas turbine model

In CAMEL-Pro™ the simple-cycle GT group could be simulated assembling its main components: an air compressor, a gas turbine, a combustion chamber and a power splitter. The model of each component is based on energy and mass balances coupled with appropriate expressions for the heat transfer coefficients calculation, thermodynamic constants, and material properties. The balance equations are written as macroscopic balances, in the form of finite equations. In order to properly analyze the different scenarios it was necessary to consider the off- design behavior of gas turbine and compressor that allow us to calculate the effective efficiency of the global GT power plant.

The characteristic equations describing the gas turbine behavior at part load included in CAMEL-Pro™ have been adapted from public domain literature sources, and are based on semi-empirical calculation methods (Zhang and Cai, 2002). The following performance formulas for compressor and turbine are proposed.

Compressor:

$$\beta^* = c_1 M^2 + c_2 M + c_3 + \text{with} \beta^* = \frac{\beta}{\beta_{des}}$$

$$\eta^* = [1 - c_4(1-k)^2] \times \frac{k}{M} \times (2 - \frac{k}{M}) \text{with} \eta^* = \frac{\eta_{ad,off}}{\eta_{ad,des}}$$

where $M = m/G_{des}$ with $m = m_i\sqrt{T_i}/p_i$ and $G_{des} = m_{des}\sqrt{T_{des}}/p_{des} k = n/\sqrt{T_i} \times n_{des}/\sqrt{T_{des}}$

c1, c2, and c3 are coefficients depending on compressor reduced velocity k and its geometry.

Turbine:

$$\frac{g}{G_{des}} = \alpha\sqrt{\frac{1/\beta^2 - 1}{1/\beta_{des} - 1}} \text{and} \eta^* [1 - 0.3(1-k)^2] \left(\frac{k}{g/G_{des}}\right)\left(2 - \frac{k}{g/G_{des}}\right)$$

where: $g = m_i\sqrt{T_i}/p_i$, $G_{des} = m_{des}\sqrt{T_{des}}/P_{des}$, $\alpha = \sqrt{1.4 - 0.4k}$ and $k = \left(n\sqrt{T_i}\right)\left(n_{des}\sqrt{T_{des}}\right)$

Appendix B.

See Table B.1

Table B.1
Balance of System (BOS) for 1 m^2 of PV. Data from (Jungbluth et al., 2012).

Balance of systems (open ground construction, on ground)	1	m^2
Materials		
Packaging, corrugated board, mixed fibre, single wall, at plant/RER U	0.0846	kg
Aluminium, production mix, wrought alloy, at plant/RER U	3.98	kg
Polyethylene, HDPE, granulate, at plant/RER U	0.000909	kg
Polystyrene, high impact, HIPS, at plant/RER U	0.00455	kg
Chromium steel 18/8, at plant/RER U	0.247	kg
Reinforcing steel, at plant/RER U	7.21	kg
Concrete, normal, at plant/CH U	0.000537	m^3
Processes		
Section bar extrusion, aluminium/RER U	3.98	kg
Section bar rolling, steel/RER U	6.15	kg
Wire drawing, steel/RER U	1.06	kg
Zinc coating, pieces/RER U	1.56	m^2
Zinc coating, coils/RER U	1.09	m^2
Transport, lorry >16 t, fleet average/RER U	0.217	tkm
Transport, freight, rail/RER U	5.14	tkm
Transport, van <3.5 t/RER U	1.14	tkm

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