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Original article

Combining Multi-Objective Optimization, Principal Component Analysis and Multiple Criteria Decision Making for ecodesign of photovoltaic grid-connected systems

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ABSTRACT

Photovoltaic grid-connected systems (PVGCS) promise to be a major contributor of the future global energy system. Even if no GreenHouse Gases (GHG) are emitted during their operation phase, emissions are generated by the use of fossil fuel-based energy during the manufacture, building and recycling of the components. An integrated ecodesign framework that simultaneously manages technical, economic and environmental criteria for the design and sizing of PVGCS (cradle-to-gate approach) is presented in this work. A Multi-Objective Optimization problem embedded in an external multi-objective Genetic Algorithm (NGSA II) optimization loop generates a set of Pareto solutions representing the optimal trade-off between the objectives considered. Then a decision-making tool (M-TOPSIS) selects the solution providing the best compromise. The Life Cycle Assessment (LCA) method was selected to assess the environmental impact. Five commercial PV technologies were evaluated to generate alternatives of PVGCS configurations through a set of 18 objectives (two technical and one economic criteria as well as the 15 midpoint categories of the IMPACT 2002+ method). After a statistical analysis of the first results, the Principal Component Analysis (PCA) method was applied to remove redundant objectives, thus leading to only four contradictory objectives. The results highlight the advantage of the use of thin-film PV modules over crystalline-Si based PV modules.

Introduction

Photovoltaic grid-connected systems (PVGCS), a "clean" energy supplier, represent an important alternative for dealing with the increasing demand for energy worldwide and the widespread damage caused by intensive use of fossil sources as well as for coping with the scarcity of fossil fuels by transforming incident solar energy to electricity [1]. Even if they do not generate any particulate matter emissions during the operation phase and require no fluid maintenance, emissions are generated by the use of fossil-fuel-based energy during the manufacture of the components, the building of the system and the subsequent recycling of the components [2,3].

The growing awareness in society for environmental issues has motivated the development of strategies that include environmental consideration through the design process of a product or service especially for those labeled as eco-friendly. Integrating the environmental dimension into system design can yet result in a complex process. Indeed, the designer must ensure that the functions, techniques and technological solutions are integrated in an appropriate manner while respecting the best possible environmental performance over the whole life-cycle of the system. Ecodesign is the term used to group almost all the processes and approaches related to the integration of environmental considerations in the product or system design throughout their life-cycle [4] ensuring similar or improved services to the end customer [5,6].

Fargnoli and Kimura [7] evaluate some ecodesign tools considering six main properties able to address designers in choosing the most suitable design tools for the development of sustainable products,

Abbreviations: AA, Aquatic Acidification; AE, Aquatic Ecotoxicity; AEU, Aquatic Eutrophication; C, Carcinogen; CdTe, Cadmium-Telluride; CIS, Copper-Indium-Selenide; CUT, cut-off value; EPBT, Energy Payback Time; GA, Genetic Algorithms; GW, Global Warming; IR, Ionizing Radiation; LCA, Life Cycle Assessment; LO, Land Occupation; MCDM, Multiple Criteria Decision Making; ME, Mineral Extraction; NC, Non-Carcinogen; NR, Non-Renewable energy; OLD, Ozone Layer Depletion; PBT, Investment Payback Time; PC, principal component; PCA, Principal Component Analysis; PV, Photovoltaic; PVGCS, photovoltaic grid-connected systems; RA, Risk Assessment; RI, Respiratory Inorganic; RO, Respiratory Organic; a-Si, amorphous silicon; c-Si, crystalline-Silicon; m-Si, mono-crystalline; p-Si, poly-crystalline; TAN, Terrestrial Acidification/Nitrification; TE, Terrestrial Ecotoxicity; TF, thin film

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Nomenclature

β	PV collector inclination angle, degree
A^+, A^-	ideal and non-ideal solution in M-TOPSIS method
a_{ij}	normalized result of alternative i into the criterion j
D	distance between PV sheds, m
D_{min}	minimum distance between PV sheds, m
D_i^+, D_i^-	Euclidean distance for ideal and non-ideal solution for alternative i
E_{max}	maximum PV collector height above ground, m
H	PV collector height, m
H_{max}	maximum PV collector height, m
K	number of PV sheds
L	solar field length, m
L_C	PV collector length, m
L_{max}	maximum solar field length, m
$Loss_{PV\eta}$	number of energy loss due to module efficiency, kWh
$Loss_{DC/AC\eta}$	number of energy loss due to DC/AC inverter efficiency, kWh
$Loss_{Shading}$	number of energy loss due to the shading effect, kWh
$Loss_{Mismatch}$	number of energy loss due to the mismatch, kWh
N_c	number of PV modules columns in the collector
N_r	number of PV modules rows in the collector
Q_{out}	yearly output energy of the field, kWh
Q_{MAX}	maximum incident energy that the PVGCS can receive, kWh
W	solar field width, m
W_{max}	maximum solar field width, m
v_{ij}	weighted normalized result of alternative i into the criterion j
w_j	weight of the individual criterion j
X_{ij}	value of alternative i into the criterion j

concluding that there is not one method that emerges significantly from others. This work highlights the advantages of using a quantitative method to assess the environmental performance of the product or service under study that has to be considered at the early design stage.

According to Sadler and Verheem [8], environmental assessment is defined as a systematic process for evaluating and documenting information on the potentials, capacities and functions of natural systems and resources in order to facilitate sustainable development planning and decision-making in general, and to anticipate and manage the adverse effects and consequences of proposed undertakings in particular. There are many different procedures and methods to assess the environmental issues or impacts such as Environmental Impact Assessment, Material Flow Analysis, Material Intensity per Unit Service, Risk Assessment (RA) and Life Cycle Assessment (LCA). LCA and RA methods are the most cited approaches in literature works to support decision-making in environmental management. The strengths and weaknesses of both methods have been reported by several authors [9,10]. It is generally highlighted that the boundaries of a risk analysis (including Risk Assessment and risk management) can be too narrow compared to those considered in LCA, encompassing the systemic environmental consequences of a typical product, process or service. The important distinction between LCA and more narrowly focused analytic approaches such as RA is the accounting of emissions and/or resource consumption such as extraction of raw materials, processing, distribution, use of the product, recycling and, disposal of final waste. This motivates the choice of LCA as a systemic environmental assessment method. Let us recall that LCA is also widely used in industry [11,12] and allows comparing the assessment of the alternatives focused on a specific functional unit. It evaluates each life-cycle stage of the product under evaluation, classifies and characterizes the emissions in several and diverse environmental categories. More generally, LCA can be integrated into an environmental decision support tool combining social, political, economic and technical considerations, as highlighted in this work.

In the quest for more sustainable energy systems, the design of PVGCS is of tremendous importance. PVGCS, the most popular type of solar PV system, is integrated with three key elements: PV modules, DC/AC inverter, and mounting system. PV modules constitute the core of the system to convert solar energy into electricity. They are also the most sensitive component because the type of material used in their manufacture, the solar irradiance and weather condition principally affect their conversion efficiency. In general, the cost of the PV modules still dominates the price of large-scale PVGCS even if the prices of PV modules have been reduced substantially in recent years.

PV modules are grouped into first, second or third generation according to the technology used for solar cell manufacturing. The crystalline-Silicon technology (c-Si), i.e., the first generation includes modules made by silicon cells as mono-crystalline (m-Si) or poly-crystalline (p-Si). The so-called thin film (TF) PV modules are considered as second-generation of PV technologies. It includes three main families:

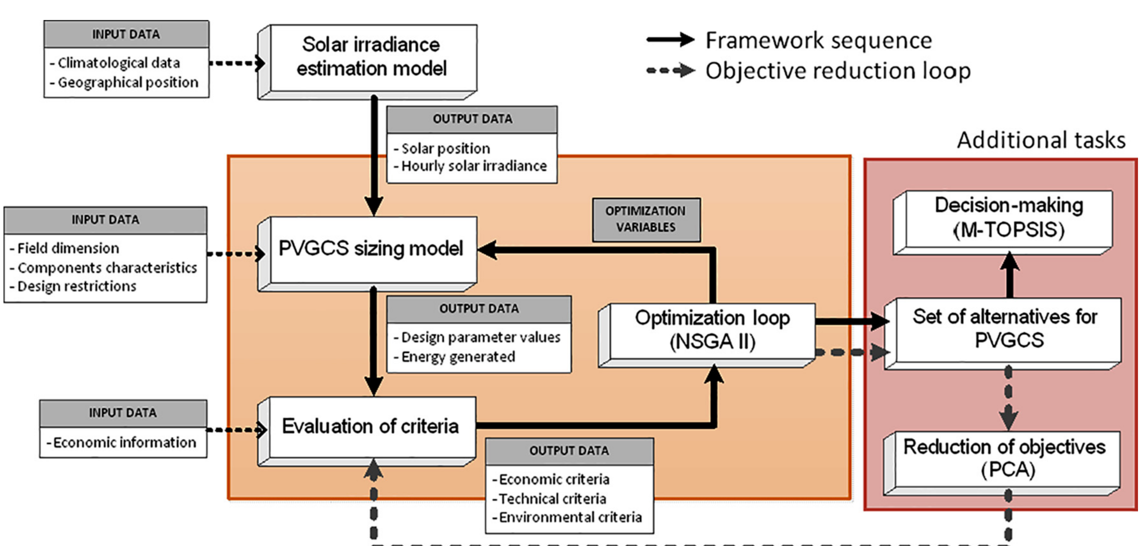

Fig. 1. Functional flow diagram of the Ecodesign methodology.