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Modeling, performance analysis and economic feasibility of a mirror-augmented photovoltaic system

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ABSTRACT

In the last years, solar photovoltaic (*PV*) systems have had great impetus with research and demonstration projects, both in Italy and other European countries. The main problems with solar *PV* are the cost of solar electricity, which is still higher compared with other renewables (such as wind or biomass), due to the cost of semi-conductors, and the low conversion efficiency. However, *PV* panel prices are rapidly decreasing benefiting from favorable economies of scale. For instance, according to the Energy Information Administration (*EIA*) the US average levelized costs for plants entering service in the 2018 should be 144.3$/MW h for solar *PV*, whereas 111.0$/MW h for biomass and 86.6$/MW h for wind (Levelized Cost of New Generation Resources in the Annual Energy Outlook, 2013). In order to increase the electric yield of *PV* modules (which can be even doubled with respect to constant tilt configurations), without significantly increasing the system costs, it was decided to consider the addition of inclined mirrors at both sides of the *PV* modules, so as to deflect more solar rays towards them, as in Mirror-Augmented Photovoltaic (*MAPV*) systems. The system preserves its constructive simplicity with commercial flat *PV* modules even though dual axis tracker must be implemented, since *MAPV* systems harness mainly the direct radiation. The performance analysis of *MAPV* systems starts from the calculation of the global irradiation on the surface of the *PV* module which is a sum of the direct sunlight on it and the irradiation reflected by the mirrors. A mathematical model of a *MAPV* system is presented, which takes into account not only the increase of direct (or beam) radiation, due to the mirrors, but also the reduction of both the diffuse and reflected radiations due to the shadowing effect of the flat mirrors. In particular, under an isotropic sky assumption, a simplified analytical expression, applicable in the case of *MAPV* systems, for the sky-view factor has been developed. The deterioration in the performance of the *PV* system as a result of the increasing cell temperature with radiation augmentation due to mirrors has been also evaluated. Moreover, in order to provide a more realistic view of the process, the energy analysis is accompanied by the exergy analysis. Finally, in order to analyse the economics of *MAPV* systems, Net Present Value, Discounted Payback Period, Internal Rate of Return and Life-Cycle Costs, have been considered and compared with both a constant tilt building-integrated photovoltaic (*BIPV*) system and a system with a dual axis tracker.

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1. Introduction

The renewable energy sources, together with flexible and intelligent infrastructures and energy efficiency measures, will represent an increasing share of European Union's (*EU*) energy with regard to electricity, heating (responsible for almost half of the *EU*'s total energy demand), cooling and transportation, helping to reduce European dependence on conventional energy sources. In the 2030, at least a 30% share of renewable energy sources is expected in the energy mix of the European Union. Furthermore, it must be considered the effect of the interaction of this ambitious target with other potential goals in the context of climate and energy policy, such as greenhouse gases (*GHG*) emission reduction, as well as it must be assessed the impact of *EU*'s industry on competitiveness, including industries related to renewable energy sources. Therefore, renewables do not only contribute to address the problem of climate change and enhance energy independence but also offer great additional environmental benefits in terms of pollutant emission reduction, waste production and water usage, as well as in terms of risk reduction associated with other forms of energy production.

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The 2012 has been a favorable year for green electricity production in Italy (the gross energy production from renewables has been estimated in 92.46 TW h by *GSE*, the state-owned company which promotes and supports renewable energy sources in Italy) and the 2013 is going to be even better since, this year, the generation of electricity from renewable sources could probably overcome the emblematic threshold of 100 TW h. Actually, if hydropower contribution will respect forecasts, in the 2013, renewables will be able to meet 31% of the Italian electricity needs (including imports), reaching 35% of national production, despite the crisis. In the 2012, the electricity demand in Italy decreased by 2.8% compared to the 2011, dropping down to a total of 325.2 TW h, compared with 334.6 TW h in the previous year, as indicated by the Terna report. At regional level, the electricity consumptions fell by 2.5%, 3.1% and 6.1% in the North, in the Center and in the South, respectively. The 2012 is the third lowest in terms of electricity consumption in the last ten years. The only energy sources that have seen an increase in their production are photovoltaic and wind. Photovoltaic, with 18.3 TW h produced in the 2012, increased by 71.8% compared to the 2011. In order to evaluate the growth rate of solar energy in Italy, it is sufficient to consider that in the 2010 the photovoltaic energy production was only 1.9 TW h and 0.7 TW h in the 2009, which means that in four years, the increase has been 2600%. The wind, with 13.1 TW h produced in the 2012, recorded an increase in production of 34.2% compared to the 2011. The two sources together, with 31.4 TW h, actually covered 9.6% of the national electricity demand. On the other hand, hydroelectric and geothermal energy productions decreased; with 43.3 TW h (−8.2% compared to the 2011) and 5.2 TW h (−1.4%) produced, they have guaranteed 13.3% and the 1.7% of the demand, respectively. Overall, in the 2012 renewables have covered 24.6% of the national electricity demand. Furthermore, the thermal power generation from fossil fuels fell down, from 218.5 TW h in the 2011 to 204.8 TW h in the 2012 (−6.3%), thus covering 62.2% of the demand. Electricity imports decreased too by 5.8% compared to the 2011 covering, with 43 TW h, the remaining 13.2% of the national electricity demand.

Naturally, the growth in electricity generation from renewables is not a peculiarity of the Italian market but is a more general trend in the industrialized world. With nearly 270 billion dollars globally invested in this sector, the 2012 proved to be worse than the 2011 (which had exceeded 300 billion dollars) but still very favorable in the context of a global economic slowdown. From data of the 2012 [2], it emerges a widening of the market beyond the borders of the major industrialized countries such as the United States, Germany, Spain and Italy, which had lead the renewable energy sector till now. Chinese investment in clean energy sources grew by 20% in the 2012, hitting a record of 65.3 billion dollars, whereas in the United States investments have not gone beyond 35.58 billion dollars (−37%). Among the new emerging markets, South Africa has reached 5.46 billion dollars of investments but investments expanded also in Australia, Morocco, Ukraine, Mexico, Kenya, Brazil, Ethiopia, Chile and South Korea: in all these countries projects have been developed, which have exceeded 250 million dollars in the 2012.

In order to further increase the electricity production from renewable sources, governments need to promote research for efficient technical solutions of renewable power generation. In the field of solar photovoltaic, the main problem is that this kind of renewable energy is still more expensive compared to other forms, such as wind or biomass, due to the high cost of semi-conductors, even though the costs of *PV* panels are rapidly decreasing benefiting from favorable economies of scale, and their relative low conversion efficiencies (between 10% and 20%). For instance, according to the Energy Information Administration (*EIA*) the US average levelized costs (2011 $/MW h) for plants entering service in the 2018 has been estimated to be 144.3 /MW h for solar *PV*, whereas 86.6 /MW h for wind, 111.0 /MW h for biomass and 149.2 /MW h for hydro [1]. As shown before, in Italy the *PV* systems have been largely diffused in the last years due to very remunerative government incentives. However, the economic crisis could determine a reduction of these incentives compromising this virtuous positive trend. In order to preserve the appeal for this kind of investment, all the technical solutions trying to increase the *PV* efficiency are really expected. Some solutions have already been introduced, as for example: hybrid collectors [3–12]; tracking systems, in order to follow the sun trajectory; concentrating *PV*, which requires smaller *PV* surfaces in order to obtain the same amount of electric energy of a conventional *PV* system [13–27]. Current status and future prospects of solar photovoltaic are well summarized in [28].

During the years, many designs of concentrating collectors have been proposed. Concentrators can be reflectors or refractors. Their concentration ratios can vary over several orders of magnitude from low values in the order of unity to high values of the order of 10^5 [29]. However, medium and high *PV* concentration systems (respectively with 20–500× and over 500× concentration levels) need expensive multijunction *PV* cells and parabolic optical systems or Fresnel lens systems for the concentration [30]. Furthermore, when the concentration ratios increase, *PV* receivers need to be cooled otherwise their temperature becomes too high with a detriment in their performance and durability. Another problem to deal with is concentrating collectors, except the ones characterized by a very low concentration ratio, need to be oriented to *track* the sun so that beam radiation will be directed onto the absorbing surface [29]. These considerations can explain why there is the interest toward low-concentration *PV* systems with concentration ratios lower than 20×. For instance, Cotana et al. [30] have proposed and built an experimental innovative *PV* low-concentration system made of a set of flat mirrors which, appropriately oriented, simulate the surface of a parabolic concentrator, allowing a double simplification with respect to the parabolic concentrators both in the manufacturing phase and the working phase of the facility. An electronic system for tracking management rotates the mirrors around the rotational axis, in such a way that the solar radiation is always concentrated on the *PV* receiver panel (made of common *PV* cells of monocrystalline silicon) during the sun daily movement. Using ASHRAE clear-sky irradiation model, Cotana *et al.* [30] have evaluated that, thanks to the their concentrating system, the annual energy which hits their *PV* panel is 4195kW h/m^2. In this work, in order to further reduce the average cost of solar energy, especially in regions where the global radiation is not particularly high, a simpler low-concentration technology is investigated. Flat mirrors are placed at both sides of commercial *PV* modules, as in Mirror Augmented Photovoltaic (*MAPV*) systems. The use of flat mirrors has been chosen in order to limit the system complexity. For instance, since the maximum achievable concentration ratio ranges only from 1.5 to 2.5, no cooling system is required. Analogous configurations have already been proposed by other authors. For instance, Solanki et al. [31] showed that, with their *PV* system with *V*-trough concentrators (made of simple metal sheets), they can double the captured solar radiation, allowing a 33.5% reduction in the area of monocrystalline silicon solar cells needed to obtain the same electric energy yield of non-augmented system. Moreover, in their experiment (performed at the Energy Area Laboratory, Agricultural Engineering Department, Federal University of Viosa, city of Viosa, Minas Gerais State, Brazil), Sant'Anna et al. [32] showed that their *PV* system, with *V*-trough concentrators (made of specular anodized aluminum mirrors) kept at a constant tilt angle equal to the local Latitude, was able to give an electric energy yield around 30% larger than the one obtained with the same *PV* modules without concentrators. Lin et al. [33], in their non-

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