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Photovoltaic solar systems for smart bus shelters in the urban environment of Turin (Italy)

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Abstract—The paper deals with the transformation of the existing bus shelters for the public transport into smart systems equipped with Wi-Fi stations, USB chargers and Air Quality Control Station. The proposed smart shelters are renewable energy producer since they are equipped with PV modules. The location of the most suitable bus shelters is defined by solar irradiation maps based on a GIS tool. Four solutions are proposed with a cost-benefits analysis.

I. INTRODUCTION

This work is part of a project promoted by the City of Turin (Italy) called “Turin living lab” in which companies and private people can experience innovative ideas and technologies on the territory of the City of Turin, located in the North-West part of Italy. The aim of “Turin living lab” is the promotion of a sustainable development from an environmental and energetic point of view. Cities play a very important role in the energy field as they have a high-energy demand, due to the high density of population and human activities. Moreover, most of the energy consumed is not produced close to consumers, it is transported and distributed through extensive networks and heat demand is usually met by small boilers or, for big condominiums connected to a district heating network.

Air pollution in the cities is due to emissions generated by the combustion of fossil fuels to distribute mainly space heating, hot water production, electric energy and transports [1, 2].

Cities account for 2% of the planet's surface, consume 75% of the generated energy, and urban growth and economic development always shared the energy demand [3]. As a significant quantity of energy is lost in transport and distribution from production centers, it is possible to affirm that the current production model is no longer sustainable because energy is produced far from cities and then transported and consumed with high dispersions. Usually in big cities, the space available for the construction of traditional ground-based plants with renewable sources is not feasible because the ground space is already occupied and used for other services. Solar technologies instead can be always used, especially in Italy due to the availability of high values of solar irradiation, even if the available surface of buildings roofs cannot satisfy the high-energy demand of a city [4, 5].

Particularly in cities, it is therefore necessary to make the most of all available surfaces for renewable solar technologies in outdoor spaces, while nowadays, only few solar collectors or photovoltaic modules are installed and mainly on building roofs. In this work, new solutions are investigated looking to bus shelters or metro stops. The proposed solutions should give a

service to the community ensuring a steady and rapid installation, easy to manage, with low costs and with a self-producing energy technologies.

II. “TO WAIT IN A NEW WAY”

This study is developed within the project “Turin living Lab” to promote urban sustainability and to develop and test new innovative solutions in the city of Turin. Citizens, companies and public administrations are working together to explore and experiment innovative products, technologies and services in the city, with the aim of testing their functionality and usefulness on the quality of life of Turin inhabitants. In this context, around 30 projects are tested in the “Campidoglio” area of Turin (district n. 4) which has become the first Turin urban space dedicated to innovation and smart city.

One of these projects is “To Wait in a New Way” [6] which consists in adapting a waiting bus shelter to a smart system with roof-integrated solar photovoltaic (PV) modules on removable polycarbonate structure. The PV system allows to provide electricity to supply various services to the users of public transport. The project “To Wait in a New Way” had also foreseen the assembly, installation and monitoring of a prototype at a bus stop near the Maria Vittoria Hospital. From this first installation, by its experimental monitoring, a costs/benefits analysis and the evaluation of people appreciation, further suggestions emerged on the possibility to extend these services to other bus stops and to evaluate any changes to the system to increase its efficiency.

The photovoltaic shelter will have to offer to citizens different services: a wi-fi connection, two USB ports to charge tablets and smartphones and an air pollution control station to monitor the surrounding air quality.

The prototype has been designed to have:

- a small size and weight of photovoltaic storage and modules without any supporting structure
- an installed PV power to cover the electric loads for as many days as possible during all the year
- PV modules with a good performance per unit area
- commercial electronic converters
- lightweight storage system.

To meet these constraints a storage system with integrated lithium batteries, a solar charge regulator and a PWM inverter was chosen. This system gives an autonomy of two days without sun irradiation because is composed by two batteries connected with two PV modules:

- “Gecko 120”, that manage the recharge system for smartphones and tablets with a maximum storage of 120 Wh, connected to the PV module “HF 40-5-16” with an installed power of 40 Wp;
- “Gecko 500”, that manage the Wi-Fi and the air pollution control station systems, connected to the PV module “HF 135-6-16” with an installed power of 135 Wp.

Both the PV modules are semi-flexible, light and thin (2 mm of thickness and a specific weight of about 2.5 Kg/m²), with mono-crystalline silicon cells (efficiency of 18,6%) and encapsulated with front and back sheets made of thermoplastic polyurethane (TPU). The layout of the plant with the modules, the batteries and the electrical devices is represented in Figure 1.

To fix the modules on the roof of the bus shelter, the PV modules were first mechanically fixed on a sheet with eyelets and a spacer allowing thermal dilatation of the modules; after the sheet was fixed on the roof using a structural bi-adhesive. Figure 2 represents the installation of the prototype at Maria Vittoria Hospital bus station (Figure 2). The air quality control system measures the concentration of particulate matters (PM) and detects the particles up to 0.5 µm. The selected system requires a continuous power of about 2 W. Also, Wi-Fi device requires a continuous power of 2 W with a daily energy consumption of 48 Wh. Finally, for new smartphones, one recharge is about 7 Wh, assuming 5 full recharges per day, it would be necessary to supply 34.57 Wh from the photovoltaic system.

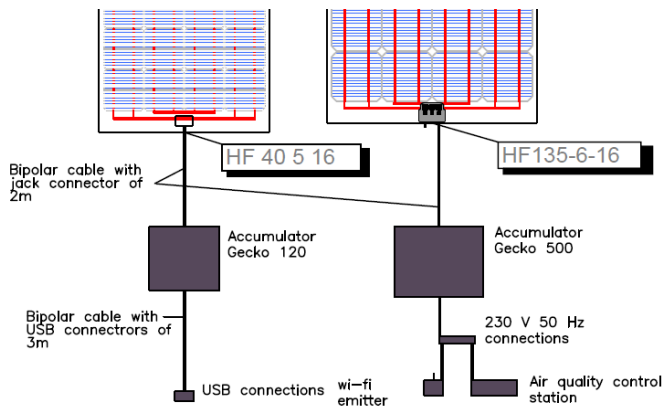


Figure 1 – Layout of the PV system with PV modules, batteries and appliances.



(a)



(b)



(c)

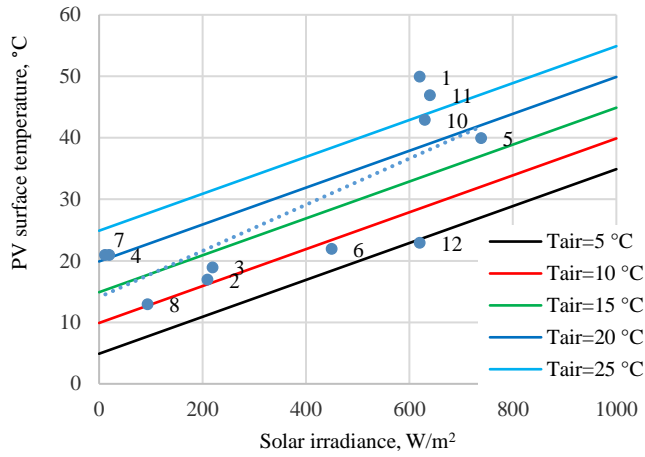


(d)

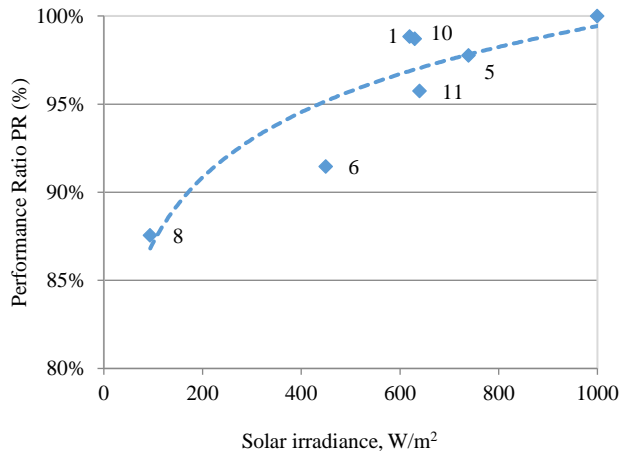
Figure 2 – (a) the Maria Vittoria Hospital bus shelter chosen for the prototype; (b) the PV modules on the roof of the bus shelter; (c) the batteries and electrical systems with the Wi-Fi and the air quality control system; (d) the closed cavity under the bus shelter in which the batteries and measurement systems are located.

TABLE I. MEASUREMENTS CAMPAIGN DATA

| Date | Measure n. | Stored power in the accumulator (W) | Module area (m ²) | Solar irradiance (W/m ²) | Sky condition | Module temperature (°C) | System efficiency (%) |
|------------|------------|-------------------------------------|-------------------------------|--------------------------------------|---|-------------------------|-----------------------|
| 27/03/2017 | 1 | 67 | 0,89 | 620 | Clear sky 12:00 | 50 | 12,14% |
| 28/03/2017 | 2 | 24 | 0,89 | 210 | Clear sky 8:30 | 17 | 12,84% |
| 29/03/2017 | 3 | 25 | 0,89 | 220 | Clear sky 8:40 | 19 | 12,77% |
| 29/03/2017 | 4 | 2 | 0,89 | 20 | Clear sky and shadow on PV module 15:40 | 21 | 11,24% |
| 30/03/2017 | 5 | 79 | 0,89 | 739 | Clear sky 13:40 | 40 | 12,01% |
| 30/03/2017 | 6 | 45 | 0,89 | 450 | Clear sky 17:00 | 22 | 11,24% |
| 31/03/2017 | 7 | 0 | 0,89 | 12 | Clear sky and shadow on PV module 17:00 | 21 | - |
| 03/04/2017 | 8 | 9 | 0,89 | 94 | Clear sky 8:00 | 13 | 10,76% |
| 04/04/2017 | 9 | 75 | 0,89 | 620 | Clear sky 11:20 | 23 | 13,59% |
| 04/04/2017 | 10 | 68 | 0,89 | 630 | Clear sky 11:40 | 43 | 12,13% |
| 05/04/2017 | 11 | 67 | 0,89 | 640 | Clear sky 12:00 | 47 | 11,76% |



(a)



(b)

Figure 3 - (a) Experimental data of surface temperature of PV module, with trends value for crystalline silicon modules [8] versus solar irradiance; (b) Experimental trend [7] of PV performance ratio varying solar irradiance.

III. EXPERIMENTAL ANALYSIS OF THE EFFICIENCY OF THE SYSTEMS

Starting from the incident global solar irradiation, in order to estimate the energy produced by the PV system during the whole year, the global efficiency of the system has to be estimated.

The performance of PV systems depends on many factors, the main ones are [7, 8]:

- the global solar irradiation received by the surface of the PV module,
- the incidence angle and the wavelength of solar irradiation,
- the temperature of PV cells,
- the uniformity of the distribution of solar irradiation on the module due as example, to climatic conditions or shadows and
- the level of battery charge.

To measure the system performance, the total solar incident irradiation on the horizontal surface was measured with a solarimeter (range 0÷2,000 W/m² and accuracy 10 W/m²), the surface module temperature was measured with a thermal camera (range -50÷800 °C and accuracy 2 °C) and the electric power at the battery bench terminals by a wattmeter.

The measurements were carried out in different times of the day, mainly at noon and in the afternoon with the same components and modules used for the prototype. The photovoltaic module was connected to the accumulator and the solarimeter was placed on the same horizontal plane. When the temperature of the PV module reaches the steady state operating value the measurements can be done.

In Table I the measurement in the middle season campaign is presented. The measures with gray background were excluded for the calculation of the average system efficiency because:

- Measures n. 4 and n.7, the solar irradiation was not enough to charge the batteries.

- Measure n. 9 was taken in thermal transient condition.
The average efficiency computed from the experimental measurements was 11.67 %.

TABLE II. COMPONENTS EFFICIENCIES

| Component | Efficiency, % |
|--------------------------------------|---------------|
| Net PV cell area / gross module area | 87.50% |
| Optical & connections | 95.05% |
| Battery Charge | 79.41% |
| PV cell | 18.60% |
| Global system | 12.28% |

In Figure 3(a) the influence of module temperature with solar irradiance is represented comparing measurements with literature trends values for crystalline silicon modules [8]. The measured experimental data cannot be directly compared with literature trend since the air temperature was not constant during the experimental measurements but in the range of literature data.

The performance of the whole system was verified with the performance ratio (PR) calculated from the ratio between the performance under reference test conditions [8] and the performance measured in field.

In Table II is reported the efficiency of each component provided by manufacturers, with a global system efficiency of 12.28%.

The area efficiency is the ratio between the useful area of PV cells (32 cells of 0.024 m² each) and the total area of the module (0.89 m²). The optical and connections performance of the system is given by manufacturer at 98.5% for the voltage and 96.5% for the current, which multiplied give an efficiency of 95.05%. As it is possible to observe in Figure 3(b), the performance ratio obtained with experimental data in the middle season can be compared with semi-empirical models based on experimental data with single and the double exponential model [7]. The measurements campaign allowed to evaluate that with a solar irradiance lower than 20 W/m² the module cannot charge the batteries.

IV. FEASIBILITY ANALYSIS ON THE WIDESPREAD USE OF THE PROTOTYPE ON TURIN BUS SHELTERS

To evaluate if the prototype can be installed in other bus shelters of the public transport network in Turin, a solar map has been specifically created to identify the most suitable areas in every period of the year, taking into account all natural and artificial shading devices. The adopted method uses GIS tools to locally define, for every area in the city, all shading devices considering the solar geometry. To consider all the shadows due to orography, buildings and vegetation, the Digital Surface Model (DSM) of Regione Piemonte made by LIDAR ICE data of 2009-2011 with a precision of 5m x 5m was used with the position of bus shelters given by the public transport company of Turin.

In Table III the description of the characteristics of the sky [4] is reported, defining the percentage of diffuse solar irradiation D

[8], the Linke turbidity factor [10] and the atmosphere transmissivity T (averaged over all wavelengths) for every month. As it is possible to observe, there are many differences during the year with in wintertime high percentage of diffuse solar irradiation and low transmissivity and vice versa during summertime.

Using the solar model represented by the parameters in Table III, twelve solar maps have been generated, one of each month of the year. From the monthly solar maps (in Figure 4 the annual solar irradiation with the bus shelters superimposed), using the average efficiency of the system, the energy produced was estimated for each bus shelter in Turin. Obviously, there are many differences of solar irradiation during the year; particularly, in December the solar map presents a maximum value of solar irradiation of 30 kWh/m²/y, while in July the maximum solar irradiation is 284 kWh/m²/y.

TABLE III. THE DESCRIPTION OF THE SKY MODEL WITH THE PERCENTAGE OF DIFFUSE SOLAR IRRADIATION (D), THE LINKE TURBIDITY FACTOR AND THE ATMOSPHERE TRANSMISSIVITY (T) IN TURIN

| Month | D, % | Linke turbidity factor, - | T, % |
|-------|------|---------------------------|------|
| 1 | 52.2 | 3.5 | 0.42 |
| 2 | 49.4 | 4.3 | 0.48 |
| 3 | 41.9 | 4.0 | 0.54 |
| 4 | 38.1 | 4.2 | 0.58 |
| 5 | 42.1 | 4.6 | 0.59 |
| 6 | 39.9 | 4.6 | 0.61 |
| 7 | 36.7 | 4.4 | 0.64 |
| 8 | 37.6 | 4.5 | 0.62 |
| 9 | 41.1 | 4.3 | 0.58 |
| 10 | 47.8 | 4.0 | 0.5 |
| 11 | 58.3 | 4.4 | 0.41 |
| 12 | 51.3 | 4.4 | 0.42 |

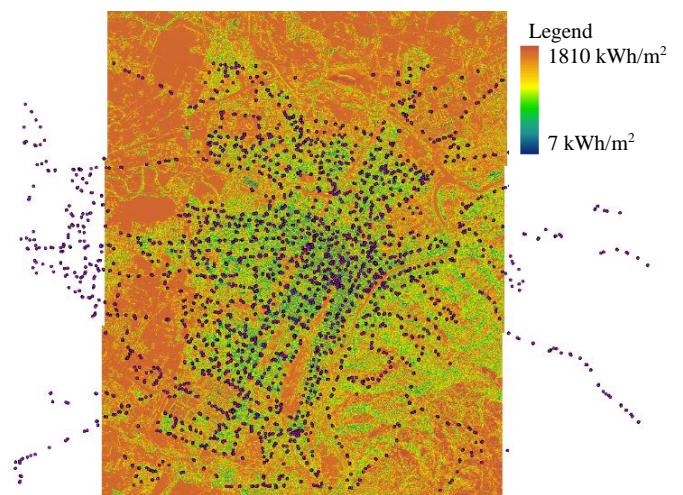
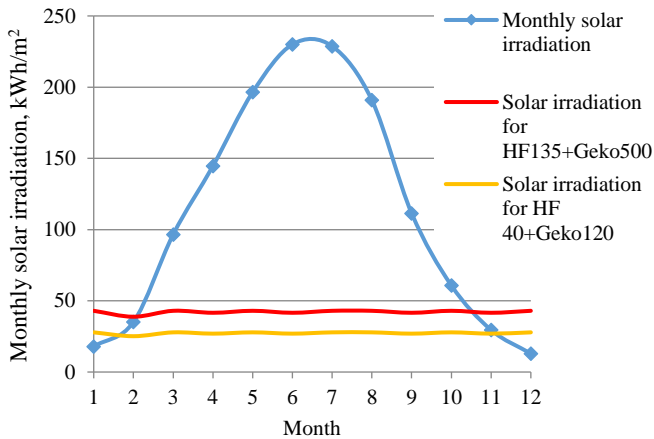
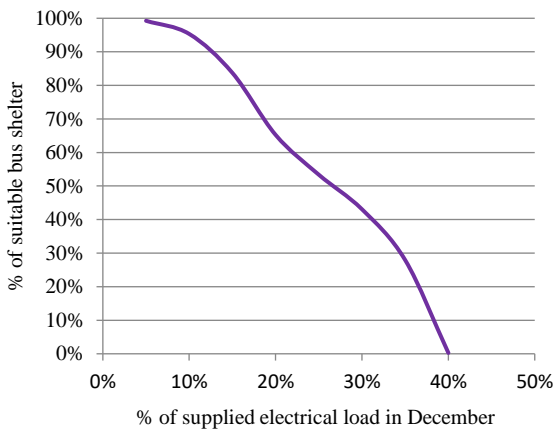


Figure 4 - Map of annual solar irradiation on the city of Turin (with a detail of 5 m x 5 m) with the bus shelters of public transport network (purple marks).

In Figure 5 (a) the monthly solar irradiation and the minimum quantity of solar irradiation needed to satisfy the electrical loads of the prototype on the bus shelter of Maria Vittoria Hospital is represented. Especially for the more powerful system (HF 135+Geko500), in wintertime the solar irradiation on bus shelters cannot cover the 100% of electrical loads. For the selection of the most effective bus shelters, were chosen the shelters having a minimum cover of electrical load of 30% in the month of December (with the lowest solar irradiation).



(a)



(b)

Figure 5 – Monthly solar irradiation vs. time and minimum solar radiation required to charge the analyzed system (a), percentage of suitable bus shelters vs. the percentage of supplied electrical load in December (b).

To choose the public transport shelters with sufficient solar irradiation for installing the PV system, the minimum cover of the loads, in the worst month December, was fixed at 30%. In Figure 5 (b) the results of this assumption can be represented: the 43.21 % of bus shelter was selected, corresponding to a number of 1161 bus shelters.

V. PROPOSAL FOR A SUSTAINABLE DEVELOPMENT OF THE PROJECT “TO WAIT IN A NEW WAY”

In the project “To wait in a new way” the prototype for smart bus shelters was studied to be flexible, easy to be installed and managed with low costs.

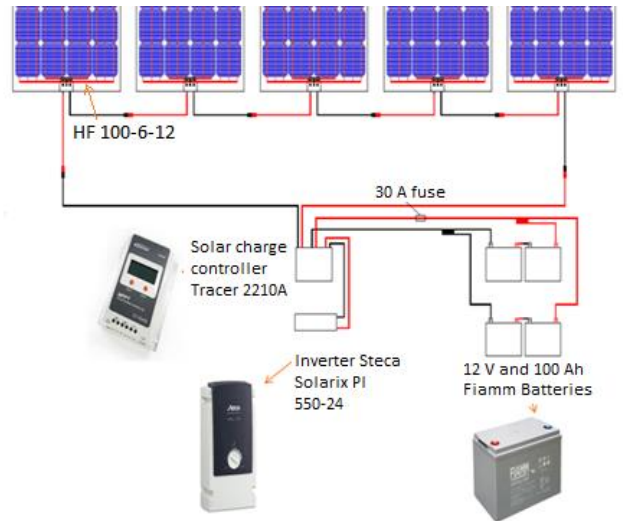


Figure 6 – Layout of the proposed stand alone PV system.

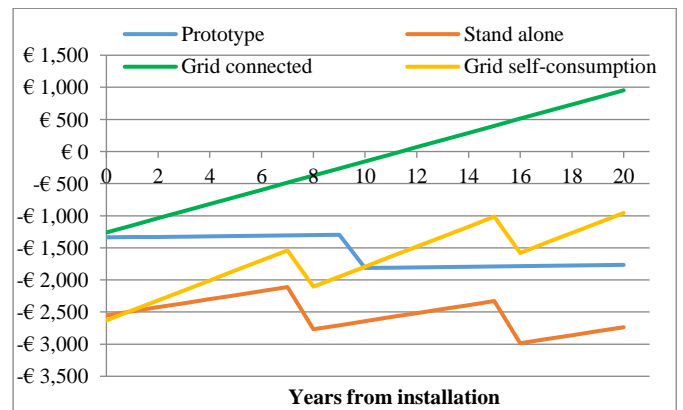


Figure 7 – Payback diagram for the proposed systems.

Further project developments may concern the local production of renewable energy for public lighting or public buildings. In this case, all the shelter surfaces should be used to maximize energy production by installing as much PV power as possible. Considering to operate with modules like those previously used for the prototype, with a standard crystalline silicon cell, a module with a power of 100 W was selected (HF 100-6-12). A first possibility is to build a stand-alone system useful to supply energy to the nearby public services as streetlights or Wi-Fi networks. In this case, integrated systems for accumulation cannot be used due to the larger size of the PV plant, but the different components can be configured as represented in Figure 6.

A second possibility is to build a grid-connected system in which the modules are connected to micro-inverters and to the electric distribution network. The micro-inverter can be fixed directly on the roof of the bus shelter. This second solution is simpler and with lower costs, since there is not the battery bench.

A costs/benefits analysis has been implemented to evaluate the economic feasibility of the projects proposed. The costs of components are taken from the project “To wait in a new way” for the construction of only 100 smart shelters. In this evaluation the costs of the provided services are not accounted. Furthermore for the grid-connect systems, the national incentives for innovative and integrated systems are considered but not the costs of connection to the electric grid.

With these assumptions, the cash flow for the different proposed layouts is represented in Figure 7. Only the grid-connected configuration, without battery, has a pay-back time around 11 years with profit of around 1,000 € after 20 years.

TABLE IV. PERCENTAGE OF TOTAL ELECTRIC ENERGY DEMAND

| Use of outdoor surfaces in Turin | % used surfaces | % supplied energy demand |
|---|-----------------|--------------------------|
| Roofs of non-residential buildings with footprint more than 10.000 m ² | 30% | 6% |
| Roofs of all non-residential buildings | 30% | 14% |
| Roofs of all buildings | 30% | 40% |
| Rivers banks | 5% | 0,30% |
| Roofs of bus shelters for public transport | 43% | 0,07% |

On the contrary, the investment on the stand-alone system is not convenient since only a part of the produced energy is used, there are no incentives and new investments are needed to replace the batteries every 8 years. For the prototype only about 15% of the energy produced is used. This solution is suggested only where the connection to the electric grid is not possible.

In the case of the system connected to the network with self-consumption, the battery capacity should be reduced in order to have an economic advantage. The types of batteries currently used are economically disadvantageous due to required replacement at least one time during the system lifetime.

VI. CONCLUSION

The prototype of the "To wait in a new way" project covers the energy needs of cellular charging station and Wi-Fi systems for most of the year. These endearing systems are increasingly spreading in cities and, with a larger battery, they may provide these services on the most “crowded” bus shelters in Torino. Also, the air quality control system could integrate the current air quality monitoring network only where there is a lack of information in the existing network.

The methodology GIS based used in this work is very versatile and can also be used for other cities overlapping all levels of information that requires the analysis. Besides solar irradiation, further analyses can also consider the traffic flows to have a second parameter of choice to find the most used bus shelters. Systems composed by two lithium-powered batteries, integrated charge controllers and general purpose inverters are very easy to install. To increase system performance, a whole battery management system should be used.

The 500 W stand-alone system can be used for public lighting or other services but has many technical and economic disadvantages compared to a grid-connected system, which should be preferred especially for a large-scale interventions.

From the economic point of view, the solution without battery is better, however, an economic optimization on the size of accumulator and the use of low-capacity batteries could make the solution more self-sufficient.

Economic benefits in city context could be analyzed since they are more advantageous for environmental sustainability and not only for energetic purpose. In fact, the energy produced during the year by the grid-connected systems on the all bus shelters in Turin could be used to supply the energy demand of 650 inhabitants [4, 11].

The analysis conducted in this work can be repeated on other territories, on any type of photovoltaic system and may be useful to identify the best installation site. The use of structures in the outdoor spaces, as bus shelter, seems to be interesting to produce renewable energy although this system is not widespread.

In Table IV is reported the percentage of total electric energy demand that can be produced using the outdoor available spaces equipped with PV systems. In an urban context, such as in Torino, the most suitable surfaces are represented by building roofs. The experimental analysis on the smart shelters carried out returns consistent results with the computed theoretical values. More measurements should be conducted especially in conditions of partial shading that would lead to a significant decrease in the efficiency and in the produced energy.

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