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Photovoltaic Roundabouts for Enhancement of Self-Sufficiency and Resiliency

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Abstract: Roundabouts have become a common type of intersection design in many countries. The area of the center island can be used to install a photovoltaic system to power local loads such as lighting systems. The objective of this study is to evaluate the degree of self-sufficiency that a roundabout can achieve depending on the availability of the area for the installation of a photovoltaic system and the energy demand for lighting. The methodology is divided into five steps aimed at calculating the parameters required to characterize the roundabouts from the point of view of the electricity that can be generated by the photovoltaic systems installed, and then to evaluate the energy consumption required to operate the different system solutions for lighting. The mini roundabouts are not considered as a location for the photovoltaic system; in fact, the minimum diameter must be between 29 and 34 m. Considering the available irradiance in Italy, systems with monocrystalline silicon modules are sufficient to ensure energy self-sufficiency at diameters of 24 m or more. Systems with polycrystalline silicon modules are suitable to ensure energy self-sufficiency at diameters of 25/26 m or more. Photovoltaic (PV) technology continues to make progress in increasing efficiency, such as bifacial PV modules. This means that even smaller roundabouts could be eligible for a PV system sized to meet local electricity needs.

Keywords: photovoltaic technology; monocrystalline silicon; polycrystalline silicon; energy demand; electricity productivity; street illumination; roundabout design

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1. Introduction

Roundabouts have become a common type of intersection design in many countries, and many intersections have been converted to roundabouts in recent years. Roundabouts are of particular interest because they are considered safer due to their ability to slow through traffic and reduce the number of conflict points. In fact, several studies indicate that roundabouts, both conventional and unconventional, are effective in reducing collisions resulting in injuries or fatalities [1–4]. The widespread use of roundabouts is also justified by their positive perception by road users [5,6].

Although accidents at roundabouts are generally less severe, Daniels et al. [7] shows a tendency for more severe accidents to occur at night at roundabouts. Several studies have provided strong evidence that drivers' ability to avoid collisions is impaired in low light conditions [2,8–10]. In addition, nighttime crashes have been shown to decrease after the installation of overhead lighting [2] and during longer days, such as the summer months. Several researchers [11–14] developed an ordered probit model considering a variety of independent variables and concluded that darkness increases injury severity. Similarly, Savolainen et al. [15] developed a nested logit model and a multinomial logit model and found that darkness increases the severity of single-vehicle crashes. In fact, Helai et al. [16] developed a hierarchical binomial logistic model and concluded that the severity of accidents increases at night compared with daytime.

Lighting is perhaps of greater interest for the modern roundabout than for any other type of highway intersection because it has unique design features, such as raised splitter islands with flared ends at the exits/entrances to the circulatory roadway and a raised center island with a radius large enough to divert traffic from the approaches into the roundabout. These features are important to reduce speeds and prevent or significantly reduce fatal and serious crashes at roundabouts. However, when travelling at night, these features must be visible, or they can become a potential source of danger to motorists. In addition, because the deflection of the roadway into the roundabout lane, a vehicle's headlight beam is often tangential to the roundabout lane and does not illuminate objects and/or colliding movements from the left side of the vehicle. This means that drivers are often looking into the darkness when entering the roundabout. Therefore, the overall safety of a roundabout at night can be improved by dedicated street lighting [17,18].

Lighting of a roundabout can be accomplished by installing lighting poles in the center island or at the edge of the intersection. Lighting at the edge of the roundabout provides the best visibility of key areas and visibility of circulating vehicles to vehicles approaching the roundabout. In addition, vertical lighting levels in crosswalks can only be achieved if approach lighting is used. Therefore, roundabouts with central island lighting may require additional approach lighting or may be combined with outdoor lighting to achieve the vertical lighting level. Figure 1 shows the significant differences in center island and circulatory roadway lighting between central and perimeter lighting. Both illumination designs include approach lighting.

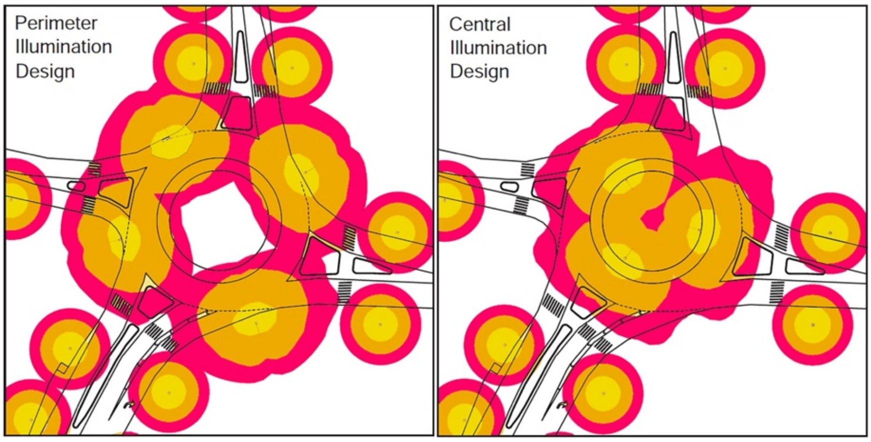

Figure 1. Photometric illustration of perimeter and central illumination design.

Worldwide, there are several normative references that regulate the illuminance for roundabouts. Most European countries have adopted the European Union standard, EN 13201 (hereafter EN), in its entirety or with some modifications, as the basis for lighting their roundabouts. Consisting of four parts, EN has been adopted by the European Committee for Standardization since 2003 (Modus 2012) and contains both warnings and standards for roadway and intersection lighting.

Table 1 summarizes the European Standard (EN 13201-2:2016) recommended illuminance levels for roundabouts located in continuously illuminated roads [19]. In particular, the CE classes mentioned in Table 1, i.e., illuminance classes (E) in conflict areas (C), are intended for motor vehicle drivers and other road users in conflict areas such as shopping streets, road intersections of some complexity, roundabouts, queuing areas, etc.

Table 1. Performance requirements for CE Series of Lighting Classes [19].

Class	Horizontal Illuminance [Lux]	
	E_i (Minimum Maintained)	U_o (Minimum)
CE0	50	0.4
CE1	30	0.4
CE2	20	0.4
CE3	15	0.4
CE4	10	0.4
CE5	7.5	0.4

CE classes can also be applied to areas used by pedestrians and cyclists, e.g., underpasses.

The average illuminance (E_i) and the overall uniformity of the illuminance (U_o) are to be calculated and measured in accordance with EN 13201-3 and EN 13201-4 [20,21].

Italy uses a translated and slightly modified version of EN Part 1, UNI 11248 Illuminazione Stradale-2012 (Roadway Illumination), as the regulation for lighting roundabouts. This document does not differ from EN with respect to roundabout lighting. Parts 2, 3 and 4 of EN are used as the standard for lighting. In 2006, the Ministry of Infrastructure and Transport established the guidelines for lighting roundabouts. Rural roundabouts with split-level maneuvers or grades must be illuminated. If a roundabout does not belong to either of these categories, the decision whether or not to illuminate it is the responsibility of the local road authorities.

In this context, there are many benefits that the road administration can gain from a photovoltaic (PV) system beyond the immediate financial and environmental benefits. The use of solar energy allows for a significant degree of energy independence and independence from utilities and power outages. The latter two aspects are critical for lighting roundabouts in the event of a power outage. On the other hand, electricity consumption for public lighting in Italy was about 6000 GWh in 2017, with a per capita consumption of 100 kWh, twice the European average of 51 kWh. In 2017, spending on public lighting in Italy amounted to 1.7 billion (1.7×10^9) euros, and per capita spending was 28.7 euros, well above the average of the main European countries (16.8 euros).

The renewal of public lighting in terms of reduced and efficient consumption of electrical energy is therefore an important priority for all public administrations.

On the other hand, many European countries are making efforts to develop solar energy as the main energy source for electricity generation in order to reach the environmental target imposed by the European Community, according to which 32% of the gross final consumption in 2030 should be covered by renewable energy sources [22]. Specifically for Italy, the PNIEC (the Integrated National Energy and Climate Plan) proposes an overall target of 30%. For the sectoral level, the target RES (Renewable Energy Sources) is set at 55.4% of gross electricity consumption, estimated at 337.3 TWh, corresponding to a production of 187 TWh from RES. To achieve these results, there is a large increase in installed RES capacity, especially photovoltaic (PV), which will reach 60 GWh of installed PV by 2030 [23].

Based on the previous considerations, there are many experiences with street lighting where PV systems are installed in each pole. This is one of the areas where off-grid PV energy systems are used, and in the last decade, interest in these systems has increased due to recent developments in both LED and PV technology [24].

The studies on the use of roundabouts for PV system installation are very limited in the literature. The most relevant study deals with the use of a PV system equipped with a vertical tracking system, called RAST (RoundAbout Solar Tracking) [25]. In this study, only the operating principle of the vertical tracking system is described, without establishing a relationship between the PV system sizing and the local electricity demand.

The proper integration of distributed renewable generators can benefit the whole energy system, and the use of energy close to the production site helps to achieve this goal.

In this context, self-consumption and self-sufficiency are two energy indicators that can be used to quantify the use of energy production at the local level.

Self-consumption (SC) is defined as the amount of electricity generated and consumed locally relative to total local generation, whereas self-sufficiency (SS) measures the amount of consumption supplied by local generation relative to total consumption [26]. Due to the complementarity between the daily load demand curve and the roundabout generation curve, the index SC would be very small. Nowadays, however, the use of PV systems with batteries is becoming more and more popular also for grid-connected systems due to the decreasing prices of batteries. Such a solution is certainly an interesting option for roundabouts, where the lighting has a limited extension with respect to its center to increase the energy consumption.

The aim of this study is to perform a parametric analysis of the degree of self-sufficiency that a roundabout can achieve depending on the availability of space for the installation of a PV system and the energy demand for the lighting of a roundabout using as parameter the diameter of the roundabout.

The technical-scientific approach of the research is based on verifying whether a PV system installed in a roundabout is capable of generating enough energy to supply the local load in a year. In other words, the lower limit of the diameter of a roundabout is determined to achieve 100% self-consumption. The PV systems assumed for the simulations are capable of meeting the entire energy demand for lighting and ancillary services through solar energy when connected to the grid. Self-consumption represents the starting point for energy self-sufficiency, i.e., the upper limit. The latter is synonymous with energy independence and, if it is 100%, it means independence from the national grid and the energy supplied by it, which currently still comes mainly from non-renewable sources. However, in terms of PV generation, the roundabout has a half-day time lag, which severely limits self-sufficiency without appropriate solutions. Thus, to be truly functional, the system must be connected to the power grid, so that the grid serves as a storage for the PV system. However, the technical sizing and evaluation of the costs associated with the storage system are beyond the scope of this work and will certainly find their place in future research development.

2. Materials and Methods

The methodology to pursue the objectives stated in the introduction is divided into 5 steps, all aimed at first calculating the parameters required to characterize the roundabouts from the point of view of the electricity that can be generated by the photovoltaic systems on the available area within the center islands, and then evaluating the energy consumption required to operate the different system solutions for artificial lighting. The geometrical characteristics of the roundabouts considered for the different calculations are in accordance with the Italian legislation (D.M. 19 April 2006) [27]. Of particular importance is the diameter of the roundabouts, which is used by the Italian legislation as a basis for the following classification of roundabouts:

- Mini roundabouts: diameter between 14 and 25 m.
- Compact roundabouts: diameter between 25 and 40 m.
- Conventional roundabouts: diameter between 40 and 50 m.

2.1. Calculation of the Available Area for the Installation of the Photovoltaic System

RAPS (Roundabout PV System) systems have been developed to use the available space in already equipped and monitored roundabouts to generate electricity with a photovoltaic system. To evaluate the space available for the RAPSs, the available space within the center islands of the roundabouts was evaluated. Specifically, the following geometric parameters were evaluated for the roundabouts with diameters between 14 and 50 m (Figure 2):

➢ Inscribed circle diameter, D [m].
➢ Width of the circulatory roadway, W_{CR} [m].

- ➢ Radius of the center island, R_{CI} [m], calculated as the difference between the inscribed circle diameter and twice the width of the circulatory roadway.
- ➢ Available area including the apron [m^2].
- ➢ Width of the apron [m].
- ➢ Available area minus the apron [m^2].

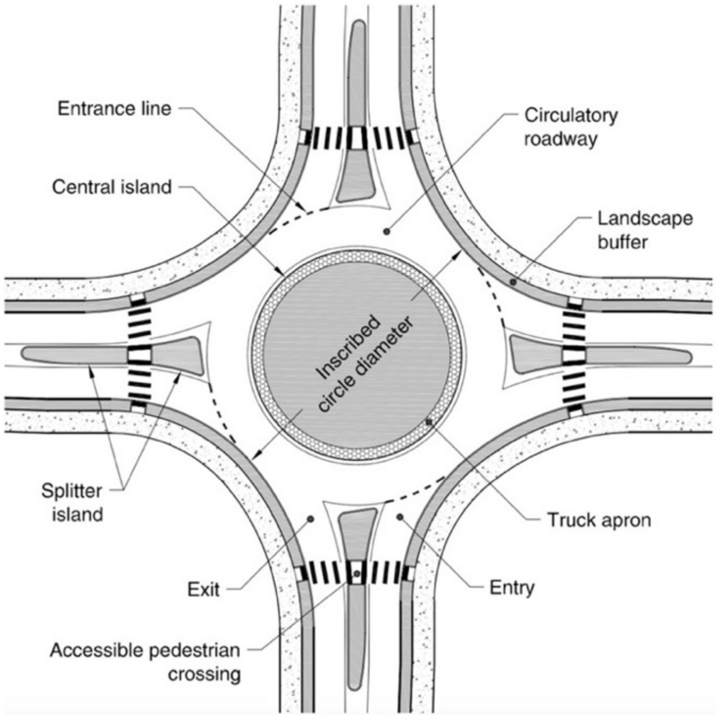

Figure 2. Roundabout Design Features [28].

The area indicated in the last item of the above list is the one needed for the photovoltaic systems characteristic of RAPSs.

2.2. Calculation of Installable Modules

Si-wafer and thin film PV technologies are available in the market. Although the efficiency of CdTe (thin film) modules has increased sharply from 9% to 19% over the past 10 years, the efficiency of average commercial wafer-based silicon modules has increased from about 15% to 20%. Si-wafer technology accounted for about 95% of total production in 2020. The share of monocrystalline technology in total c-Si production is now about 84% (compared with 66% in 2019) [29]. Therefore, this is the reason for choosing Si-wafer-based PV technology in this study.

The number of kilowatts that a photovoltaic system can generate thanks to RAPS was determined by multiplying the available area inside the central islands of the considered roundabouts by the values of the net area occupied by the modules, estimated using the following relationships [29]:

- ➢ A total of 6.2–7.7 m^2 per installed kWp, at 0° tilt angle, for the monocrystalline silicon modules;
- ➢ A total of 6.6–10 m^2 per installed kWp, at 0° tilt angle, for the polycrystalline silicon modules.

2.3. Calculation of Electricity Productivity

The annual analysis of PV generation versus demand has been carried out considering the variations within the Italian territory from South to North. These results can be applied to all Mediterranean locations in the same latitude range. In particular, in order to quantify the electricity (EPV) generated by the RAPS envisaged in the roundabouts simulated in this study, the following solar radiation values (expressed in equivalent hours) were considered for the Italian territory [30]:

- Northern Italy: 1000–1200 h/year.
- Central Italy: 1200–1300 h/year.
- Southern Italy: 1350–1500 h/year.

By multiplying the above values for equivalent hours (referring to the maximum value for each class) by the number of kW potentially installable, productivity was calculated in kWh/year. The calculation was performed for each diameter of each type of roundabout considered with respect to Northern, Central and Southern Italy, both for the monocrystalline and polycrystalline silicon modules.

2.4. Calculation of the Energy Demand for Lighting Roundabout

To determine the electricity demand for the lighting of the roundabouts and the roads that lead into them, we used DIALux (version 9.2), a free software package that can be used to determine the technical characteristics of a street lighting system.

The software provides a constantly updated archive of lighting fixtures from the world's leading manufacturers, described in detail with all technical data such as power, intensity and luminous flux, luminance diagrams and isometric isolux curves. The specific placement of the lamps allows to realize a complete lighting project. As for the lighting of roundabouts and legs, DIALux allows modelling, simulation and obtaining accurate results in compliance with the current legislation, EN 13201: 2015, which defines the classes of lighting systems for street lighting that meet the visual needs of road users and allow the consideration of the environmental aspects of street lighting.

In this particular case, the simulations were performed for the configurations summarized in Table 2.

Table 2. Configurations chosen for the simulations (roundabouts and lighting system).

Type of Roundabout	**Lighting System**					
	Roundabout Only (High Mast Poles)	**Roundabout Only (Poles)**	**Roundabout (High Mast Pole) and Legs (Single-Sided Arrangement) ***	**Roundabout (High Mast Pole) and Legs (Double-Sided Arrangement) ***	**Roundabout (Poles) and Legs (Single-Sided Arrangement) ***	**Roundabout (Poles) and Legs (Double-Sided Arrangement) ***
20 m $\leq$ Diameter $\leq$ 50 m (5 m increments)	×	-	-	-	-	-
20 m $\leq$ Diameter $\leq$ 50 m (5 m increments)	-	×	-	-	-	-
20 m $\leq$ Diameter $\leq$ 50 m (5 m increments)	-	-	×	-	-	-
20 m $\leq$ Diameter $\leq$ 50 m (5 m increments)	-	-	-	×	-	-
20 m $\leq$ Diameter $\leq$ 50 m (5 m increments)	-	-	-	-	×	-
20 m $\leq$ Diameter $\leq$ 50 m (5 m increments)	-	-	-	-	-	×

* for a longitudinal extension of 100 m on each leg.

The choice of the 100 m spacing on each leg was motivated by the desire to consider the range of influence of roundabouts on user behavior. In fact, road users approaching the roundabout begin to slow down from 100 m from the center of the roundabout itself. [30]. Therefore, leg lighting at a distance of 100 m is undoubtedly an important means to ensure safe entry into the roundabout at night.

2.5. Evaluation of the Critical Diameter

The final phase of the methodology used in this study was to evaluate the self-sufficiency of the roundabouts in terms of the power required for lighting. In particular, a dimensional parameter was introduced for the geometry of the roundabouts, which represents the threshold for achieving the aforementioned self-sufficiency.

This parameter, called "critical diameter", was defined as the value of the inscribed diameter at which the balance between the energy generated by the photovoltaic system and the energy required for the artificial lighting of the roundabout is guaranteed. This means that choosing an effective diameter larger than the critical diameter guarantees the generation of a surplus of electricity that can be used for other purposes (e.g., charging electric vehicles, reselling energy to commercial companies, etc.).

The critical diameter values were estimated for all configurations that were the subject of the previous assessments. In addition, the final discussions were articulated with reference to two specific critical diameter values:

(1) Lower critical diameter: value of the critical diameter corresponding to the balance between the energy required by the lighting configuration with the lowest consumption among the configurations simulated in the previous point and the electricity generated by the photovoltaic systems considered.
(2) Upper critical diameter: value of the critical diameter corresponding to the balance between the energy required by the lighting configuration with the highest consumption among the configurations simulated in the previous point and the electricity generated by the photovoltaic systems considered.

3. Results and Discussion

Table 3 shows the available areas within the center islands of the roundabouts included in the analysis. In the case of the mini roundabouts, it is useful to refer to configurations with a diameter of 20 m or more. In fact, below this size, the available surfaces offer an area of less than 5 m^2, which is not suitable for the installation of photovoltaic systems. Table 4 presents the values of the performances that can be achieved by the installation of photovoltaic modules, related to the two options considered: monocrystalline silicon and polycrystalline silicon.

With reference to the roundabouts identified on the basis of the diameter values that represent the size thresholds of each of the categories defined by D.M. 19 April 2006 (with the exception of configurations with a diameter of less than 20 m), Table 5 shows the values of electricity productivity differentiated by the types of photovoltaic modules and in relation to the geographical areas into which the Italian territory is normally divided.

Table 3. Areas available for the installation of the RAPS.

Type of Roundabout	Inscribed Circle Diameter [m]	Available Area [m^2]
Mini roundabout	14	Negligible
Mini roundabout	15	Negligible
Mini roundabout	20	7.07
Mini roundabout/Compact roundabout	25	27.34
Compact roundabout	30	116.90
Compact roundabout	35	274.65
Compact roundabout/ Conventional roundabout	40	483.05
Conventional roundabout	45	855.30
Conventional roundabout	50	1134.11

Table 4. Power supplied by the photovoltaic modules.

Type of Roundabout	Inscribed Circle Diameter [m]	Power Obtainable from Monocrystalline Silicon Modules [kW]	Power Obtainable from Polycrystalline Silicon Modules [kW]
Mini roundabout	20	0.92	0.71
Mini roundabout/ Compact roundabout	25	3.55	2.73
Compact roundabout	30	15.18	11.69
Compact roundabout	35	35.67	27.46
Compact roundabout/ Conventional roundabout	40	62.73	48.31
Conventional roundabout	45	111.08	85.53
Conventional roundabout	50	147.29	113.41

Table 5. Electricity productivity of the RAPS (E_{PV}).

Type of Roundabout	Inscribed Circle Diameter [m]	Productivity, E_{PV} [kWh/Year] Monocrystalline Silicon Modules			Productivity, E_{PV} [kWh/Year] Polycrystalline Silicon Modules		
		North	Center	South	North	Center	South
Mini roundabout	20	1009.80	1193.40	1377.00	777.54	918.92	1060.29
Mini roundabout/ Compact roundabout	25	3905.67	4615.80	5325.92	3007.37	3554.16	4100.96
Compact roundabout/ Conventional roundabout	40	69,007.33	81,554.11	94,100.90	53,135.64	62,796.67	72,457.69
Conventional roundabout	50	162,016.42	191,473.95	220,931.48	124,752.64	147,434.94	170,117.24

The calculation of the energy demand for the self-sufficient lighting of the roundabouts (E_L) was carried out with the DIALux software through a series of simulations of system configurations characterized by the use of different types of lamps on the market, from the classic lamps to newer applications such as the LED lamps. The results presented in Tables 6 and 7 refer to the minimum (E_{Lmin}) and maximum (E_{Lmax}) consumption required to meet the lighting requirements in the case of the six system configurations considered. In all cases, the system solutions with the lowest consumption (expressed in kWh/year) were those where the luminaire was equipped with a LED lamp. It is well known that the LED lamps (Light Emitting Diode) represent, to date, the best technology on the market to meet the requirements of public lighting systems in general and specifically for use in road roundabouts. Street lighting systems equipped with LED lamps not only have a significantly lower consumption than the classic discharge lamps, but also numerous other advantages, such as a very long life (greater than or equal to 100,000 h), high luminous efficiency, high color rendering index, low maintenance, flexible installation, easy maintenance, long durability of materials and components, and easy replacement of elements. These advantages mean significant benefits, both in terms of maintenance, thanks to the long operating time and installation flexibility, and in terms of energy consumption, thanks to the remarkable luminous efficacy and high color rendering index.

The energy consumption required to light the simulated roundabouts was then compared with the energy generated by photovoltaic systems that could be installed on the center islands of the roundabouts. Figure 3 shows examples of the diagrams of the configurations that require the most energy consumption. These are roundabouts illuminated high mast poles and where the legs are equipped with an artificial lighting system on both sides for a length of 100 m. The diagrams refer to the three configurations with monocrystalline silicon modules (geographical areas: northern, central and southern Italy) and to the three configurations with polycrystalline silicon modules (geographical areas: northern, central and southern Italy).

Table 6. Minimum energy consumption requirements for lighting systems in roundabouts.

Type of Roundabout	Inscribed Circle Diameter [m]	Minimum Energy Consumption Requirement for Lighting System, E_{Lmin} [kWh/Year]					
		Roundabout Only (High Mast Poles)	Roundabout Only (Poles)	Roundabout (High Mast Pole) and Legs (Single-Sided Arrangement)	Roundabout (High Mast Pole) and Legs (Double-Sided Arrangement)	Roundabout (Poles) and Legs (Single-Sided Arrangement)	Roundabout (Poles) and Legs (Double-Sided Arrangement)
Mini roundabout	20	2040	3040	16,872	15,224	17,782	16,224
Mini roundabout/ Compactroundabout	25	2960	5456	17,792	16,144	20,288	18,640
Compact roundabout/ Conventional roundabout	40	8660	16,320	23,492	21,884	31,152	29,504
Conventional roundabout	50	11,400	67,808	26,232	24,584	82,640	80,992

Table 7. Maximum energy consumption requirements for lighting systems in roundabouts.

Type of Roundabout	Inscribed Circle Diameter [m]	Maximum Energy Consumption Requirement for Lighting System, E_{Lmax} [kWh/Year]					
		Roundabout Only (High Mast Poles)	Roundabout Only (Poles)	Roundabout (High Mast Pole) and Legs (Single-Sided Arrangement)	Roundabout (High Mast Pole) and Legs (Double-Sided Arrangement)	Roundabout (Poles) and Legs (Single-Sided Arrangement)	Roundabout (Poles) and Legs (Double-Sided Arrangement)
Mini roundabout	20	33,968	17,600	119,728	186,384	103,360	170,016
Mini roundabout/ Compactroundabout	25	33,968	17,600	119,728	186,384	103,360	170,016
Compact roundabout/ Conventional roundabout	40	42,460	33,968	128,220	194,876	119,728	186,384
Conventional roundabout	50	42,460	67,936	128,220	194,876	153,696	220,352

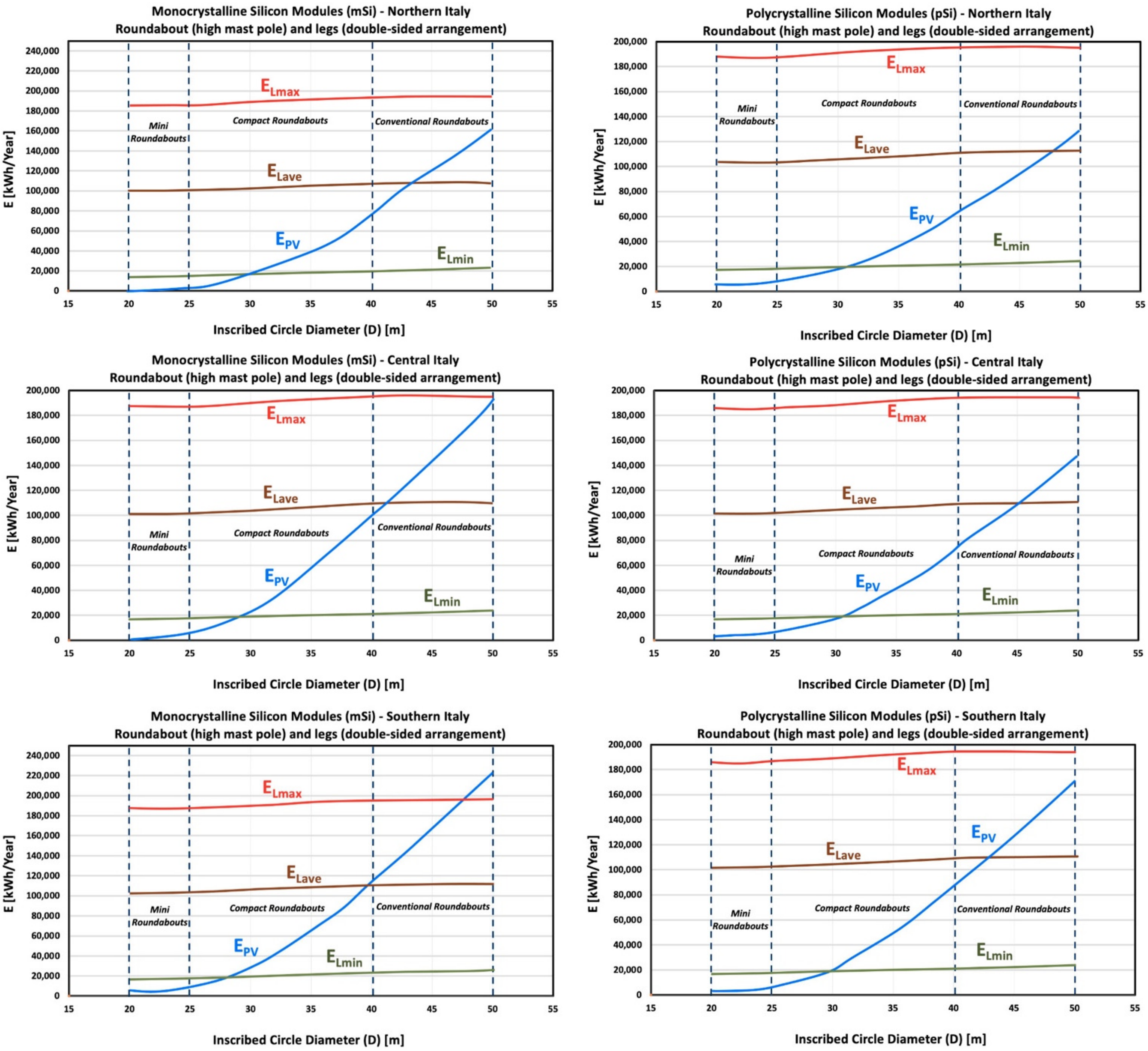

Figure 3. Comparison diagrams between the energy generated by RAPSs and the energy required by lighting systems.

Regarding the curve of maximum consumption, it can be noted that only in one configuration out of 6, self-sufficiency is always guaranteed (the curve of generated energy intersects the curve of maximum energy demand): This is the configuration in southern Italy, where the photovoltaic system was built with monocrystalline silicon modules.

On the other hand, the curves representing the minimum energy consumption are always intersected by those associated with the productivity guaranteed by the RAPSs. The intersection of the two curves is always at the values of the diameter (D) of about 30 m. From this, we can deduce the following important result: Lighting solutions with low-consumption luminaires (e.g., LEDs) can be operated with RAPSs for any geometric configuration of roundabout within the range of diameters between 30 and 50 m.

Table 8 summarizes the results of all the elaborations performed. In particular, Table 7 shows the values of the critical diameters (lower and upper) estimated for all the configurations analyzed. The main considerations that can be drawn from the analysis of the results are the following:

Table 8. Critical diameters (lower and upper) for the different system configurations analyzed.

Critical Diameter [m]	Features of the Photovoltaic System: Monocrystalline Silicon Modules-Northern Italy					
	Roundabout Only (High Mast Poles)	Roundabout Only (Poles)	Roundabout (High Mast Pole) and Legs (Single-Sided Arrangement)	Roundabout (High Mast Pole) and Legs (Double-Sided Arrangement)	Roundabout (Poles) and Legs (Single-Sided Arrangement)	Roundabout (Poles) and Legs (Double-Sided Arrangement)
Lower	24	26	31	30	32	31
Upper	35	32	46	-	49	-
	Features of the Photovoltaic System: Monocrystalline Silicon Modules-Central Italy					
Critical Diameter [m]	**Roundabout Only (High Mast Poles)**	**Roundabout Only (Poles)**	**Roundabout (High Mast Pole) and Legs (Single-Sided Arrangement)**	**Roundabout (High Mast Pole) and Legs (Double-Sided Arrangement)**	**Roundabout (Poles) and Legs (Single-Sided Arrangement)**	**Roundabout (Poles) and Legs (Double-Sided Arrangement)**
Lower	24	26	30	29	31	30
Upper	33	30	43	-	43	-
	Features of the Photovoltaic System: Monocrystalline Silicon Modules-Southern Italy					
Critical Diameter [m]	**Roundabout Only (High Mast Poles)**	**Roundabout Only (Poles)**	**Roundabout (High Mast Pole) and Legs (Single-Sided Arrangement)**	**Roundabout (High Mast Pole) and Legs (Double-Sided Arrangement)**	**Roundabout (Poles) and Legs (Single-Sided Arrangement)**	**Roundabout (Poles) and Legs (Double-Sided Arrangement)**
Lower	24	26	29	28	30	29
Upper	32	29	41	48	40	50
	Features of the Photovoltaic System: Polycrystalline Silicon Modules-Northern Italy					
Critical Diameter [m]	**Roundabout Only (High Mast Poles)**	**Roundabout Only (Poles)**	**Roundabout (High Mast Pole) and Legs (Single-Sided Arrangement)**	**Roundabout (High Mast Pole) and Legs (Double-Sided Arrangement)**	**Roundabout (Poles) and Legs (Single-Sided Arrangement)**	**Roundabout (Poles) and Legs (Double-Sided Arrangement)**
Lower	25	27	33	33	34	34
Upper	37	33	-.	-	-	-

Table 8. *Cont.*

Critical Diameter [m]	Features of the Photovoltaic System: Polycrystalline Silicon Modules-Central Italy					
	Roundabout Only (High Mast Poles)	Roundabout Only (Poles)	Roundabout (High Mast Pole) and Legs (Single-Sided Arrangement)	Roundabout (High Mast Pole) and Legs (Double-Sided Arrangement)	Roundabout (Poles) and Legs (Single-Sided Arrangement)	Roundabout (Poles) and Legs (Double-Sided Arrangement)
Lower	25	26	31	31	32	32
Upper	36	32	47	-	-	-
Critical Diameter [m]	**Features of the Photovoltaic System: Polycrystalline Silicon Modules-Southern Italy**					
	Roundabout Only (High Mast Poles)	**Roundabout Only (Poles)**	**Roundabout (High Mast Pole) and Legs (Single-Sided Arrangement)**	**Roundabout (High Mast Pole) and Legs (Double-Sided Arrangement)**	**Roundabout (Poles) and Legs (Single-Sided Arrangement)**	**Roundabout (Poles) and Legs (Double-Sided Arrangement)**
Lower	25	26	30	30	31	31
Upper	35	31	45	-	46	-

Only in relation to the lighting of the roundabouts, that is, without considering the option related to the artificial lighting of the access legs, a diameter of at least 24 m (when lit by a high mast pole) and at least 26 m (lighting with poles at the edge of the circular roadway) is required for the RAPS to be truly effective. This means that the mini roundabouts, according to the classification of roundabouts provided by the Italian legislation, are not eligible as a location for the photovoltaic system. If we then consider the lighting systems with classic luminaires, i.e., equipped with discharge lamps and therefore characterized by a high energy demand, the energy self-sufficiency is possible starting from a roundabout with a diameter between 29 and 37 m.

➢ In the case of roundabouts where the lighting of the entry legs is foreseen along a length of 100 m, in order to ensure optimal night-time driving safety requirements, it should be noted that for all the system configurations considered, the minimum diameters of the roundabouts must be between 29 and 34 m for the RAPS to be effective, which in any case should be combined with lighting systems with minimal consumption (such as LEDs). In fact, it should be noted that energy-intensive lighting systems (with luminaires equipped with discharge lamps) in many cases do not guarantee energy self-sufficiency for any of the diameters allowed by the standards (for example, almost all configurations of roundabouts equipped with lighting poles and double-sided arrangement of the lighting poles on the legs). In cases where the RAPS also applies to such energy-intensive configurations, roundabouts with a diameter of at least 40 m are also required. This means that in these cases only the conventional roundabouts need to be considered and the other two categories of roundabouts (compact roundabouts and mini roundabouts) are left out.
➢ The RAPS solutions, which foresee the use of monocrystalline silicon, are sufficient to guarantee energy self-sufficiency for the lighting of roundabouts only from an external diameter of 24 m, regardless of the geographical location of the installation. If one wanted to ensure the lighting of routes over an extension of 100 m, RAPS with monocrystalline silicon modules would require roundabouts with diameters starting from 28 m in Southern Italy, from 29 m in Central Italy and from 30 m in Northern Italy.
➢ Systems with polycrystalline silicon modules are only suitable for ensuring energy self-sufficiency for lighting roundabouts from an external diameter of 25/26 m, regardless of the geographical location of the system. The overall lighting of the intersection area (roundabouts and legs) requires that RAPSs with polycrystalline silicon modules be installed on roundabouts with diameters from 30 m in Southern Italy, from 31 m in Central Italy, and from 32 m in Northern Italy.

4. Conclusions

The most important result of this study is the possibility of evaluating the level of self-consumption by considering different configurations associated with the combination of different crucial variables such as: annual irradiation, annual demand, photovoltaic technology and diameter of the roundabout. The most interesting output of this analysis is the "critical diameter" of the roundabout, with which 100% self-consumption can be achieved for each case studied.

The self-consumption represents the starting point for energy self-sufficiency, specifically it is the theoretical upper value.

Therefore, it can be said that the roundabout whose inscribed diameter coincides with the critical diameter could potentially achieve self-consumption.

The quantitative results reported in this paper are based on the assumed efficiency of the two PV technologies used. Moreover, the annual analysis based on hourly simulations based on long-term meteorological data (global irradiance, ambient temperature, wind speed) is justified by the consideration that the PV system is connected to the grid.

The bifacial PV modules that have just entered the market, which convert sunlight into DC electricity on both the front and back sides of the PV modules (and which can be used with either a fixed or tracking structure), can significantly increase annual production depending on the ratio between diffuse and global solar radiation. This means that roundabouts with smaller diameters can also be used to supply local loads.

Moreover, the results reported in this paper refer to the typical values of irradiance and lighting demand in the Mediterranean region, whereas towards the north the annual PV production decreases and the demand increases. To extend the use of roundabouts to such locations, it is necessary to increase the area performance and energy density of PV systems. The bifacial modules are very effective in the Northern countries, where the diffuse component of the radiation is high, and the optimal tilt angle is larger than in the Southern countries.

On the other hand, the presence of lighting poles (central pole or perimetral poles) can lead to shading patterns that negatively affect the electrical energy production of RAPS systems. Additionally, in this case, there is a technological solution based on the idea of Distributed Maximum Power Point Tracking (DMPPT) techniques. It allows each photovoltaic module in a system to operate at its Maximum Power Point. This is highly desirable from an efficiency point of view when operating conditions do not match. As for the larger roundabouts, the surplus from production could be used to provide charging stations for electric vehicles.

Finally, it should be noted that the level of mismatch between the energy demand of the roundabout and the photovoltaic generation profile is very large, so a storage system is required to achieve a good degree of self-sufficiency. Only in this context, among others, the variability of weather conditions during the year is a crucial information. However, a further distinction should be made as the storage system can be considered as a grid-connected or stand-alone system. Since roundabout lighting plays an important role in safety, a grid-connected system can provide a high degree of reliability in powering roundabout lighting. The optimal technical and economic sizing of the storage system is beyond the scope of this paper, but is certainly one of the further developments of this research.

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References

1. Polders, E.; Daniels, S.; Casters, W.; Brijs, T. Identifying crash patterns on roundabouts. *Traffic Inj. Prev.* **2014**, *16*, 202–207. [CrossRef] [PubMed]
2. Elvik, R. Road safety effects of roundabouts: A meta-analysis. *Accid. Anal. Prev.* **2017**, *99*, 364–371. [CrossRef] [PubMed]
3. Vujanić, M.; Savićević, M.; Antić, B.; Pešić, D. Safety effectiveness of converting conventional intersections to roundabouts: Case study in the city of Niš. *Promet–Traffic Transp.* **2016**, *28*, 529–537. [CrossRef]
4. Ciampa, D.; Diomedi, M.; Giglio, F.; Olita, S.; Petruccelli, U.; Restaino, C. Effectiveness of unconventional roundabouts in the design of suburban intersections. *Eur. Transp./Trasp. Eur.* **2020**, *80*, 1–16. [CrossRef]
5. Leonardi, S.; Distefano, N.; Pulvirenti, G. Multiple Correspondence Analysis (MCA) for the evaluation of risk perception of roundabouts for young people. *Eur. Transp. Trasp. Eur.* **2019**, *72*, 1–23.

6. Distefano, N.; Leonardi, S.; Consoli, F. Drivers' Preferences for Road Roundabouts: A study based on stated preference survey in Italy. *KSCE J. Civ. Eng.* **2019**, *23*, 4864–4874. [CrossRef]
7. Daniels, S.; Brijs, T.; Nuyts, E.; Wets, G. Externality of risk and crash severity at roundabouts. *Accid. Anal. Prev.* **2010**, *42*, 1966–1973. [CrossRef]
8. Owens, D.; Sivak, M. The role of visibility in nighttime traffic accidents. In Proceedings of the 2nd International Symposium on Visibility and Luminance in Roadway Lighting, Orlando, FL, USA, 26–27 October 1993; pp. 133–147.
9. Rice, T.M.; Peek-Asa, C.; Kraus, J.F. Nighttime driving, passenger transport, and injury crash rates of young drivers. *Inj. Prev.* **2003**, *9*, 245–250. [CrossRef] [PubMed]
10. Sullivan, J.M.; Flannagan, M.J. The role of ambient light level in fatal crashes: Inferences from daylight saving time transitions. *Accid. Anal. Prev.* **2002**, *34*, 487–498. [CrossRef]
11. Chimba, D.; Sando, T. The prediction of highway traffic accident injury severity with neuromorphic techniques. *Adv. Transp. Stud.* **2009**, *19*, 17–26.
12. Lee, C.; Abdel-Aty, M. Comprehensive analysis of vehicle–pedestrian crashes at intersections in Florida. *Accid. Anal. Prev.* **2005**, *37*, 775–786. [CrossRef] [PubMed]
13. Pai, C.-W.; Saleh, W. Modelling motorcyclist injury severity by various crash types at T-junctions in the UK. *Saf. Sci.* **2008**, *46*, 1234–1247. [CrossRef]
14. Yannis, G.; Kondyli, A.; Mitzalis, N. Effect of lighting on frequency and severity of road accidents. *Proc. Inst. Civ. Eng. Transp.* **2013**, *166*, 271–281. [CrossRef]
15. Savolainen, P.; Mannering, F. Probabilistic models of motorcyclists' injury severities in single- and multi-vehicle crashes. *Accid. Anal. Prev.* **2007**, *39*, 955–963. [CrossRef] [PubMed]
16. Helai, H.; Chor, C.H.; Haque, M.M. Severity of driver injury and vehicle damage in traffic crashes at intersections: A Bayesian hierarchical analysis. *Accid. Anal. Prev.* **2008**, *40*, 45–54. [CrossRef]
17. Lutkevich, P.; Hasson, P. *Transportation Research Circular E-C083: An Examination and Recommendation for Current Practices in Roundabout Lighting*; Transportation Research Board: Washington, DC, USA, 2005.
18. Rodgers, M.O.; Hunter, M.; Samoylov, A.; Gbologah, F.; Berrebi, S. Evaluation of Current Practice for Illumination at Roundabouts; Safety and Illumination of Roundabouts (Phase I). Final Report. Georgia DOT Research Project 12-01, March 2016. Available online: https://rosap.ntl.bts.gov/view/dot/35850 (accessed on 7 July 2021).
19. *UNI EN 13201-2:2016*; Road Lighting-Part 2: Performance Requirements. UNE Standards: Brussels, Belgium, 2016.
20. *UNI EN 13201-3:2016*; Road Lighting-Part 3: Calculation of Performance. UNE Standards: Brussels, Belgium, 2016.
21. *UNI EN 13201-4:2016*; Road Lighting-Part 4: Methods of Measuring Lighting Performance. UNE Standards: Brussels, Belgium, 2016.
22. Direttiva (UE) 2018/2001. Available online: https://eur-lex.europa.eu/legal-content/IT/TXT/PDF/?uri=CELEX:32018L2001&from=en (accessed on 11 January 2022).
23. Proposta di Piano Nazionale Integrato per L'Energia ed il Clima; Ministero dello Sviluppo Economico. Available online: https://www.mise.gov.it/images/stories/documenti/Proposta_di_Piano_Nazionale_Integrato_per_Energia_e_il_Clima_Italiano.pdf (accessed on 1 February 2022). (In Italian)
24. Duman, A.C.; Güler, Ö. Techno-economic analysis of off-grid photovoltaic LED road lighting systems: A case study for northern, central and southern regions of Turkey. *Build. Environ.* **2019**, *156*, 89–98. [CrossRef]
25. Rosa-Clot, M.; Rosa-Clot, P.; Tina, G.M.; Ventura, C. RAST: Roundabout solar tracking. *Energy Procedia* **2017**, *134*, 598–606. [CrossRef]
26. Jiménez-Castillo, G.; Rus-Casas, C.; Tina, G.; Muñoz-Rodriguez, F. Effects of smart meter time resolution when analyzing photovoltaic self-consumption system on a daily and annual basis. *Renew. Energy* **2021**, *164*, 889–896. [CrossRef]
27. Italian Ministry of Infrastructure and Transport. Ministerial Decree No 19/04/2006-Norme Funzionali e Geometriche per la Costruzione delle Intersezioni Stradali (Translation: Functional and Geometric Rules for the Construction of Road Intersections), GU n. 170, 24/07/2006. Available online: https://www.stradelandia.it/wp-content/uploads/2022/01/DES_04.pdf (accessed on 7 July 2021).
28. Federal Highway Administration. Roundabouts: An Informational Guide. Report No. FHWA-RD-00-067. 2000. Available online: http://www.fhwa.dot.gov/publications/research/safety/00068/ (accessed on 7 February 2022).
29. Fraunhofer ISE. Photovoltaics Report. 2020. Available online: https://www.ise.fraunhofer.de/en/publications/studies/photovoltaics-report.html (accessed on 24 February 2022).
30. GSE. Solare Fotovoltaico. Rapporto Statistic. 2020. Available online: https://www.gse.it/documenti_site/Documenti%20GSE/Rapporti%20statistici/Solare%20Fotovoltaico%20-%20Rapporto%20Statistico%20GSE%202020.pdf (accessed on 24 February 2022).