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Article

Development of a Geographical Information System (GIS) for the Integration of Solar Energy in the Energy Planning of a Wide Area

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Abstract: Energy planning has become one of the most powerful tools for urban planning even if several constraints, (*i.e.*, aesthetic, archaeological, landscape) and technological (low diffusion of Renewable Energy Sources, RES) reduce its spreading. An efficient and sustainable urban planning process should be based on detailed energy issues, such as: (i) the effective energetic characteristics and needs of the area like urban density and energy consumption, (ii) the integration of different RES and (iii) the diffusion of high efficiency technologies for energy production like cogeneration and district heating. The above-mentioned energetic issues and constraints must be constantly updated, in order to evaluate the consequences on environment and landscape due to new distributed generation technologies. Moreover, energy strategies and policies must be adapted to the actual evolution of the area. In this paper the authors present a Geographical Information Database System (GIS DB) based on: (i) the availability of land use (Land Capability Classification, LCC) to evaluate the productive potential; (ii) the estimation of residential energy consumptions (e.g., electricity), (iii) the integration of RES. The GIS DB model has been experimented in a wide area of Central Italy, considering exclusively the solar energy source for energy generation.

Keywords: energy planning; Geographic Information System (GIS); land use; multicriteria decision analysis

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1. Introduction

The rapid increase in world population, together with the progressive urbanization has led more than 50% of the world population to live in urban areas. Moreover, according to United Nations (UN) more than 70% of the total population is going to live in cities by 2050 [1]. Therefore, management and environmental issues of the cities are on the rise and environmental regulations become more strict and numerous [2–4]. Nevertheless, for an effective management of the cities, not only environmental issues but also human needs must be considered, providing adequate infrastructures for the increasing number of citizens despite the limited availability of resources, especially the energetic ones. Furthermore, at the current rate of urbanization and considering the actual social and environmental needs, urban energy networks (*i.e.*, gas, water, electricity, and heat) are to be necessarily extended and, possibly, integrated with RES. As regards buildings, the new constructions are requested to be designed with energy efficiency criteria in mind, whereas the existing ones should be adequately renovated to get a more effective energy performance. As a consequence, actual cities are going to be reorganized and modern tools must be appropriately designed for urban management and planning.

To achieve a real sustainable development, European Union (EU) needs efficient tools to facilitate the urban planning and management process. The last 50 years deeply changed urban planning approach. In fact, in the 1960s a systemic approach was in force. Cities were considered as a sum of subsystems in which quantitative top-down models were used capable of providing reliable predictions of public decisions. Later, firstly in the United States (US) and then in EU, the "planning business type" model had spread and the strategic planning tools typical of large enterprises were used also for cities management needs. At the end of the 1990s, finally, a strategic "reticulated structure" planning has spread, with multiple levels, able to allow expertise in urban and environmental planning at administrative bodies level (*i.e.*, regions, provinces and municipalities). For reasons of clarity, the Province is an Italian Administrative body which groups together more neighbouring municipalities. As an example, the Province of Frosinone, investigated by the authors in the present paper, presents a territorial extension of 3.243 km^2 and it is made up of 91 municipalities.

However, all the above traditional approaches were addressed exclusively to rule the expansion of existing urban areas without taking into account the principles of a real sustainable development (e.g., economic, social and environmental sustainability). Only in recent years, urban planning tools integrated with energy issues were adopted [5–7], defining primary targets in terms of reduction of energy consumption and of the introduction of Renewable Energy Sources (RES) [8], especially in residential sector (that is responsible of about 40% of energy consumptions and of about 36% of CO^2 emissions [9]). As a consequence, self-sufficient buildings with low energy consumption (the so-called "*nearly zero energy buildings*") [9] are more and more spreading.

The "interference" between the buildings and the urban context is not only due to architectural and landscape aspects, but also (and especially) to energetic ones, like: (i) solar gains; (ii) soil or groundwater cooling/heating (*i.e.*, low enthalpy geothermal energy); (iii) the variable intensity and direction of the wind in the so called "street canyons" (*i.e.*, wind energy); (iv) the environmental impact of biomasses [10]. On the other hand, the need to maximize efficiency of cities should increase the knowledge of any excess/deficit of energy and promote "smart grid" in urban contexts [11,12].

In the literature some solar energy availability models in urban districts are available [13–15]. Further models provide issues related to orientation and shape of solar energy panels [16,17] in order to maximize the production of solar energy [18]. Cellura *et al.* [19] evaluated the relationship between the surface of the rooftops and the height of the buildings, providing a first tool to analyze the influence of the density of the built environment on the availability of solar energy. Furthermore, in [20,21], the evolution of energy supply in specific areas is evaluated through the use of GIS, to predict the energy demand and to estimate the optimal location of new RES in respect to the existing power grids. However, the aspects related to a strict integration between RES and high-efficiency power generation systems, such as cogeneration and district heating, have been not fully investigated in high-density urban contexts.

In the so-called "Smart City", the involvement of the population in the design of urban interventions and the use of new information technologies, should improve the life quality. However, being "smart" means that city must have a "brain". This means that an effective information system must be available to integrate and manage huge amount of data on mobility, air and environmental conditions, waste, energy efficiency and utilities, *etc.* All the above-mentioned data present very fast spatial dynamics and the use of proximity, inclusion, adjacency criteria, and so on, are strongly encouraged. This is the reason why the "Geographic" characteristic of any Information System adopted plays a crucial role.

Several GIS applications in Smart Cities are now available. In [22], the implementation of a GIS allows to: (i) locate sport facilities in Rome and to analyze the demand and supply of sports; (ii) to access and update many aspects of urban life in Modena (*i.e.*, building heritage, energy consumption, city companies, and maintenance of green areas); (iii) to evaluate energy consumptions and to test some bio-architecture and green building strategies on a medium-size urban area; (iv) to plan the exploitation of lands with poor agricultural potential (or unsuitable for residential purposes) for biofuel crops production [23].

In this paper the authors describe the results of the application of a Geographical Information Database System (GIS DB) energy-planning model, taking into account some crucial energetic parameters for urban sustainability. The GIS DB model proposed has been experimented in the Province of Frosinone, which is a wide area in the Lazio Region in Central Italy. The investigated area is particularly interesting for the morphology, for the poor energetic performance of the existing buildings and for the climatic, environmental, and landscape peculiarities of the territory.

2. Methodology

According to Directive 2009/28/CE [6] on the promotion of RES, all EU members States are committed to adopt a national action plan based on the principles of sustainability. This means to analyze the status of each territory and to predict future scenarios in terms of energetic demand, availability and production of RES and greenhouse gas emissions. Therefore, knowledge of available energy sources together with the localization of energy production facilities and of transmission and distribution infrastructures are crucial tasks for any urban planning at local level. These information, on extended territories, such as Provinces in Italy, often need a "multicriteria analysis" of different variables such as: (i) geographical (latitude, longitude, exposure, altitude above sea level); (ii) physical-morphological characteristics (slope, hydraulic jumps, presence of hills and obstacles) of the territory; (iii) the land use (e.g., the presence of forests and crops); (iv) the distance of RES from cities or from the connection infrastructure to the national grid; *etc*.

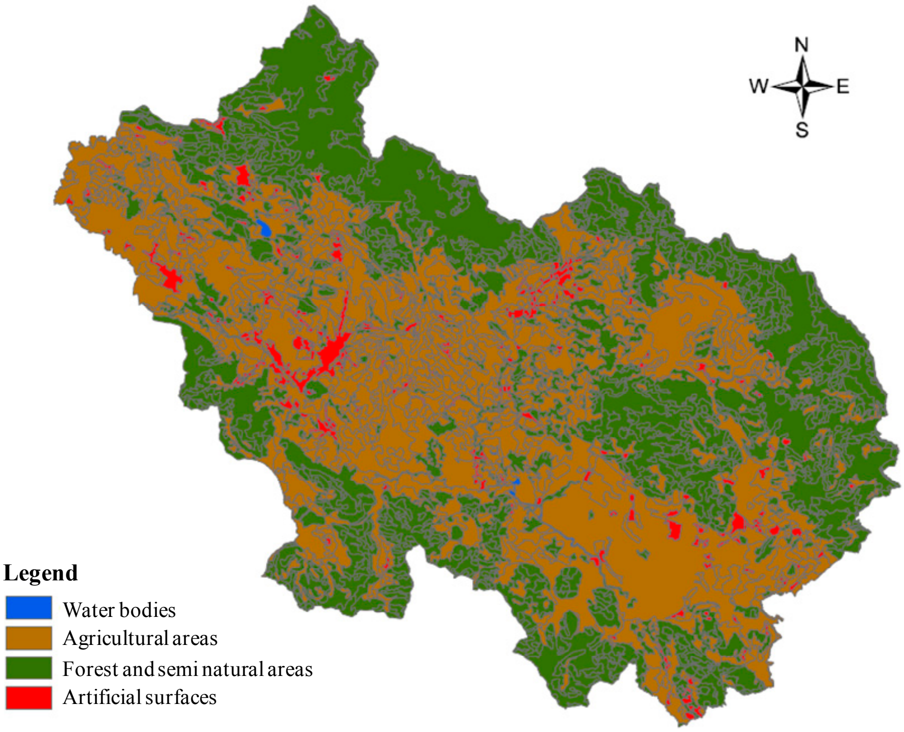
In this paper, the authors present a model, which uses the functions and raster data-grid as a tool for the analysis of the many quantitative assessments necessary in the planning phase. The model has been developed and experimented in the Province of Frosinone, which is an area particularly interesting for its morphology, the poor energetic performance of buildings, and climatic peculiarities of the territory. The model manages the data related only to the "solar energy", and it is aimed to analyze, exhaustively, the different energy production scenarios in the Province of Frosinone. The area is surrounded by mountain ranges (the Central Apennines to the north and the pre-Apennines of Lazio to the south) separated by a vast territory (the Valle Latina) in which the Sacco and Liri rivers flow. Since topography influences the area from a climatic point of view (without predominant winds and periods of high rains and humidity), industrial and urban settlements cause serious environmental problems in terms of pollution of soil, rivers, and air. The Province of Frosinone, in fact, is crossed from NW to SE by the A1 highway from Rome to Naples, which is characterized by large volumes of vehicular traffic. Along the A1, numerous industrial settlements are present (*i.e.*, the industrial districts of Frosinone-Anagni in the north and Cassino in the south) with several large, medium, and small factories. Moreover, the presence of different industry typologies (e.g., food, chemical-pharmaceutical, automotive, mills) causes different impacts on the environment and present very different energy needs.

The analysis of production from solar energy cannot be separated from a detailed knowledge of the real solar energy availability in the area. Therefore, the use of updated maps and spatially distributed databases to evaluate the potential solar energy distribution should be strongly encouraged. To correctly determine the spatial variations of solar radiation into morphologically complex areas, such as the Province of Frosinone, it is necessary to integrate analytical models of solar radiation on a GIS basis with the information provided in high-resolution data sets, such as DEM (Digital Elevation Model). These models [23–28] are based on empirical physical equations, providing accurate estimates of solar radiation as well as the geographical location and the morphological characteristics of the area. In the proposed model, data are managed using the Solar Analyst model developed by ESRI ArcGIS 10® and modified according to [29]. The GIS DB model for the Province of Frosinone was further implemented with raster grid for the analysis of: (i) the real land use, (ii) the possibility of exploitation of photovoltaic technology in urban areas, (iii) the electricity consumption and their geographical distribution, and (iv) the power generation facilities installed and their energy production estimates.

2.1. Land Use

In order to get a complete representation of the use of the soil, thematic maps developed by the CORINE-Land Cover Project [30] were analyzed, classifying the Province of Frosinone into artificial surfaces (territories morphologically altered by human presence, such as the urban centers), agricultural, forest, and water bodies (Figure 1).

Figure 1. Land use of the Frosinone Province.



In particular, agricultural areas have been classified according to the actual land use as reported in Table 1.

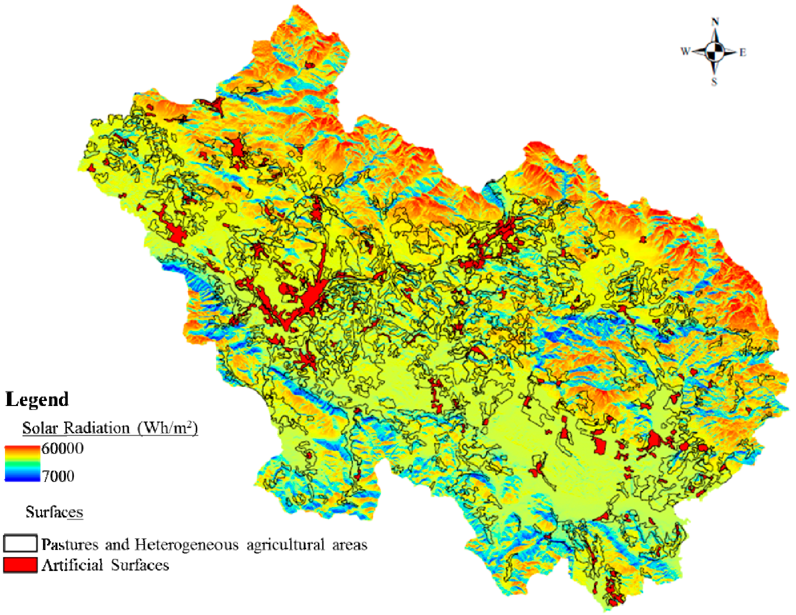
Table 1. Agricultural surface classification.

Arable land	Non-irrigated arable land Permanently irrigated land
Permanent crops	Vineyards Fruit trees and berry plantations Olive groves Other permanent crops
Pastures	Pastures
Heterogeneous agricultural areas	Annual crops associated with permanent crops Complex cultivation patterns Land principally occupied by agriculture, with significant areas of natural vegetation Agro-forestry areas

Since forest and semi natural areas are subject to environmental protection, solar energy exploitation is really obtainable only in agricultural lands and in urban contexts. As regards agricultural lands, it has be pointed out that the Italian Decree n. 28 of 2011 [31] sought to limit the spread of solar energy plants on land intended for other uses by providing that, for the same owner: (i) nominal power of each plant do not exceed 1 MW; (ii) different solar plants are to be placed at a minimum distance of 2 km; (iii) solar plant area not exceeding 10% of the land of the owner. The Decree Law n. 1 of 2012 [32] reinforced these constraints, prohibiting access to government incentives to any plant with solar panels located on land in agricultural areas.

With the end of government incentives in Italy [33], all the above constraints are now automatically forfeited and landowners have full autonomy in sizing photovoltaic systems on their land. Moreover, all the agricultural lands of the Province of Frosinone sum about 1901 km^2, corresponding to a potential annual net energy production of 30.0 × 10^4 GWh, considering an average radiation annual of 1600 kWh/m^2 and an average efficiency of 14% for solar panels. Although the lack in Italy of a specific regulation, the authors exclude from this estimation the permanent crops (the so-called "*Prime farmland*" [34]) in order to avoid the loss of soils fertility. Therefore, the available area exploitable for solar energy production should be limited to pastures and heterogeneous agricultural lands (Table 1) and the total available area reduces to about 778 km^2 (corresponding to 12.4 × 10^4 GWh of annual net energy production potentially obtainable). The overlap of solar radiation and potentially exploitable lands for the Province of Frosinone, is shown in Figure 2.

Figure 2. Overlapping of solar radiation in the areas exploitable for solar energy production.



From Figure 2, it can be noticed that the actually exploitable lands are located in the valley areas of the Province, and often close to cities. Therefore, the installation of solar energy plants will allow the requalification of such areas and, moreover, solar energy production facilities will be close to urban areas where the higher energy demand and the lower possibility of RES integration are present.

2.2. The Urban Context

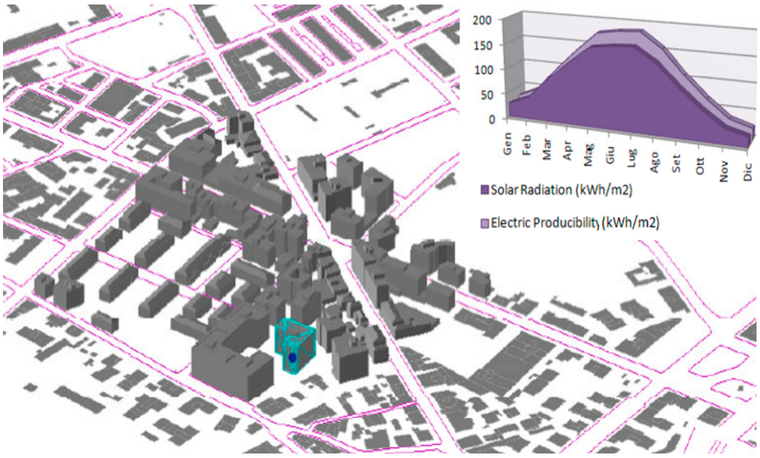
The energetic producibility of RES plants, and the convenience to integrate solar energy panels in urban contexts with high building density, must be evaluated taking into account: (i) the typology, slope, aspect, and useful surface of the roofs [13,17,35]; (ii) the theoretical energy production of solar panels; (iii) the economic analysis (*i.e.*, the payback time) according to the real energetic needs of users (e.g., single apartments, condominiums, and blocks) [19]. Firstly, it is necessary to analyze the roofs typology based on morphology and building materials. In this paper two main classifications are considered: tile roofs (pitched) and flat roof. The developed algorithm firstly identifies the roof typology from the color (*i.e.*, from average value of pixels) of the roofs. Subsequently, the photogrammetric image is crossed with the digital orthophotography. As an example, Figure 3 shows the displaying of digital orthophotography and the identification of the geometry of roofs in residential areas.

Figure 3. Roofs classification of residential units.

The data related to the slope of pitched roof are not directly obtainable from photogrammetric since the heights of gutters and hipped roofs are not evaluable. Consequently, theoretical data based on average slopes related to precipitations have been used. In particular, for the present case of study, an average slope of 30% has been considered.

When the classification of the roofs is completed, it is important to evaluate the useful area of solar radiation incidence. The presence of obstacles (e.g., windows, chimneys, and stairwells) causes a reduction of useful spaces for the installation of solar panels. Since it is impossible to take into account the presence of obstructions on the roofs, it was assumed a useful area of about 80% for flat roofs, and 25% for pitched roofs. All the structural information obtained have been integrated in a 3D building model (Digital Elevation Model-DEM) and detailed in a specific database of the investigated buildings. Then, building database was used to estimate both the global solar radiation and the theoretical energy production of buildings through the specific tool of the Solar Radiation ArcGIS [36]. A typical result of this analysis is shown in Figure 4.

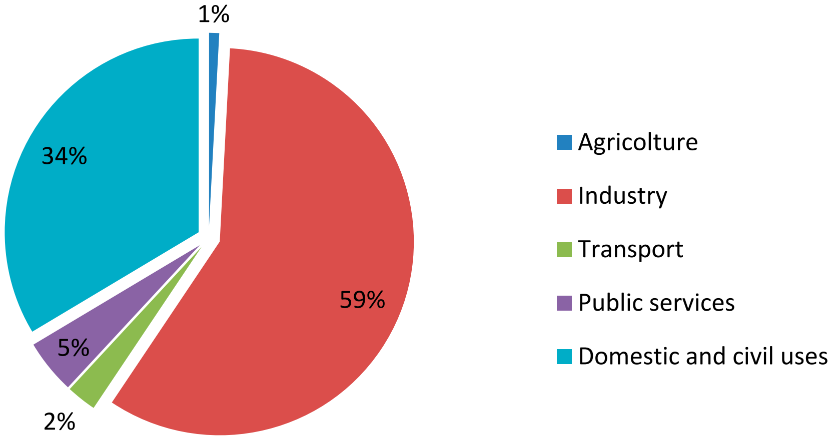
Figure 4. Theoretical energy production of individual residential units (kWh/m^2).



2.3. Analysis of Local Consumption

An adequate energy planning cannot neglect its energetic balance through the estimation of energy consumption distribution in the territory. In Figure 5, the 2011 Energy Balance of the Province of Frosinone is reported for different sectors [37].

Figure 5. Energy consumption in the Province of Frosinone (2011) for different sectors.



As regards energy consumptions in the investigated area, the authors considered only electricity ones, for which it is evident an unbalance between industrial (59%) and residential, commercial and public (34%) and sectors. Different demographic and socioeconomic data [38] have been also considered, such as, the total floor area of the buildings, the population density, the number of residential buildings, *etc*. In fact, the domestic energy consumption and the population density are useful indicators to estimate human impact on the environment. However, this latter is strongly influenced by the geophysical characteristics of the area, which may include low-density areas (*i.e.*, high mountains, water surfaces, *etc*.), as well as urban or rural settlements. As an example, the assessment of domestic consumption is difficult because of numerous aspects: geographical location, season of the year, day of the week, energy habits of the households, characteristics of housing, household electrical appliances and so on.

Therefore, adopting for the investigated area the data of electric energy consumption available at national level [39], the following relationships emerge: (a) a direct proportionality between energy consumptions and the total floor area of the buildings in the domestic sector; (b) a direct proportionality of consumption with the Gross Domestic Product and the territorial extension for the tertiary sector (hotels, banks, commerce, transport, *etc*).

As regards industrial energy consumptions, the developed model considers the economic activities classification [38], reported in Table 2, assuming a direct proportionality between national electric energy consumptions and the number of workers for each industrial activity. The energy consumption data for the different economic activities in the main municipalities of the investigated Province are shown in Table 3. The total industrial electric energy consumption, in different municipalities have been reported in Table 4, together with domestic and tertiary ones.

Table 2. Economic activities classification according to Istituto Nazionale di Statistica (ISTAT) [38].

Number of Activities	Description of Activities
13–14	Mineral processing
15	Food and beverage manufacturing
16	Tobacco industry
17	Textile industry
18	Articles of clothing; fur productions
19	Tanning and dressing of leather, manufacturing of travel goods, bags, saddlery and footwear
20	Manufacturing of wood and products of wood and cork; manufacturing of articles of straw and plaiting materials
21	Paper manufacturing
22	Publishing, printing and reproduction of recorded media
24	Chemical products and synthetic and artificial fibers manufacturing
25	Rubber and plastic manufacturing
26	Other non-metallic mineral process manufacturing
27	Metal production
28	Metal product manufacturing, except machinery and equipment
29	Machinery and equipment manufacturing, including installation, assembly, repair and maintenance
30	Computers manufacture
31	Machinery and apparatus electrical manufacturing
32	Radios, televisions and communication equipment manufacturing
33	Medical equipment and optical instruments, watches and clocks manufacturing
34	Motor vehicles, trailers and semi-trailers manufacturing
35	Other transport equipment manufacturing
36	Furniture manufacturing, other manufacturing industries

Table 3. Electric energy consumptions (toe) for the different economic activities in the larger municipalities of the Province of Frosinone.

Number of Activities	Alatri	Anagni	Cassino	Ceccano	Ferentino	Frosinone	Isola del Liri	Piedim. San Germano	Pontecorvo	Sora	Veroli
13–14	311	1,300	283	0	254	0	311	0	57	0	28
15	1,793	4,850	1,724	919	5,218	3,149	1,310	322	965	3,011	2,184
16	0	0	0	0	0	0	0	0	0	0	0
17	1,261	110	110	55	2,522	28,294	4,113	0	329	1,042	1,700
18	103	132	383	88	162	3,045	427	235	206	1,986	397
19	0	141	0	0	56	103	0	0	0	0	0
20	332	317	202	548	1,225	2,350	274	58	317	389	259
21	0	1,827	17,945	0	1,719	645	10,745	0	860	44,056	322
22	376	228	524	148	27	1,021	363	0	27	403	27
24	0	23,640	3,637	0	28,239	8,878	0	0	107	535	1,391

Table 3. *Cont.*

Number of Activities	Alatri	Anagni	Cassino	Ceccano	Ferentino	Frosinone	Isola del Liri	Piedim. San Germano	Pontecorvo	Sora	Veroli
25	332	32,457	1,992	415	15,564	8,343	125	0	83	1,702	3,486
26	3,006	9,896	5,324	2,317	6,764	4,259	1,315	251	2,004	2,505	1,002
27	424	1,555	2,121	2,828	9,755	4,948	566	0	2,121	1,555	0
28	2,811	8,046	11,968	4,988	5,760	10,702	371	633	216	0	1,344
29	738	3,460	8,267	1,094	3,714	2,849	1,933	941	1,374	2,086	483
30	7	13	20	12	6	41	3	0	1	10	18
31	53	525	2,022	345	0	199	19	461	4	90	19
32	81	242	254	19	198	1,511	105	12	0	180	384
33	5	5,824	0	0	0	15	413	0	0	93	0
34	3,943	1,979	8,732	48	1,373	4,550	48	67,732	0	0	0
35	0	4,192	0	0	0	6,067	0	0	0	0	0
36	110	81	190	256	542	1,047	88	7	395	710	183

Table 4. Electric energy consumptions for different uses, in the larger municipalities in the Province of Frosinone.

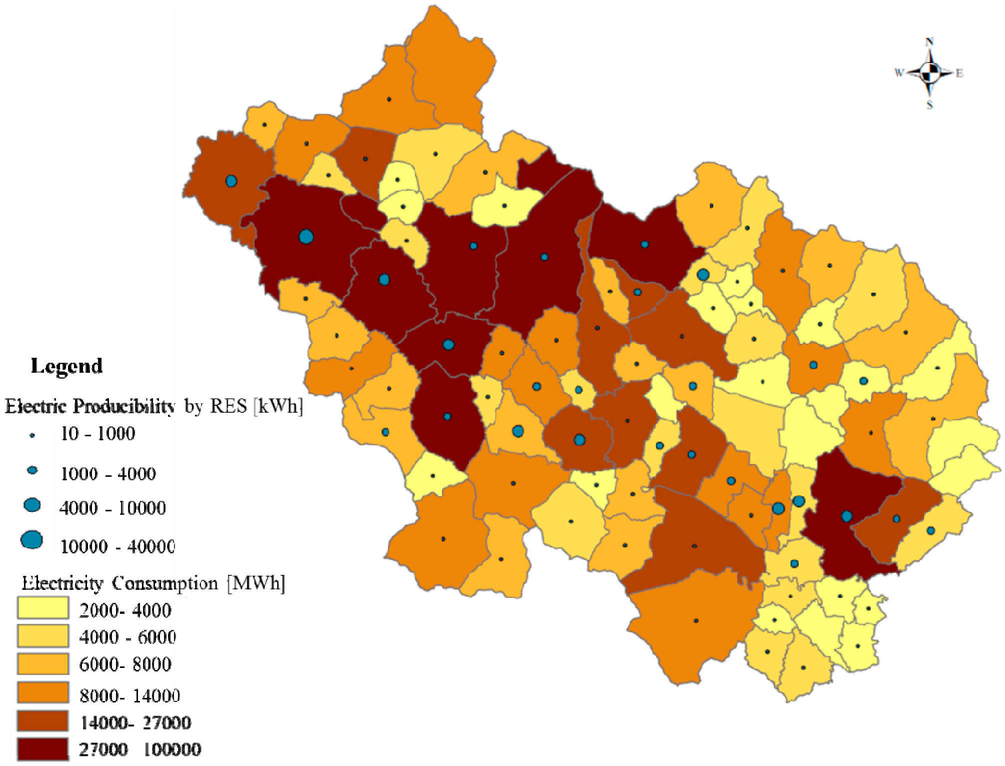
Municipalities	Domestic [MWh]	Tertiary [MWh]	Industrial [MWh]
Alatri	24,651	29,705	182,408
Anagni	21,074	26,799	1,172,468
Cassino	33,347	40,615	764,055
Ceccano	19,294	23,533	163,751
Ferentino	20,163	23,428	966,457
Frosinone	56,632	56,260	1,070,136
Isola del Liri	10,598	12,394	261,997
Piedimonte San Germano	5,412	5,741	821,695
Pontecorvo	11,186	15,998	105,435
Sora	25,703	27,848	701,913
Veroli	19,638	22,618	153,834

From the data in Table 4, it can be pointed out that: (i) energy consumptions for residential and tertiary activities can be attributed to the high population density and to the age of the buildings, more than 50% of which have been built between 1962 and 1981; (ii) industrial consumptions are strongly dependent on the specific activity; (iii) automotive industries show the highest energy consumptions.

2.4. The Distribution of RES Production at the Local Level

As a consequence of the recent *government incentives* [40] for the diffusion of photovoltaic plants through a specific feed-in tariff, Italy has experienced a rapid spread of this technology all over its territory. The lack of appropriate wind conditions and the bureaucratic difficulties associated with licensing of wind power plants and/or cogeneration plants led the Frosinone district to be strongly dependent on energy imports from neighboring regions. The only exception is the production of electricity from photovoltaic plants, which generated [41] a total installed power on 18 March 2014 of about 152.644 MW, and to an average production in 2012 of about 156.100 GWh [42]. In Figure 5, the estimated annual energy consumption is compared against the corresponding production of electrical energy (mainly from RES), for each municipality. The data processing in GIS shows the significant imbalance between actual demand and energy production at a local level. This can be effectively managed by a GIS DB, which can represent a useful tool for integrated design, able to dynamically adjust energy policies to the energy and architectural evolution of the territory.

Figure 6. Electricity consumptions and electric producibility through RES.



Photovoltaic plants are mainly installed in the central area of the district where a higher solar radiation and a bigger population density are present, they are still far from meeting the high electric energy demands in the residential sector.

3. Conclusions

In this paper the authors present a GIS DB model for estimating the energy balance in a wide area and evaluate its potential for possible integration of new solar energy production plants in high population density contexts and in extra-urban ones. The model has been experimented in the Province of Frosinone, in the Lazio Region in Central Italy, which represents a particular case of study for the morphology, for the poor energetic performance of existing buildings and for climatic peculiarities of the territory. The most innovative aspects, of proposed model compared to those already present in the literature, are:

(a) forest constraints: the model take into account the classification of land use to evaluate the energy productive potential from RES;

(b) technological constraints: in the model, different data about buildings (such as typology, slope, aspect, and useful surface of the roofs) and theoretical characteristics of solar panels have been integrated;

(c) economic constraints: the electric energy consumption for different uses (industry, domestic, and tertiary) in the most relevant municipalities, in the investigated district, were evaluated.

It is important to point out that the management and control of a real effective project planning requires the acquisition and updating of a large amount and specific data at multidisciplinary level (e.g., economic, social, environmental, landscape, aesthetic, *etc.*) to monitor and update data in real time.

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Author Contributions

Andrea Frattolillo and Marco Dell'Isola designed this research; analytical and numerical simulations and the methodology were performed by Angelamaria Massimo and Andrea Frattolillo; the results' interpretation and English editing were done by Giorgio Ficco. The research supervisor is Marco Dell'Isola. All authors have read and approved the final manuscript.

Conflicts of Interest

The authors declare no conflict of interest.

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