CAMPUS AND COMMUNITY MICRO GRIDS INTEGRATION OF BUILDING INTEGRATED PHOTOVOLTAIC RENEWABLE ENERGY SOURCES – CASE STUDY OF SPLIT 3 AREA, CROATIA – PART A

by

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Micro grids interconnect loads and distributed energy resources as a single controllable entity. New installations of renewable energy sources in urban areas, such as building integrated photovoltaic, provide opportunities to increase energy independence and diversify energy sources in the energy system. This paper explores the integration of renewable energy sources into two case study communities in an urban agglomeration to provide optimal conditions to meet a share of the electrical loads. Energy planning case studies for decentralized generation of renewable energy are conducted in highways 2 renewable systems energy planning software for hourly energy balances. The results indicate that building integrated photovoltaic and photovoltaic in the case study communities can cover about 17% of the recorded electrical demand of both areas. On a yearly basis, there will be a 0.025 GWh surplus of photovoltaic production with a maximum value of 1.25 MWh in one hour of operation unless grid storage is used. This amounts to a total investment cost of 13.36 million EUR. The results are useful for proposing future directions for the various case study communities targeting sustainable development.

Key words: *micro grid, H2RES, photovoltaic, campus, residential building, smart grid*

Introduction

A micro grid is by definition *a group of interconnected loads and distributed energy resources with clearly defined boundaries that act as a single controllable entity with respect to the grid, and can connect and disconnect from the grid to enable it to operate in both connected or island mode* [1]. The optimized design and control of micro grids can increase energy independence and diversify energy sources in the energy system. New installations of renewable energy sources (RES) in urban areas, such as building integrated photovoltaic (BIPV), provide opportunities to develop such micro grid applications. The scope of this paper is based on analysing scenarios for case study communities and extends to multiple areas of energy planning, micro grid operation, smart grid and systems, electricity distribution operation, and introduction of RES based on BIPV into existing energy systems. This work is among the first to study electrical energy consumption with the purpose of potentially creat-

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ing a roadmap towards a 100% RES powered campus in Croatia. Related previous work on the demand side was conducted by University of Zagreb, Faculty of Electrical and Computer Engineering with the goal of load forecasting for optimising building energy usage [2]. In this research work, an integrated approach of data acquisition on the supply and demand side was applied to case study communities in Split, Croatia, with the results modelled in Highways 2 renewable systems (H2RES).

Literature review

Numerous tools, software programs and methods are available for energy planning at various levels. One of the most useful oversights of 43 such resources, including EnergyPLAN that simulates energy systems at the national level on an hourly basis, was presented by Connolly *et al*. [3]. In contrast, Mendes *et al*. [4] provided specific insight into integrated multiple energy vector operations in urban areas. In order to properly estimate what is the long-term need for energy generation of an energy system, detailed time-wise resolution needs to be employed, on the order of one hour or less [5]. In cases that potentially require even higher resolution, such as electric vehicle operation and interaction with the grid, *i. e.* vehicle to grid (V2G), intervals of 15 min or less are also investigated [6]. Optimization of micro grid systems refers mainly to forecasting loads in the system while keeping track of multiple goals of emissions reduction, supply security or quality of supply [7]. Multiple energy vector optimizations, spanning electrical, heating and cooling demands provides multiple options to shift loads, influence demand side management and affect overall pricing of the system [8]. Another energy vector is introduced with hydrogen as grid storage in fuel cells [9]. While micro grid operation and RES generation improves robustness of an energy system, it brings costs that should be addressed properly. One example is the use of game theory and Nash bargaining to reduce the cost of energy transfers [10].

Smart grid assumes a mean of two-way exchange of information between the participants within an energy system. The simplest device for such use would be a smart meter or automated meter reader (AMR) that feeds consumption information back to the grid operator. Along with the proposal of BIPV installations, a system such as the one proposed by Al-Ali *et al*. is based on a two-way communication protocol for a smart home renewable energy management system [11]. At no time should there any additional demand on the distribution network that may cause capacity issues. Such issues may be mitigated by a smart scheduling system taking technical constraints into account [12]. Impacts of uncoordinated micro grid operations, such as charging or discharging of electric vehicles as investigated by Clement-Nyns *et al*. [13, 14], can have negative effects on the local distribution network in terms of lack of installed capacity in the transformer substations, voltage drops during high-load operations, and frequency deterioration. The sustainability of a system is based on data collection from various data sources, such as national statistics bureau and aggregated data by sector of activity (transport, housing, *etc*.) [15]. General overview of the methods is presented by Banos *et al*. [16]. Particularly large consumers of energy is the building and housing sector, and as such possess the cheapest way of tackling the reduction of energy use through efficiency and use of renewable technologies to implement a zero energy building (ZEB) [17]. On the urbanism side, an ever-increasing need for sustainability attracts increasing studies into decentralised energy initiatives. Nine such cases are presented by Chmutina *et al*. in [18]. Rollout of such novel RES and smart grid projects is often hindered by many involved sides in the process, from distribution operators, to local authorities, through businesses and finally the state. Mah *et al*. investigated the role of government in pilot smart grid cases in Japan

[19]. One of the areas with most potential for integration of RES is the water supply system. Integrated small hydro power plants can be implemented into existing major water supply lines as well as wastewater systems [20].

Aims of the research work

This work contributes to the literature by being among the first to study electrical energy consumption and production with the purpose of potentially creating a roadmap towards a 100% RES powered district and university campus in Croatia. Related previous work on the demand side was conducted by University of Zagreb, Faculty of Electrical and Computer Engineering, with the goal of load forecasting for optimising building energy usage [2]. In this research work, an integrated approach of data acquisition on the supply and demand side was applied to case study communities in Split, Croatia with the results modelled in H2RES.

Method

The hypothesis of the work is that through detailed mapping of renewable resources and existing potential at the location of the case study, it is possible to offset a part of the energy production by employing local generating potential with minimum interference in the existing state. Figure 1 provides the main steps that were involved in analysing the synthesis of RES into the case study communities. The data acquisition for the case study communities was undertaken at the building and power grid levels (Step 1). Available building surfaces were estimated to determine the potential area for BIPV and roof top photovoltaic (PV) applications. Empirical inputs for the electricity demand at hourly time steps were analysed to determine the electricity demand profile. Such data was used in the modelling of energy scenarios in H2RES to compare the potential BIPV and PV production and electricity demand in the time dimension. The results provide an insight into sustainable communities.

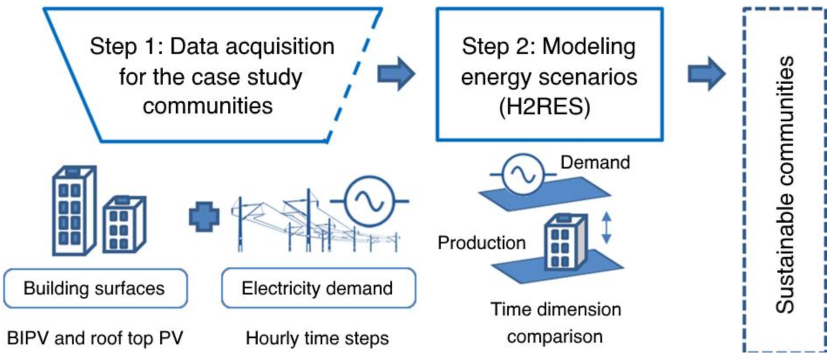

Figure 1. Main steps for the synthesis of RES in the case study communities

H2RES is a software model designed by the University of Zagreb, Faculty of Mechanical Engineering, to provide optimal generation of energy based on optimising the individual components of the energy system. Firstly, the model was used for island regime simulations, with emphasis on large-scale integration of RES into the system [21, 22]. From there the research moved to test various other energy vectors and storage systems [23, 24]. Finally, grid storage was introduced for 100% RES scenarios [25, 26]. New versions of H2RES continue to be developed, with further emphasis on optimization [27, 28]. H2RES involves the stepwise approach of mapping the needs, mapping the resources, devising scenarios, and modelling the scenarios. The scenarios considered in the case study are based on options of installing BIPV to the case study communities of University of Split campus and the neighbouring residential district of Split 3. Two options for BIPV are examined. First, façade integrated PV retrofitted into the existing residential high-rises of the district, and second, roof mounted PV on the roofs of public buildings on the campus buildings.

Case study

The case presented in this paper focuses on two case study communities in the urban agglomeration of Split as defined by the recently signed contract [29]. The urban agglomeration of Split has a population of 325,000 determined by the 2011 census [30], divided into six cities and seven municipalities with a total area covering 1,270 km^2. The composition of the agglomeration varies widely from heavily urbanised areas, with high density of living, 2,246 residents per km^2, to just 27 residents per km^2. Average density is 256 residents per km^2 [31]. While not geographically part of the agglomeration, three more cities and ten municipalities with over 33,000 residents and 907 km^2 gravitate heavily towards Split, as it is the regional capital of Split-Dalmatia County and a major administrative centre.

Energy generation of the region is favourable towards RES. There is a large hydropower-generating river basin of Cetina, with 960 MW of installed capacity and several large accumulations, totalling 1,380.6 million m^3. The hydro electric system (HES) is connected to 110 kV and 220 kV transmission lines supplying all of Dalmatia and parts of neighbouring Bosnia and Herzegovina. From transformer station (TS) Konjsko near Dugopolje, the system is connected to 400 kV transmission lines to other parts of Croatia. Also from TS Konjsko, two 110 kV branches are routed towards the Split agglomeration over different physical routes. The input points for the 110 kV voltage level are several transformer stations in the city of Split itself and other cities. Other RES sources include wind power plants (WPP) and small hydro power plants (SHPP), along with limited installations of PV panels. Installations regulated through feed-in-tariffs (FIT) are included in the overview via the Ministry of Economy website [32]. The only publicly available data regarding non-FIT installations in Split-Dalmatia County are a 300 kW PV installation in a quarry of a local cement factory [33], and a 2 MW PV installation on the island of Vis, currently under construction [34]. Additionally, a 30 kW PV installation is in operation on the roof of the local University of Split Engineering Department, also for research purposes, with plans for further extensions [35]. Energy planning for the Elektrodalmacija Split distribution area is determined by the characteristic Wednesday method, with the third Wednesday in January and July taken into account (tab. 1). In addition, the maximum day is also taken into account, in tab. 2, as taken from the DSO yearly report for 2013 [36]. Estimated power losses in the distribution network for 2013 are 10.92%, for a total of 212.658 GWh. Sales of electrical energy on low voltage level are provided in tabs. 3-6, respectively.

Table 1. Characteristic Wednesday power readings

Characteristic Wednesday					
3rd Wed. in January			3rd Wed. in July		
Power [MW]	Date	Time	Power [MW]	Date	Time
343.13	16.01.	22:30	309.85	17.07.	22:30

Table 2. Maximum day power readings

Distribution area	Maximum day		
	Power [MW]	Date	Time
Split	435.29	11.02.	19:45

Table 3. Gross consumption of electrical energy [GWh]

Distribution area	Split
From TSO	1,951.72
From other DSO	0.60
From cross-border trade	0.79
From small power plants	1.00
To other DSO	0.00
To cross-border trade	7.22
Total	1,946.89

Table 4. Structure of electrical energy consumption [GWh]

Distribution area	Split
Tariff buyers and buyers without suppliers	1,104.50
Privileged buyers	629.73
DSO consumption	4.03
Other subjects	0.70
Own + other consumption	4.73
Total	1,734.23

Table 5. Sales of electrical energy [GWh]

Distribution area	Split
High voltage	9.25
Medium voltage	190.18
Commercial	560.82
Public lighting	50.10
Residential	923.87
Total	1,534.79
Total sales	1,734.23

For the micro grid case study, several sections of the grid and associated transformer substations were detected and used. The principal 110/10 kV TS is the TS Sucidar, which uses five of its 10 kV fields to power the area, and TS Visoka, with six 10 kV field. There are a total of 46 10 kV substations connected to the two 110 kV substations. The installed power is delivered through 51 transformers combining 30.08 MVA in total.

Table 6. Sale structure at low voltage [GWh]

	Distribution area	Split
Commercial tariffs	Blue	24.52
	White	200.00
	Red	336.30
	Orange	0.00
	Yellow-public lighting	50.10
	Total commercial	610.92
Residential tariffs	Blue	128.66
	White	795.21
	Orange	0.00
	Black	0.00
	Total residential	923.87
	Total low voltage	1,534.79

Table 7 lists the 10 kV fields of both TS Sucidar and Visoka. Several major city streets, arranged in a rectangular shape, forming two city blocks, surround the designated area. The northern block houses the University of Split urban campus, while the southern block forms the district of Split 3, as provided in fig. 2. The campus portion, along with the departments contains three blocks of housing, high school complex and several smaller houses, while Split 3 contains four major streets with high-rise residential buildings, along with an elementary school, market and a row of commercial buildings along the southern row, facing the D410 road. Overall population is close to 13,000 based on the 2011 census.

Table 7. Transformer 10 kV fields feeding micro grid areas

TS	Visoka	TS	Sucidar
TS Field	Name	TS Field	Name
K38	Smrdecac 16	K02	Sucidar 14
K55	Smrdecac 34	K09	Sucidar 13
K56	Sucidar 31	K17	G.S.C. 1
K71	Smrdecac 15	K19	Sucidar 15
K72	Sucidar 27	K33	Sucidar 16
K73	Lidl		

Figure 2. Map of the case study area

Implementation and results

The method was implemented to the case study communities based on the steps for data acquisition and modelling of the energy scenarios in H2RES as provided in fig. 1. The method was used to determine whether detailed mapping of renewable resources and existing potential at the location of the case study can make it possible to offset a part of the energy production by employing local generating potential with minimum interference in the existing state.

Data acquisition for BIPV and PV potential

For the mapping portion of the method, three of the streets are positioned in an almost exact east-west orientation (for the purposes of the study it will be considered to face south at 180° azimuth), making it optimal to implement BIPV on southern-facing vertical façades. The fourth street, running south-west to north-east was not considered due to the unevenness in the façade structure and large areas of shade caused by the unevenness. Roof area is also not considered due to the small footprint of the building, locations of elevator machine rooms, and various telecommunications equipment on roof surfaces. The commercial row is also not considered for the same reasons. An elementary school along with the high school building is considered for installation only on the roof section, due to the larger footprint and the fact that there is a 30 × 15 m gym adjacent to the elementary school. Estimate for BIPV total area of coverage is given as 40% of all south-facing surfaces above the second floor. The estimate is based on the fact that approximately 40% of the area is covered in glass surfaces, and the rest as 20% is discarded area due to shading caused by the uneven surfaces of the façades and technical unfeasibility of covering smaller or inadequate surfaces. The average number of floors for all streets is 12 and average external height of one floor is 3.5 m. Houses on the south side of each street are not considered due to a low average height of 2 floors and potential shading from the green growth close to the ground. As the buildings are laid out as monolithic units, it was estimated that the average length of one façade is equal to the average length on the online map service, Google Maps.

Table 8 provides the layout of all streets with number of buildings, lengths and estimated areas available for BIPV surfaces. Following the measuring, all façade lengths are added (total sum 1,285 m) and multiplied by 35 m, the average height of 10 floors. The total area covered by BIPV is estimated to be 34,825 m^2. Given the average efficiency of a solar panel of 135 W_p/m^2, the installed power is projected at 6.072 MW. Additionally, another 3,700 m^2 may be installed on the roofs of the elementary and high school, giving further 0.499 MW installed, for a total of 6.572 MW. For measurement of the campus part, three streets with BIPV were added to the residential sector sum, along with the roof of the high school. All other campus buildings were calculated towards the campus micro grid operation. For the calculation, the same methodology of 40% usable surface has been kept. Several buildings on the campus have glass façades, and these will have to have transparent BIPV installations, increasing the overall investment. The average height for these buildings is 4 floors at 3.5 m each. Table 9 lists all campus buildings and their surface area, either façade or roof.

Final calculation puts the available area for BIPV on the campus at 2,940 m^2 of façade BIPV and 6,600 m^2 of roof mounted PV. That amounts to 0.397 MW BIPV and 0.891 MW of roof PV, for a total of 1.288 MW. Overall installation sums up to 6.469 MW BIPV and 1.787 MW roof PV and a total of 8.256 MW. For PV production, the PV-GIS tool [37] was used to calculate average monthly production of 1 kW_p of installed PV panels, both on façade (vertical, 90° inclination) and optimally inclined slope (36°, Split area). The production results are displayed further below (see section *Case study PV integration results*).

Table 8. Available surfaces for BIPV installation

Street	Building	Length [m]	Street	Building	Length [m]
Street 1	1	50	Street 4	1	55
(E-W)	2	80	(E-W)	2	70
	3	60		3	150
	4	120		4	120
Street 2	1	180		5	110
Street 3	1	100	Street 5	1	100
			Street 6	1	90
Elementary school			High school		
Overall surface	2,100	m^2	Overall surface	2,600	m^2

Data acquisition of electricity demand

The electricity data consumption from DSO HEP Elektrodalmacija Split was obtained from their SCADA system and covers a timespan of one year, from 01.01.2013 until 31.12.2013 [38]. The data has been provided in one-hour time steps as direct measurements of electrical current in Ampere on the low voltage side of the transformer substation. Since the measurement was conducted on a three-phase system, to convert it into units of energy *E* [kWh], the formula is given in eq. (1):

Table 9. University of Split Campus buildings

Building	Area [m^2]	Length [m]
Student dormitory		70
Economy main		55
Economy annex		30
Library		55
Civil eng. & Arch. & Urbanism	1,800	
Elec. & Mech. eng. & Naval arch.	1,800	
Natural sciences	3,000	

$$E = \sqrt{3} \times U \times I \times PF \tag{1}$$

where *U* [V] is the nominal voltage of the low voltage grid network (10 kV), *I* [A] is the actual power reading for a given time period and *PF* stands for power factor of the grid, determined by measurements to be on average 0.99. Minimum and maximum values were 0.95 and 1.00, respectively (see fig. 3). The measurements for *PF* were conducted in the period from 23.09.2014 to 30.09.2014 in 10-minute intervals. Global irradiation on a horizontal plane in Croatia in Split area receives about 1,500 kWh/m^2 of annual global irradiation [39]. After running the raw power readings through the formula, a complete set of all results was available for analysis. The data included all 110 kV and lower voltage level substations for the agglomeration of Split. The dataset consisted of data from 14 substations and 266 10 kV fields. This allowed for the combined electrical demand of the Split agglomeration to be presented during one year in one-hour intervals, as provided for a typical day in July in fig. 4. Table 10 presents basic statistical data for the demand for the year 2013.

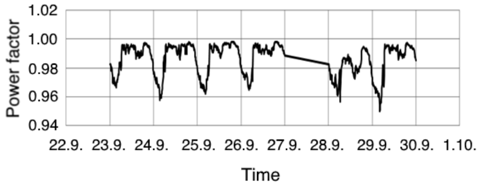

Figure 3. ***PF*** **readings from DSO SCADA system**

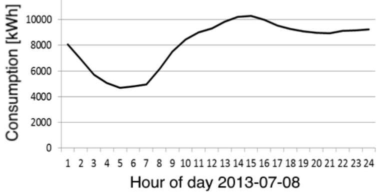

Figure 4. Yearly electrical demand

Table 10. Agglomeration Split electrical demand

	Max. demand	Min. demand	Average demand	Consumption
Agglomeration Split electrical demand	265.95	64.68	137.86	1,207.68
Combined electrical demand Split 3 + campus	14.14	2.05	4.92	43.13
Electrical demand Split 3	7.77	0.46	2.26	19.80
Campus electrical demand	6.37	1.12	2.66	23.34
Units	MWh	MWh	MWh	GWh

The data in tab. 10 correlates with the official DSO report for the same year, with minor differences since the DSO covers a larger area than the data obtained. Column C summarizes the basic electrical demands for the combined and separate summations. Subsequently, the electrical demand for Split 3 was obtained from substation field related to the locality of TS Visoka, with fields K38, K17, K71, and K73. This data represents the residential part of the micro grid. The electrical demand for the campus was obtained from substation field related to the locality of TS Sucidar, with fields K02, K09, K19 and K72. This data represents the campus part of the micro grid.

Case study PV integration results

Table 11 indicates that the production data from BIPV and PV for both the Split 3 district area and Campus area are 5.88 GWh and 1.50 GWh, respectively. This data is combined with the recorded electrical demand data, which is 19.8 GWh and 23.34 GWh for the case study areas (see tab. 10). The results indicate that on a yearly basis, BIPV and PV production can cover approximately 29.7% and 6.43%, respectively, of each case study area, or 17.11% of both areas combined. Within this amount, 75.6% of the solar power production is based on façade BIPV and 24.4% on roof PV. The reason for a lower amount of coverage of electrical demand for the campus area lies in the fact that there is substantially lower area of possible PV installations, primarily since campus buildings are significantly lower rises compared to the Split 3 residential district. There is more area available for roof PV, which was taken into account. It would be possible to further extend the coverage of campus demand by installing parking PV on uncovered areas, of which there is a significant area currently in use. This area will be reduced in the future with additions of departments to the campus and building of underground garages, however, this might be offset in some percentage by roof PV.

Table 11. BIPV and PV production per case study community

Case study	Campus	Split 3
BIPV [kW_p]	397	6,072
PV [kW_p]	891	499
Production BIPV [GWh per year]	0.34	5.23
Production PV [GWh per year]	1.15	0.65
Total per case study	1.50	5.88

There is a noticeable trend of less difference between peak and base usage in the campus demand, most likely due to balancing of the energy needs for campus purposes and less need for daily activities originating from daily living activities. The overall usage of energy is also higher on the campus, suggesting either more intensive energy usage, or more occupants on the assigned substation fields. There is a noticeable sharp increase in demand at the beginning of November, coinciding with the beginning of cold weather. For campus demand, this might indicate an inadequate central heating system that some of the departments use, as users probably operate the air-conditioning units to additionally heat up the space.

H2RES model and results

H2RES energy planning software is a supply-side energy planning software designed to work on an hourly basis and provide optimal solutions to long-term energy planning issues. An essential feature of H2RES is that it provides options for individually controlling the operation of each component in an energy system, thus making it capable of detailed modelling of an energy system through individual components. H2RES was used in the case study to determine whether it is possible to govern the production of solar derived energy for the grid. It was determined that on a yearly basis, there is a 0.025 GWh (0.003% of PV production) surplus of PV production, with a maximum value of 1.2516 MWh in one hour of operation. This suggests that the PV installation has reached the border of potential economical amount of installation and that the next step in the case study should be the installation of grid storage. The ratio of intermittent RES in H2RES was calculated at 17.95%, a 0.84% difference compared to PV-GIS, since H2RES also takes as the input the actual electrical demand of the case study for each of the 8,760 hours of the year.

An overview of the market offers opportunities for turnkey solutions of PV installations in Croatia. In this context, an average installation cost of nearly 1,700 EUR per kW of installed power is forecasted [40], with 25% VAT, import duties and profits included in the price. Based on the results of the case study communities, this amounts to a total investment cost of 13.36 million EUR for the potential capacity. Return on Investment calculation using PVCalc software demonstrates a 12 year period of amortization. All inputs for the model can be found on the link [41]. The investment could be lowered if energy cooperatives would be considered and the project regarded as a single installation, with reduced cost of equipment acquisition. The PV installations will further represent other social benefits to the communities, including new jobs, academic research opportunities, and CO_2 reductions. Another potential factor that could lead to the wider adoption is government's energy efficiency in buildings program, which subsidizes up to 40% for Split area in installation cost for renewable energy systems in multi-unit housing [42].

Conclusion

The mapping of the potential to use building surfaces for renewable energy production in both of the case study communities has indicated the possibility to offset about 17% of the electricity purchase from the national electricity grid. This corresponds to a renewable energy production of 5.88 GWh in the Split 3 district area and 1.50 GWh in the University of Split campus area. The comparison of such a renewable energy production with the electricity demand in hourly time step in H2RES has further indicated that there will be 0.025 GWh surplus of PV production unless grid storage is used. The storage option was not considered at the moment, since it was out of scope of the study, and the strategy for storage management and also interconnection with the thermal energy vector was not yet developed. It is an area of investigation for future studies. The method that is deployed in the research work has contributed to the literature by putting forth scenarios for employing local generating potential in the micro grid with minimum interference in the existing state that can initiate a first step in the roadmap towards a 100% RES powered district and university campus in Croatia. Ultimately, micro grid applications need to be taken together with other dimensions of sustainable development for better integrated planning and assessment.

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