POTENTIAL OF VILLAGE HOUSE FOR SUSTAINABLE ENERGY PRODUCTION

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Abstract
Concept of energetically self-sufficient one-family house and study of its feasible technical potential for energy production from renewable energy sources are presented. Urgent necessity of eco-friendly buildings development is explained and substantiated. Scheme of the building's microgrid is proposed, its equipment used for power and heat production and local universally available free from payment renewable energy resources are described. Monthly power production by the microgrid is computed and compared with demands of the building. Main findings of this study are presented and discussed. They confirmed that one-family house can produce more power and heat energy than it is necessary. Results of this study allow designing of pilot building and to perform further researches in the natural conditions.

Key words: microgrid, solar energy, wind energy, renewable energy, efficiency.

INTRODUCTION

Rates of eco-friendly buildings development in the world are not sufficient and adequate to the current level of knowledge in ecology and climatology sciences. Therefore necessity of rapid development in this area must be well explained and substantiated. Many arguments can be given in favour of self-sufficient RES-based energy production in the buildings of various types. First of them should be mentioned protection of environment pollution by the greenhouse gases (GHG) and the climate change. The updated mental picture of the greenhouse effect is explained well enough by BENESTAD (2016) and other authors. Reasons of this phenomenon, environmental damages and other negative consequences of these processes are described in thousands of scientific papers, monographs, scientific reports and books. Available information on this subject makes up a solid scientific background, which allows accepting the decision to take urgent actions in order to phase out environment pollution by the GHG. This can be done by the transition from fossil fuels to the renewable energy sources as soon as possible. Such and similar proposals are strongly expressed in many reports by IPCC WGIII (2014), IEA (2013), documents – COP21 (2015) and many other sources of information.

Renewable energy sources have many advantages against fossil fuels. Primarily, as it is depicted in Fig. 1 presented by ADOMAVICIUS AND KAMINICKAS (2014), RES-based power plants (and nuclear power plants – NPP) have a huge superiority regarding the carbon intensity of power generation: amounts of CO2 equivalent emissions in grams per kWh of produced electricity for hydroelectric power plants (HPP), oceanic hydroelectric power plants (OHPP), wind power plants (WPP), concentrated solar power plants (CSPP), geothermal power plants (GTPP) and photovoltaic power plants (PVPP) are from tenths to hundreds times less than emissions from power plants based on fossil fuels, which are natural gas power plants (NGPP1 and NGPP2), running on the ecologically best (1) and worst (2) natural gas, furnace oil power plants (FOPP), coal power plants (CPP) and lignite power plants (LPP). Low carbon intensity of the RES-based power plants is one of the strongest drivers accelerating development of the clean power production technologies.

Second important driver of RES-based power production development is economic: costs of solar and wind power production and costs of batteries used for power storage are rapidly falling down. Impact of only ecological and economic drivers is the main factor in the powerful breakthrough of RES-based power production technologies what is evidently indicated in Fig. 2, where indicators of growth are compiled on basis of data found in report of REN21 (2014) and in EPI DATA CENTER (2015). The first five positions in Fig. 2 have photovoltaic, wind, biomass, hydro energy and geothermal power plants. Growing awareness about destructive impact of fossil fuels on biosphere and global climate change is inducing growing opposition of the world population to the dirty fuels. More and more people understand and support the necessity to leave the fossil fuels underground. It is supposed that this generation is the last, which still can solve or mitigate the climate change problem before it is not too late, but the time for actions is short. And this is another important driver (social) of green revolution, which is in process from the first years of 21-st century and up to now.

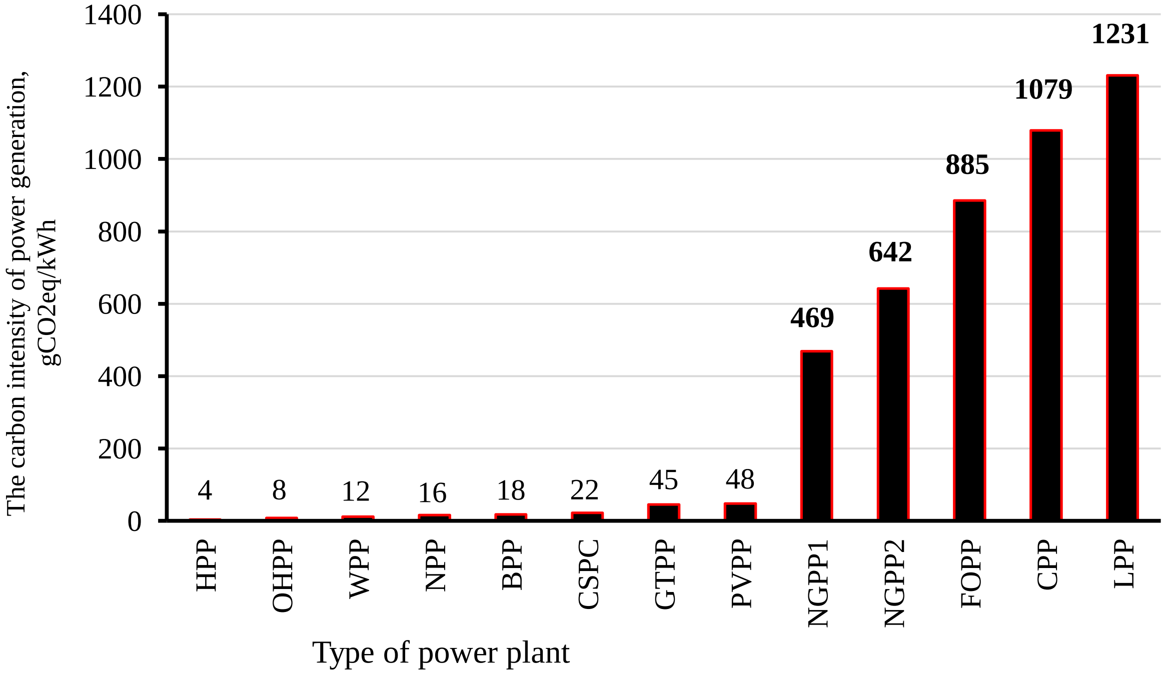


Fig. 1. – Comparison of power generation technologies by carbon intensity

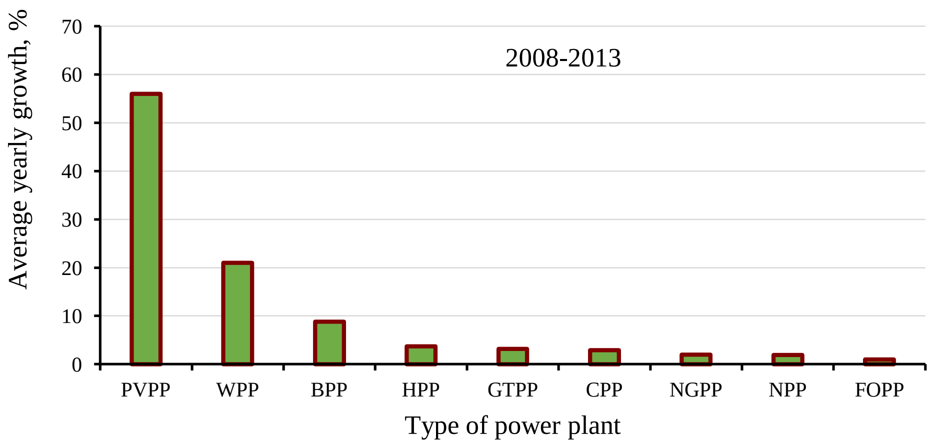


Fig.2. – Global annual growth of electricity production by type of power plant

Buildings consume about 41 % of energy in the EU countries. They have a huge potential for reduction of GHG emissions. It can be achieved in many ways in all types of buildings:

- ✓ by reducing of energy demands necessary for space heating or cooling in buildings (relevant thermal insulation of buildings);
- ✓ by using smokeless heat energy generation equipment (heat pumps, electric heaters);
- ✓ by installing local microgrid based on solar, wind, hydro energy sources and low temperature heat energy sources for power and heat production in buildings;

- ✓ by using of highly efficient domestic electric appliances (energy class A+) and efficient well controlled lighting system.

In this paper we present a concept and case study of energy self-sufficiency feasibility of one-family house. Presently majority of traditional houses already existing in towns and cities of many countries have three energy inlets – electric power, natural gas and district heating, or at least one or two inlets in a majority of villages (electricity, natural gas). In our case study we are exploring a variant of house, which in principle need not outside energy input and can function self-dependently. In this study all power and heat energy necessary for the house, including charging of electric vehicle batteries, is designed to produce in local microgrid running on free from payment and self-delivering renewable energy sources.

MATERIALS AND METHODS

In general case resources of renewable energy depends on the geographic coordinates of locality under consideration and on the time. Resources of renewable energy in any locality can be evaluated approximately by the average perennial data of variable energetic parameters of the energy source. It can be sum of average perennial global irradiation on the conventional planes per squire meter for solar energy, average perennial wind speed per year together with parameters of Weibull distribution of wind speed for wind energy and average perennial outdoor temperature of air in shadow for the certain period of time (e.g., month, week, day), when renewable energy source is the mass of low temperature air existing around the house under investigation. Resources of the chosen renewable energy sources in the chosen locality are presented in Tab. 1. Their potential possibilities will be checked in this study in regard of their capability to cover all necessary power and heat needs of the experimental house.

Tab. 1. – Resources of self-delivering renewable energy in the locality of building

Conditions	**Months**												**Per year**
	01	**02**	**03**	**04**	**05**	**06**	**07**	**08**	**09**	**10**	**11**	**12**	
Geographic coordinates of locality													
55˚18’46” North; 22˚01’52” East (in Lithuania)													
Average perennial monthly sum of global solar irradiation, kWh/m^2													
Inclination 35˚	23.9	43.1	112	152	176	168	167	149	113	66.4	27.2	17.2	1120
Inclination 90˚	25.6	42.1	98.1	108	103	90.8	94.2	97.1	91.2	62.5	28.5	18.7	860
Average perennial outdoor temperature of air, ºC													
In shadow	–4.0	–3.7	–0.4	5.1	11.3	14.9	16.3	15.9	11.9	7.6	2.5	–1.5	6.3
Average annual parameters of wind speed													
Hub height 25 m	v = 5.7 m/s; Weibull parameters: a = 6.4 m/s; K = 2.07												

Data in the Tab. 1 show rather good wind energy resources in the chosen locality, however solar energy and low temperature heat energy resources of atmosphere air are moderate. But it is worthy to note that during the years of 21-st century average temperatures of air of all months of entire Earth planet are significantly higher than perennial average of the 20-th century due to the climate change. Therefore average temperatures of air in February, March and December in Lithuania already are positive and exceed zero degree very significantly.

Overall view of the house under investigation is depicted in Fig.3 and short description of its characteristics is presented below in Tab. 2. The building is designed and oriented in line with principles of solar architecture – slope of the roof is turned southward (azimuth – 0 deg.). Roof-top photovoltaic (PV) array is mounted on the building’s roof on the plane, which has optimal inclination to the horizontal plane for this geographic latitude (35 deg.). A small-scale wind turbine is mounted on the ground from the west side of the building (the main direction of wind). The glassed-in added greenhouse is designed mainly for the preheating of air in order to have a higher efficiency of heat pump intended to use for space heating and producing of domestic hot water. In this case it is operating as the collector for air heating. Additionally, in some periods of year it also can be used as a greenhouse – for growing of early vegetables, or for drying of wet wash.

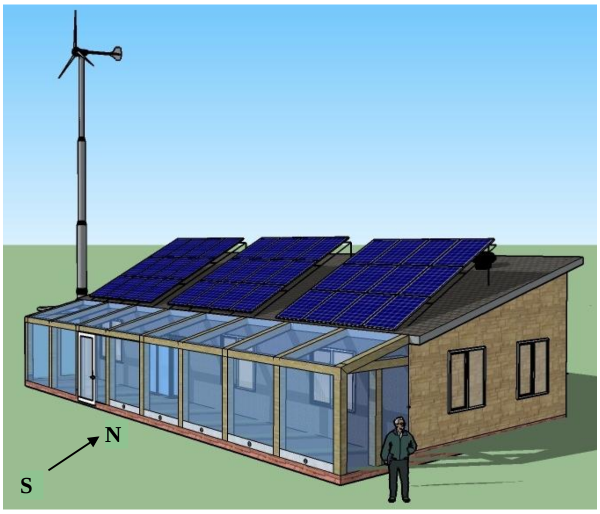


Fig. 3. – Overall view of energy independent one-family house

Benefit of air preheating in the added greenhouse can be explained using Fig. 4, where typical curves of power demand and heat energy output of heat pump "air to water" are depicted. The curve of heat energy output (the upper one) clearly shows that efficiency of heat pump operation is significantly higher at higher temperatures of the ambient air: the power demand curve remains approximately stable, but the heat energy output is increasing together with increase of the ambient air temperature. In our case outdoor module of the heat pump is intended to install in the loft of the house. Preheated air finds the way from the greenhouse to the outdoor module via the specially designed air ducts.

Tab. 2. – Characteristics of the one-family house

Parameters of the building	Unit	Value	Note
Building's energy class	–	A+	15 kWh/m^2 annually
Total living area	m^2	105	
Total heating area	m^2	95	
Temperature of air in heating spaces	ºC	18–22	Lithuanian standard
Number of inhabitants	–	4	
Temperature of domestic hot water (DHW)	ºC	50	
Consumption of DHW per month per inhabitant	m^3	2	Average data
Consumption of DHW per month per building	m^3	8	Average data
Roof area	m^2	120	
Area of glassed-in wall of the added greenhouse	m^2	~30	Vertical windows
Area of glassed-in roof of the added greenhouse	m^2	~28	Roof windows
Number of electric vehicles	units	1	

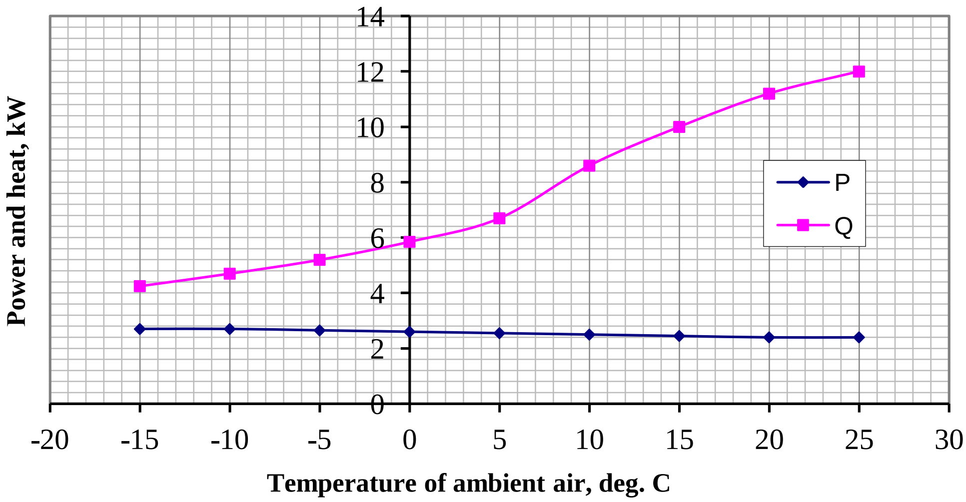


Fig. 4. – Typical curves of power demand and heat energy production by the heat pump

The greenhouse will operate efficiently in sunny and half-sunny days of autumn, winter and spring. Increment of inside air temperature can be achieved approximately up to 30–40 º C in sunny winter days at negative outdoor temperatures, if the greenhouse has perfect thermal insulation. Thus, the greenhouse added to the house will allow saving of electric energy used by the heat pump. Operation of the greenhouse as solar collector for air heating is not essential in summer but it also will help save energy in colder days.

The main parameters of power and heat generating equipment designed to use in the experimental microgrid are shortly described in Tab. 3. Apart from the RES-base power generation system, it would be expedient to have connection of the building's microgrid to the distribution grid of electric power system. It allows increasing of power supply flexibility and reliability. It also enables cooperation between the microgrid and the distribution grid. Microgrid can perform some functions useful for the distribution grid (e.g., function of power storage, support of the power distribution grid during the peak demand hours, when surplus of electric power produced and stored in the microgrid can be supplied into the power system). The distribution grid also can support microgrid at emergency.

Tab. 3. – Main parameters of energy generators in the building's microgrid

Parameters of power and heat generators	Unit	Value	Note
Small-scale wind turbine of horizontal axes			
Rated capacity of wind turbine	kW	9.5	At wind speed 10 m/s
Maximum capacity of wind turbine	kW	12	At wind speed ≥ 12 m/s
Hub height	m	24	
Rated wind speed	m/s	10	
Diameter of wind rotor	m	6.5	3 blades x 14 kg
Swept area of wind rotor	m^2	20.4	
Weight of wind turbine	kg	~160	Without tower
Roof-top photovoltaic power plant			
Rated capacity of one module	Wp	300	Crystalline Silicon
Number of PV modules	–	36	
Rated capacity of PV power plant	kWp	10.8	At irradiance 1 kW/m^2
Optimal inclination angle of PV array	deg.	35	
Azimuth of PV array	deg.	0	Oriented to South
Heat pump „air to water" for space heating and domestic hot water			
Rated power demand by the heat pump (HP)	kW	~ 2.3	
Range of heat generation capacity	kW	4.4–12.0	(Fig. 5)
Lowest average ambient temperature of month	º C	– 4.0	January
Highest average ambient temperature of month	º C	16,3	July
Rated temperature of water in output of HP	º C	50	

Possible variant of electrical scheme of the building's microgrid power conversion system is presented in Fig. 5. The system comprises the following subsystems:

1) the small-scale wind turbine SWT includes the generator G, the rectifier R, the step up chopper DC/DC–1, the switch S1 and the charger Ch1 of the battery B;
2) the small-scale photovoltaic power plant consists of the PV array, the step up chopper DC/DC–2, the switch S2 and the charger Ch2 of the battery B;
3) the electric power storage subsystem consists of the battery B, the step up chopper DC/DC–3 and the switch of the battery Sb;
4) mutual for the microgrid power conversion system consists of the grid-tied inverter GTI, the capacitor for short-time power storage C, the switch Si and

the inverters control system, which is included in the united control system of the microgrid CS;

5) the united control system of the building's microgrid has the unit of the control system CS and the switch Sc.

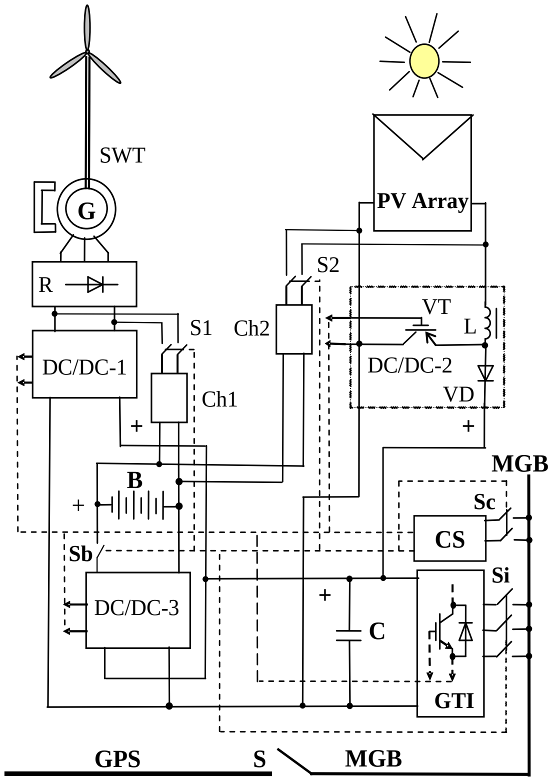


Fig. 5. – Electrical scheme of the house microgrid power conversion system

Microgrid's bus MGB can be connected to the distribution grid of power system GPS through the switch S. The microgrid can function both in grid-connected and stand-alone (islanded) modes of operation.

All three DC/DC choppers have the same electrical scheme, which is revealed in Fig. 5 and depicted under the PV array. It consists of the shorting transistor VT, the inductor L and the flyback diode VD. The DC/DC choppers are used for stepping up the input voltages of the GTI inverter. Three phase grid-tied bridge inverter with short-time power storage capacitor C is used for the power supply into the bus of microgrid MGB for feeding of all electricity users in the building. The main elements of the inverter are six transistors connected with six diodes as it is shown in this figure. Inverters of this type can be exploited in any power sources having variable DC voltage in the inlet. Specific feature of this type converter is the possibility to have a few inlets from different and intermittent power sources connected through the DC/DC converters to one mutual DC/AC inverter.

Battery B of electric power storage subsystem is important part of the building's microgrid, when high reliability of power supply is required and operation in stand-alone mode during long periods is probable. A huge progress made in power storage technologies during the last decade paved the way not only for rapid development of electric vehicles but also for breakthrough of installations of RES-based power plants and microgrids. Significant improvements of batteries and rapid decrease of their prices are described by LUO ET AL. (2015), WANG ET AL. (2014), JOHN (2015), AMBRI (2015) and by many other authors.

Batteries of electric vehicles also can be used in microgrids for power storage in two ways:

- ✓ second use of batteries retired from electric vehicles;
- ✓ according to the vehicle-to grid (microgrid) concept.

Technical, economic and commercial viability of these implementations is analysed by MULLAN ET AL. (2013), PETERSON ET AL. (2013), STANDRIDGE AND CORNEAL (2014) and by many other authors.

Control pulses for the inverter, for all DC/DC choppers and switches are generated in the microgrid's control system CS. There are many versions of microgrids control and energy management systems design, which are reviewed by MENG ET AL. (2016). Aspects of optimal control and stability of operation are among the main problems for designers of microgrids. They were analysed by MAJUMDER (2013) and many other authors. It has to be taken into consideration in order to design optimal and efficient microgrids for feeding all necessary domestic electrical appliances.

RESULTS AND DISCUSSION

Probable monthly power amounts of power production in the building's microgrid were computed on basis of data presented in Tab. 1 and Tab. 3. Results of the computations are presented in Tab. 4, where *Ewi* is the power produced by the small-scale wind turbine per month "*i*"; *Esi* is the power produced by the rooftop photovoltaic power plant per month "*i*" and *Ei* is the total power amount produced in the microgrid by both small-scale power plants.

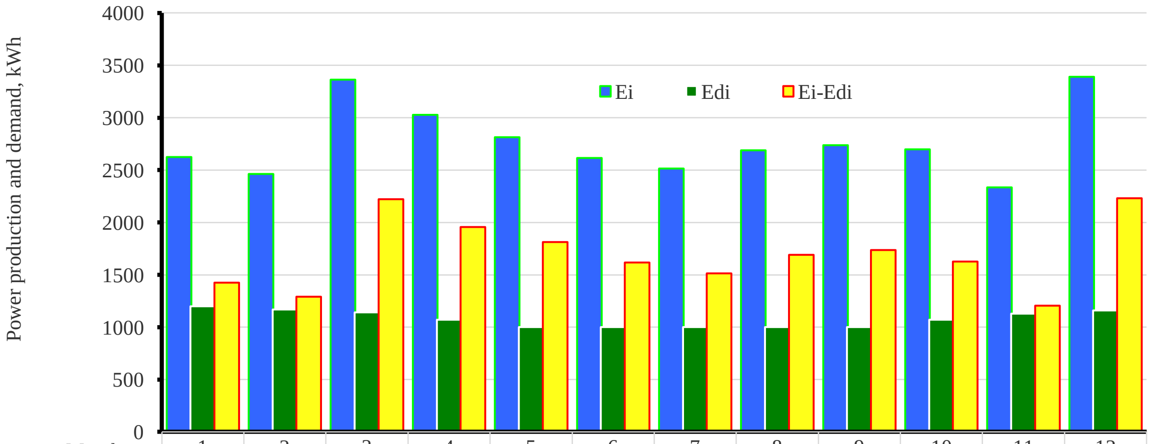
Tab. 4. – Monthly power production and power demands in the building's microgrid

Month	*Ewi*	*Esi*	*Ei*	*Edi*	*Edai*	*Eshi*	*Ehwi*	*Eevi*
	kWh							
1	2356	270	2626	1200	700	200	80	220
2	2008	454	2462	1170	700	170	80	220
3	2282	1080	3362	1140	700	140	80	220
4	1710	1318	3028	1070	700	70	80	220
5	1340	1473	2813	1000	700	0	80	220
6	1226	1391	2616	1000	700	0	80	220
7	1149	1365	2514	1000	700	0	80	220
8	1428	1262	2690	1000	700	0	80	220
9	1739	998	2736	1000	700	0	80	220
10	2062	635	2697	1070	700	70	80	220
11	2075	261	2336	1130	700	130	80	220
12	3210	180	3390	1160	700	160	80	220
Year	22 584	10 686	33 270	12 940	8 400	940	960	2 640

Total power demands in the building *Edi* per month "*i*" comprises of the power expenditures by the domestic appliances *Edai*, by the heat pump for space heating *Eshi* and domestic hot water *Ehwi* and by the charger of electric vehicle batteries *Eevi*. Power demands for domestic appliances are assumed above the average demands of a typical house. Demands for space heating depend mostly on the size of heating area, energy class of building and local meteorological conditions. High energy class of building and energy saving measures are extremely important for substantial reducing of energy demands for space heating and simultaneously for reducing emissions of the greenhouse gases because presently in many cases heat energy is generated using fossil fuels.

Electricity consumption by the electric vehicles is not considerable. It mostly depends on the mileage, size, speed, aerodynamic characteristics of the car, and on the quality of roads. Approximately it was assumed that average daily mileage of the electric vehicle in Lithuania is 35 km. Power consumption rate for middle-sized electric vehicle is about 200 Wh·km^{-1}.

Total monthly power production, total power demand and their balance in the building's microgrid under investigation are shown in Fig. 6.



Months	1	2	3	4	5	6	7	8	9	10	11	12
Ei	2626	2462	3362	3028	2813	2616	2514	2690	2736	2697	2336	3390
Edi	1200	1170	1140	1070	1000	1000	1000	1000	1000	1070	1130	1160
Ei-Edi	1426	1292	2222	1958	1813	1616	1514	1690	1736	1627	1206	2230

Fig. 6. – Monthly power production by the microgrid, total power demand and power balance

Analysis of information depicted in this chart evidently shows that potential of power production in the buildings microgrid at the mentioned above local renewable energy resources covers all electricity demands (including electric vehicle) more than two times. Thus, this microgrid could feed one more house having the same power demands, or to supply electricity into the distribution grid of power system. Secondly, it is not the limit of power production potential for this house: under the necessity it would be possible to choose higher capacity of the turbine, to install additional wind turbine or to install additional (ground mounted) photovoltaic power plant.

A wide variety of microgrids and small-scale power plants based on renewable energy sources exists in practice or are described in papers. Advantages of the microgrid of energetically self-sufficient house proposed in this paper are following:

- ✓ convenience and almost universal availability of chosen self-delivering renewable energy sources (solar, wind and low temperature heat energy source of ambient air),
- ✓ exploitation of the loggias for enhancing efficiency of heat energy production,
- ✓ low operation and maintenance expenditures (no expenses for fuel and fuel supply, no ash and other waste materials, water is not used for power production),
- ✓ versatility of the microgrid (covers all power and heat energy demands of the house for electrical appliances, space heating, domestic hot water and electric vehicle),
- ✓ power conversion system based on innovative converter (it has three inlets from intermittent solar, wind power sources and power storage battery, all connected through the DC/DC converters to one mutual DC/AC inverter).

Results of researches of power conversion systems with mutual inverter are described in papers by RAMONAS ET AL. (2009), RAMONAS AND ADOMAVICIUS (2013) and in their other publications. As a rule, traditionally every electricity generating or storing unit in the microgrids has their own inverter and majority of domestic RES-based power plants are roof-top solar (in this case shortage of electricity in winter is unavoidable). Other renewable and non-renewable energy sources are also used. It is described in the report performed by MARNAY ET AL. (2012) and in other references. But it makes the system more expensive.

Previously many hopes and expectations in transport sector were related with biofuels. It was believed that biofuels is the main way of transport sector to the green future. However, production of biofuels in many cases is linked with considerable use of land, which preferably is necessary for agriculture, and usage of soil polluting chemical materials as pesticides, fertilizers and other. Thus, possibilities of biofuel production are limited and this type of fuel is rather expensive. Presently it is clear that, most probably, the main way of transport sector to the green future will be through the electric power. Batteries of electric vehicles can be charged from the RES-based power plants without any combustion of fuels, which release the GHG. Additionally, according to the United Nations Framework Convention on Climate Change and other documents, our way to the sustainable future goes directly towards the zero emissions of GHG and it is not a matter of far future – it is happening now. Transition to the epoch of clean energy production is ongoing now rather rapidly and smoothly: total capacity of wind turbines installed in the world in 2015 made up 63 GW (2014 – 50.2 GW), solar power plants – about 50 GW (2014 – 40 GW) and hydroelectric power plants – 33 GW (2014 – 39 GW). Meanwhile increases of total capacities of power plants based on fossil fuels during the same years are few times lesser at the best case (natural gas power plants) or even are shrinking (coal, lignite, furnace oil, nuclear) because of their decommissioning. So, public electric grid is becoming greener and greener every year. Most probably, biofuels in transport sector will be used in future in cases when usage of electricity is hardly applicable. It could be sectors of maritime and aviation.

CONCLUSIONS

The necessity of urgent development of eco-buildings can be easily substantiated on basis of scientific information proved by the ecologists and climatologist of the world. Pollution of environment by massive long-term burning of fossil fuels is inducing frequent and strengthening catastrophic disasters and dangerous climate change. The main remedy for solving this problem is sustainable development by the decisive, urgent and deep reduction of the greenhouse gases emissions into the atmosphere. There are many ways to do this in every sector of economy and it must be done as soon as possible. All sectors of world‘s economy must be reconsidered in this aspect and agriculture as well.

A huge untapped potential for reduction of the greenhouse gases emissions have buildings. A permanent decline of costs of photovoltaic modules, batteries and photovoltaic systems caused unprecedented growth of their markets and paved the way for economically reasonable implementation of RES-based microgrids in buildings. Principles of renewable energy systems implementation in buildings are energy conservation (perfect thermal insulation), efficient exploitation of the primary source (wind, solar irradiance) and efficient usage of the produced energy (energy efficient equipment). Microgrids have very good environmental characteristics of energy production and they are attractive for possibilities to exploit local, free, non-fuel and non-emitting greenhouse gases primary energy sources in high extent.

The presented microgrid has not any expenses for fuels and fuels supply, because it is running on a free local primary energy sources. Therefore maintenance and operation of this system do not require much expenditure and time. Besides, the system does not produce any waste (ash), does not use water for power production, and solar power plant has not moving parts.

The main finding in this study is justified conclusion that potential of this experimental house for power production significantly exceeds all intentionally enhanced power demands of the building. Results of this study allow taking further steps: to implement a pilot experimental project of the house fed by the power generated in its own microgrid, which is based exclusively on local, free, self-delivering and smokeless renewable energy sources. The microgrid operating in natural conditions will be useful as basis for researches to be carried out in order to enhance efficiency of power production, to find optimal sizes of wind and solar power plants, heat pump and added greenhouse, and to find optimal algorithm of overall system control for microgrids of this type.

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