Feasibility Study of Renewable Energy Systems in Households

Janis Zakis, Alexander Suzdalenko, Oskars Krievs, Leonids Ribickis
Institute of Industrial Electronics and Electrical Engineering
Riga Technical University
Riga, Latvia
janis.zakis@ieee.org, aleksandrs.suzdalenko@rtu.lv, oskars.krievs@rtu.lv, leonids.ribickis@rtu.lv

***Abstract*— This paper cover analysis of market available technological solutions and equipment for household energy system modification with respect to available solar energy generation data obtained by existing installed photovoltaic generation monitoring data. Focus on available nanogrid combinations utilizing market available power electronic converters and energy storage solutions has been done. Comparative economic impact of various system design scenarios based on real renewable resource energy market conditions and equipment investment has been provided.**

Keywords—Renewable energy systems; nanogrid design; energy storage;

I. INTRODUCTION

Support of the use of renewable energy sources (RES) is an important element of European Union policy. One of the targets for 2030 is at least 27% share of renewable energy consumption [1]. Thus, there are many changes coming in power generation systems, electricity networks and markets of member countries. From the power generation point of view, the photovoltaics and wind generators are main power sources widely used in industry and residential applications [2]–[4]. Depending on different legislation aspects in EU countries the use of RES can differ. In the market sector of residential applications of many EU countries the power generation from RES is feasible only for self-consumption due to local market legislation e.g. if there is no consumption then power could be sold in market, but not for the utility company price [5]. This price will be approximately one third of price for which utility companies sell. That is why it is not feasible to sell. This leads to implementation of power harvesting system or small scale nanogrid [6] (grid connected system connected to medium voltage grid) together with storage in order to create feasible and efficient use of power from RES. According to [7] nanogrid is defined as “a small electrical domain connected to the grid of no greater than 100 kW and limited to a single building structure or primary load or a network of off-grid loads not exceeding 5 kW, both categories representing devices (such as DG, batteries, EVs [electric vehicles], and smart loads) capable of islanding and/or energy self-sufficiency through some level of intelligent DER management or controls”. Fig. 1 presents the general power consumption tendency in households together with power production from PV panels. As it can be seen there can be marked out main periods of power consumption and power generation.

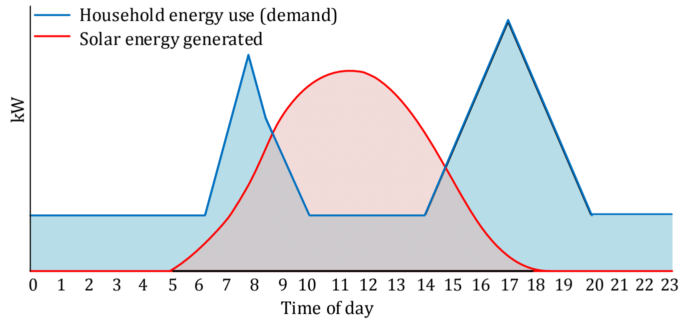


Fig. 1. General power consumption tendency in households and power production from PV panels over 24 hours.

Usually mornings and evenings are power consumption periods, but day and night (in case if wind generator is used) are power generation periods. To make power consumption from renewables feasible it is recommended to use it when it is generated or supplement the system with energy storage capability.

It means that use of maximal power from RES is very essential. This research work is devoted to comprehensive comparison and evaluation of hardware equipment available in market which is verified by local energy company.

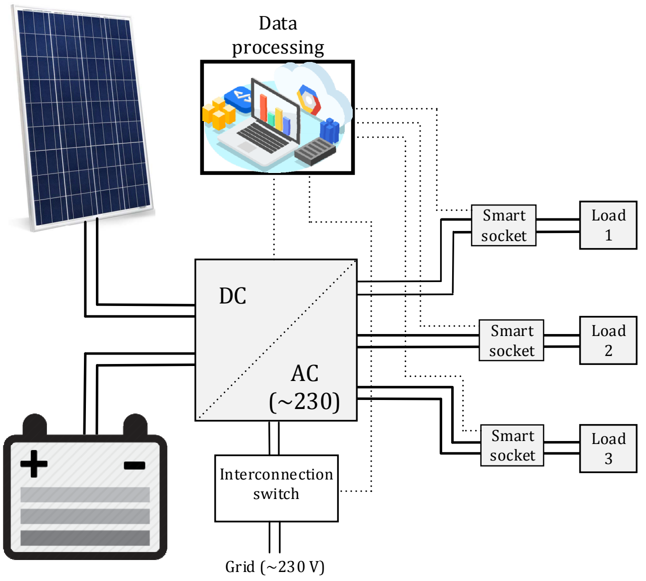


Fig. 2. General circuit diagram of RES powered household.

II. SYSTEM DESCRIPTION

Comprehensive and comparative evaluation of hardware was carried out based on needs of practical household case. Fig. 2. presents general circuit diagram of conventional RES powered system including several loads. Since the RES cannot provide constant power flow for loads it is considered to add also energy storage buffer for short term power demand [8]. Energy storage is usually not designed for long term power supply that is why it is recommended to divide loads in priorities. To realize that, there is one smart switch coupled with each load. The smart switch is connected to main data processing device which allows connecting or disconnecting a load. Connection and disconnection of load is controlled by algorithm based on two parameters. One is connected with solar irradiation intensity. For instance, if the voltage level from RES and energy storage cannot keep the voltage at rated value, then lower priority loads are disconnected. The second parameter is the maximum current demand. If high power is demanded for short time, then other loads are disconnected. The connection/disconnection order can be managed by users according to their settings.

Each country defines the rules and procedures of connection micro-generation sources to the main grid. Mainly, there is limitation by inverter's power (16 A per phase or 3.7 kW for single-phase and 11.1 kW for three-phase system in Latvia). Due to national grid code each inverter model must receive approval from local distribution company before connecting it to the grid. Client can also use one of already approved inverter model taken from the list that is publicly available from local distribution company. In case of necessity to use specific inverter not listed before, new inverter model should successfully pass compliance tests for which the client must pay. Even though most of EU countries allowed consumers with micro-generation systems to store energy in the grid (or NET payment system), the client saves only cost of electrical energy, while still needs to pay transportation and "green component" proportionally to consumed electrical energy. Moreover, NET payment system do not refund money at the end of billing period (from 1 April till 31 March) in Latvia, but just starts new period with zero balance even though previous period was left with excess of generated energy. As a result, the rule of thumb for Latvian case: 1) client saves 45% of 1 kWh price if energy is stored in the grid and consumed later; 2) client saves 100% of 1 kWh price if generated electrical energy is consumed at the same time.

III. SELECTION OF HARDWARE COMPONENTS FOR SMART GRID SYSTEM

The smart household grid contains various key components that allow implementing different level of autonomy and functionality. Some of the projects might need only PV inverter for their grid just to implement utilization of RES. However other projects might require operation in islanding mode that specifies additional list of required components, like transfer switch and battery inverter. Some manufacturers provide interoperable interfaces and protocols that allows selecting components from different vendors, while others provide full range of devices to run the nanogrid. This section will explain main functions of various key components.

A. RES Interface Converter

PV or wind inverters are one of the main components of smart household grid powering it from renewable energy sources. Different vendors have small divergence in efficiency values, while implemented list of features and functions should be considered to select proper model: graphical display, integrated web-server, historic data analysis over online portal, communication port, warranty, operating conditions etc.

RES inverter can operate without any external device and perform basic function – feed energy into the grid. However, some specific function like "zero feed-in" (or "zero-export" or "self-consumption compensation") will require additional digital energy meter that is connected directly to RES inverter or through another grid coordination device.

One of the basic requirements for the RES inverter is islanding detection to interrupt energy generation in case of mains failure. However, islanding should not interrupt energy generation if RES is used as part of back-up energy source or if stand-alone system is considered. Thus, RES inverter should work in tandem with battery inverter, which forms voltage and frequency of local grid and regulates the power output of RES inverter by means of frequency drop.

Producers of the RES inverters allows configuring multiple single-phase inverters to run three-phase system. This feature is useful, when it is planned to expand the small scale nanogrid from single-phase into three-phase system in several years, otherwise single three-phase inverter would be reasonable from economical and physical dimensions point of view.

B. PV Panels

Big number of traditional PV panel models are available on the market with various parameters being considered for selection to match specific project requirements: PV technology, efficiency, open circuit voltage, dimensions, price, warranty etc. Among traditional panelised PV solutions, market provides building-integrated solar panel solutions: for roof installations (like Solar Roof by Tesla), for facades (like LIBERTA™ SOLAR FAÇADE by RUKKI) or window integrated transparent PV solutions (like PV skylights by Onyx Solar).

C. Battery Interface Converter

Battery inverter expands the functions of the smart grid. It allows implementing demand control (by shifting charge/discharge periods) and islanding operation. This device is also necessary to maximize the self-consumption of power coming from RES by storing it in batteries during surplus of RES energy and releasing stored energy at RES energy shortages. On top of that, the control of battery inverter could be implemented based on electrical energy prices, thus, providing additional economy factor for the end-client.

The power rating of the battery inverter and capacity of the battery bank are selected depending on the requirements of particular project. However, there are devices with built-in battery with fixed capacity around 2 or 3 kWh, suitable for most applications (like Victron Energy ECOMulti). Besides individual battery inverter control, some of producers provides cooperative control feature that implements virtual power plant or energy sharing possibility at lower electrical energy (like sonnenComunity by sonnengroup) prices.

D. *Energy Meter*

Energy meter provides smart grid with electrical consumption data at the point of common coupling. It is often a required component, especially for implementation of self-consumption compensation, when PV inverter is limiting generation power based on present consumption data acquired from energy meter. Energy data might also be stored on online management platform, where end-client can further analyse the historical data and estimate the balance between generated and consumed energy or oversee the overlapping of both energy curves.

E. *Nanogrid Coordinator or Energy Manager*

Energy manager is necessary to coordinate all devices of the smart household grid – energy sources and sinks (like Sunny Home Manager by SMA or Color Control GX by VictronEnergy). Usually, this type of device supports data protocols to communicate with intelligent loads, while dummy loads can be controlled by means of radio-controlled sockets. Thus, by configuring energy manager with various load triggering scenarios advanced demand response algorithms could be implemented. In case energy manager analyses historical consumption data, forecast-based charging control of battery inverters can be realized.

F. *Interconnection Switch*

The nanogrid is connected to main grid by means of interconnection switch (“automatic transfer switch” as defined in SMA terminology) that is necessary to run in islanding mode. In most cases, this device contains of single or three-phase contactor, meanwhile, might be additional phase coupling circuit and/or grounding circuit. It is controlled by grid forming inverter (battery inverter) that measures quality of external grid and drives the interconnection switch. The reaction time of battery inverter on grid failure is 16 ms (for Sunny Island 6.0H by SMA) before it starts forming local grid’s voltage and frequency. That is slightly longer than industrial uninterruptable power supply (UPS) system with 4 ms reaction time. Nevertheless, most household electrical appliances will not even notice disconnection from the main grid.

G. *Implementation of Demand Control*

Basic idea of smart grid is to have stable power supply of critical loads independent from main grid failures and minimize electricity bill by using RES. As was mentioned previously, it is much better to utilize generated energy at the same time and exclude energy exporting and storing in the grid. It is well known, that consumption and generation curves usually do not match well as regular household has two peaks in morning and evening periods, while PV generates energy in midday period and wind energy is not predictable. For this reason, demand control is implemented by at least one of the following methods:

- Intelligent load control by automatic triggering based on availability of PV energy or cheap electricity price;
- Dummy load control by means of RC sockets and automatic triggering similarly to previous case;
- Regulate the power of adjustable loads;
- Use of electrical energy storage system with corresponding battery capacity.

Of course, not all the loads can be shifted or shedded, and not all of them can operate at reduced power consumption. However, various producers of nanogrid components provide specific device that allows using excess of PV energy for water heating by continuously adjusting consumed power of water boiler (OHMPILOT made by Fronius or MYPV ELWA-E supported by SMA). Similarly, the surplus of generated energy can be used to charge electrical vehicle, that is done if certain model of EV charger is supported by energy manager. In case of SMA-based nanogrid, Sunny Home Manager supports only one EV charger by now (MENNEKES AMTRON® EV charging point models of Xtra or Premium class).

H. *System Structure*

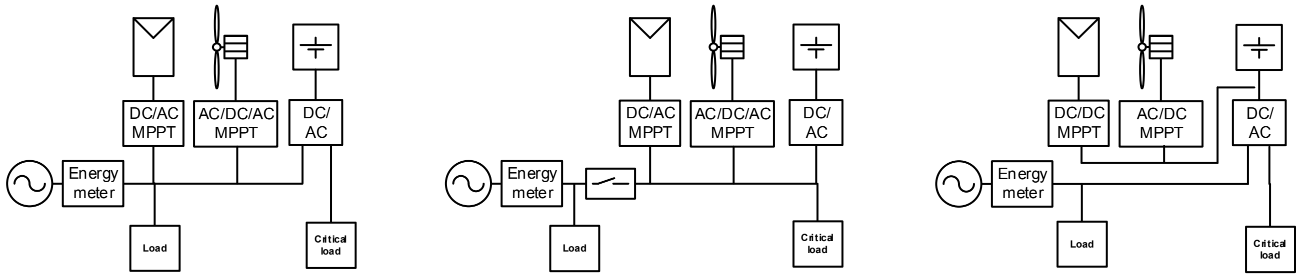
The Fig. 3 demonstrates different power configuration options for the nanogrid, which inherited limitations are summarized in the TABLE I.

I. *Summary*

As can be seen from the hardware list overview above, performance of the nanogrid depends not only on specific set of electrical appliances and load patterns of private household, but also depends on the producer of the nanogrid components, based on which end-user can implement different control options. This obstacle requires proper selection of list of the nanogrid functional elements, based on specific feature requirements that are summarized in the Table II.

TABLE I. COMPARISON OF NANOGRID STRUCTURE AND INHERETED LIMITATIONS

Configuration **Feature**	**Fig. 3. (a)**	**Fig. 3. (b)**	**Fig. 3. (c)**
Minimal configuration	PV Inv.	PV Inv., Bat. Inv., Bat., Intercon. Sw.,	Bat Inv., Solar DC/DC charger with MPPT
Energy export to main grid	Yes	Yes	Yes/No
Powering critical loads	Yes	Yes	Yes
RES utilisation during islanding	No	Yes	Yes



a) AC coupled Nanogrid with PV inverter connected from main grid side *b) AC coupled Nanogrid with PV inverter connected on critical load side* *c) DC coupled Nanogrid (without energy exporting)*

Fig. 3. Nanogrid's different power configuration options.

It's worth mentioning, that each producer mostly uses standard data exchange protocols (such as MODBUS for communication over local bus and MQTT for communication over Internet). That in turn, allows implementing additional features not mentioned in Table II, at a price of extra development time.

IV. ENERGY STORAGE SOLUTIONS

Implementation of energy storage solution is required for coordinated household nanogrid system level operation combined with RES and demand by various household loads. Appropriate energy storage technology for given use case is related to fundamental physical properties defined by basic chemical composition of electrolyte as well as auxiliary materials for electrode and separator resulting in battery cell designs. Consideration of household application located in Europe urban area with rather stable power grid infrastructure would present operation of energy storage unit for power peak shifting purpose in collaboration with RES generation in form of photovoltaic panels in most cases. Therefore, specific power capacity of energy storage unit is to be considered. Also ability to store specific amount of energy is important considering need for energy storage within defined time period of one day typically corresponding to double peak character of household consumption. Observing various battery technologies Li-Ion based solutions provide significant freedom of battery cell design with respect to tradeoff between both specific energy and power capabilities of final cell and respective battery modules as presented in Fig. 4. Since battery developments within electro mobility applications result in reduction of final battery cell manufacturing prices over time as result of economy of scale and production capacities worldwide [9].

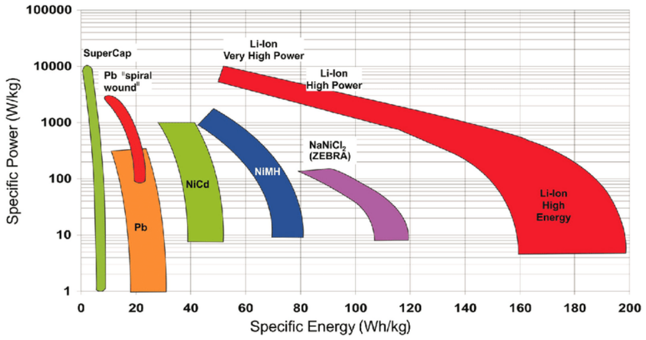


Fig. 4. Energy and power density comparison of various energy storage technologies [10].

By selection of requirements for battery storage system to have energy storage capacity of 3 kWh as well as ability to be interfaced with market ready inverter solutions has led to following overview of market available battery storage units for household use with respective parameter comparison based on [11] (see TABLE III.). Analysis support observation of lithium based chemistry as state of the art solution by all major manufacturers presenting energy storage product for interfacing with solar energy harvesting as well as back up and off grid applications. In terms of operational costs with respect to claimed battery warranty time and guaranteed performance one would observe final price per stored energy volume from 0.086 to 0.222

TABLE II. COMPARISON OF SPECIFIC FEATURES IMPLEMNETED BY DIFFERENT MANUFACTURERS

	Feature	SMA	VE and Fronius
Grid structure	DC coupled	+	+
	AC coupled, RES connected to main grid side	+	+
	AC coupled, RES connected to critical load side	+	+
Demand control	RES inverter power limit for zero-export	+	+
	Battery inverter control to maximize self-consumption	+	+
	Battery inverter control depending on electricity price	+	-
	Intelligent control of heat pump/boiler/dish washer/washing machine/EV charger	+/+/+/+/+	-/-/-/-/-
	RC-socket control based on calendar/daytime/PV potential/battery SOC/ Frequency drop control	+/+/+/+/-	-/-/-/+/+
	Adjustable loads used for space heating/water heating/EV charging	+/+/+	+/+/-

TABLE III. COMPARISON OF HOUSEHOLD ENERGY STORAGE PRODUCTS

Manufacturer	Lg Chem	Lg Chem	BYD	Pylon Technology	Simpliphi
Model	RESU	RESU H	B-Box L3.5	US2000B	PHI 3.8
Price (Basic module), Eur	2 350	4 275	1 825	1 487	2 337
Energy capacity (basic module), kWh	3.30	7	3.5	2.4	3.4
Max capacity - several modules, kWh	12.4	-	14.0	2.4	-
Usable capacity, basic module, %	88.0	94.3	100.0	91.5	100.0
Power output nominal (per module), kW	3.0	3.5	3.0	2	1.92
Peak power output (per module), kW	3.3	4.2	5.0	2.2	3.07
Chemistry type	Lithium NMC	Lithium NMC	lithium LFP	lithium LFP	lithium LFP
Voltage, V	48	400	51.2	48	48
Lifetime cycle performance / Warranty according to manufacturer	6000 cycles (90% DoD) / 10 years	6000 cycles (90% DoD) / 10 years	Not stated (80% DoD) / 10 years	6000 cycles (90% DoD) / 5 years	10000 (80% DoD) / 10 years
Round trip energy efficiency (if stated), %	-	-	>95.3	-	96.0
Use case: Back Up/Solar storage/Off grid	+/+/+	+/+/+	+/+/-	+/+/+	+/+/+
Lifetime energy turnover according to manufacturer, kWh	15 682	35 645	8 200*	11 858	27 200
Price vs Lifetime energy turnover Eur/kWh	0.150	0.120	0.222	0.125	0.086

*NMC - Nickel-Manganese-Cobalt; LFP - Lithium-Iron-Phosphate; * - guaranteed by warranty;*

Eur/kWh. Another aspect to consider is claimed end of life capacity stated by some of manufacturers to be 100% and could be explained by initial over dimensioning of unit for capacity loss over operational life span. Since all products are lithium technology based batteries integrated BMS solutions are applied thus presenting safety related precautions for integration with many commercial inverter manufacturer solutions.

V. CASE-STUDY ANALYSIS

According to statistics average monthly consumption of Latvian household is 338 kWh per month, while biggest group (50 % of clients) consume from 201 to 600 kWh per month. In this study monthly consumption of 600 kWh of electrical energy will be considered, where 40 % is spent for hot water preparation. Also we assumed that 10 % of daily consumption is overlapping with PV generation curve. PV generated energy data are taken from real installation of 3.3 kWp PV panels located on the roof of Department of Power and Electrical Engineering of Riga Technical University in Riga (azimuth 180°, tilt 56°).

Knowing that 3.6 kWp PV panels can generate about 3600 kWh per year for given location, it would be enough to use PV panels connected to two phases to power household, which annual energy demand is 7200 kWh. In case, all three phases would be used to connect maximal allowed PV power (with estimated yearly generation of 10 800 kWh), it would generate a lot of excess energy that would be stored in grid. Presently, Latvian NET payment system do not refund money for excess of generated energy and just put zero at the end of NET period (31 March), thus it is not economically feasible to use maximal allowed PV power.

Hereby, several configuration of nanogrid were studied from economic feasibility point of view with the following case scenarios:

- Case 0 – reference case without any nanogrid component;
- Case 1 – utilisation of maximal allowed PV power per phase;
- Case 2 – previous case with energy manager, energy meter and adjustable load for hot water preparation;
- Case 3 – previous case with battery inverter and energy storage 2.5 kWh and 12 kWh for two phase and three phase system correspondingly.

The defined scenarios were studied for single phase and three phase power systems. The aim of performed analysis was:

- to estimate the amount of energy could be instantaneously consumed,
- to estimate the amount of energy that was initially stored in the grid and later consumed (NET export and import).

The results are summarized in the Fig. 5. Based on given results the payback period was calculated for each case-study that also depends on different producers of nanogrid components (see TABLE IV.). The electrical energy price is 0.169 EUR/kWh, while NET energy cost is 0.094 EUR/kWh.

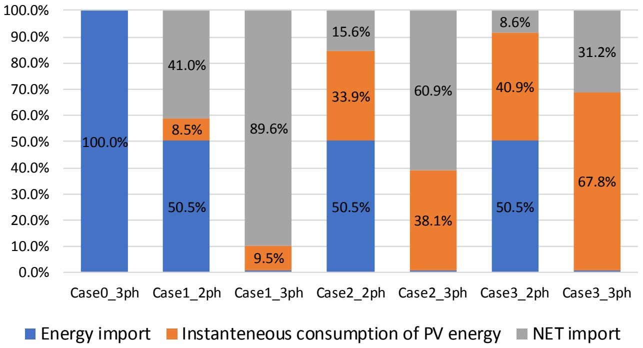


Fig. 5. Structure of consumed electrical energy for different case scenarios.

TABLE IV. PAYBACK PERIOD DEPENDING ON CASE-STUDY SCENARIO AND PRODUCER OF NANOGRID COMPONENTS

Solution	Phase count	Case 1		Case 2		Case3	
		Investm. €	Payback	Investm. €	Payback	Investm. €	Payback
SMA	2 ph	2 646 [a,b]	8.0	4 140 [a,b,c]	8.3	7 942 [a,b,c,d,e]	14.6
	3 ph	5 292 [a*2,b*2]	8.7	6 786 [a*2,b*2,c]	8.5	13 548 [a*2,b*2,c,d,f]	10.8
VE+ Fronius	2 ph	2 723 [a,g]	8.3	4 046 [a,g,i]	8.1	7 466 [a,g,j]	13.7
	3 ph	5 408 [a*2,h]	8.9	6 731 [a*2,h,i]	8.4	11 270 [a*2,h,i,]	11.3

[a] PV panels 3.6 kWp (AXITEC AC-300M/156-60S) - € 1 620

[b] PV inverter (SMA SB3800) - € 1 026

[c] Energy manager (SMA Sunny Home Manager 2.0)-579€, Energy meter (SMA Energy Meter)-309€ Intelligent water boiler controller (MYPV ELWA-E)-606 €; - € 1 494

[d] Battery inverter(SMA Sunny Island 6.0H) - € 2 349

[e] Battery storage (BYD Battery-Box Pro 2.5) - € 1 453

[f] Battery storage (BYD Battery-Box Pro 10.0) - € 4 539

[g] PV inverter (Fronius Symo 3.7-3-M) - € 1 103

[h] All-in-one MPPT/AC inverter/DC charger(Fronius Symo Hybrid 5.0-3-S) - € 2 168

[i] Energy manager (Fronius Datamanager Box 2.0), Electrical meter (Fronius Smart Meter 63A-3), Intelligent water boiler controller (Fronius OHMPILOT)-€ 1 323

[j] Battery inverter (VictronEnergy MultiPlus-II 48/5000/70-50) - € 1 967

CONCLUSIONS

The overview of the nanogrid's hardware components revealed that some specific features (like intelligent load control or RC socket control) are available not from all producers, thus, it should be carefully reviewed, which product to use for future nanogrid. At the same time, producers support custom control scenarios by using standard data exchange protocols that allows implementing custom control algorithms.

Operational costs of energy storage system greatly depends on warranty conditions declared by manufacturer that specifies (a) certain number of cycles at specific depth of discharge or (b) total lifetime energy turnover.

The payback period of the nanogrid project varies a lot depending on its configuration. Most economically feasible structure is just PV inverter with or without basic demand control options with about 8 years payback. This configuration however, do not assume islanding operation. Those nanogrid solutions with possibility to operate in islanding mode have payback period of more than 11 years, while provide bigger comfort for the end-user, such as powering critical loads during main grid failure, smaller electricity bills, bigger "eco-friendly" feelings. In present study, only two strings of PV panels connected only to two phases were selected, as it was enough to cover typical household electrical energy needs, while third string would generate excess of energy and literally would operate without any profit. However, in case the household would have EV charging station and consequently bigger consumption, it would be necessary to use third string of PV panels to compensate additional electrical load.

ACKNOWLEDGEMENTS

This research is funded by the Ministry of Economics of the Republic of Latvia, project RTUAER, project No. VPP-EM-AER-2018/3-0004.

The authors thanks State owned company AS "Latvenergo" for help with power consumption data in households.

REFERENCES

[1] "2030 Energy Strategy," *European Commission*, 2014. [Online]. Available: https://ec.europa.eu/energy/en/topics/energy-strategy-and-energy-union/2030-energy-strategy. [Accessed: 02-Sep-2019].

[2] L. Petrichenko, L. Zemite, A. Sauhats, K. Arturas, and K. Grickevics, "A Comparative Analysis of Supporting Policies for Solar PV systems in the Baltic Countries," in *2019 IEEE International Conference on Environment and Electrical Engineering and 2019 IEEE Industrial and Commercial Power Systems Europe (EEEIC / I&CPS Europe)*, 2019, pp. 1–7.

[3] A. Jasevics, L. Zemite, and L. Petrichenko, "A Comparative Assessment of the Deployment of PV Technologies in the Baltics and in the European Union," in *2018 IEEE 6th Workshop on Advances in Information, Electronic and Electrical Engineering (AIEEE)*, 2018, pp. 1–6.

[4] L. Zemite, L. Petrichenko, A. Sauhats, and A. Jasevics, "Small-Scale Renewable Generation Support in Latvia," in *2018 IEEE 59th International Scientific Conference on Power and Electrical Engineering of Riga Technical University (RTUCON)*, 2018, pp. 1–6.

[5] J. Dehler *et al.*, "Self-Consumption of Electricity from Renewable Sources," in *Europe's Energy Transition - Insights for Policy Making*, Elsevier, 2017, pp. 225–236.

[6] B. Nordman and K. Christensen, "Local power distribution with nanogrids," in *2013 International Green Computing Conference Proceedings*, 2013, pp. 1–8.

[7] P. Asmus and A. Wilson, "Microgrids, Mini-grids, and Nanogrids: An Emerging Energy Access Solution Ecosystem," *Energy Access Practitioner Network*, 2017. [Online]. Available: http://energyaccess.org/news/recent-news/microgrids-mini-grids-and-nanogrids-an-emerging-energy-access-solution-ecosystem/. [Accessed: 02-Sep-2019].

[8] K. Kroics, L. Zemite, and G. Gaigals, "Analysis of advanced inverter topology for renewable energy generation and energy storage integration into AC grid," in *Proceedings of 16th International Scientific Conference ENGINEERING FOR RURAL DEVELOPMENT*, 2017, pp. 941–950.

[9] D. Tarvydas, I. Tsiropoulos, and N. Lebedeva, "Li-ion batteries for mobility and stationary storage applications - Scenarios for costs and market growth," Publications Office of the European Union, Luxembourg, 2018.

[10] H. Budde-Meiwes *et al.*, "A review of current automotive battery technology and future prospects," *Proc. Inst. Mech. Eng. Part D J. Automob. Eng.*, vol. 227, no. 5, pp. 761–776, May 2013.

[11] J. Svarc, "Hybrid Energy Storage Systems And Inverters Summary," *CleanEnergyReviews.info*, 2018. [Online]. Available: https://www.cleanenergyreviews.info/hybrid-solar-battery-energy-storage-system-review. [Accessed: 02-Sep-2019].

This is a post-print of a paper published in Proceedings of the 2019 IEEE 60th International Scientific Conference on Power and Electrical Engineering of Riga Technical University (RTUCON 2019) and is subject to IEEE copyright.
https://doi.org/10.1109/RTUCON48111.2019.8982297
Electronic ISBN: 978-1-7281-3942-5.
USB ISBN: 978-1-7281-3941-8.
Print on Demand (PoD) ISBN: 978-1-7281-3943-2.