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Feasibility study of a local power supply system for sparsely populated areas in Estonia

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Abstract. The paper analyzes the reasonability of using an off-grid hybrid power supply system or in other words a local grid for sparsely populated areas as well as the necessary components selection and price development of such system. Typical consumers are selected and all estimations and calculations are based on them. Consumer profiles are set and analyzed as well as different elements of the local power supply grid and the possibility of connecting to the traditional grid. Estonian example is used in this paper as the country lies relatively north and has some remote areas, where local power supply grids can be implemented. All prices in the paper are derived from the Estonian example. Necessity of further study is proposed.

Key words: Distributed generation, PV panels, renewable energy, wind energy.

INTRODUCTION

The world consumes approximately 85 million barrels of oil every day but there are only 1,300 billion barrels of proven reserves of oil (Mi et al., 2011). At the current rate of consumption, the world will run out of oil approximately in the next 40 years (Owen et al., 2010). The emissions from burning fossil fuels increase the carbon dioxide (CO_2) in the Earth's atmosphere (Owen et al., 2010). For example, the total electric energy consumption in Estonia for the year 2015 was 8.1 TWh (Annual Report of Elering, 2015), which represent 3.24 Mt of CO_2 emissions. The increase of CO_2 is a cause of greenhouse effect and climate change. As a consequence, it will lead to instability of ecosystems and, perhaps, rising sea levels. Reducing fossil fuel usage and as a result, reducing carbon emissions are the main goals of humanity nowadays. The production of electricity, a complex process, is not always friendly to the environment, being often connected with burning of fossil fuels (Rassõlkin, 2014). The world today is moving towards smart grids and distributed electricity generation. This is a challenge for traditionally centralized systems, because instead of the big generation units, many smaller units distributed all around the system are starting to emerge (Vaimann et al., 2012). On the other hand, wider usage of renewable energy sources and efficient use of electricity can be the way to solve most of the problems in electricity generation today.

An estimated (WEO, 2015) it is about 1.2 billion people (17% of the global population) did not have access to electricity in 2015. Many more suffer from supply that is of poor quality. More than 95% of those living without electricity are in countries in sub-Saharan Africa and developing Asia, and they are predominantly in rural areas (around 80% of the world total). While still far from complete, progress in providing electrification in urban areas has outpaced that in rural areas two to one since 2000. Using of renewable energy sources gives a broader scale of possible solutions to consumers situated in sparsely populated areas, where no near distribution lines have been built (Vaimann et al., 2013).

The price of electricity consumed from the grid consists of three main parts – costs of electricity production, costs of distribution and taxes, the fourth component that can be also added in electricity bills is regulated policy costs. With the usage of renewable energy sources and dispersed generation a principle possibility emerges, to generate electricity at the spot of consumption. This opportunity can be realized in the situation, when electricity is needed in a place where there are no existing transmission or distribution lines. In certain conditions, usage of electricity generated from local renewable sources can become cheaper, than building a new distribution line to consume electricity from the grid.

To judge if local grid would be the cheaper solution, expenses of both possibilities must be known. This comparison is a simple task when both solutions have already been designed, but as designing those solutions in every individual case is expensive and time consuming, simplified criteria of evaluation must be developed to decide quickly and easily on the feasibility of the mentioned possibilities.

To set the needed criteria, typical electricity consumers and their consumer profiles must be found. After that, it is necessary to calculate expenses of every typical consumer on electricity in case of building a new distribution line. This is followed by designing local electricity supply for each consumer group and calculation of expenses of typical consumers on electricity in case of local grid. In this paper we are going to compare two alternatives of rural power supply: grid extension and local power supply. Finally, the expenses of local grid and new distribution line situations must be compared, generalized and the final criteria must be set. Comparison of the expenses can very well be made according to the price of kWh, but sum of the yearly costs of the consumer could very well be the subject of the comparison as well.

The analysis given in this paper is derived and updated from the authors' previous investigations (Kallaste et al., 2013; Vaimann et al., 2013). As during the past few years there has been major changes in the local electricity market in Estonia, an updated analysis and calculation methodology on the topic is presented.

TYPICAL CONSUMERS AND CONSUMER PROFILES

For the setting of typical consumers, it is obvious that such consumers can be found in remote rural areas, as towns and larger settlements are connected to the traditional grid. In case of rural areas, some remote regions can be found, where people have been living for decades, but due to various reasons, no distribution lines have been built. In Estonia, the estimation of such households reaches to a few hundred. Other similar case are old deserted villages, where people have lived, but moved to towns years ago. Roads to such places have been preserved to some extent and renovation of them is not too expensive.

On the other hand, there are huge amounts of people in towns, who desire to have a rural cottage to use as a summer house or year-round living during their retirement. Interest towards expanding agricultural production and reusing of former farmlands is rising. All of the listed reasons bring with them a need for electricity in places, where no connection points exist at the moment.

Taken into account the aforementioned possibilities, two possible typical consumers should be chosen under investigation:

1. Summer house, which is used seasonally and thus has a widely varying electricity consumption;
2. Cottage for a single household, that is used the whole year-round.

To simplify the investigation, this paper will be based on only those two consumer types. To carry out the analysis, typical electricity consumption of both the two cases is needed. The important information is the consumed kWh of one day in the time span of one year and the needed maximum power of the two consumers. This is called a consumer profile. When setting a consumer profile, it must not be forgotten, that the profile depends amongst other variables also in the fact if the consumed electricity is coming from the traditional grid and is relatively cheap, or is local grid used, which makes electricity more expensive. In case of local grid devices with lower power consumption such as LED- lights, economical refrigerators etc. can be expected.

Fig. 1 presents a typical annual electricity consumption of a summer house in Estonia. Values are given month by month. Monthly consumption varies 35–80 kWh. Main consumers in the summer house are lighting, refrigerator, electrical oven, partial heating (in addition to traditional wood fueled oven), and water pump. Annual consumption of the summer house is 622 kWh and monthly average is 51.7 kWh.

Fig. 2 presents a typical annual electricity consumption of a cottage used by one family. The household consists of four people living in the house throughout the whole year. Main consumers in this house are refrigerator, TV-set, personal computer, electric oven, lighting and a washing machine. Monthly consumption varies 150–340 kWh. Annual consumption of the household is 2,960 kWh and monthly average is 247 kWh.

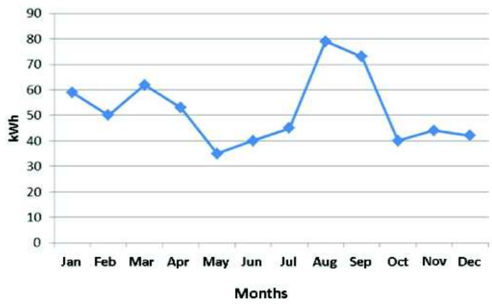

Figure 1. Annual electricity consumption of a summer house presented month by month.

Figure 2. Annual electricity consumption of a cottage used by one family presented month by month.

To estimate the consumption, calculations must be based on either metering data from summer houses or a selection of typical consumers in the aforementioned buildings and their usage times.

Using the data available for authors, a typical summerhouse has the maximum consumption of 80 kWh per month. It can be assumed that in case of local grid connection, the consumption will drop about two times and will be around 40 kWh per month. This means that the daily consumption will be 1.33 kWh in average.

According to Table 1 (Lõokene, 2011), daily consumption of a small one-family cottage based on the typically used devices is 1.75 kWh per day. As the consumption of a summer house is generally smaller, the calculated 1.33 kWh per day seems quite realistic and it means that the weekly consumption is in average 9.3 kWh. The consumption period in a summer house lasts for 7 months from April (week 9) to October (week 44), in total of 35 weeks.

Table 1. Daily consumption of a small one-family cottage based on typically used devices

Device	Power (W)	Daily usage (h)	Daly consumption (Wh)
TV-set	50	3	150
Refrigerator			356
Vacuum cleaner	1,500	0.1	150
Water heater 1.5 l	1,700	0.1	170
Pump	700	0.5	350
Lighting LED 8x11W	88	3	264
Laptop	60	3	180
Washing machine	2,200	0.06	132
TOTAL			**1,752**

Chosen cottage had the annual consumption of 2,960 kWh from the grid and maximum monthly consumption of 340 kWh. Average daily consumption in the maximum consumption month is then 11.33 kWh. There are significant variations between the consumption of individual days, but on the other hand the consumption can be expected to decrease when local supply system is applied. Considering these tendencies and the battery autonomous time of 2 days (less than in the example with the summer house) maximum daily consumption of 10 kWh can be set.

CONNECTION TO NEW DISTRIBUTION LINE

Calculations for consumer connections to new distribution lines are based on the methodology and prices used by the Estonian largest distribution grid company Elektrilevi. According to the company policy, all connection fees for consumers situated further than 400 m from the existing MV line are set separately for each individual case taking local conditions into account.

For the investigation purposes a simplified method for assessing grid connection costs must be found. 0.4 kV line is not suitable for supply in the distance of more than 400 m from the substation (or MV line respectively). MV line must substitute for the 0.4 kV LV cable. All new connections to the grid should be done using earth cables. This is a default requirement in most Nordic countries as well as in Estonia. Lowest voltage MV line suitable for such purposes is 10 kV as previously used 6 kV lines are not being installed anymore. There is a possibility of using a 1 kV line, but precedent of its usage does not exist in Estonian practice. In this paper calculations for connections are done based on 10 kV lines.

As seen from the consumer profiles described before, load currents are low, so minimal cross-section (25 mm^2) 10 kV earth cable is suitable for servicing the connection. 1 km of such cable line costs 50,000 € according to the information from Elektrilevi. Assuming that the new connection point is situated in the distance of 2 km from the existing MV line and 0.4 kV LV is needed for the consumers, at least two possible alternatives can be thought of.

Firstly, it is possible to use a 2 km MV line and install a substation in the vicinity of the connection point. Other solution would be moving the substation to 1600 m from the existing MV line and use LV cable between the substation and the connection point. As LV cable is cheaper for such load currents, the other option seems more reasonable. Schematic of the substation placement is presented on Fig. 3.

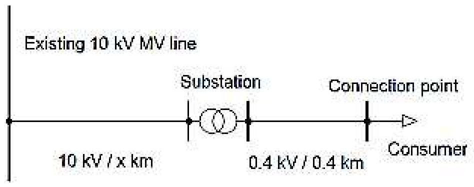

Figure 3. Schematic of substation placement for new connection point.

In the given case, connection to grid further than 0.4 km away is analyzed. This means that the connection fee consists of two parts. First part consists of the price of 10 kV 25 mm^2 MV line, the length of which depends on the exact placement of the connection point and the price of which can be set according to the price per meter and length of the needed line. This can be considered as the variable part of the connection fee.

Second part of the fee is made up from the costs of substation, transformer, switch board, metering system and the 0.4 kV LV line. This part depends on the main fuse amperage. Most used fuse rated values in Estonia are 16 A, 25 A and 32 A, just some of the households using more than 40 A fuses. In Table 2 the prices range for the mostly used valued is presented.

Table 2. Most used fuse rated values in Estonia

Main fuse amperage	Price without VAT	Price includes VAT
16 A	2,080 €	2,496 €
25 A	3,250 €	3,900 €
32 A	4,160 €	4,992 €

Around 15% of additional costs can be expected for other related work such as design and drawings. After this, simplified equation to calculate the costs of connection to the grid can be written:

$$c = [c_c + (d - 400)c_v + c_a]K_{VAT} \qquad (1)$$

where: c – connection costs (€); c_c – constant part of the connection fee (€); d – distance of the connection point from the existing MV line (m); c_v – variable part of the connection fee (€ m^{-1} of the 10 kV line); c_a – additional costs of the connection (€); K_{VAT} – value added tax factor (in case of Estonian 20% VAT; K_{VAT} = 1.2)

New kWh price must be found that already considers the costs of new connection to grid. It can be found so that connection costs in a certain time period (e.g. 10 or 30 years) must be divided with consumed electric energy (kWh) and electricity price from sold by provider companies and fixed with contracts must be added to the equation. Following equation can be derived:

$$P_{nem} = P_{con} + \left(\frac{c_c + (d - 400)c_v + c_a}{K_{kWhy}} \right) \frac{K_{VAT}}{c_{el}} \qquad (2)$$

where: P_{new} – new price of electricity taking connection fees into account (€ kWh^{-1}); K_{kWhy} – annual consumption in the connection point (kWh y^{-1}); c_{el} – calculated elimination period of the connection fee (years); P_{con} – price of electricity set by the contracts with provider companies (€ kWh^{-1}).

The price paid by consumers for electricity can be divided into three parts: electricity, the network service fee, and state taxes and fees, which cover the renewable energy fee (6.8%), electricity excise (3.9%) and VAT (16.7%). Base transmission fee in package 'Võrk 1' by Elektrilevi 0.054 € kWh^{-1}, electricity price by Eesti Energia AS with fixed value and a single year contract is 0.063 € kWh^{-1} (01.01.2016), including state taxes (Elektrilevi, 2015) and fee the final price will be 0.163 € kWh^{-1}.

Using Eq. 2, different situations can be investigated how the distance of connection point d and different amount of consumed electric energy will affect the electricity price P_{new}. Some of the possibilities are described in Table 3. The main contribution of the new price calculation is that the significant influence on the long term price value is made by the annual electricity consumption. Consequently, the separately connecting of the summer houses to the grid is not reasonable, particularly if they are located far away from the MV line.

Table 3. New prices of kWh (P_{new}) relating from distance of the connection point (d), annual electricity consumption (K_{kWhy}) and calculated elimination period of the connection fee (c_{el})

	P_{new}, € kWh^{-1} (c_{el} = 10 years)							P_{new}, € kWh^{-1} (c_{el} = 20 years)					
	d (m)	$K_{kWh\,y}^{-1}$ (kWh)						d (m)	$K_{kWh\,y}^{-1}$ (kWh)				
		500	1,500	3,000	4,500	6,000			500	1,500	3,000	4,500	6,000
16A	400	0.74	0.35	0.26	**0.23**	**0.21**	16A	400	0.45	0.26	**0.21**	**0.19**	**0.19**
16A	1,000	7.94	2.75	1.46	1.03	0.81	16A	1,000	4.05	1.46	0.81	0.59	0.49
16A	3,000	31.94	10.75	5.46	3.69	2.81	16A	3,000	16.05	5.46	2.81	1.93	1.49
16A	5,000	55.94	18.75	9.46	6.36	4.81	16A	5,000	28.05	9.46	4.81	3.26	2.49
25A	400	1.02	0.45	0.31	**0.26**	**0.23**	25A	400	0.59	0.31	**0.23**	**0.21**	**0.20**
25A	1,000	8.22	2.85	1.51	1.06	0.83	25A	1,000	4.19	1.51	0.83	0.61	0.50
25A	3,000	32.22	10.85	5.51	3.72	2.83	25A	3,000	16.19	5.51	2.83	1.94	1.50
25A	5,000	56.22	18.85	9.51	6.39	4.83	25A	5,000	28.19	9.51	4.83	3.28	2.50
32A	400	1.24	0.52	0.34	0.28	**0.25**	32A	400	0.70	0.34	**0.25**	**0.22**	**0.21**
32A	1,000	8.44	2.92	1.54	1.08	0.85	32A	1,000	4.30	1.54	0.85	0.62	0.51
32A	3,000	32.44	10.92	5.54	3.75	2.85	32A	3,000	16.30	5.54	2.85	1.96	1.51
32A	5,000	56.44	18.92	9.54	6.42	4.85	32A	5,000	28.30	9.54	4.85	3.29	2.51

LOCAL POWER SUPPLY FOR TYPICAL CONSUMERS

Consumer profiles described before are the basis for choosing an appropriate power supply for the typical consumers. The profiles were set for the situation, where the relatively cheap electricity from the grid is consumed. When using a local grid, it should be noted that price for 1 kWh is several times higher than in case of the traditional grid. Due to this, consumer profile usually changes when the transmission to local grid is made.

Sadly, as the investigation is made in Estonia, there are not so many local grid users and a systematic research on their consumption has not been followed through. It is clear however, that finding them in a new situation, consumers try to choose devices with lower power consumption (e.g. LED-lights instead of traditional bulbs) and try to avoid using electricity for heating. In a similar way the consumers try to avoid useless electricity consumption (e.g. using lighting for no apparent reason). Taken this into account, it can be assumed that in case on local grid the energy consumption can decrease up to two times compared to traditional grid consumption.

To choose the needed devices for local grid, a selection of devices available freely in the market has been made. Devices still in the development process have been discarded in this investigation. The chosen power generation devices are as follows: wind generator; PV panel; diesel generator and battery.

In the case of similar price, devices with less need of maintenance and unpleasant side-effects are preferred during the choosing of the generation devices. The device with the lowest maintenance need is the PV panel, followed by batteries, wind generator and eventually diesel generator, which is also a source for loud noise.

In every case, battery is the essential part of the local power system as the energy production of wind generators and PV panels is unsteady in time and the noise of the generator might become disturbing during night hours. In addition to that, the resource of the generator would be used up too quickly when kept working constantly. Price of the battery is mainly set by its energy capacity – the smaller the capacity the lower the price.

The time when energy supply is coming solely from the battery is called battery autonomous time. When the local power supply system contains a diesel generator, the suggested battery autonomous time is two days. If the generator is left out of the system, the suggested autonomous time rises to four days. In some cases, it is wise to optimize the battery autonomous time in relation to total cost of the system or price of the kWh.

If the system contains no generator, it is not worth to pursue 100% supply reliability from the system. This would simply make the battery too large in dimensions and of course more expensive. In rear occasions (a few percent of the time) one should accept the lack of electricity or limited usage of it (e.g. emergency lighting only). When the system has a generator installed, such limitations are generally not necessary, but in case of generator down time there is the chance of exhausting the batteries and losing the possibility of electricity consumption.

There are two main renewable energy generation units that can be utilized in a local power supply grid. These are either a PV panel, or a wind generator. The biggest drawback in case of PV panels is the inconsiderable amount of energy production during December and January in countries sharing the latitude with Estonia. In some weeks during those two months the energy production can decrease to zero.

Wind generator is not suitable for places, where the annual average wind speed is under 5 m s^{-1}. In such cases the needed power of the wind generator will grow too high, which makes the generator economically not feasible. In case of Estonia, annual average wind speed on the coast and islands at 10 m high exceeds 5 m s^{-1} (Fig. 4 usual high for small households and summer cottages). Inland however, there are many places where the 5 m s^{-1} margin is not reached. In the places where the winds are not sufficient, yet supply reliability is needed, a combination of PV panel and diesel generator should be preferred. The usage of PV panel and wind generator together will level the energy production in time, but will also make the system more complicated and expensive.

Anyway, the usage of battery would still be essential, as silent nights with no wind are not rare. Thus it is reasonable to use a system with just one renewable energy source – either PV panel or wind generator.

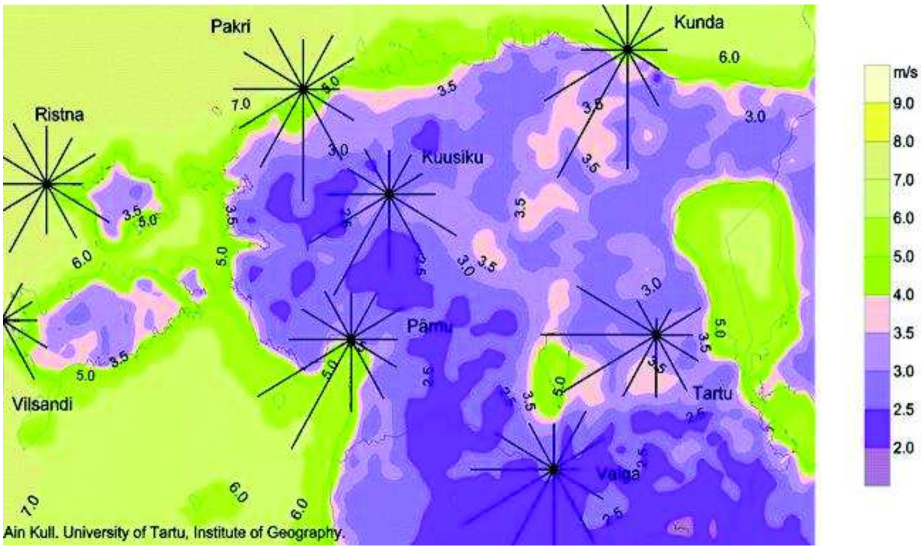

Figure 4. Annual average wind distribution in Estonia at 10 m high (Kull, 1995).

Usage of wind generator and batteries would in principle grant a reliable electricity supply. It should be investigated however, what should be the optimal battery autonomous time. It would also be good to know, if adding a diesel generator to the system would lower the price for the whole system, as diesel generators lowers the needed energy capacity of the batteries and thus the price, which is normally relatively high.

Taking all of this into account it would be reasonable to assemble the local power supply grid with the following energy sources:

1. PV panel and battery for the summer house (it is assumed that the house is not used during winter months);

2. PV panel, diesel generator and battery or wind generator and battery for the places in need of reliable supply with winds less than 5 m s^{-1}.

Table 4. Electricity prices of local power supply grids

Consumer	Elements of local grid	Annual consumption (kWh)	Price of electricity (€ kWh^{-1})
Summer house	PV panels (+ inverter), batteries	326	0.87
Cottage 1	PV panels (+ inverter), diesel generator, batteries	3,650	0.93
Cottage 2	Wind generator (+ inverter), diesel generator, batteries	3,650	0.96

Complete choosing process of the elements of local power supply grid is not presented in this paper. Results of the analysis are shown on Table 4. Those prices can now be compared to the prices of building new distribution lines shown in Table 3, where traditional power supply grid alternatives that are economically more effective are shown in bold. Other possibilities that suggest cheaper prices for local grids are shown in regular font.

CONCLUSIONS

If the case with a one family household living in a cottage is observed, it can be said that building new distribution lines is economically feasible, when the life span of the object is at least 20 years and the distance to the nearest 10 kV line is less than 800 m. With object life span of 30 years, the distance to the 10 kV line will grow to 1,000 m. In any longer distances building a local grid would be the reasonable choice.

There is an ecologically friendly and economically feasible alternative to traditional construction of substations and distribution lines, which is the autonomous local grids which are generating electricity from renewable energy sources. The solution is always applicable in the case of low consumption (up to 1,400 kWh y^{-1}) and long distances to nearest MV lines.

It can be concluded that in the case of small consumption, such as the summer house, local grid based on PV panels is always a more cost effective solution if compared to the building of new distribution line and substation even in the latitudes as north as Estonia. As studies show, the usage of wind generators on the coast or islands of Estonia with batteries energy storage system would also grant a reliable electricity supply that can be located far away from the substations.

Further study in the topic is needed to take into account the rising electricity prices due to open markets and rising prices of traditional power plant fuels. On the other hand, more accurate modelling of local grids and optimization using more precise data is needed to evaluate the prices of similar off-grid hybrid power supply systems.

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REFERENCES

Annual Report of Elering. 2015, 120 pp. (In Estonian). 2015.

Elektrilevi. 2015. 'Price for the Network Service – Elektrilevi'. https://www.elektrilevi.ee/en/hind Accessed 01.01.2016

Kallaste, A., Vaimann, T., Janson, K. & Bolgov, V. 2013. Components selection of local power supply system for sparsely populated areas. In *Proceedings of the 14th International Scientific Conference Electric Power Engineering*. pp. 181–186.

Kull, A. 1995. *Eesti tuuleatlas (In Estonian) (Estonian Wind Atlas)*. University of Tartu.

Lõokene, S. 2011. *Autonomous electric system (In Estonian)*.

Mi, C., Masrur, M.A. & Gao, D.W. 2011. *Hybrid Electric Vehicles: Principles and Applications with Practical Perspectives* 1st ed., Publication A John Wiley & Sons, Ed. United Kingdom: A John Wiley & Sons, Ltd, 468 pp.

Owen, N.A., Inderwildi, O.R. & King, D.A. 2010. The status of conventional world oil reserves—Hype or cause for concern? *Energy Policy* **38**(8), 4743–4749.

Rassõlkin, A. 2014. *Research and Development of Trial Instrumentation for Electric Propulsion Motor Drives.* Tallinn University of Technology, 127 pp. http://digi.lib.ttu.ee/i/?1078& (March 25, 2015).

Vaimann, T., Belahcen, A., Martinez, J. & Kilk, A. 2012. Detection of broken bars in frequency converter fed induction motor using Park's vector approach. In *2012 Electric Power Quality and Supply Reliability*. IEEE, pp. 1–4.

Vaimann, T., Janson, K., Bolgov, V. & Kallaste, A. 2013. Analysis of off-grid hybrid power supply for sparsely populated areas. In *Proceedings of the 14th International Scientific Conference Electric Power Engineering*. pp. 175–179.

'World Energy Outlook (WEO) – Energy Access Database 2015'. 2015