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Financial evaluation of using off-grid as an alternative to the traditional power line construction

Abstract. *Off-grid solutions usually consist of a renewable power plant, a storage battery, an inverter and a diesel generator. As the prices for these components have a negative trend, the use of off-grid becomes more feasible as a cost effective alternative to the traditional power line construction in the rural areas. This article provides a methodology to evaluate the financial feasibility of either alternative. The results show that in some cases off-grid can be the better alternative, even if both alternatives provide a negative net present value.*

Streszczenie. *Rozwiązanie typu off-grid składa się zazwyczaj z odnawialnych żródeł energii, zasobników, przekształtników, silników Diesla. Tego typu rozwiązania stają się konkurencyjne dla rozwiązań tradycyjnych dzięki temu że koszt wymienionych urządzeń jest coraz mniejszy. W artykule zaproponowano metodologię analizy finansowej tych systemów.* ***Analiza finansowa użycia systemów typu off-grid jako alternatywy dla tradycyjnych metod zasilania***

Keywords: Off-grid, renewable energy, distribution network, 1 kV system, financial evaluation, power line construction.
Słowa kluczowe: rozwiązanie typu off-grid, sieci zasilające, odnawialne źródła energii

Introduction

Off-grid solution is an alternative to the traditional building of power lines and its meaning can be taken literally: the customer is situated outside the grid, in other words, they have no connection point and are instead connected directly to a power generator. For example, off-grid solutions to water systems can be completed using artesian wells. Power networks usually comprise of a small renewable power plant (e.g. solar battery or wind-mills), a storage battery, an inverter and a diesel generator which is a combination of the two alternatives provided by Qoaider and Steinbrecht [1]. Off-grid is not a new concept. There are many places, where providing the traditional connection is impossible (e.g. on small islands or in the mountains).

The manufacturing cost of the solar panels decreased by more than twice between 2006 and 2011 [2], indicating technological advancements and an increase in the supply that could offset the demand. The cost of battery storage is also decreasing. UBS reports that the storage cost could fall under $100/ kWh compared to $720-2800/kWh that it costs right now [3]. This is probably due to Tesla building its new Gigafactory in Nevada USA, which will produce more than the total output of global cell supply in 2013 [4]. Taking into account this reduction in the prices, the off-grid becomes more feasible as a cost effective alternative to the traditional power line construction in the rural areas, where the density of population is small.

The fast development in the renewable energy generation technology will create new opportunities that have a large impact on the distribution networks. The distribution networks can either passively react to this change (develop their network according to the customers' needs) or take an active role and try to direct the development of the microgeneration by becoming one of the providers of this product. Most of the research done this far has focused on the first alternative: how to integrate these generation units into the network. Some of the examples are:

- Intelligent control of a grid-connected wind-photovoltaic hybrid power systems [5].
- The future of low voltage networks: Moving from passive to active [6].
- Optimal PV–FC hybrid system operation considering reliability [7].

In addition, there is a lot of research on the effectiveness of the off-grid solutions. Some examples of these studies are:

- Techno-economic analysis of off-grid renewable energy power station [8].
- Feasibility analyses of hybrid wind-PV-battery power system in Dongwangsha, Shanghai [9].
- Reliability and management of isolated smart-grid with dual mode in remote places: Application in the scope of great energetic needs [10].
- Study on stand-alone power supply options for an isolated community [11].

However, there seems to be no study on how to use off-grid solutions to optimize the investments of the distribution network itself, which is the main topic of this article. The main reason for this might be, that currently most distribution networks are forbidden to generate electrical power, except to cover their electricity losses. Also, it is important to note, that off-grid is an alternative to some uses of the 1 kV system proposed in [12]. There is already a lot of study on the effects of the 1 kV system [13, 14].

This article provides a methodology for the distribution networks to analyze the financial feasibility of off-grid solutions as an alternative to the traditional power line construction and provides an example from Estonia's biggest distribution network Elektrilevi OÜ. As a simplification, only solar power will be considered as the source of renewable energy generation.

Methodology for financial evaluation

The two alternatives are evaluated using net present value (NPV), which is the difference between the present value of cash inflows and the present value of cash outflows and is used in capital budgeting to analyze the profitability of an investment or project. NPV can be calculated by using eqn. 1:

$$NPV = \sum_{t=1}^{T} \frac{C_t}{(1+r)^t} - C_0 \quad (1)$$

where: NPV – Net present value (€), C_t – Net cash flow during the period (€), C_0 – initial investment (€), r – discount rate, t - period number, T – number of time periods.

Net cash flow during a period is the net sum of incomes and expenses.

Initial investment cost

The initial cost of power line construction depends on the length of the power lines and number of substations used (eqn. 2). The average useful lifetime for the power lines in Elektrilevi OÜ is approximately 40 years.

$$(2)\ C_{0P} = C_{mv} \times L_{mv} + C_{lv} \times L_{lv} + C_S \times n_S + C_{Sw}$$

where: C_{0P} – the initial cost of building a power line (€), C_{mv} – unit cost of building a medium-voltage line (€/km), L_{mv} – length of the medium-voltage line (km), C_{lv} – unit cost of building a low-voltage line (€/km), L_{lv} – length of the low-voltage line (km), C_S – unit cost of the substation (€), n_S – number of substations, C_{Sw} – cost of the switching to connect to an existing network or substation (€).

The initial cost of building the off-grid alternative is based on the power consumption needs of the customer and can be calculated using eqn. 3. The average lifetime of the off-grid unit is approximated to 20 years, which is half of the useful lifetime of the power lines. Therefore, to compare the two alternatives, two cycles of the off-grid alternative will be compared to one cycle of the power line construction.

$$(3)\ C_{0O} = (C_{RG} + C_B + C_G + C_{IU}) \times P + C_{In}$$

where: C_{0O} – the initial cost of building an off-grid solution (€), C_{RG} – unit cost of the renewable generator (€/kW), C_B – unit cost of battery bank (€/kW), C_G – unit cost of the diesel generator (€), C_{IU} – unit cost of the inverter (€/kW), P – power consumption of the customer (kW), C_{In} – installation and other costs (€).

Net income

The first part of the net cash flows is net income. The Estonian pricing model is used in this paper. The customer pays a total energy price consisting of three parts: price for generating the electricity, price for the network service and the renewable energy fee and excise [15].

In case of the power line alternative, the distribution network receives all three parts of the total energy price but has to pay for the generation of electricity to a third party who actually generated it and the renewable energy fee to the state. Therefore, for the power line alternative, the net income for a certain period equals the price of network service for that period (eqn. 4). We assume that the average price increase follows the changes in consumer price index.

$$(4)\quad I_{Pt} = V_t \times I_N \times (1 + THI)^t$$

where: I_{Pt} – net income for the power line alternative for period t (€), V_t – the amount of electricity consumed for period t (kWh), I_N – base unit price of network service (€/kWh), THI – average change in consumer price index.

Because the off-grid alternative generates the electricity on the spot, the distribution network can retain the price of generating the electricity, assuming that it can make the necessary changes in the regulation. In addition, since part of the energy generated is renewable, the distribution network is eligible to receive the renewable energy subsidy [16]. The change in the price for generating the electricity can be estimated using the Electricity Nordic DSFuture prices [17]. The renewable energy subsidy is constant in the calculations used in this paper, as it is extremely difficult to predict its trend. Eqn. 5 shows the net income calculation for the off-grid alternative.

$$(5)\quad I_{Ot} = (I_E \times (1 + i_e)^t + I_N \times (1 + THI)^t + I_R \times (1 - V_G)) \times V_t$$

where: I_{Ot} – net income for the off-grid alternative for period t (€), I_E – base unit price of generating the electricity (€/kWh), i_e – yearly increase in the electricity price, I_R – renewable energy subsidy unit price (€/kWh), V_G – percentage of energy generated with the diesel generator.

Net expense

The net expense is the second part of the net cash flows. Because the middle-voltage power lines use underground cables, it has no maintenance or inspection costs. Low-voltage power lines and substations, however, have to be periodically inspected and maintained. In Estonia, the typical period for maintenance and inspection is five years. If the power lines pass through a forested area, there is also a deforestation cost, which is also periodic and as a simplification occurs every five years. On the 40th year there is no periodic cost, as the power line should be either dismantled or refurbished at the end of its useful lifetime. The change in the periodic costs follows the construction cost index. Eqn. 6 shows the net expense for the power line alternative.

$$(6)\quad E_{Pt} = \big((E_{MOHL} + E_{IOHL}) \times L_{lv} + (E_{MS} + E_{IS}) \times n_s + E_D \times L_D\big) \times (1 + CCI)^t$$

where: E_{Pt} – net expense for the power line alternative for period t (€), E_{MOHL} – base unit cost for the overhead power line maintenance (€/km), E_{IOHL} – base unit cost for the overhead power line inspection (€/km), L_{lv} – length of the low-voltage line (km), E_{MS} – base unit cost for substation maintenance (€), E_{IS} – base unit cost for substation inspection (€), E_D – base unit cost for deforestation (€/km), L_D – length of deforestation area for period t (km), CCI – average change in the construction cost index.

Solar panels need very little maintenance and only need to be cleaned a couple of times a year (especially in case of heavy snows). Nowadays battery banks and generators also need very little maintenance and what little is needed can be completed during the refueling process. Because of the routine refueling, there is also no need for additional inspections and the inspection cost for off-grid alternative can be approximated to zero.

There are four factors affecting the refueling cost: power generated through the diesel generator, average fuel consumption, the cost of the fuel and the cost of transportation to the site. Crude Oil Brent Future Prices should be used as a reference for diesel fuel price changes. The price increase for the future prices is fixed on 0.6 % each month for the last three years presented [18]. Therefore, an average yearly increase of 7.4 % in the price of diesel fuel will be used. This change is also very similar to the average change in the Brent Crude Oil prices for the past 45 years [19]. Eqn. 7 shows the net expense for the off-grid alternative.

$$(7)\quad E_O = V_G \times V_t \times V_{AD} \times \left(E_F \times (1 + i_d)^t + \frac{E_{Dr}}{V_f} \times (1 + THI)^t\right)$$

where: E_O – net expense for the off-grid alternative (€), V_{AD} – average fuel consumption for the diesel generator (l/kWh), E_F – base cost of the diesel fuel (€/l), i_d – yearly increase in the diesel price, E_{Dr} – base cost for driving to the site (€), V_f – size of the fuel tank (l).

Risks

There are a total of four risks identified by the authors, that affect the power line construction alternative: the risk of the customer leaving and canceling his/her contract, the risk of some of the technology becoming obsolete, the risk of vandalism and the risk regarding the quality of construction. The first two affect the net income only, because the power lines cannot be dismantled and used for other customers. The last two can be mitigated through insurance, which is a periodic cost that is based on the initial cost of the power lines. The added risk will adjust the net cash flows for the power line construction, resulting in eqn. 8:

$$(8) \qquad C_{Pt} = \frac{1}{(1+r)^t} \times \left(\frac{V_t \times I_N \times (1+THI)^t}{(1+R_1+R_2)^t} - \left((E_{MOHL} + E_{IOHL}) \times L_{lv} + (E_{MS} + E_{IS}) \times n_S + E_D \times L_D\right) \times (1+CCI)^t - (C_{mv} \times L_{mv} + C_{lv} \times L_{lv} + C_S \times n_S + C_{Sw}) \times (R_3 + R_4)\right)$$

where: C_{Pt} – net cash flow of the power line alternative during the period t (€), R_1 – the risk of the customer leaving and canceling his/her contract, R_2 – the risk of some of the technology becoming obsolete, R_3 – the risk of vandalism, R_4 – the risk regarding the quality of construction.

The off-grid alternative has the same risks as the power line alternative, but the first two affect both the net income and the net expense, as the system can be dismantled and installed for other customers. In addition, the added risk will adjust the net cash flow for the off-grid alternative, resulting in eqn. 9.

$$(9) \qquad C_{Ot} = \frac{1}{(1+r)^t \times (1+R_1+R_2)^t} \times \left((I_E \times (1+i_e)^t + I_N \times (1+THI)^t + I_R \times (1-V_G)) \times V_t - V_G \times V_t \times V_{AD} \times (E_F \times (1+i_d)^t + \frac{E_{Dr}}{V_f} \times (1+THI)^t) \times (1+R_5) - ((C_S + C_B + C_G + C_{IU}) \times P + C_{In}) \times (R_3 + R_4)\right)$$

where: C_{Ot} – net cash flow of the off-grid alternative during the period t (€), R_5 – the risk of increased expenses due to small scale integration of the off-grid alternative.

Finalised equasions

Using the aforementioned eqn.s the finalized eqn. for calculating the NPV for the power line alternative is presented in eqn. 10:

$$(10) \qquad NPV_P = \sum_{t=1}^{T} \frac{1}{(1+r)^t} \times \left(\frac{V_t \times I_N \times (1+THI)^t}{(1+R_1+R_2)^t} - \left((E_{MOHL} + E_{IOHL}) \times L_{lv} + (E_{MS} + E_{IS}) \times n_S + E_D \times L_D\right) \times (1+CCI)^t - (C_{mv} \times L_{mv} + C_{lv} \times L_{lv} + C_S \times n_S + C_{Sw}) \times (R_3 + R_4)\right) - (C_{mv} \times L_{mv} + C_{lv} \times L_{lv} + C_S \times n_S))$$

where: NPV_P – net present value for the power line alternative (€).

Using the aforementioned eqn.s the finalized eqn. for calculating the NPV for the off-grid is presented in eqn. 11:

$$(11) \qquad NPV_O = \sum_{t=1}^{T} \frac{1}{(1+r)^t \times (1+R_1+R_2)^t} \times \left((I_E \times (1+i_e)^t + I_N \times (1+THI)^t + I_R \times (1-V_G)) \times V_t - V_G \times V_t \times V_{AD} \times (E_F \times (1+i_d)^t + \frac{E_{Dr}}{V_f} \times (1+THI)^t) \times (1+R_5) - ((C_{SB} + C_B + C_G + C_{IU}) \times P + C_{In}) \times (R_3 + R_4)\right) - (C_{SB} + C_B + C_G + C_{IU}) \times P + C_{In})$$

where: NPV_O – net present value for the off-grid alternative (€).

Results

Using the methodology presented in this article, the connection alternatives for customer A on Elektrilevi OÜ's Villa substation feeder 2 are evaluated. Solutions for the customer will be evaluated as if the other customer's connection does not need any refurbishment (e.g. the consumption of the other customers is nonexistent). As a simplification the customers' yearly consumption and the initial cost for the second off-grid cycle (on the 20th year) do not change in time. The initial cost is affected by the discount rate in the NPV calculations.

On all figures, color red represents existing middle-voltage power lines and green represents existing low-voltage power lines. Blue is used to represent new low-voltage power lines, while purple is used for new middle-voltage power lines. The red square represents the existing substation, while the purple square represents a new substation or a new off-grid solution (if there is no connecting middle-voltage power line). Brown line represents dismantled low-voltage power line.

The first alternative, to provide a connection point for this customer is using an off-grid solution and dismantling the low-voltage line between customer A and customer B, with a total length of 0.47 km (figure 1).

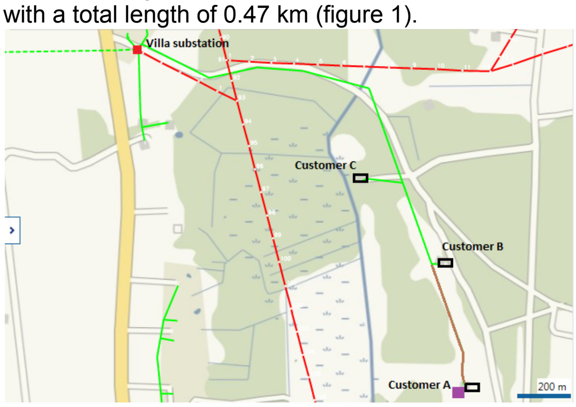

Fig. 1 Off-grid alternative for customer A (Villa F2)

Customer A is situated 2,065 km from the substation. The approximated figures used in the calculations are presented in Table 1. These figures have mostly been derived through the authors' expert opinion. If a risk differs for either alternative, an additional index "*P*" (the power line alternative) or "*O*" (the off-grid alternative) is used.

Table 1 Approximated values used in the calculations

Fig.	Value	Fig.	Value	Fig.	Value	Fig.	Value
P	0.6	r	5.02%	E_{MOHL}	630	R_1	1.00%
V_t	300	C_{lv}	15000	E_{IOHL}	35	R_{2P}	3.30%
I_E	0..0296	C_{mv}	25000	E_{MS}	370	R_{2O}	0.00%
I_N	0..0364	Cs	10000	E_{IS}	40	R_3	0.00%
I_R	0..0537	C_{Sw}	5000	E_D	1200	R_{4P}	0.00%
V_{RG}	72.50%	C_{SB}	1152	E_F	1.25	R_{4O}	0.50%
THI	3.30%	C_B	1500	V_{AD}	0.303	R_5	0.00%
CCI	3.60%	C_G	308	V_G	27.50%	L_{lv}	0.47
i_d	7.40%	C_{Iu}	346	E_{Dr}	40.06	L_{mv}	0.93
i_e	2.70%	C_{In}	18058	V_f	150	n_s	1

The initial cost for the first iteration of the off-grid alternative is C_{01} = 20 042 €. Because in this paper the off-grid alternative has a useful lifetime of 20 years, a second investment on the 20th year is needed. The present value of this investment is 7 525 €, making the total investment cost 27 566 €.

The second alternative for customer A is to build a middle-voltage power line, a new substation to the area's load center and refurbishing the low-voltage line between customer A and customer B, with a total length of 0.47 km (figure 2).

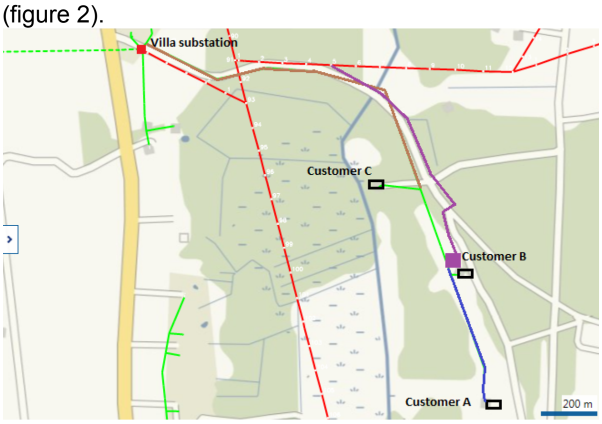

Fig. 2 Power line alternative for customer A (Villa F2)

The total length of the middle-voltage power line depends on the distance of the existing power lines. Although there is an existing middle-voltage power line situated relatively close to the load center, Elektrilevi's standards dictate that new cable lines (preferred method for building middle-voltage power lines in this paper) have to be built along the roads, as it helps to decrease access problems and problems with the land owners. This is also necessary for future prospects, as the power line heading south will most likely also be refurbished as a cable line along the existing road during the useful lifetime of power line alternative. Therefore the total length of middle-voltage power lines for the second alternative is 0.93 km and the initial cost of the alternative C_{02} = 40 300 €.

There is no need for deforestation in the area that is refurbished. A total of 1.28 km of low-voltage power lines can be dismantled. As an additional benefit, the network reliability for customers B and C improves greatly. The distance between customer C and the new substation is almost three times shorter than the current one.

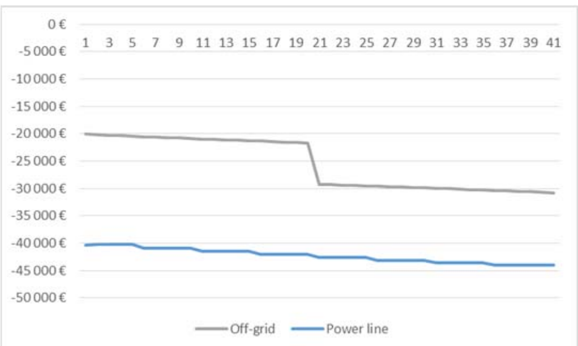

Figure 3 NPV for both alternatives for customer A (Villa F2)

Even before NPV calculations, it is doubtful that the power line alternative can compete with the off-grid in this case, as the initial cost for the power line alternative is more than 30 % higher than the total investment cost of the off-grid alternative. The best way to evaluate the financial feasibility of both alternatives is to plot the discounted net cash flows on the same chart (figure 3).

As seen from the figure, neither alternative can provide a positive NPV. As one alternative has to be chosen, off-grid creates smaller losses and therefore should be chosen as the preferred alternative.

Conclusions

Even at current prices, there are cases where off-grid already provides a better result than the traditional power line alternative. As off-grid solutions are technology intensive while the traditional power line construction is labor intensive, the off-grid alternative will become more and more financially feasible as time goes by. The distribution networks can either concentrate on their current core business and passively react to this change or take an active role and try to direct the development of the microgeneration by becoming one of the providers of this product. Using off-grid solutions provides an opportunity for the distribution networks to optimize their investments and potentially grow their market share.

Further studies are needed to create a methodology for finding all the customers whose connection points need refurbishment, and in which cases the refurbishment should be done using the off-grid alternative. Also additional uses of the off-grid alternative or its components (battery banks, microgeneration etc.) should be researched, in order to better evaluate the impact that the off-grid will have for the future network.

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