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Introduction to Minimize Sunk Costs in Electricity Network Tariff

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Declaration:
Hereby I declare that this doctoral thesis, my original investigation and achievement, submitted for the doctoral degree at Tallinn University of Technology has not been submitted for doctoral or equivalent academic degree.

Tarmo Mere

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signature

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Sissejuhatus uppunud kulude minimeerimiseks elektrivõrgu tariifis

TARMO MERE

TALTECH KIRJASTUS

Contents

List of Publications

The present doctoral thesis is based on the following publications, which are referred to in the text using Roman numbers I-IV:

I Tarmo Mere, Arvi Hamburg, Tiit Hõbejõgi, Marti Laidre, Juhan Valtin (2016). Financial evaluation of using off-grid as an alternative to the traditional power line construction. Przeglad Elektrotechniczny, 08/2016, 206–210.

II Ots, M.; Hamburg, A.; Mere, T.; Kisel. E (2016). Estonian experience in implementation of incentive type of price regulation. 57th International Scientific Conference of Riga Technical University (RTUCON), 13–14 October 2016, Riga. IEEE, 1−5.RTUCON.2016.7763082.

III Hõbejõgi, T.; Reinberg, A.; Last, K.; Laanetu, M.; Mere, T.; Valtin, J.; Hamburg, A. (2014). Methodology for finding investment sites that can be refurbished from a nearby middle voltage line element instead of using the existing low voltage line corridor. Przeglad Elektrotechniczny, 10, 199–202.

IV Ots, Märt; Hamburg, Arvi; Mere, Tarmo; Hõbejõgi, Tiit; Kisel, Einari (2016). Impact of price regulation methodology on the managerial decisions of the electricity distribution network company. Energy Conference (ENERGYCON), 2016 IEEE International: IEEE ENERGYCON 2016 Leuven, Belgium, 4–8 april 2016. IEEE, 1−6.10.1109/ENERGYCON.2016.7513963.

Copies of publications I-IV are included in Appendix.

Author's Contribution to the Publications

Contribution to the papers in this thesis are:

I Tarmo Mere wrote the paper and was the main author. He was responsible for the data collection and analyses.

II Tarmo Mere was the co-author. He was responsible for the data collection, analyses and wrote part of the article.

III Tarmo Mere was the co-author. He was responsible for the data collection and analyses.

IV Tarmo Mere was the co-author. He was responsible for the data collection and analyses.

Introduction

Electricity distribution company's production assets have life expectancy of 40-50, up to 70 years, depending on the asset type. Factors among others like development speed of the technology, urbanization and increase in consumption mobility determine how, where and when the electricity is produced or consumed. Therefore, the value of network assets can diminish before their initial payback time and cause sunk costs in network tariff.

Distribution companies are regulated natural monopolies and faster amortization of assets results in higher distribution tariff for the society.

Current thesis addresses technical, regulatory and administrative alternatives to minimize the loss of value in distribution assets during the asset's lifetime. These alternatives are:

- Using off-grid as an alternative solution to the traditional power line construction;
- Supporting innovation through different type of regulation;
- Using different methodologies to minimize investment costs in rural network.

In practice, applying those alternatives is a complex task because of many related stakeholders in electricity market, author of the thesis also provides a methodology for implementing these alternatives into practice.

The rise in efficiency and decline in price of photovoltaic and battery technology is causing more changes to the network structure than any other innovation in the past. This change is about to generate more sunk network costs in rural areas in coming decade than in any period in the past. The sunk network costs have not gained enough attention in the past because of the regulation models, which have been designed to cover all cumulative network costs independent whether they are efficient or not. Sunk costs in the context of current thesis are irretrievable costs which have lost their economic value before initially calculated lifetime.

The author of the thesis has been closely involved in distribution network asset management for more than fifteen years, from which 9 years as a CEO of Estonia's biggest electricity distribution network operator Elektrilevi. Currently working closely with different European distribution network companies, it is worrisome for some extent how little attention is being put to potentially accumulating sunk costs in network tariff and how burdensome it can be for the network customers. Even if the problem is recognized the regulatory mechanism prevents acting accordingly or is not creating the right motivation for the network companies to address the problem properly.

The purpose and the task of the thesis is to analyze the impact of technical innovations to the network, analyze the role of regulation in coping with changes in the external environment, analyze other possibilities to minimize the risk of increase in sunk costs and finally open the discussion about applying methodology to commit involved parties behind common goal to reach optimal ruleset for network investments.

The task of the thesis is to find answers to the following questions:

1. Is it reasonable for the network operator to consider off-grid solution in rural areas as an economic alternative to the traditional powerline and does it have financial impact to the sunk costs in network tariff?

2. What type of regulation methodology best supports the innovation and long-term sustainable network development in order to reduce sunk costs?
3. What are the other possibilities network operators can use to minimize investments not designed to last?
4. Is there a practical methodology to use in order to involve all related market participants behind the one common coal?

Author uses several different methodologies to address questions outlined above. In economical calculation of off-grid as an alternative to the traditional power line is used traditional NPV (Net Present Value) methodology. Different price regulation methodologies are used while analyzing regulation effectiveness. Custom methodology is introduced while analyzing other possibilities to minimize long term sunk network costs. Finally, under further discussion section appropriate methodology is introduced for practical involvement of related market participants.

Different studies have addressed different problems related to network cost allocation and tariff efficiency. The viewpoint of those studies has mainly been customer behavioral influence on the network cost or tariff structure [1]. The novelty of current thesis stands in the viewpoint of Network operator itself being able to affect sunk costs in the tariff by utilizing new technologies in network design instead of traditional network construction technologies. To reach maximum effect in keeping the future network sunk costs down, the regulatory measures and actions are needed. The current thesis provides also methodology for involving different parties to the discussion and execution of the ideas.

Ideas about the regulation that aims of long-term sustainability and support for innovation can be considered novelty as well. Currently the main task of regulation is to distribute network costs between electricity consumers as fairly as possible, but less effort is going to answer the question whether those network costs are reasonable or not. Sunk costs are considered inevitable, at the same time looking at the development of technology trends it is reasonable to ask question what kind of sunk costs these trends will cause in the future and can they be avoided before they turn irreversible. Another question will rise, what kind of mechanism we need in order to motivate network operators and regulator to take actions now?

Abbreviations

CEER	Council of European Energy Regulators
UBS	UBS Group AG - Swiss multinational investment bank and financial services company
CEO	Chief Executive Officer
DS Future	Deferred Settlement Future
DSO	Distribution System Operator
LRAIC BU	Long Run Average Incremental Cost Bottom Up
LV	Low Voltage
MV	Medium Voltage
MVLE	Middle Voltage Line Element
NPV	Net Present Value
OFGEM	Office of Gas and Electricity Markets
PV	Photo Voltaic
RIIO	Revenue using Incentives to deliver Innovation and Outputs
UK	United Kingdom

1 Current relevance

Electricity network business is going through significant transformation disrupted by new technology, urbanization trends and massive increase in distributed energy resources. Current network is designed to transport energy form big power stations through transmission network to the end customer. New solar, wind and other renewable energy sources are spreading all over the network feeding energy into the network form any point, forcing network companies to re-design their network which was designed to last much longer. Uncertainty is growing along with the development of new technology. Power lines and substations are rebuilt and relocated well before their initially designed end of life. Any distribution asset demolished before its end of lifetime generates sunk costs into the network tariff. Growing sunk costs are relatively little recognized topic because current regulation absorbs all costs irrespective weather, they are effective of not. To prevent sunk costs piling up in accelerated pace in coming decades there is a great need for studies addressing the problem. Current thesis analyses different technical and administrative methods to address the problem.

It is extremely difficult to illustrate the magnitude of the problem because sunk costs are not separately accounted. One empirical way to describe the nature of the problem is to look how efficiently are network assets used. Good example from Estonia is Elektrilevi’s assets in rural area where 58% of total assets by its length is in rural area which is serving only 13% of total number of customers in the network and only 5% of total distributed energy is transferred through that network and the numbers are becoming worse. There are 57 000 connection points out of 650 000 with very low or without any consumption [2], which is 9% of total of connection points in the network. All this underutilized network needs to be maintained and refurbished to maintain the level of security or find other innovative ways to replace their function.

Network business is highly dependent on regulatory environment they are acting in. Regulation is the strongest influencer of network companies’ decisions. Without changes in regulation it is highly unlikely that new business models emerge which support network company’s willingness to address sunk cost problem or otherwise innovate to reduce asset volume in future network tariff. The regulation can either motivate network companies to find ways to reduce sunk costs or motivate to build up new business models that complement current network business and compensate the lost value of underutilized network assets. Current thesis analyses different regulatory regimes to expose their weaknesses and find the best method to encourage innovation in distribution network and help network companies to address rising sunk cost problematics in tariff.

Reducing sunk cost in network tariff is not only network companies or regulator’s problem, there are also other market participants involved like network customers, society, environmental groups, politicians etc. To initiate significant change in the regulation and in the way network business is being operated there is a need for methodology to manage the process. Backcasting methodology is introduced in order to handle such large-scale change.

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

2.1 Introduction to off-grid solution

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 windmills), a storage battery, an inverter and a diesel generator which is a combination of the two alternatives provided by Qoaider and Steinbrecht [3]. 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 [4], indicating technological advancements and an increase in the supply that could offset the demand.

The median installed cost per W of the solar panels for residential customers decreased by approximately 3 times between 2000 and 2017 [4].

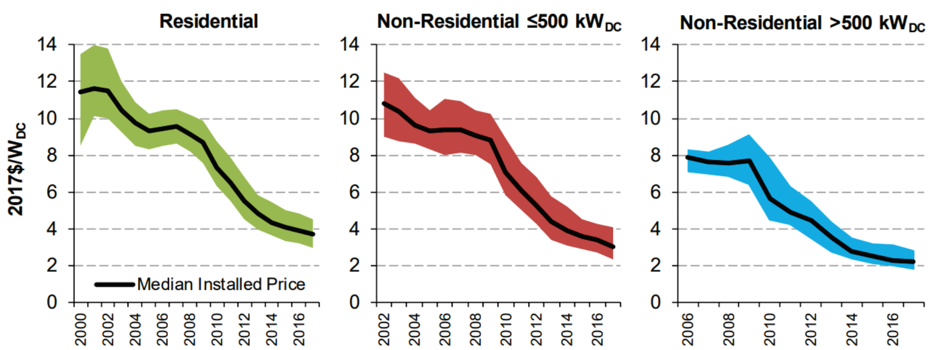

Figure 1: Installed solar panel price trends over time [4]

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 in 2017 [5].

The newer reports [6] show the steady price decline towards $100/kWh, currently the long-term storage capacity-weighted cost per unit energy capacity price is $399/kWh.

Taking into account the declining trend 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 and their future sunk costs. 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 [7].
- The future of low voltage networks: Moving from passive to active [8].
- Optimal PV–FC hybrid system operation considering reliability [9].

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 [10].
- Feasibility analyses of hybrid wind-PV-battery power system in Dongwangsha, Shanghai [11].
- Reliability and management of isolated smart-grid with dual mode in remote places: Application in the scope of great energetic needs [12].
- Study on stand-alone power supply options for an isolated community [13].

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 thesis. The main reason for this might be, that currently most distribution networks are disallowed to generate electrical power, except to cover their own electricity losses in the network. Also, it is important to note, that off-grid is an alternative to some uses of the 1 kV system proposed in [14]. There is already a lot of study on the effects of the 1 kV system [14]. This part of the thesis 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.

More detailed description of financial evaluation of off-grid solution feasibility can be found in authors article [I] in the appendix 1.

2.2 Methodology and equations 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 the following equation:

$$NPV = \sum_{t=1}^{T} \frac{Ct}{(t+r)^t} - Co \qquad [1]$$

where:
NPV – Net present value (€),
Ct – Net cash flow during the period (€), C0 – initial investment (€),
r – discount rate,
t - period number,
T – number of time periods.

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

$$C_{0P} = C_{mv} * L_{mv} + C_{lv} * L_{lv} + C_s * n_s + C_{Sw} \quad [2]$$

where:
C0P – the initial cost of building a power line (€),
Cmv – unit cost of building a medium-voltage line (€/km),
Lmv – length of the medium-voltage line (km),
Clv – unit cost of building a low-voltage line (€/km),
Llv – length of the LV line (km),
CS – unit cost of the substation (€),
nS – number of substations,
CSw – 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 the following equation. 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.

$$C_{0O} = (C_{rg} + C_B + C_g + C_{IU}) * P + C_{In} \quad [3]$$

where:
C0O – the initial cost of building an off-grid solution (€),
CRG – unit cost of the renewable generator (€/kW),
CB – unit cost of battery bank (€/kW),
CG – unit cost of the diesel generator (€),
CIU – unit cost of the inverter (€/kW),
P – power consumption of the customer (kW),
CIn – installation and other costs (€).

The first part of the net cash flows is **net income**. The Estonian pricing model is used in this thesis. 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, customer pays energy price to the energy retailer and the distribution network receives other parts of the total price but forwards 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 the following equation. We can assume that the average price increase follows the changes in consumer price index.

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

where:
IPt – net income for the power line alternative for period t (€),
Vt – the amount of electricity consumed for period t (kWh),
IN – 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, if it can make the necessary changes in the regulation.

It is important to notice the views of the Agency for the Cooperation of Energy Regulators and National Regulatory Authorities in the Council of European Energy Regulators (CEER) on the European Commission's proposals related to the role of the electricity Distribution System Operator (DSO), where DSOs must act as neutral market facilitators performing regulated core activities and not activities that can efficiently and practicably be left to a competitive market [16]. This suggestion does not foreclose the possibilities to take new innovations into use by DSOs but sets possible additional obligations to procure these services from other market participants.

In addition, since part of the energy generated is renewable, the distribution network is eligible to receive the renewable energy subsidy [17]. The change in the price for generating the electricity can be estimated using the Electricity Nordic DS Future prices [18]. The renewable energy subsidy is constant in the calculations used in this thesis, as it is extremely difficult to predict its trend. The following equation shows the net income calculation for the off-grid alternative.

$$I_{Ot} = \left(I_E * (1 - i_e)^t + I_N * (1 + THI)^t + I_R * (1 - V_G)\right) * V_t \quad [5]$$

where:
IOt – net income for the off-grid alternative for period t (€),
IE – base unit price of generating the electricity (€/kWh),
ie – yearly increase in the electricity price,
IR – renewable energy subsidy unit price (€/kWh),
VG – percentage of energy generated with the diesel generator.

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, must 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. The following equation shows the net expense for the power line alternative.

$$E_{Pt} = \left((E_{MOHL} + E_{IOHL}) * L_{lv} + (E_{MS} + E_{IS}) * n_S + E_D * L_D\right) * (1 - CCI)^t \quad [6]$$

where:
EPt – net expense for the power line alternative for period t (€),
EMOHL – base unit cost for the overhead power line maintenance (€/km),
EIOHL – base unit cost for the overhead power line inspection (€/km),
Llv – length of the low-voltage line (km),
EMS – base unit cost for substation maintenance (€),
EIS – base unit cost for substation inspection (€),
ED – base unit cost for deforestation (€/km),
LD – 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 [19]. 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]. The following equation shows the net expense for the off-grid alternative.

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

where:
EO – net expense for the off-grid alternative (€),
VAD – average fuel consumption for the diesel generator (l/kWh),
EF – base cost of the diesel fuel (€/l),
id – yearly increase in the diesel price ,
EDr – base cost for driving to the site (€),
Vf – size of the fuel tank (liter).

2.3 Risks related to building power line or off-grid alternative

There is a total of four risks identified, that affect the power line construction alternative: the risk of the customer leaving and cancelling 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 the following equation:

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

where:
CPt – net cash flow of the power line alternative during the period t (€),
R1 – the risk of the customer leaving and canceling his/her contract,
R2 – the risk of some of the technology becoming obsolete,
R3 – the risk of vandalism,
R4 – 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 the following equation.

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

where:
C0t – net cash flow of the off-grid alternative during the period t (€),
R5 – the risk of increased expenses due to small scale integration of the off-grid alternative.

Using the aforementioned equations, the finalized equation for calculating the NPV for the power line alternative is presented in the following equation:

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

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

Using the aforementioned equation, the finalized equation for calculating the NPV for the off-grid is presented in the following equation:

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

where:

NPVo – net present value for the off-grid alternative (€).

2.4 Final calculations of using off-grid as an alternative to the traditional power line construction

Using the methodology presented in this thesis, the connection alternatives for customer A in Figure 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 non-existent). 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 on the following figure.

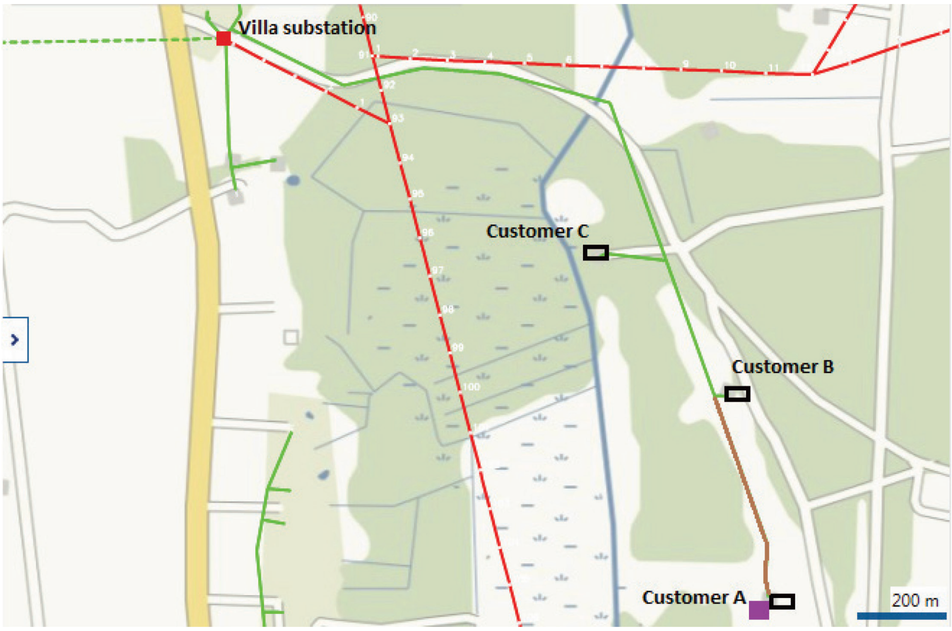

Figure 2: Off-grid alternative for customer A (Villa F2)

Customer A is situated 2,065 km from the substation. The approximated figures used in the calculations are presented in article [I] 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.

The initial cost for the first iteration of the off-grid alternative is C_{01} = 20 042 €. Because in this thesis 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 3: Power line alternative for customer A

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 thesis) 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 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 in Figure 3 improves significantly. The distance between customer C and the new substation is almost three times shorter than the current one.

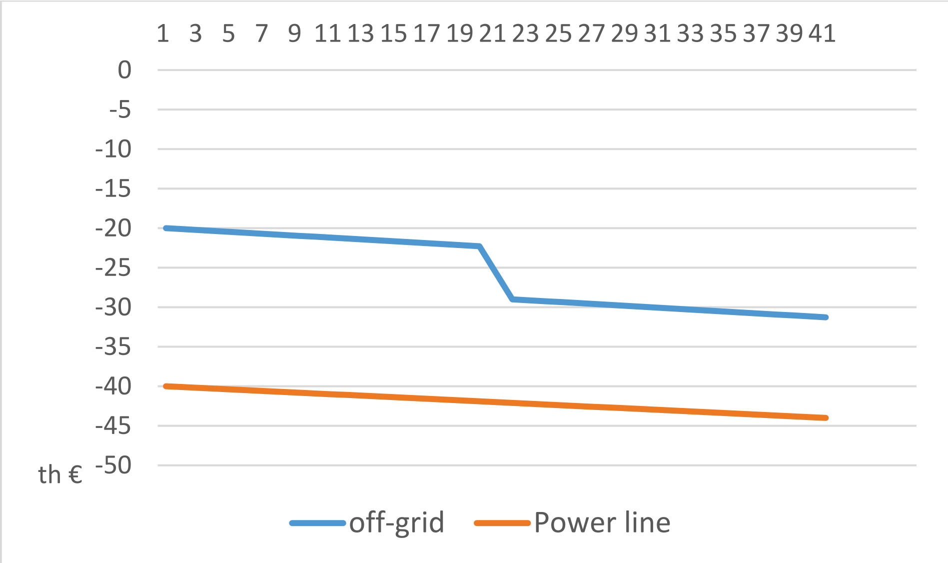

Figure 4: NPV for both alternatives for customer A

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 as can be seen on previous figure.

As seen from the figure 4, neither alternative can provide a positive NPV. As one alternative must be chosen, off-grid creates smaller losses and therefore should be chosen as the preferred alternative.

3 The regulatory impact on taking off-grid into use as an alternative to traditional power line

Electricity distribution networks are natural regulated monopolies and their business is largely driven by the regulation regime they are acting in. Regulator is influencing every decision in network company through price regulation.

The first objective of the price regulation is sustainability - the regulated company must be able to finance its operations and make any required investment, so that the company can continue operating in the future [20]. From customers' perspective, high quality of the service provided, and minimum price are the expectations. From shareholders' point of view reasonable rate of return on invested capital shall be guaranteed. Theoretically, it is possible to reach a theoretical maximum of the quality by building double or triple power lines or gas pipes, exceeding the n-1 criteria. However, one must agree that these types of technical solutions are only theoretical. Depending on the legislation of the specific jurisdiction, the task of the regulator is to select or to assist in selection of the regulatory methodology which corresponds to the main objective of price regulation. The summary of different regulatory objectives indicates, that the main criterion for selecting of regulatory methodology is to reach the maximum efficiency where the customers´ and the companies´ interests are in balance.

It has been balance seeking over many decades since the electricity networks grow larger. The technology used in distributing the energy from the regulation point of view has been unchanged since the beginning of electricity network history. Therefore, the regulatory systems are relatively unresponsive in reckoning new technology and its impact to the network system and customers. In this thesis, different regulatory methodologies are evaluated and compared in order to point out aspects which need to be considered in order to allow off-grid solutions to take part in the evolution of electricity networks and make it possible to lower the sunk costs in the future.

In the context of current topic, it is important to find answers to the initial question of the study: What type of regulation methodology best supports the innovation and long-term sustainable network development in order to reduce sunk costs? This question can be split into two sub-questions:

- Does current regulation incentivize the distribution network operator to invest into alternative solutions to address the problem of aging network, declining usage of network and possible sunk cost problem in rural areas?
- Does regulation accept innovative ways of delivering the service to the customers which are out of the range of traditional distribution activity?

3.1 Traditional regulatory methods

On a high level, the regulatory methods can be divided into two main categories: ex-ante and ex-post. By using of ex-ante regulation, the prices are fixed by the regulator. By using of ex-post regulation, the prices or fees are applied by the company without any coordination by the regulator and the regulator may control later whether these prices or fees meet the criteria set by the legislation. Price regulation methods can be divided into four categories:

- Price cap;
- Revenue cap;

- Rate of return;
- Long Run Average Incremental Cost Bottom Up (LRAIC BU).

Each method triggers different economic actions from companies and regulators. If the pure rate of return method is used, then the risks associated with controllable and uncontrollable costs are covered, or in other words, the company has no risk associated with the costs. This method allows the company to apply for a tariff adjustment as soon as the price is not based on the costs of the company anymore. Quite the contrary, pure price cap method leaves all these risks to be covered by the company and leaves options for the company to decide how to eliminate those in different ways. The only difference of the revenue cap is the elimination of sales volume risk.

The price cap method presumes that if the company can manage more efficiently on its own, it can earn extra profits, and also vice versa: if the company does not fulfil the expectations set by the regulator or manages less efficiently, its profit will be lower and it cannot earn profit agreed by the regulator.

The basis of the price cap method is fixing of prices for a certain time period. Doing so, the time period must be chosen long enough to guarantee that the company can reach the expected efficiency. On the other hand, the time period should not be too long in order to avoid high risk of forecasts. Each year the prices are adjusted in accordance with inflation and factor x, which reflects the cost efficiency target, or in other words, prices should not increase faster than inflation minus the efficiency goal x. The value x can be any value, but usually it is in the range of 0–5%.

According to the (LRAIC BU) or hypothetical network model, an ideal network is modelled assuming that the most modern and optimal technological solutions for the network configuration to supply all customers with highest quality standards is used. In case of a distribution network, it should be modelled considering the geographical location of consumers and producers and with inputs from the transmission network. The distribution network is then configured as an ideal system and is assumed to be built in the most economical way to guarantee the supply of existing customers. It is assumed that the most economical solution is applied, and the network is built as a Greenfield project.

The most efficient economic model is assumed to be free market where similar products are competing and every regulatory methodology aims to simulate it in best possible way in given context. But no artificial system can simulate the natural environment well enough to take into consideration all the needed factors. Usually, the implications more far away from the current moment are less favorable and get less attention from the regulator. This seems to be the reason for the sunk cost not being considered in current regulatory mechanisms.

Each regulatory method triggers a different logic of the managerial decisions taken by network companies. Different methods for assessment of regulatory methodology were analyzed through the viewpoint of different managerial decisions. The relevant managerial decisions of a network company can be divided into three wider groups as follows:

1) The Quality of Network Service
2) Cost of Network Service to Society
3) Risks of owners and lenders

Usually the selection of a regulatory method depends on the priorities of the government. Depending on the development stage of the electricity network, the priorities of the state may be either increasing the network quality, aiming for the lowest network tariffs to society, or providing low risks for the owners and lenders. The table below describes overall results of the assessment carried out in research work associated to current thesis in article[II]. The higher the number the more favorable the regulatory methodology is for given managerial decision.

	Price Cap	Revenue Cap	Rate of Return	LRAIC BU
Quality of Network Service	2,4	3,4	4,4	1
Cost of Network Service to Society	4,3	3,7	3	2
Risk of Owners and Lenders	2,8	3,6	3,4	2,6

Table 1: Average scores of the assessment per method

Different conclusions can be drawn from the results in table above, but the Rate of Return method seems to be the most appropriate solution for a long-term policy selection for the electricity distribution network regulation. However, the maximum regulatory period considered in analysis was 5 years which is industry standard in Estonia but is far from being considered long-term in context of distribution network asset lifetime.

The other important conclusions from the analysis were:

- If Price Cap or Revenue Cap method is used and when a company has reached a high level of efficiency, the further efficiency can only be reached at the expense of long-term future. And it deteriorates the willingness to innovate and the worsens the sunk cost situation in future network tariff.
- If Rate of Return method is used the cost-based price guarantees the development of the network at the agreed pace. The agreement on the allowed rate of return is the key to success. When allowed rate of return is not attractive for the owner of network company, the investment level will be lower. Also, the changes in economic environment assume from regulator to be agile in opening the regulation and implementing the needed changes but that is usually not the case.
- It should also be noted that for the sake of a long-term stable investment climate of the network business, it is advisable to avoid frequent changes of the regulatory methods. Frequent changes of regulatory methods may ruin the attractiveness of any investment in the energy sector [21].

The above-mentioned reasoning about the level of desire to use one or the other regulatory method is based on optimizing the efficiency within the current regulatory period but not over series of regulatory periods or over the lifetime of network assets. The length of the regulatory period is set by the regulator or is determined by the need to adjust the prices.

The ability of the revenue setting mechanisms to induce efficient investment decisions is likely to be reduced by the limited duration of the regulatory period. For illustrative purposes, consider a system based on pre-determined total revenue cap, possibly dependent on some output variables. Under this scheme, during the regulatory period revenues are independent from total actual cost. The distributor has to deliver the outputs agreed with the regulator and bear the corresponding cost, in exchange for the pre-determined revenues. As a consequence, the network operator's profit maximizing strategy consists in minimizing total cost. However, in order to provide correct investment incentives, the regulatory period has to be at least as long as the time-horizon relevant for the network operator's investment assessment. If, for example, the benefit of an investment in terms of lower operating costs is expected to materialize in 15 years, total revenues must be fixed for at least 15 years for the network operator to receive the correct incentives to invest. If, on the contrary, a tariff review is expected to transfer the benefit of the investment to the consumers in the form of lower tariffs after only 5 years, the incentive for the firm to substitute capital for operating cost would be curbed [22].

All the regulatory methods mentioned above are using different methods to optimize network operator tariff, revenue or cost-base within certain regulatory period which are relatively short compared to lifetime of network assets. The most widely used regulatory method RPI-X and its modifications incentivize network operator to maximize its revenue by reducing cost-base within the regulatory period. After the end of the regulatory period the tariffs are adjusted, and any excess revenue is deducted. Innovation and especially long-term innovation projects are out of favor because innovation is mostly related to higher costs without immediate return or return within the regulatory period. This logic is creating false motivation for the network operators to think in short time intervals instead of innovating and optimizing asset investments and its lifetime over long period. In other words, most if not all the regulatory methods incentivize the short-term goals and do not favor network operators to innovate and address sunk cost problematics. In addition, there is even opposite motivation for network companies to maximize their asset value in order to maximize their rate of return on invested assets which creates potentially more sunk costs.

In context of using off-grid solutions, one other aspect of regulation needs to be addressed. Distribution network operators in Europe need to be unbundled form production and supply of energy. Using off-grid solution by network operator as an alternative to the traditional power line construction creates a situation where network operator becomes an energy producer and seller, although the objective is not to produce or sell the energy but reduce future sunk cost of the network. Both these aspects have a workaround and do not create regulatory restrictions for network operator to use the off-grid solution.

First, production of electricity is allowed for the network operator for their own needs like for covering the network losses. Practically producing electricity within the limits of network losses can be considered as production for own needs. As the off-grid solution is the solution only for rural areas and for limited connection points the production of energy never exceeds the level of network overall losses and there will be no conflict with the regulation. Then again even the described workaround is a solution for the current situation the regulation could be developed towards allowing this kind of innovations as a standard in regulation.

Second, the sale of electricity is out of network operator scope if the number of end customers is over hundred thousand and needs to be handed over to local energy supplier. Also, this problem has the workaround although the solution is not standard. Any energy supply company can buy the electricity form network company based on the electricity sales regulation of energy islands where network company will be paid „general service" fee for the electricity and the customer can buy electricity on market price.

Summary of findings of the traditional regulatory methods analysis:

- The Rate of Return method is the most balanced and got highest average score through most important traditional criteria.
- Revenue Cap method is the most supportive to network owners and Lenders, being also the most innovation supportive.
- All the traditional methods
    - are lacking the support for the long term sunk cost reduction;
    - seek the balance between customer and network operator owner interest only within regulatory period;
    - are too short compared to average network asset lifetime;
    - are relatively unresponsive in reckoning new technology and its impact to the network system and customers;
    - do not incentivize innovation as additional revenues are levelled out between regulatory periods.

No other regulatory limitations where identified during the analysis of traditional methods.

3.2 Regulation for the long-term

Traditional regulatory systems, analyzed in previous chapter, are designed for regulatory periods of 4–6 years and they do not encourage network owners and management to think long-term to reduce network asset volume. But there are also different kind of regulatory systems which aim to incentivize also long term thinking and the innovation over long period of time. One good example is Offgem regulation in Great Britain called RIIO. Under this approach regulator will set **R**evenue using **I**ncentives to deliver **I**nnovation and **O**utputs.

The UK electric regulator, OFGEM, created RIIO to implement new government policies for the electric sector requiring meeting national climate goals. RIIO builds on the price cap regime that has been used in the UK for the past 20 years for energy companies (called ''RPIX''). RIIO adds to price regulation a system of rewards and penalties tied to performance on desired outcomes (or ''outputs'') to be achieved by regulated companies. Because RIIO also employs revenue decoupling, it is probably best described as ''revenue cap regulation'' coupled with ''output-based incentive regulation.'' RIIO differs from most utility regulation by focusing much less on the utilities' earned rate of return and focusing much more on the utilities' performance. By its own terms, this new UK model seeks ''value for money.'' Rewards and penalties comprise an incentive system to encourage operational efficiencies, as well as funding for innovation and opportunities for utilities to involve third parties in the delivery of energy services. Importantly, RIIO contemplates a relatively long period of regulation – the basic price and revenue trajectories for utilities, along with the system of rewards and penalties, will persist for eight years. This means that operational efficiencies achieved by regulated companies can result in higher profitability during the term of regulation, clearly rewarding efficiency. Under RIIO, utilities are measured for the performance on seven output measures [23]:

- customer satisfaction,
- reliability and availability,
- safe network services,
- connection terms,
- environmental impact,
- social obligations, and
- price.

While some may view the U.K. move to the RIIO model as a partial retrenchment in the UK's march toward electric industry disaggregation, others suggest that it simply builds new goals into a reasonably workable regulatory structure that maintains a prominent reliance on market forces. Seen in the former light, RIIO begins to reassemble aspects of a policy-driven, integrated electric system, reinserting additional public policy goals into the regulatory formula. By its own terms, RIIO critical utility functions that include [23]:

- reliability,
- environmental stewardship,
- innovation,
- price management,
- efficiency, and
- social responsibility.

Utilities are required to submit new business plans for approval by OFGEM that show how their business models will change, how they propose to provide these critical functions, and how they propose metrics and measurements by which their success (or failure) to do so can be judged. By monetizing success in these functions through a system of incentives and penalties, RIIO links financial success for the utilities to achievement of public policy goals. In this way the utilities begin to own the policy outcomes. By focusing on outputs instead of inputs, RIIO moves from accounting cost regulation to a style of regulation that emphasizes the utility's business plan and measures the firm's ability to deliver on commitments [23].

RIIO regulatory model is designed to operate within eight-year regulatory term which is one of the longest regulatory periods in Europe and in other countries outside of Europe. Although eight-year term is the longest it is still relatively short compared to the lifetime of network assets but still it sets the utilities focus on longer term projects which is natural for network business. RIIO is relatively new regulatory system and after a few first successful cycles it can be set for even a longer period.

Innovation is key to enabling network companies to deliver the objectives of the RIIO model namely, to play their role in the delivery of a sustainable energy sector and to deliver long-term value for money for existing and future consumers. This innovation could take many forms, including deployment of new technologies or the implementation of new operational processes and commercial arrangements. Under an incentives-based regime, network companies will innovate where they have confidence that they will achieve commercial benefits from doing so (the profit motive and reputational motive will be relevant here). In the context of delivering innovation related to meeting the requirements of the wider sustainable energy sector, where the commercial benefit of the innovation may not be as clear, network companies may be slow to deliver the level of innovation in the timescales required. In these circumstances the regulatory framework needs to provide the encouragement or stimulus to enable innovation on energy networks that stakeholders agree is needed for a sustainable energy sector but that the network companies might otherwise have little incentive to pursue. Under the RIIO model this encouragement is provided using a two-pronged approach:

- the longer-term, outputs-led, incentive-based, ex ante price controls will provide their own incentives to innovate, by giving companies commitment around the potential rewards that they could earn from successful innovations and committing not to penalize them for unsuccessful innovations; and
- providing partial financing for innovation related to delivery of a sustainable energy sector through an electricity networks innovation stimulus and a gas networks innovation stimulus [24].

The RIIO regulation in UK is the first regulation in European Union to address all the needed aspects in order to support long term developments around network business. The guidelines by European Parliament for the member states emphasize efficiency first principle. Off-grid and other long-term efficiency seeking solutions are very well aligned to this principle and every member state should redesign its regulation to incentivize it.

Member States should use the energy efficiency first principle, which means to consider, before taking energy planning, policy and investment decisions, whether cost-efficient, technically, economically and environmentally sound alternative energy efficiency measures could replace in whole or in part the envisaged planning, policy and investment measures, whilst still achieving the objectives of the respective decisions. This includes, in particular, the treatment of energy efficiency as a crucial element and a key consideration in future investment decisions on energy infrastructure in the Union. Such cost-efficient alternatives include measures to make energy demand and energy supply more efficient, in particular by means of cost-effective end-use energy savings, demand response initiatives and more efficient conversion, transmission and distribution of energy. Member States should also encourage the spread of that principle in regional and local government, as well as in the private sector [25].

Currently the regulatory model introduced in Estonia can be characterized as having set up the goal to save on administrative costs of the regulatory body. There is no requirement for systematic data collection, the historical data and prognosis are prepared only by applying of new tariff. This system can be defined as regulatory deterrence where the company knows that applying of tariffs will rise notably heavy administrative burden. This is motivation system to rely on existing tariffs and not to turn to the regulator for fixing new tariffs. And it is certainly not encouraging innovation and long-term minimizing of sunk costs in network tariff.

4 Network Optimization Method to Reducing Sunk Costs

Investing to the network always includes the risk of not getting the expected benefits before its end of lifetime. Eliminating the risk totally is an impossible task but one can minimize the risk by targeting network configuration that is minimal in terms of volume of assets or by investing assets that can easily be relocated with minimal extra cost. Using off-grid as an alternative described in the first part of the current thesis and it is a good example of building network assets that are relocatable.

This part of the thesis analyses possibilities of keeping network asset volume low while refurbishing the network, which also reduces possible sunk costs in network tariff. The problematics around the topic is like any field of activity where investments are made for a long period of time. Long term investment usually meets the reality where investments are made and will be fixed for decades, but conditions like optimal location, efficiency of technology or need of use are changed before the payback time. One cannot possibly foresee all the future properties of the environment but can make the investment as flexible as possible for the future needs. One way to address this problematic in the electricity network is regular analyses of optimal network configuration and minimization of the volume of network assets. Doing it regularly assumes methodology in order to address to automate the activity.

In this thesis a method which helps network analysts find the most favorable investment sites, by finding non optimal medium voltage (MV) configurations that can be effectively used to decrease underutilized LV network will be examined.

By considering the surrounding MV network, this method can find investment sites where renovation costs can be much lower than simple algorithms using only LV network would suggest which keeps the volume of network assets low and therefore also minimizes possible sunk costs in future network tariff.

Every electricity distribution network operates in different environment and uses different components and methods of work, therefore only methodology to find these sites will be provided and not the actual solutions. The methodology provided here was tested in Estonia's largest distribution network, Elektrilevi OÜ (ELV).

4.1 Methodology for finding investment sites to optimize underutilized LV network

Firstly, we exclude all connection points that are closer to their subsequent substation than the critical distance (*Crit_Dist)*, using the length of the existing LV line. Secondly, we find those connection points, where the closest Middle Voltage Line Element (MVLE) is closer than desired distance (*Max_Dist)*. MVLE can be any medium voltage cable or overhead line part, which begins (and ends) with a pole, switchboard or a turning point for a cable line.

Thirdly, we need to include some background information for suitable connection points: x and y coordinates (latitude and longitude), connection point ID-code (used to distinguish different connection), size of the main fuse, yearly electrical energy consumption, name of the substation and the feeder.

Fourthly, we find the shortest distance between the connection points and the nearest MVLEs, using connection point coordinates and the start and end coordinates of the MVLEs. Finding the distances of all the MVLEs from all the connection points would be too resource consuming. To counter this problem, we compare the coordinates of connection point $P_3(x_3;y_3)$ and MVLE starting point $P_1(x_1;y_1)$. We only calculate the exact distance if the distance is less than the sum of our desired distance Max_Dist and the length of the MVLE. We use this sum because the closest part of the MVLE can just as well be the ending point. More detailed description of the methodology can be found in [III].

The overall process is depicted in the following figure.

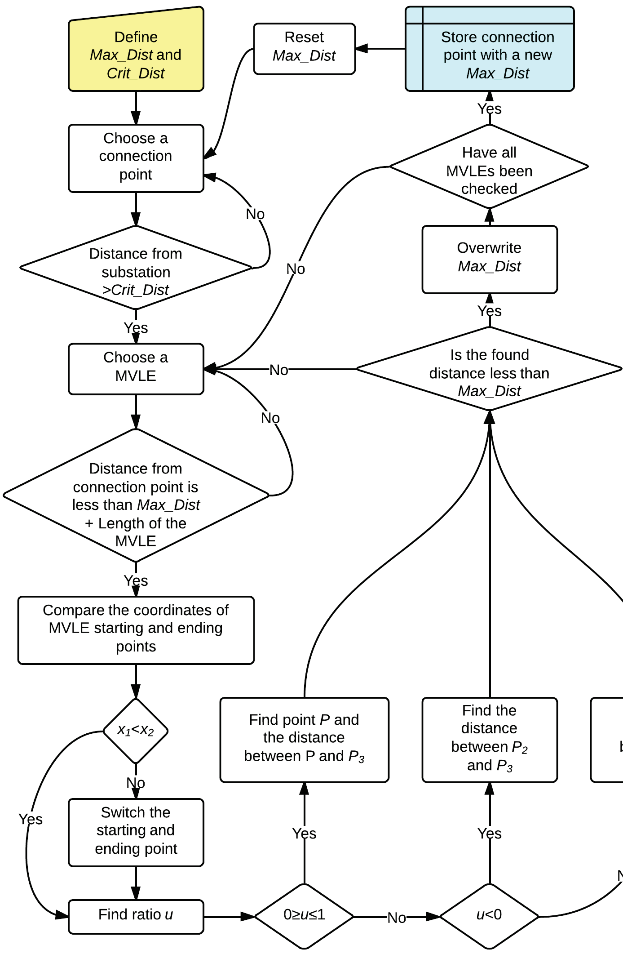

Figure 5: Schema depicting the overall investment finding process

We find this distance using the theory of distance between a point and a straight. This straight passes through the starting point $P_1(x_1;y_1)$ and ending point $P_2(x_2;y_2)$ of our MVLE. Perpendicular for straight P_1P_2, that passes through $P_3(x_3;y_3)$ (the connection point), intersects with the straight passing through MVLE P_1P_2 in point $P(x;y)$ as can be seen in the following figure.

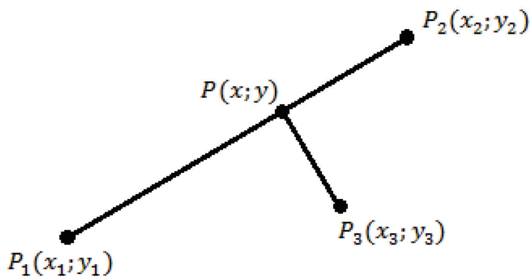

Figure 6: Distance between P3 and straight line between P1 and P2 if 0≤u≤1

The positioning of point P can be calculated using the following equation.

$$P = P_1 + u \cdot (P_2 - P_1) \quad [12]$$

where:
u – ratio, that represents the relative distance between P and P_1.

If point P is situated on straight P_1P_2, then the distance between P_1P_2 and P_3 equals the distance between P and P_3 and $0 \le u \le 1$. The dot product of two orthogonal vectors equals to zero, therefore:

$$(P_3 - P) \cdot (P_2 - P_1) = 0 \quad [13]$$

We replace P using equation 12:

$$\left[P_3 - P_1 - u \cdot \left(P_2 - P_1\right)\right] \cdot \left(P_2 - P_1\right) = 0 \quad [14]$$

Using equation 4, we can find ratio u:

$$u = \frac{\left(x_3 - x_2\right) \cdot \left(x_2 - x_1\right) + \left(y_3 - y_2\right) \cdot \left(y_2 - y_1\right)}{\left(x_2 - x_1\right)^2 + \left(y_2 - y_1\right)^2} \quad [15]$$

We can find the coordinates *(x;y)* for point P by replacing u in equation 12.

$$x = x_1 + u \cdot \left(x_2 - x_1\right)$$
$$y = y_1 + u \cdot \left(y_2 - y_1\right) \quad [16]$$

Because MVLE are parts with a definite length, then we also need to consider situations where point P is situated outside MVLE and $u<0$ or $u>1$.

The following figure depicts a line with a MVLE part P_1P_2. The distance between the straight passing through MVLE part P_1P_2 and our connection point P_3 is not the same as the distance between MVLE P_1P_2 and connection point P_3. In this case the distance we are looking for is either the distance between P_1 and P_3 or P_2 ja P_3.

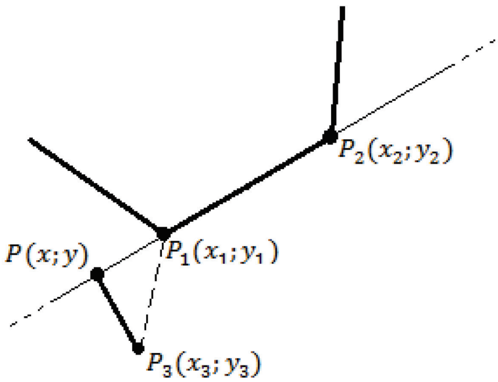

Figure 7: Distance between P3 and P1P2 if u<0

$$P_1P_3 = \sqrt{(x_3 - x_1)^2 + (y_3 - y_1)^2} \quad [17]$$

where:
$P_1(x_1;y_1)$ – MVLE starting point,
$P_3(x_3;y_3)$ – connection point.

In order to find out our current situation, we evaluate the corresponding u ratio. If 0≥u≤1, then point P is situated on MVLE part P_1P_2 and the distance we are looking for is PP_3. If u<0, then we must find the distance between P_1 (MVLE starting point) and P_3 (connection point). If u>1, then we must find the distance between P_2 (MVLE ending point) and P_3 (connection point).

This method only works if the x-coordinate of the starting point P_1 of MVLE is smaller than the x-coordinate of the ending point of MVLE ($x_1<x_2$). If this is not the case, we need to switch the coordinates of our starting and ending points before using the method. Also, for the same reasons if $x_1=x_2$ and $y_1<y_2$, then we must switch the y-coordinates of our starting and ending points before using the method.

4.2 Testing the investment sites finding methodology

Testing the methodology in Elektrilevi's network with the restrictions Crit_Dist = 1500 m and Max_Dist = 100 m gave 92 connection points in 78 feeders as a result to be further examined. In order to increase the sample size, we must increase Max_Dist value but for optimal testing purposes the initial result was appropriate. With further analysis the connection points and feeders with no consumption perspective, with data errors and objects already refurbished were eliminated. Finally, 47 projects with 48 feeders where determined to be refurbished.

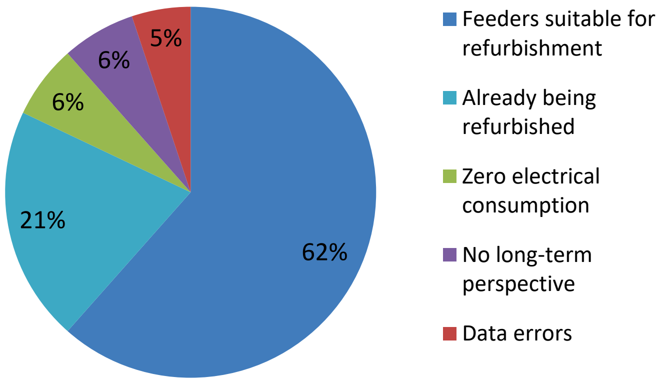

Figure 8: Distribution of feeders found by the methodology

Refurbishing all the selected feeders means replacing 30 km of LV line, 2,3 km of high voltage line and 42 substations. But also 33 km of underutilized low-voltage lines can be dismantled which will be out of the future asset value and decreases future sunk costs of the network. Other benefits of the methodology will be presented in the next paragraph.

4.3 Benefits of the optimization methodology

This methodology helps to find the optimal investment projects, when using algorithms that calculate the cost for solutions along the existing LV line corridor appears too expensive.

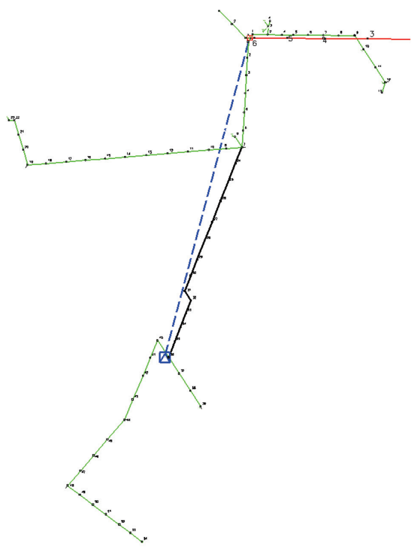

Figure 9: Solution along the existing LV line corridor

To illustrate this, the previous and the following figure describe the same network area. On these figures MV lines are indicated in red and LV lines in green, blue line indicates the new MV network and black lines indicate dismantled LV network. Because the existing LV line is too long for providing proper voltage quality, let us assume that a new substation is required to refurbish the whole LV area.

Standardized simple solutions are based only on the existing LV feeder in previous figure. However, proposed method can detect the nearby MV line, which will clearly result in a more feasible solution. The cost difference between the standardized solutions and new proposed solution is determined by the cost of length difference of old and new cable line like shown in the following figure. More accurate cost calculations will help the network planner to find more favorable investment sites.

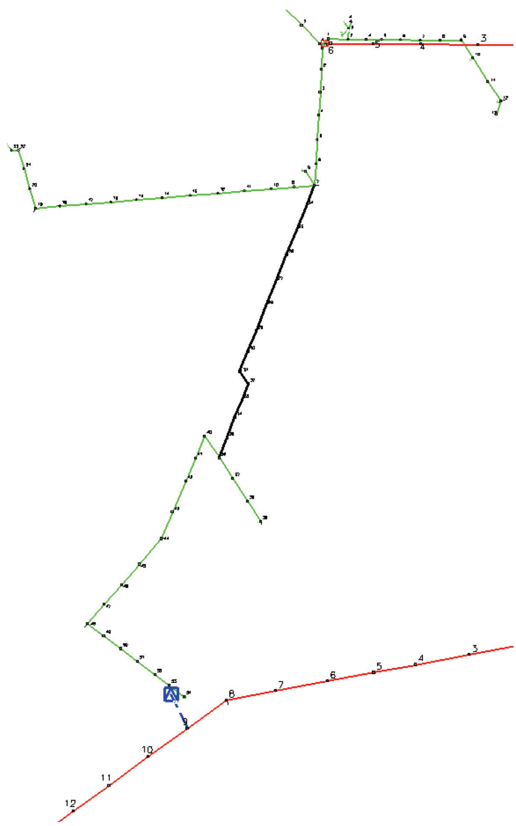

Figure 10: Solution using a nearby MV line

The following figure shows MV/LV substation feeder F3, one of the network sites found using the proposed methodology.

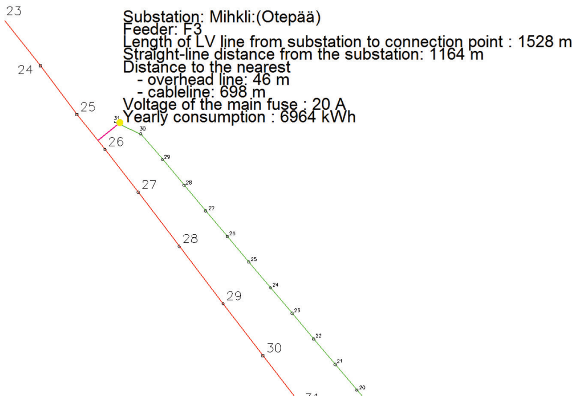

Figure 11: Example: MV/LV substation feeder 3

As seen on previous figure, the closest MV line (shown in red) is only a few dozen meters away from the customer connection point, while the distance from the old substation along the existing LV line (shown in green) is more than 1,500 meters. Straight line distance from the nearest MV line is marked violet. As this client consumes electricity all year round, the refurbishment of the given project seems to be reasonable. The decision to go forward with any investment should always be done case by case and cannot be added to the methodology based on simple grounds.

4.4 Summary of the Methodology for finding investment projects that can be refurbished from a nearby medium voltage line element instead of using the existing LV line corridor

The methodology described in this paragraph helps network companies to determine by algorithm investment sites which can be refurbished from nearby medium voltage line element. The outcome of the analysis helps to significantly reduce the network asset volume in rural areas, reduce network failures and resolve voltage quality problems. The outcome of testing the methodology returned 83% effective results and therefore can be considered as a very effective method for helping the network planners and reducing network sunk costs.

In the context of current thesis this methodology is effective way for the network company to approach the sunk cost problematics.

5 Discussion

The results of this study confirm that off-grid solution used by distribution network operator is practical alternative to the traditional powerline in LV network in rural areas. The price and the efficiency of the solar and battery technology is improving, which makes the solution more and more favorable in reducing the sunk costs in future network tariff. The off-grid solution is also a tool for leveraging the risk of urbanization trend where rural network connections are left unused and helps to avoid building or refurbishing unnecessary distribution powerlines that increase ineffective asset value. When other efficiency related investment methods also contribute to the lower asset value, they still are fixed to the location where they are built, off-grid solution is flexible and can be relocated if consumption moves. There are also additional benefits of off-grid for society like higher supply reliability, smaller environmental impact, higher consumer awareness of their electricity consumption and its influence to save energy.

The study also confirms that most regulatory environments are oriented to short time optimization of network costs (3–6 years) and do not encourage distribution network companies to optimize asset value over sequence of regulatory periods and in longer term. There are examples of more long-term and innovation-oriented regulation like RIIO in UK, but it is rather uncommon in other countries in Europe.

The sunk costs in future network tariff can be decreased by using any investment optimization related method which decreases current asset value. Methodology for finding investment projects that can be refurbished from a nearby medium voltage line element instead of using the existing LV line corridor is a confirmed tool analyzed in current thesis for supporting the statement. This methodology is not related to any innovative and risky new technology, therefore, it provides additionally to long-term value, also an immediate cost effect without the need to change the regulatory methodology.

5.1 The meaning of the main findings of current thesis

The task of the thesis as it was stated in the Introduction was to find answers to the following questions:

1. Is it reasonable for the network operator to consider off-grid solution in rural areas as an economic alternative to the traditional powerline and does it have financial impact to the sunk costs in network tariff?
2. What type of regulation methodology best supports the innovation and long-term sustainable network development in order to reduce sunk costs?
3. What are the other possibilities network operators can use to minimize investments not designed to last?
4. Is there a practical methodology to use in order to involve all related market participants behind the one common coal?

Off-grid power production units are well known solutions for remote places to get electricity, but they have not been used by electricity distribution networks to replace existing powerlines before. Current thesis answers to the **first question** and proves its economic feasibility in replacing the power lines in rural areas and proves to be a good solution to reduce future network asset value as sunk costs in future network tariff.

The idea is certainly innovative and initiates many new opportunities as new risks for distribution network operators as for other market participants. There is therefore a need for the development of a new type of regulation which supports innovation, optimizes long-term sunk cost development and supports new business models in energy market.

Current regulations in most European countries do not have long-term cost saving motivational mechanisms and they accumulate sunk cost into network tariff. If network companies are not motivated to innovate, more capital is being sunk into old technology which in rural areas may become useless when urbanization accelerates or customers themselves take new technology into use. Current thesis answers to the **second question** and proves that RIIO type of regulation is needed in order to incentivize innovation and target long-term sunk cost reduction. Long-term incentive type of regulation boosts not only innovation and sunk cost reduction but initiates new business models for distribution network operators.

One of the aims of the current thesis was also to analyze other, more traditional possibilities to address sunk cost problem in the network. In order to answer to the **third question**, analytical approach was introduced to easily find investment projects which have much more economically feasible solution to refurbish LV network from nearby MV line instead of refurbishing it along the existing LV line corridor. Avoiding unnecessary powerlines is clear way to reduce sunk costs in the future network tariff.

The **last question** raised in the introduction of current thesis was to study if there is a practical methodology to use in order to involve all related market participants behind one common coal. This common goal in context of the thesis is the recognition of sunk cost problematics in network tariff by all the market participants and find the framework to change the regulation towards incentivizing the innovation inside network companies. The goal of finding the methodology was reached by introducing in general the Backcasting methodology, but it is out of the scope of current thesis to go any further with the study.

5.2 Previous studies

The **sunk cost problematics** in network tariff is directly recognized in article [1]. The unrecoverable or stranded network cost problematic from different angles are recognized in several studies [27] [28] [29]. There seems to be a tendency to approach sunk cost problematics rather from the point of view how to cover not how to reduce or avoid them.

There are many studies published about **off-grid** renewable energy solutions, their economic feasibility, their use in different situations in rural and other environments. Most of the research done this far has focused on how to integrate generation units into the network. Some of the examples are:

- Intelligent control of a grid-connected wind-photovoltaic hybrid power systems [7].
- The future of low voltage networks: Moving from passive to active [8].
- Optimal PV–FC hybrid system operation considering reliability [9].

No comparable study has been made to use the system as a tool for distribution network company to address the network efficiency and future sunk cost problem.

The **network tariff regulation problematics** is also recognized in number of studies, for example [1], but again the analysis approaches tariff design from consumer point of view not from the network companies motivational point of view to reduce sunk costs in the tariff. Regulation inconsistency to incentivize innovation and guarantee investment payback time over several sequent regulatory periods is analyzed in [30].

5.3 Sunk cost problematics

The sunk cost problematics has been hidden from the public and has been treated as an inevitable part of network tariff. There are obvious reasons like relatively unchanged technology used in networks until the recent decade, urbanization effect being visible in network usage just recently and mainly because of network tariff regulation which has been absorbing all costs related to underutilized networks. One could argue that tariff regulation has always been pushing network companies towards greater efficiency and this has been pushing down also the level of sunk costs but the regulation addresses mainly network companies operational cost efficiency and much less of capital cost efficiency, sunk costs at the same time are mainly related to investments which is capital cost and has been therefore out of focus.

There might also rise a question why do network companies keep „empty" substations and powerlines in their balance sheet and burden the tariff with their cost? The simplified answer in Estonia to this question is that network company do not have any legal solution to cancel existing contracts with customers with zero consumption and customers are motivated to keep the contract because of the added value to their property. The more sophisticated answer to this question needs further country-based analysis and can be the follow-up study to current thesis. Off-grid solution could in many cases be a very effective solution to replace the existing network and remove the sunk cost burden from network tariff.

5.4 Backcasting as a framework to address sunk cost problematics

The sunk cost problematic can be a complex topic. It starts from the regulation to keep the network tariffs as low as possible for many decades to come and continues with research to find the correct technical solutions to address the problematic within the environment where technology is changing rapidly and ends with building overall framework to ensure the continuous process as it involves many stakeholders in society. It is out of the scope of current thesis but during the research the Backcasting methodology emerged as possible framework to engage different stakeholders related to the topic.

The Backcasting analysis is a process with steps to specify goals and objectives within the context of future operating environment in order to formulate a range of scenarios, and to identify the changes that would need to be made to the current system to realize these futures. The approach is based on generic Backcasting methodology developed by Robinson [31]. The range of alternative possible futures are explored which are „oriented towards testing the feasibility and impacts of such futures „, to aid in the decision making process to determine policy direction [31].

The Backcasting as a term was first mentioned by Robinson [32] in 1982 but the idea of approaching complex problems backwards was proposed by Lovins [33] in 1976. The focus of Backcasting has always been to reach different policy goals and interestingly in early times it has mostly been used in energy field although later it has been exploited in many other sectors as well. From the beginning, Robinson has strongly emphasized that the purpose of Backcasting was not to produce blueprints, but to indicate relative feasibility and implications of different energy futures (including social, environmental and political implications) on the assumption of clear relationship between goal setting and policy planning [31].

There are no references of Backcasting in scientific literature for being used in development scenarios of electricity distribution networks but Backcasting has been broadly used in relation to other energy related topics in the past.

The problem of regulated environment is its short-sightedness. Majority of regulation methodologies operate within the range of 3 to maximum of 6 years, but electricity network assets lifetime is up to 60–70 years. Only the most sophisticated regulation methodologies, like RIIO in UK, address the sunk cost problematics and motivate the network operator to be efficient in the long run.

The traditional forecasting methods tend to prolong current and known trends and are unlikely produce anything revolutionary. But history has proven that the future is not direct enhancements of today's solutions. Our limited thinking may be a major obstacle to invent something new. Backcasting is especially promising in case of complex problems, a need for major change, dominant trends are part of the problem, externalities that cannot be satisfactorily solved in markets and long-time horizons [34].

Backcasting seems to be the right methodology to engage all stakeholder groups behind one common goal and can be a good solution addressing sunk cost problematic in society. To study the Backcasting methodologies suitability in deep for sunk cost problematic can be the topic for further studies.

6 Conclusion and Future Work

Current thesis proves sunk cost as an important component in network tariff which has got little to no attention in regulatory guidelines. Until recent years there was no efficient technology nor urgency to address the topic but now there is technology available and many reasons to study it as a tool for network companies to lower the network tariff.

The off-grid solution is economically feasible alternative for electricity network in rural areas and is the most rewarding solution to reduce sunk costs in network tariff. Off-grid solution effectiveness mainly depends on network lifetime cost it replaces and its property to be easily relocated if consumption disappears. While photovoltaic and battery technology is getting cheaper and more efficient it can be used more often in the future. The current thesis analyzed off-grid solution economic feasibility and suitability for single customer connection point in rural area, but it is possible that development of technology and legislation can provide off-grid also as a solution for several nearby situated customer connection points. Analyzing suitability of off-grid solution as an alternative to electricity network for several customers is many times more complex task and can be the topic for future studies.

Applying new technologies to network is not only question of availability of the technology. Electricity networks are natural monopolies and strongly dependent on a market regulation. Regulation can be encouraging or discouraging towards different kind of initiatives in those networks. Therefore, it is extremely important for regulation to keep pace with technological advancements and supplement motivational criteria for network companies to innovate. Current thesis analyses different regulatory methodologies and regimes and concludes that innovation should be incentivized by rewarding criteria in the regulation and such regulation should be continuous over several regulatory periods which duration better matches with the lifetime of network assets.

Current thesis also proves sunk cost to be reduced with more traditional methodologies which does not assume new technologies to be present or specially incentivized by the regulation. The methodology to analytically find cost efficient solutions to refurbish low-voltage network for nearby middle-voltage line is provided in current thesis. As the methodology significantly reduces the volume of network assets, it is provided as a good solution for reducing sunk costs in network tariff.

While analyzing regulatory regimes and their difficulties to change in relatively short timeframe Backcasting methodology game up as a possible methodology to align different market participants behind one common goal and make the regulatory analysis results of current thesis not only theoretical but bring those changes to life as an innovation in electricity domain. Deeper analysis of Backcasting methodology was out of the scope of current thesis but is strongly recommended to be future work in speeding up regulatory changes in any country or domain.

Electricity networks have become well digitally documented and more real time data is coming into databases which is giving new analytical possibilities to develop new methodologies to address sunk cost problematics in electricity networks. As a general suggestion, sunk cost metric should be among the other success metrics of the network operator.

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Abstract

Introduction to Minimize Sunk Costs in Electricity Network Tariff

This thesis analyzes the possibilities to minimize sunk costs in the electricity network tariff and the changes needed to be made in regulation to support targeted innovation in electricity networks. The importance of the topic is increasing because the changed consumption patterns and the introduction of new technology by consumers have changed or made the electricity network in areas with low population density sometimes unnecessary before the end of its useful life.

There are three main topics analyzed:

1. The economic efficiency of off-grid solution deployment by the network operator itself to replace regular network connections in areas with low population density;
2. Most commonly used regulatory methodologies, their impact on innovation in electricity networks, and their influence to sunk costs in network tariffs;
3. Analytical method for eliminating inefficiency in network planning, which proposes a methodology for finding LV investment objects that can be reconstructed from the nearest medium voltage line instead of an existing LV line corridor.

The binding topic of the doctoral thesis is to reduce the sunk costs in the network tariff. First, the overall concept of an off-grid solution is proposed to replace traditional network connections, and then the economic feasibility of an off-grid solution is analyzed. An off-grid solution is a small-scale electricity production complex consisting of solar panels, a battery bank, an inverter and a diesel generator. This production complex is autonomous and requires minimal maintenance. The result of the analysis shows that, although the discounted cash flow for both alternatives is negative, it is less negative for the off-grid solution and therefore the preferred option. The analysis also highlights the efficiency gains and price reductions resulting from the development of solar panels as well as battery bank technology, both of which support the wider deployment of off-grid solutions by network operators. An important feature of an off-grid solution in the context of sunk costs is its mobility to be relocated when the need for a network connection disappears on its current location. The supply of electricity to customers through the off-grid solution differs from the traditional network connection in terms of technical and contractual features. The analysis of these specifications is beyond the scope of this thesis.

In the second part of the doctoral thesis, the most used regulatory methods are analyzed from the standpoint of their suitability to support innovative solutions for making the network service more efficient. The analysis shows that the more commonly used regulatory methodologies are lacking an economic incentives for network operators to use innovative solutions. The main shortcomings are:

1. low attention to sunk costs;
2. the relative difference in the length of the regulatory periods compared to the useful life of the network asset;
3. continuity of regulatory periods and zeroing of economic benefits for the network operator;
4. not favoring the innovation.

As a result of the analysis of regulatory methodologies, a solution is proposed, based on the RIIO regulation, to be considered as the appropriate solution for reducing of sunk costs and to promoting innovative solutions.

In the third part of the doctoral thesis, an analytical method is proposed to find objects that can be reconstructed from the nearest medium voltage line instead of using an existing LV line corridor. The methodological solution is to find the smallest distance between the point and the vector. In the context of this thesis, this methodology is important in terms of reducing sunk costs by enabling more cost-effective reconstruction projects and reducing sunk costs in rural areas.

Lühikokkuvõte

Sissejuhatus uppunud kulude minimeerimiseks elektrivõrgu tariifis

Antud doktoritöö analüüsib võimalusi „uppunud“ kulude minimeerimiseks elektrivõrgu tariifis ning muudatusi, mida on vaja teha regulatsioonis, et toetada sellele suunatud innovatsiooni elektrivõrkudes. Teema aktuaalsus on suurenemas, kuna muutunud tarbimisharjumused ning uue tehnoloogia kasutuselevõtt tarbijate poolt on muutnud või muutmas elektrivõrgu madala asustustihedusega piirkondades kohati mittevajalikuks enne selle kasuliku eluea lõppu.

Analüüsitakse kolme peamist teemat:

1. Võrguvabade lahenduste (off-grid) kasutuselevõtu majanduslik efektiivsus võrguettevõtte enda poolt asendamaks võrguühendusi elektriliinidega madala asustustihedusega piirkondades;
2. Enimkasutatavad regulatsioonimetoodikad, nende mõju innovatsioonile elektrivõrkudes ning seeläbi ka uppunud kulude suurusele võrgutariifis;
3. Analüütiline meetod ebaefektiivsuse kõrvaldamiseks elektrivõrgu planeerimisel, kus pakutakse välja metoodika leidmaks madalpinge investeerimisobjekte, mida on võimalik rekonstrueerida lähimast keskpinge liinist olemasoleva madalpinge liinikoridori asemel.

Doktoritöö seob läbivalt tervikuks eesmärk vähendada uppunud kulusid võrgutariifis. Esmalt pakutakse välja off-grid lahenduse üldine kontseptsioon traditsiooniliste võrguühenduste asendamiseks ning seejärel analüüsitakse off-grid lahenduse majanduslikku otstarbekust. Off-grid lahenduse all mõistetakse väikesemahulist elektrienergia tootmiskompleksi, mis koosneb päikesepaneelidest, akupangast, inverterist ning diiselgeneraatorist. Antud tootmiskompleks on autonoomne ning vajab minimaalselt hooldust. Analüüsi tulemus näitab, et kuigi mõlema alternatiivi puhul on diskonteeritud rahavoog negatiivne on see off-grid lahenduse puhul vähem negatiivne ja seetõttu eelistatum valik. Samuti toob analüüs välja nii päikesepaneelide , kui ka akupanga tehnoloogia arengust tuleneva efektiivsuse kasvu ja hinna languse, mis mõlemad toetavad off-grid lahenduse laialdasemat kasutuselevõttu võrguettevõtete poolt. Oluline off-grid lahenduse omadus uppunud kulude vähendamise kontekstis on selle mobiilsus ehk teisaldatavus võrgus uude asukohta, kui võrguühenduse kasutusvajadus kaob. Off-grid lahenduse kaudu klientide elektrienergiaga varustamine erineb tehniliste ja lepinguliste omaduste poolest traditsioonilisest võrguühendusest. Antud erisuste analüüs on väljaspool käesoleva doktoritöö mahtu.

Doktoritöö teises osas analüüsitakse enamkasutatud regulatsioonimetoodikaid nende sobivuse seisukohast toetada innovatiivseid lahendusi võrguteenuse efektiivsemaks muutmise eesmärgil. Analüüsist järeldub enamkasutatud regulatsioonimetoodikate puudus majanduslikult motiveerida võrguettevõtteid kasutama innovatiivseid lahendusi võrgus. Peamiste puudujääkidena järeldatakse:

1. vähest tähelepanu uppunud kuludele;
2. regulatsiooniperioodide pikkuse suhtelist erinevust võrreldes vara kasuliku elueaga;
3. regulatsiooniperioodide mittejätkuvust ning majandusliku kasu nullimist võrguettevõtte seisukohast;
4. innovatsiooni mitte soosimist.

Regulatsioonimetoodikate analüüsi tulemusena tuuakse välja lahendus RIIO regulatsiooni näitel sobivast lahendusest uppunud kuludega arvestamiseks ning innovatiivsete lahenduste soosimiseks.

Doktoritöö kolmandas osas pakutakse välja analüütiline meetod leidmaks suure hulga madalpinge rekonstrueerimisprojektide hulgast objektid, mida on võimalik rekonstrueerida lähimast keskpinge liinist, mitte olemasolevat madalpinge liinikoridori kasutades. Metoodiliseks lahenduseks on punkti ja vektori vahelise vähima kauguse leidmine. Käesoleva doktoritöö kontekstis on antud metoodika oluline uppunud kulude vähendamise seisukohast, kuna võimaldab kuluefektiivsemaid rekonstrueerimisprojekte ning vähendada uppunud kulusid hajaasustus piirkondades.

Appendix. Original publications

Publication I

Tarmo Mere, Arvi Hamburg, Tiit Hõbejõgi, Marti Laidre, Juhan Valtin (2016). Financial evaluation of using off-grid as an alternative to the traditional power line construction. Przeglad Elektrotechniczny, Aug. 2016, pp. 206–210.

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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:

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

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.

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

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.

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

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.

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

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:

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

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.

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

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:

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

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:

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

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).

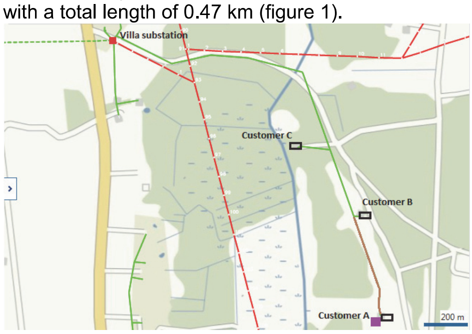

Fig. 1 Off-grid alternative for customer A (Villa F2)

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).

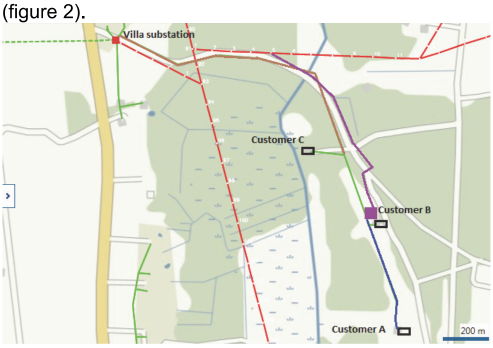

Fig. 2 Power line alternative for customer A (Villa F2)

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.

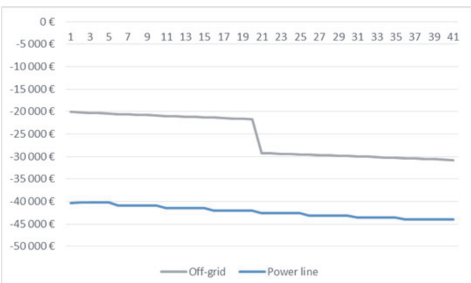

Figure 3 NPV for both alternatives for customer A (Villa F2)

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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Publication II

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Estonian Experience in Implementation of Incentive Type of Price Regulation

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***Abstract*—Administrative resources of the regulatory body and the number of regulated utilities is an important criteria in selection of price regulation methodology. Estonian experience is based on a large number of relatively small utilities. The price regulation methodology implemented is incentive type of Rate of Return where the important element is the regulatory deterrence, where the company can select whether to apply for new tariff or to rely on the existing one. The administrative burden is minimized in this case. The results of price regulation indicate significant savings on energy losses and stable service tariffs.**

Keywords—economics, power distribution, power system management, power system reliability.

I. INTRODUCTION

The first objective of the price regulation is sustainability - the regulated company must be able to finance its operations and make any required investment, so that the company can continue operating in the future [1]. From customers' perspective, high quality of the service provided and minimum price are the expectations. From shareholders' point of view reasonable rate of return on invested capital shall be guaranteed. Theoretically, it is possible to reach a theoretical maximum of the quality by building double or triple power lines or gas pipes, exceeding the n-1 criteria. However, one must agree that these type of technical solutions are only theoretical. Depending on the legislation of the specific jurisdiction, the task of the regulator is to select or to assist in selection of the regulatory methodology which corresponds to the main objective of price regulation. The summary of different regulatory objectives indicates, that the main criterion for selecting of regulatory methodology is to reach the maximum efficiency where the customers´ and the companies´ interests are in balance.

The regulatory methods can be divided to two main categories: ex-ante and ex-post [2]. By using of ex-ante regulation, the prices are fixed by the regulator. By using of ex-post regulation, the prices or fees are applied by the company without any coordination by the regulator and the regulator may control later whether these prices or fees meet the criteria set by the legislation. At present, the Natural Gas Act in Estonia has applied such a regulation, whereby the market dominant gas company must base its prices on the costs and earn justified return of the investment made [3]. A similar regulation is applied in the district heating sector in Finland and Sweden, where the companies apply prices designed by themselves and the regulator has the right to control their justification [4]**.** The same type of ex-post price control is implemented by the Competition regulation. According to the article 102 of the Treaty on the Functioning of the European Union the abuse of the dominant position by imposing of unfair selling prices is prohibited [5]. The same type of principles are established in Estonian national Competition Act [6]. In Estonia there are several practices by implementation of the Competition Act in cases of abuse of the market dominating position by unfair pricing [7], [8].

The ex-ante methods can be divided in three main categories:

- Rate of return (RoR);
- Price cap
- Long Run Incremental Costs Bottom UP (LRAIC).

According to different sources the above mentioned regulatory methods have different definitions. The price cap is defined as incentive type of regulation and named as retail price index minus x (RPI-x) in a number of sources [1], [9]-[11].

The RoR and RPI-x are more or less based on existing network installations and to the historical costs associated to the operation of those existing assets. In contrast to RoR or RPI-x the LRAIC model is based on hypothetical system [2]**,** [12]. By using LRAIC the only data corresponding to the existing situation are the demand, capacity and geographical location of the existing customers. It means that the basic approach of those methods is totally different, as provided in Table 1.

TABLE 1. PROFIT ELEMENTS COVERED BY ALTERNATIVE REGULATORY REGIMES

Regulatory System	Covered by Regulation	Ignored by Regulation
Price cap	P	Q, C_x, C_n
Price cap with cost pass-through	P, C_x	Q, C_n
Revenue cap	P, Q	C_x, C_n
Rate of return	P, Q, C_x, C_n	-

Furthermore, each method can have different subdivisions, depending on which economical risks are left to be handled by the company. From companies point of view, the profit is the main result of the regulation [11]. The profit is dependent on different inputs as described in equation (1).

$$R= PQ - C_x\,(Q) - C_n\,(Q) \qquad (1)$$

where

- R - company's profit
- P - price
- Q - sales volume
- C_x - exogenic or uncontrollable costs
- C_n - endogenic or controllable costs

The profit covered by classic type of RPI and RoR is described in Table 1 [11]. In a simplified approach, the classic type of RPI-x seems to be the most desirable, due the fact that it is more oriented to the efficiency gains, where the RoR seems to cover all risks related to the regulation. In practice, the regulatory methods are hybrids, containing elements from different alternative methods.

Another issue is the administrative cost of economic regulation. In the case of a small number of large size utilities it is efficient to apply an advanced and costly regulatory system. It pays off due to the fact that the efficiency for the society is higher than the resources spent on regulation. Another issue is the large number of small utilities, as is the situation of regulated sectors in Estonia.

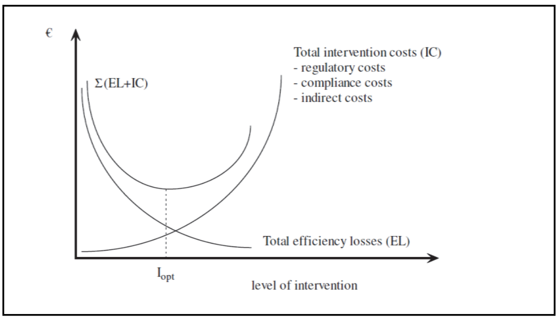

Fig 1. Optimal level of welfare loss control.

The effect of economic regulation on the level of whole society is analysed by Hertog [13], [14]. It is important to find the optimal level of intervention by the regulator. Beyond an optimal point, the additional resources spent on regulation will give no additional effect, but in contrast to desired result will be an additional burden for the society. The core of this basic framework is captured in the diagram on Fig 1.

II. ESTONIAN CASE OF REGULATION OF LARGE NUMBER SMALL SIZE UTILITIES

In the case of large number of small utilities, the cost of regulation shall be especially considered by selecting of regulatory methodology. In Estonia the number of utilities regulated by the regulatory body – Estonian Competition Authority (ECA) - is 260. This includes energy and water utilities [15]-[21]. The annual turnover of the smallest companies may not exceed 50 000 €. It can be assumed that by applying of economic regulation, it is possible to save 5% for the society. From this perspective it is reasonable to apply the regulation which annual costs are not exceeding 2,500 €. The 2016 annual budget of ECA is 1.8 m€, with the proportion of 60% (i.e 1.1 m€) for the regulatory activities [22]. In addition to the energy and water regulation the budget for regulatory activities includes the regulation of postal, railway and airport sectors [23]. If all resources available for regulatory activities would be spent for price regulation of energy and water utilities, the budget per utility would be 4 231 € per annum. In practice this amount is much lower due to the fact that besides the price regulation the regulatory body is responsible for a number of tasks, like EU co-operation, surveillance of electricity and gas markets, solving of customers complaints, etc. However, it is clear that within this budget is impossible to introduce advanced type of RPI-x regulation. From utilities point of view, the administrative burden by selecting of regulatory methodology shall be considered. If a large utility is on higher or at least on equal level with regulator to present data or to have discussions, a small utility suffers lack of resources for that. Beside direct administrative costs, also indirect costs related to the regulation exist, like the cost of capital. The level of regulatory risk is included to the cost of capital [12]. This shall be also considered by selecting of regulatory methodology.

The RoR implemented in Estonia includes a number of elements from RPI-x, where various risks shall be covered by companies. There is a 15 years of experience of using this methodology in economic regulation of energy and water utilities in Estonia [24]. One of the main principles in using this methodology is the companies right to present the application to fix the new tariff on any time. Companies are obliged to monitor the cost base, in case the tariff is not covering all costs, the company can apply for a tariff increase. This moment occurs for example where the sales volume has declined, uncontrollable costs like fuel or electricity have increased or the cost of capital has changed. For implementation of new tariffs the regulator´s approval is needed. This can be a time-consuming process with administrative burden, especially for small-size utilities.

Referring to Table 1, by using of classical type of RoR method, the controllable costs are covered by the regulation

[11]. That is the case where the company carefully monitors costs and the tariffs are actually fixed by the regulator in accordance to the basis of the historical costs of the company. The method used in Estonia differs a lot from the classical type of RoR where the costs included to the tariffs in principle differ from the company´s historical cost base and the regulator is actively demanding implementation of cost saving measures: reducing energy losses, saving on operational costs, etc. By using of so called "incentive type of RoR", controllable costs are not covered by the regulation.

To reach the energy conservation target, the obligation to reduce the power losses has been set to the utilities [25], [26]. The reason of obligation was the extremely high power losses in distribution companies up to 20% by starting the price regulation in the beginning of 2000s. The fulfilment of the obligation is company´s risk, similar to the efficiency target x used by RPI-x regulation. The company can maximise the return on capital by saving more than established by the regulator. In an opposite case, the difference shall be paid from the company´s return.

By using classic type of RoR, the risk of sales volume is covered by the regulation [11]. Based on forecasted sales volume, the weighted average of last three years is used as a rule in Estonian price regulation. If there are significant changes in customer structure, the detailed analyses are prepared [26]. By using the weighted average consistently, it is possible to eliminate this risk. Special situation may emerge in case of constantly declining sales volumes, like in district heating sector in Estonia, where the sales is declining due to the demographic situation and energy efficiency measures implemented by the customers. In this case, the sales volume is a clear risk for companies. In order to address cases like this, an under/over recovery system similar to revenue cap could be used [27]. This type of system was used in energy regulation in Estonia until 2012. In order to decrease the administrative burden, the under/over recovery is not used anymore. This is clear evidence, that the risk on sales volume is not automatically covered by the regulation.

By using the classical type of RoR the risk of uncontrollable costs is covered by the regulation as well [11]. Despite the companies right to turn to the regulator by applying for a new tariff, this type of risk exists. The cost pass-through principle combined with cost under/over recovery should be used for full coverage of the risk of uncontrollable costs. If the company is earning more or less than expected return due to the changes in uncontrollable costs, this will be over- or under-recovered by fixing the tariffs [1], [27]. For example, if the electricity cost for compensation of losses of a power DSO is more than expected, it will be compensated to the company during the next regulatory period. Or *vice versa*, if the electricity price is cheaper than expected, this amount will be paid back to the customers during the next regulatory period. This type of scheme was used in Estonian price regulation but is abolished now in order to simplify the price regulation. Similarly to the sales volume, the risk on uncontrollable cost is not automatically covered by the regulation.

All in all, the general target of Estonian price regulation has been to ignore the risk on controllable cost, but to cover the risk on sales volume and uncontrollable costs. The risks on sales volume and on uncontrollable costs shall be covered by the company, by presenting of tariff application to the regulator.

The regulatory model introduced in Estonia can be characterised as having set up the goal to save on administrative costs of the regulatory body. There is no requirement for systematic data collection, the historical data and prognosis are prepared only by applying of new tariff. This system can be defined as some kind of regulatory deterrence where the company knows that applying of tariffs will rise notably heavy administrative burden. This is motivation system to rely on existing tariffs and not to turn to the regulator for fixing new tariffs.

III. Analysis of results of implementation of incentive type RoR price regulation method

The main results of 15 years price regulation in Estonia are the efficiency gains in energy savings and the fact that the companies' actual return is mostly equal or below the WACC set by the regulator. The prices in real terms have been almost stable or even declining [15]. The outcome clearly indicates that the incentive type of RoR implemented in Estonia does not guarantee the required return which is one of the main characteristics of the classic type of RoR. On Fig 2 the average return on invested capital of the largest Estonian power utilities is presented.

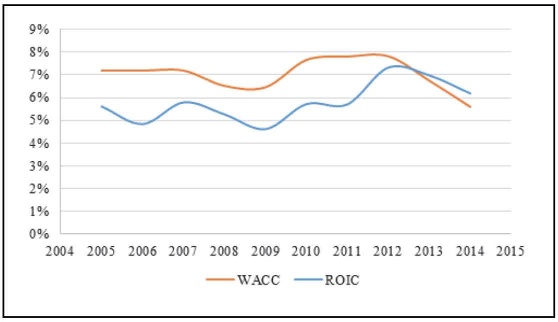

Fig 2. Average Return on invested capital of power networks incl. Elering, Elektrilevi, Imatra, and VKG.

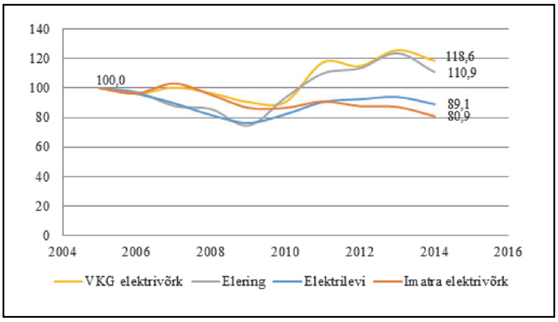

Fig 3. Relative change of tariffs of the largest power networks in real terms. The tariff in 2005 is 100 units.

The main target of RPI-x regulation is the decline of tariffs in real terms, this is included to the price formula as a negative value of the x-factor. By using of RoR, the price development in line with inflation could be expected. The analyses of power networks indicate that the tariffs have been stable or declining in real terms (Fig 3). The tariffs of Elering (TSO) have been increased by 11% (Fig 4). The main reason of tariff increase is the intensive investment program carried out by building international links whereby the regulatory asset base (RAB) of the company has increased 1.55 times. Without building of those international links, the tariffs would have been decreased from 100% to 83% in real terms. [15].

The reduction of electricity losses in power distribution networks is a success story of Estonian price regulation. 15 years ago, before the start of economic regulation, the power losses of 20% were commonly observed. Today the losses are close to the technical minimum where the further reduction is not much possible. The reduction of electricity losses of 3 largest DSO's with summary market share of 93% is presented on Fig 5 [28], [15].

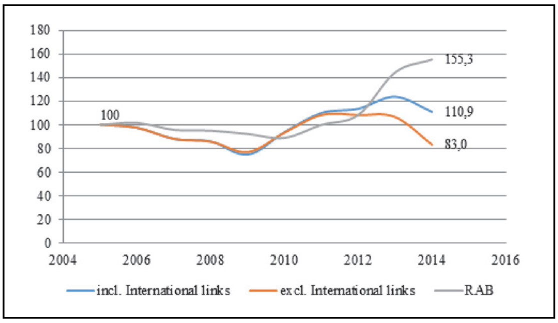

Fig 4. Relative change of tariffs and RAB of Elering in real terms. The tariff in 2005 is 100 units.

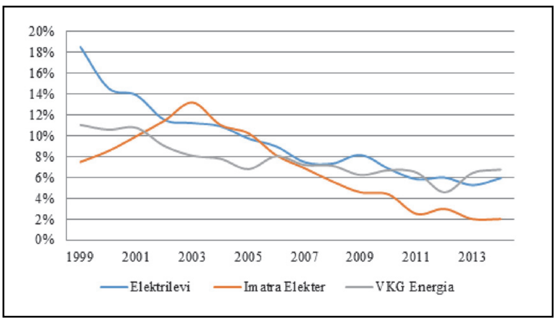

Fig 5. Electricity losses of distribution operators in percentages.

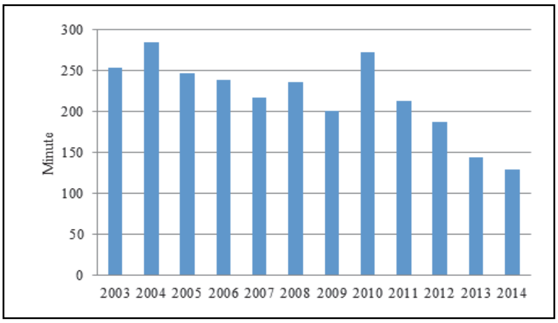

Fig 6. Changes in network reliability indicator SAIDI in Elektrilevi OÜ

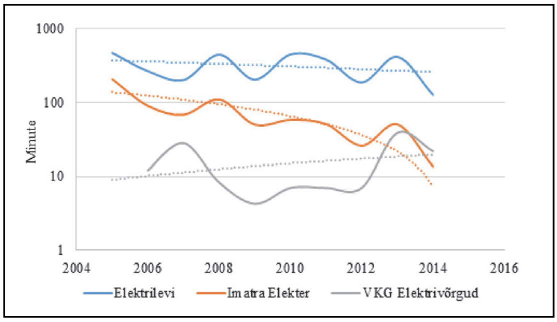

Fig 7. Changes in network quality indicator SAIDI in largest DSO's on the logarithmic scale.

Fig 6 presents the changes of the System Average Interruption Duration Index (SAIDI) of the largest power DSO Elektrilevi OÜ from 2003 to 2014. SAIDI indicates the average outage duration for each customer served. The calculations of SAIDI on Fig 6 do not take into account the impact of occasional weather impacts [2]. The calculations of SAIDI of three largest power DSO's is presented on Fig 7, this includes the impact of weather as well [15]. The conclusion is that the network reliability indicators have been improved during this period.

IV. CONCLUSION

The aim of the paper was to analyse the impact of the price regulation methods in the case of a large number of small size utilities with restricted administrative resources of the regulatory body. The "incentive type of RoR" model has been implemented in Estonia, where the regulator is inventively regulating the company's costs, including the energy efficiency. The results of the price regulation indicate that the tariffs have been declining in real terms and significant energy savings have been reached.

The conclusion is that the incentive type of RoR has the biggest impact on company's operational costs. The clear indicator is the reduction of energy losses, where the regulator is pushing the company toward of efficiency in operating costs. The similar indicator is the actual return on capital that has been mostly below the allowed return by the regulator. This is indicating that a part of the operational costs, not included to the tariff by the regulator is financed from company's return. This fact is also indicating, that the RoR implemented in Estonia is not a classical one, where the allowed return is guaranteed to the company. The fact that the tariffs are declining in real terms is indicating some relation to the RPI-x, which is indicating, that the incentive type of RoR implemented in Estonia has some elements of RPI-x. The "incentive type of RoR" is suitable by regulating a large number of small utilities with limited administrative resources where the effect of regulatory deterrence is motivating the utilities to manage within the budgets set by the regulator.

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Publication III

Hõbejõgi, T.; Reinberg, A.; Last, K.; Laanetu, M.; Mere, T.; Valtin, J.; Hamburg, A. (2014). Methodology for finding investment sites that can be refurbished from a nearby middle voltage line element instead of using the existing low voltage line corridor. Przeglad Elektrotechniczny, No. 10, pp. 199–202.

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Methodology for finding investment sites that can be refurbished from a nearby medium voltage line element instead of using the existing low voltage line corridor

Abstract. *This paper proposes a methodology for highlighting alternative investment solutions from a large number of investment projects. The methodology identifies remote connection points located far from the sub-station where electricity can be provided from a nearby medium voltage line element. The methodology uses a mathematical model to find the smallest distance between a point and a vector. This methodology was tested in Elektrilevi OÜ where it proved to be very effective. This article also includes an example of using the provided methodology.*

Streszczenie. *W artykule przedstawiono metodę rozwiązań inwestycyjnych dla dużej liczby projektów inwestycyjnych. Metoda identyfikuje punty podłączenia oddalone od podstacji gdzie zasilanie może być dołączone do najbliższego elementu średniego napięcia.* ***Metodologia wyszukiwania lokalizacji inwestycji możliwej do zasilania z najbliższego źródła średniego napięcia zamiast linii niskiego napięcia***

Keywords: network quality, investments, distribution network, finding refurbishment projects.
Słowa kluczowe: sieci zasilające, lokalizacja źródła zasilania.

doi:10.12915/pe.2014.10.48

Introduction

The lifespan of distribution networks infrastructure (power lines and substations) is very long and investments extremely resource intensive. Therefore, it is essential to invest as efficiently as possible. Distribution networks are created over a long period of time and the principles that govern these investments can change. Because of that, the original configuration of the distribution network will not always be the most optimal.

In this article we examine a method which helps network analysts find the most favorable investment sites, by finding non optimal medium voltage (MV) configurations that can be effectively used to decrease underutilized low voltage (LV) network. By taking into account the surrounding MV network, this method can find investment sites where renovation costs can be much lower than simple algorithms using only LV network would suggest. The objective of this method is to find parts of long LV feeds that can be refurbished by building a new substation area from a nearby medium voltage line element (MVLE). Ideally, we can then dismantle a large part of the LV line, thereby reducing underutilized network and increasing the overall network quality.

Because every distribution network has its own principles (which materials and solutions should be used in different situations), we only provide the methodology to find these sites and not the actual solutions.

This methodology was initially designed for the Trimble Network Information System (NIS) but can also be applied to other information systems. The Trimble NIS is a software application that can be used for asset management, network development and planning of repairs as well as documenting and managing network assets that are central to its system. Trimble NIS includes several modular industry applications:

- Power System Analysis,
- Network Planning and Construction,
- Asset Management,
- Maintenance,
- Network Investment Management [1].

This methodology was tested in Estonia's largest distribution network, Elektrilevi OÜ (ELV). ELV provides power to about 500,000 customers with a total consumption of approximately 6.5 TWh as recorded in 2013. The company manages around 63,700 km of power lines and 23,100 substations [2].

Network quality in this article, is measured by security of the supply (number of failures) and the voltage quality. For measuring voltage quality, we are going to use the Estonian standard EVS-EN 50160:2010. The standard nominal voltage for LV network is U_n = 230 V and under normal operating conditions excluding the periods with interruptions, supply voltage variations should not exceed ± 10% of the nominal voltage [3]. If the voltage does not meet the standard, then the customers in ELV network are entitled to receive a discount for the network service price.

Overview of previous studies

Previous studies have:

- Discussed problems of simulation models for modernization of regional LV and MV distribution networks and showed a computational algorithm for the needs for the network modernization [4].
- Discussed various methods of economical analysis of cross-country power networks and presented a modified variant of the annual cost method and the costs of cross-country network unreliability [5].
- Presented a method based on evolutionary strategies [6] and dynamic programming optimization [7] for designing distribution networks.
- Discussed the mixed-integer programming and the evolutionary programming methods of distribution network system planning [8].

The method discussed in this article is also designed for optimal solutions in the investments for the regional LV and MV distribution networks, but uses an approach previously overlooked.

Methodology

Firstly, we exclude all connection points that closer to their subsequent substation than the critical distance $Crit\_Dist$, using the length of the existing low voltage line. Secondly, we find those connection points, where the closest MVLE is closer than desired distance Max_Dist. MVLE can be any medium voltage cable or overhead line part, which begins (and ends) with a pole, switchboard or a turning point for a cable line.

Thirdly, we need to include add some background information for suitable connection points: x and y coordinates (latitude and longitude), connection point ID-code (used to distinguish different connection), size of the main fuse, yearly electrical energy consumption, name of the substation and the feeder.

Fourthly, we find the shortest distance between the connection points and the nearest MVLEs, using connection point coordinates and the start and end coordinates of the MVLEs. Finding the distances of all the MVLEs from all the connection points would be too resource consuming. To counter this problem, we compare the coordinates of connection point $P_3(x_3;y_3)$ and MVLE starting point $P_1(x_1;y_1)$. We only calculate the exact distance if the distance is less than the sum of our desired distance Max_Dist and the length of the MVLE. We use this sum because the closest part of the MVLE can just as well be the ending point.

The overall process is depicted in Fig. 1 (starting with yellow and ending with blue.

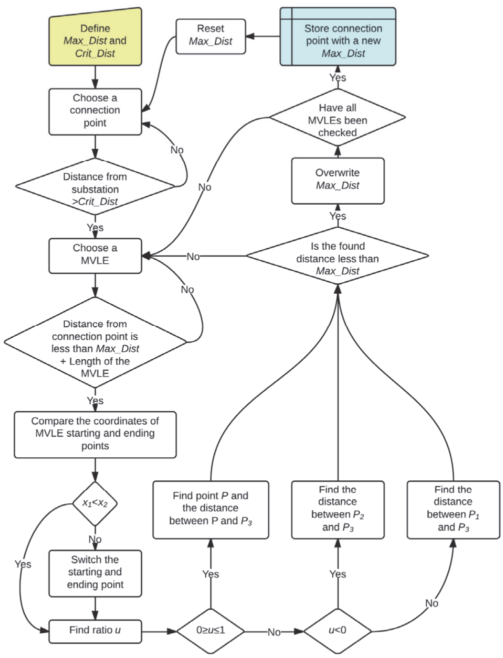

Fig.1. Schema depicting the overall process

We find this distance using the theory of distance between a point and a straight [3]. This straight passes through the starting point $P_1(x_1;y_1)$ and ending point $P_2(x_2;y_2)$ of our MVLE. Perpendicular for straight P_1P_2, that passes through $P_3(x_3;y_3)$ (the connection point), intersects with the straight passing through MVLE P_1P_2 in point $P(x;y)$ (Fig. 2 and 2). The positioning of point P can be calculated using formula 1.

(1) $$P = P_1 + u \cdot (P_2 - P_1)$$

where: u – ratio, that represents the relative distance between P and P_1.

If point P is situated on straight P_1P_2, then the distance between P_1P_2 and P_3 equals the distance between P and P_3 and $0 \leq u \leq 1$ [9]. The dot product of two orthogonal vectors equals to zero, therefore:

(2) $$(P_3 - P) \cdot (P_2 - P_1) = 0$$

We replace P using formula 1:

(3) $$\left[P_3 - P_1 - u \cdot (P_2 - P_1)\right] \cdot (P_2 - P_1) = 0$$

Using formula 3, we can find ration u (4):

(4) $$u = \frac{(x_3 - x_2) \cdot (x_2 - x_1) + (y_3 - y_2) \cdot (y_2 - y_1)}{(x_2 - x_1)^2 + (y_2 - y_1)^2}$$

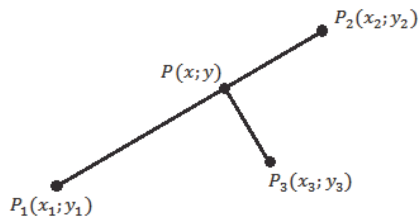

Fig.2. Distance between P_3 and P_1P_2 if $0 \leq u \leq 1$

We can find the coordinates $(x;y)$ for point P by replacing u in formula 1 (5).

(5) $$x = x_1 + u \cdot (x_2 - x_1)$$
$$y = y_1 + u \cdot (y_2 - y_1)$$

Because MVLE are parts with a definite length, then we also need to consider situations where point P is situated outside MVLE and $u<0$ or $u>1$.

Fig. 3 depicts a line with a MVLE part P_1P_2. The distance between the straight passing through MVLE part P_1P_2 and our connection point P_3 is not the same as the distance between MVLE P_1P_2 and connection point P_3. In this case the distance we are looking for is either the distance between P_1 and P_3 or P_2 ja P_3.

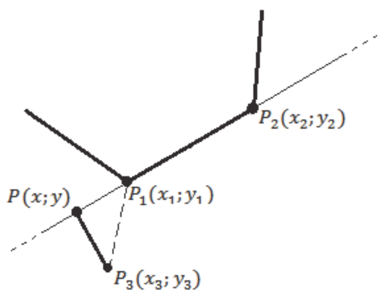

Fig.3. Distance between P_3 and P_1P_2 if $u<0$

The distance between P_1 and P_3 can be found with formula 6 [10].

(6) $$P_1P_3 = \sqrt{(x_3 - x_1)^2 + (y_3 - y_1)^2}$$

where: $P_1(x_1;y_1)$ – MVLE starting point, $P_3(x_3;y_3)$ – connection point.

In order to find out our current situation, we evaluate the corresponding u ratio. If $0 \geq u \leq 1$, then point P is situated on MVLE part P_1P_2 and the distance we are looking for is PP_3. If $u<0$, then we have to find the distance between P_1 (MVLE starting point) and P_3 (connection point). If $u>1$, then we have to find the distance between P_2 (MVLE ending point) and P_3 (connection point).

This method only works if the x-coordinate of the starting point P_1 of MVLE is smaller than the x-coordinate of the ending point of MVLE ($x_1<x_2$). If this is not the case, we

need to switch the coordinates of our starting and ending points before using the method. Also for the same reasons if $x_1=x_2$ and $y_1<y_2$, then we have to switch the y-coordinates of our starting and ending points before using the method.

Testing the methodology

The methodology was tested in the ELV network. The query that supports the methodology was written in SQL query language and the query was run in Oracle SQL Developer software. Oracle SQL Developer is a free integrated development environment that simplifies the development and management of Oracle Database [11].

In order to reduce the sample size, we used the following restrictions:

- $Crit\_Dist$ = 1500 m,
- Max_Dist = 100 m.

Using these restrictions, a total of 92 connection points was found on a total of 78 feeders. The location of these connection points is shown in Fig. 4 (connection points which are located close to each other are displayed as a single dot). This sample size was considered optimal for an initial testing on the basis of expert judgment, taking into account the budget size reserved to test the methodology. In order to increase the sample size, we should start with increasing the Max_Dist component as the increase in the solution cost would be rather insignificant.

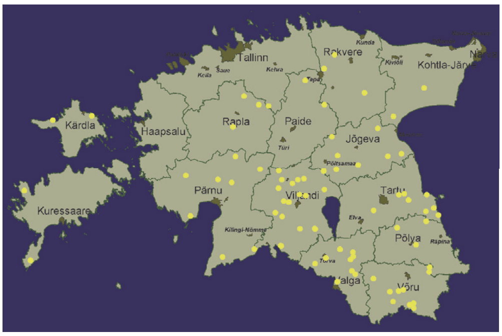

Fig.4. Connection points found by applying the proposed Methodology

Fig. 4 shows that the majority of the connection points found are located in the south-eastern region. Generally, this is in rural region where consumption is rather fading and, therefore, large-scale investment does not have perspective. Therefore, it is necessary to invest optimally, which this methodology strongly supports.
All found feeders were further examined to ensure that:

- Investment is sensible,
- There is no error in the data,
- They not currently being refurbished.

Investment is considered not sensible, if there is currently no valid network contract or the last year's electrical consumption was 0 kWh. It is not clear whether the consumption in these connection points will recover or if the connection point vanishes completely (e.g. with the old homestead). Five feeders were left out because of zero consumption. Also, after completing finalized investment solutions, five feeders were considered without long-term perspective because of changing MV network.

After further examination, 47 solutions were sketched to refurbish a total of 48 feeders. Two feeders are being refurbished with a common solution because they were located side by side. The diagram of found feeder's distribution is shown in Fig. 5.

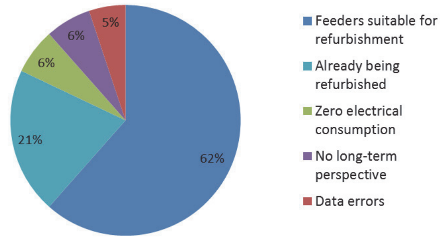

Fig.5. Distribution of feeders found by the methodology

To refurbish all of the 48 feeders, ELV would need to install approximately 30 km of LV line, 2.3 km of MV line and 42 substations. By this refurbishment, they can also dismantle approximately 33 km of underutilized low-voltage network, which prevents ca 200 failures a year and resolves voltage quality problems for 102 connection points.

The benefits of the methodology

This methodology helps to find the optimal investment sites, which using algorithms that calculate the cost for solutions along the existing LV line corridor appear to be too expensive.

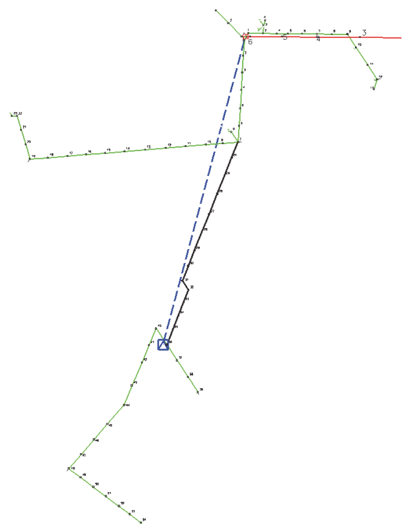

Fig.6. Solution along the existing LV line corridor

To illustrate this Fig. 6 and 7 describe the same network area. On these figures MV lines are indicated in red and LV lines in green, blue line indicates the new MV network and black lines indicate dismantled LV network. Because the existing LV line is too long for providing proper voltage quality, let us assume that a new substation is required to refurbish the whole LV area.

Standardized simple solutions are based only on the existing LV feeder (Fig. 6). However, our proposed method is able to detect the nearby MV line, which will clearly result in a more feasible solution. The cost difference between the standardized solutions and our new proposed solution is determined by the cost of length difference of old and new cable line (Fig. 7). More accurate cost calculations will help the planner to find more favourable investment sites.

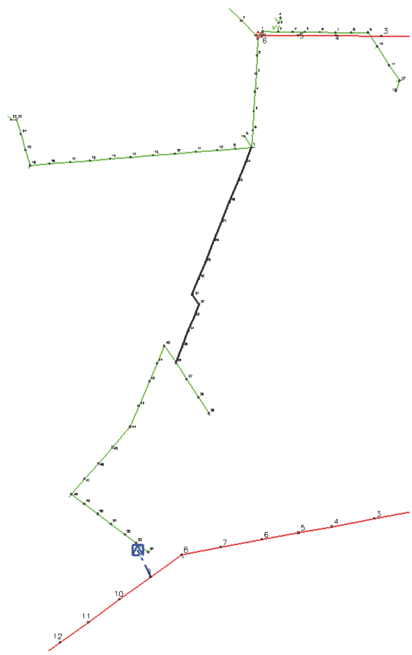

Fig.7. Solution using a nearby MV line

Fig. 8 shows Mihkli substation feeder F3, one of the network sites found using the proposed methodology.

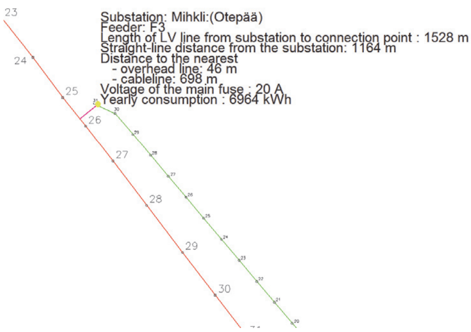

Fig.8. Example: Mihkli substation feeder 3

As seen on Fig. 8, the closest MV line (shown in red) is only a few dozen meters from the customer connection point, while the distance from the old substation along the existing LV line (shown in green) is more than 1,500 meters. Straight line distance from the nearest MV line is marked violet. As this client consumes electricity all year round, the refurbishment of the given project seems to be reasonable. The decision to go forward with any investment should always be done case by case and cannot be added to the methodology based on simple grounds.

Summary and outlooks

To conclude, this paper describes a methodology that helps network planners to find favourable investment sites. This method calculates the distance between a connection point and the nearest MVLE. If this distance is a lot smaller than the distance between the connection point and its substation (using the existing line corridor), then the optimal solution may be to build a new substation area and connect our customers to the new substation.

This method was tested in ELV network and 83% of the connection points found were considered effective (21% of which were already being refurbished). Therefore, the results were very good and this method can and should be used for network investment planning. However, the decision to go forward with the investment should always be done case by case. The restrictions used to test the methodology were chosen to provide a suitable number of feeders for testing and do not pose any actual limitations. The restrictions can be changed in order to provide more potential investment sites.

With small changes, this method should also be able to find nearby substations or LV line elements, therefore negating the need for a new substation and reducing the potential investment cost even further. Future research should evaluate how to implement such a methodology in an actual planning process. Also, there is a need for a methodology that evaluates the actual needs of a customer and its future outlooks.

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Publication IV

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Impact of price regulation methodology on the managerial decisions of the electricity DSO

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Abstract **Electricity distribution network companies' activities and managerial decisions depend substantially on the applied regulatory methodology. The impact of different regulatory methodologies on different results like security of supply, investors' attractiveness and network tariffs level has been evaluated. The rate of return method has been used for the regulation of the electricity network tariffs in Estonia since 2004. The results of 10-year regulation period have been evaluated in comparisons to other methods available.**

Index Terms **Economics, power distribution, power system management, power system reliability**.

I. INTRODUCTION

Electricity distribution network companies' activities and managerial decisions depend substantially on the applied regulatory methodology. In this article, the impact of different regulatory methods on the strategic priorities of the companies with the aim of finding the best methodology for the main strategies that a distribution network company may have, are evaluated.

Some of the previous studies have assessed the impact of quality regulation on investment decisions [1] or have looked at the financial risks associated with performance based regulations [2] [3]. Up to now there seems to be a very limited number of studies exploring connections between a regulatory method and the managerial decisions of distribution network companies.

II. METHODOLOGY OF PRICE REGULATION

Price regulation methods [4] [5] can be divided into four categories: Price cap, Revenue cap; Rate of return and Long Run Average Incremental Cost Bottom Up (LRAIC BU). Pedell [6] has described all these three methods. Several sources as Green and Pardina [7], Netz [8], Armstrong and Sappington [9], Alexander et al. [10], Hertog [11], Joskow [12] [13] have described Price Cap and Rate of Return methods. The impact of regulatory practices have been described in a number of articles and regulators' reports [14] - [18].

If the pure rate of return method is used, then the risks associated with controllable and uncontrollable costs are covered, or in other words, the company has no risk associated with the costs. This method allows the company to apply for a tariff adjustment as soon as the price is not based on the costs of the company any more. Quite the contrary, pure *price cap* method leaves all these risks to be covered by the company and leaves options for the company to decide how to eliminate those in different ways. The only difference of the revenue cap is the elimination of sales volume risk.

The price cap method presumes that if the company can manage more efficiently on its own, it can earn extra profits, and also *vice versa*: if the company does not fulfil the expectations set by the regulator or manages less efficiently, its profit will be lower and it cannot earn profit agreed by the regulator.

The basis of the *price cap* method is fixing of prices for a certain time period. Doing so, the time period must be chosen long enough to guarantee that the company can reach the expected efficiency. On the other hand, the time period should not be too long in order to avoid high risk of forecasts. Each year the prices are adjusted in accordance with inflation and factor x, which reflects the cost efficiency target, or in other words, prices should not increase faster than inflation minus the efficiency goal x.

According to the (LRAIC BU) or hypothetical network model, an ideal network is modelled assuming that the most modern and optimal technological solutions for the network configuration to supply all customers with highest quality standards is used. In case of a distribution network, it should be modelled considering the geographical location of consumers and producers and with inputs from the transmission network. The distribution network is then configured as an ideal system and is assumed to be built in the most economical way to guarantee the supply of existing customers. It is assumed that the most economical solution is applied and the network is built as a Greenfield project.

All in all, the challenge in application of different regulatory methods for DSOs often comes back to the "management of strategic gaming" [19]. Each method triggers different economic actions from companies and regulators. Even in the most advanced British utility regulation one can observe constant urge to find better regimes for the companies concerned [20] [21].

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Since detailed sector-specific regulatory rules were introduced in Estonia in 2002 [22], the authors of the present article have more than 10 years of experience in the application of the described regulation methods. For 10 years the rate of return method has been used in Estonia for price regulation of distribution network companies [23] - [25]. In Figure 1 we can explore the actual return on capital[1] for four largest network companies in Estonia (Elering, Elektrilevi, Imatra Elektrivõrk and VKG Elektrivõrk[2]) and it has been compared with the WACC applied by the regulator [26]. As one can see from the results, the network companies have usually not reached the WACC level applied by the regulator. During its 10 years of existence the largest distribution Network Company Elektrilevi has never reached the WACC applied by the regulator, its actual result has always been below the expected level. The RoR implemented in Estonia differs from the classical type of RoR. The costs included to the tariffs are not based on historical cost base and the regulator is actively demanding implementation of cost saving measures: incl. reducing of energy losses, saving on operational costs, etc. The outcome clearly indicates that the RoR implemented in Estonia does not guarantee the required return.

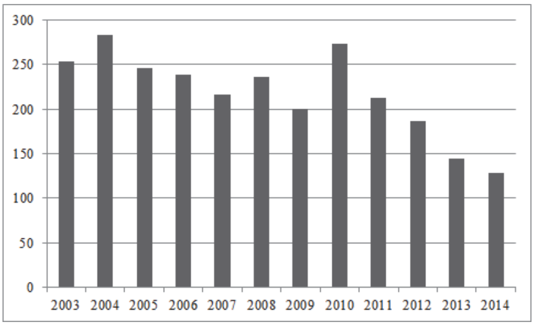

Figure 1. Return on capital of Estonian electricity network companies

III. METHOD FOR ASSESSMENT OF REGULATORY METHODOLOGY

Each regulatory method triggers a different logic of the managerial decisions taken by network companies. In the following sub-chapters one can find a comparison of the impacts assessed from the company's management perspective - how they would prioritise their activities and strategy having in mind different incentives provided by different methods.

Different methods for assessment of regulatory methodology were analysed. As it became clear to the authors that it would be impossible to provide reasonable impact assessment of regulatory methodology in monetary or technical terms without speculative assumptions, the assessment was carried out as an expert opinion of the authors on 5-point Linkert scale. The authors had to find a consensus in score in order to be approved. For each grade the rationale of the assessment discussed by the authors is also added.

Although this method is based on the authors' subjective judgements, it was considered to be the only appropriate way forward. The subjectivity is decreased by the fact that the authors represent opponent parties of the regulation. The assessments represent their long experience as practitioners in the energy sector in Estonia. As all the previously described regulatory methods have been applied in different sectors in Estonia, the assessments are based on the real practical experience.

The relevant managerial decisions of a network company can be divided into three wider groups as follows:

1) The Quality of Network Service presented in table 1
2) Cost of Network Service to Society presented in table 2
3) Risks of owners and lenders presented in table 3

On the basis of the method and criteria described above one can assess the impact of the different regulatory methods. In tables 4 to 7 the assessments of impact of regulatory methods on the managerial decisions of a power network company are described.

TABLE 1. CRITERIA FOR ASSESSMENT OF THE QUALITY OF NETWORK SERVICES SCORES

	1	2	3	4	5
Security of Supply level	Level decreases substantially	Level decreases	Current level remains	Level increases	Improvements faster than the level agreed on
Quality of Customer Service	Level decreases substantially	Level decreases	Current level remains	Level increases	Improvements faster than the level agreed on
Readiness to manage disruption crises	Very low, lack of needed financial and human resources	Below average	Average, needed financial and human resources are covered partly	Above average	High, sufficient financial and human resources are available
Long-term investments	Only critical investments are carried out to retain minimum standards	Below average	Sufficient investments in infrastructure, but not in technological development of the network	Above average	Investments are made as agreed, including also investments in innovative solutions
Stability of construction market	Investment volumes stable for 1-2 years	Below average	Investment volumes stable for 5 years	Above average	Investments volumes stable for 10 years

[1] Return on Capital is calculated on the basis of book records. Operating profit is divided by the sum of residual value of capital assets and working capital. The amount of working capital is used in calculations as 5% of the annual revenues.

[2] Elering is the TSO; Elektrilevi, VKG Elektrivõrk and Imatra Elektrivõrk are three largest DSOs in Estonia, with market shares of 87,3%; 3,0% and 2,7%.

TABLE 2. CRITERIA FOR ASSESSING NETWORK SERVICE TO SOCIETY

Score	1	2	3	4	5
Price Level	Highest price level	Slightly higher price	Average price level	Slightly lower price level	Lowest price level
Attractive-ness of the country for investors	Lowest level	Low level	Average level	High level	Highest level of attractive-ness
Admi-nistrative burden	The highest	High	Average	Low	The lowest

TABLE 3. CRITERIA FOR ASSESSING RISKS FOR LENDERS AND OWNERS

	Score				
	1	2	3	4	5
Risk of un-controllable costs and sales volume	Very high	Above average	Average	Below average	Very low
Objective regulatory lag	Very high risk	Above average risk	Average risk	Below average risk	Very low risk
Subjective regulatory lag	Very high risk	Above average risk	Average risk	Below average risk	Very low risk
Underinvestment risk	Very high	Above average	Average	Below average	Very low
Overinvestment risk	Very high	Above average	Average	Below average	Very low

TABLE 4. ASSESSMENT OF IMPACT OF PRICE CAP METHOD

Criteria	Score	Rationale for Score
Level of Security of Supply	2	Realisation of risks of increase of uncontrollable costs brings along a decrease of the operating costs; it may happen most promptly and influence first and foremost the maintenance and repair costs and investments in the network. Therefore the security of supply would be lower.
Quality of Customer service	3	As long as the company has a strong incentive to reduce its costs to raise its profit, the quality of customer service remains the same (if there is some inefficiency in the management) or decreases (by curtailing of existing services: e.g. reducing the number of people in call-centres extends the waiting time there).
Readiness to disruption crises	2	In order to increase efficiency the reserves of appliances are reduced; it makes the crises management more difficult.
Interest of the network company to carry out long-term investments	2	As long as there is some inefficiency in the management of a company, there is no impact on its long-term investments. However, when a company has reached a high level of effectiveness, the RPI-x can be only reached at the expense of long-term investments.
Stability of construction market	3	Realisation of risks of increase of uncontrollable costs brings along some reduction of investments (e.g. by restraining of works, prorogation to the future, etc.); that in turn restrains the construction market and makes the investment climate worse.
Price level to consumers	5	Price Cap should in principle give a lower price increase than RPI (however, if the investments exceed depreciation or the costs are evaluated inadequately, the regulator can also apply RPI+x in some cases,).
Attractiveness of the country to investors	3	As long as the company covers all the costs associated with connecting to the network, the cost for connection is high and attractiveness for investors low. Still, a presumed decrease of the network price can be attractive for some investors.
Administrative burden for the company	4	As the prices are adjusted for a fixed period (3-5 years), the administrative burden is rather low.
Risk of un-controllable costs and sales volume	1	All uncontrollable risks are borne by the company.
Objective regulatory lag	1	The price is fixed for a long period on the basis of the historical data: the Regulator sets the price for the following 5 years on the basis of the data from the previous full year.
Subjective regulatory lag	5	Fixed regularity, the risk is low.
Underinvestment risk	2	Strong pressure to reduce costs may lead to a decrease in the required investments.
Overinvestment risk	5	Constant requirement to reduce the costs limits the capability to invest.

TABLE 5. ASSESSMENT OF IMPACTS OF REVENUE CAP METHOD

Criteria	Score	Rationale for Score
Level of Security of Supply	3	Cost-effective network company can reduce its costs only at the expense of long-term investments, that hinders improvements in security of supply in long-term. Hedged risks help to keep the existing level of security of supply.
Quality of Customer service	4	As long as the company has a strong incentive to reduce its costs to raise its profit, the quality of customer service remains the same (if there is some inefficiency in the management) or decreases (by curtailing of existing services). Lower risk due to hedging of some associated risks.
Readiness to disruption crises	3	To increase efficiency the reserves must be reduced. Still, partly hedged risks provide possibilities to keep larger „hot reserve“ of appliances.
Interest of the network company	3	As long as there is some inefficiency in the management of a company, there is

to carry out long-term investments		no impact on its long-term investments. However, when the company has reached a high level of effectiveness, the RPI-x can be only reached at the expense of long-term investments.
Stability of construction market	4	Stable for 3-5 years, but during the regulatory period some changes in investment volumes may occur and that may impact the network construction and maintenance price and quality. A complicated situation from the partners' point of view (no long-term stability).
Price level to consumers	4	Revenue Cap should in principle give a lower price increase than RPI (however, if the investments exceed depreciation or the costs are evaluated inadequately, the regulator can also apply RPI+x in some cases).
Attractiveness of the country to investors	3	As long as the company covers all the costs associated with connecting to the network, the cost for connection is high and attractiveness for investors low. Still, a presumed decrease of the network price can be attractive for some investors.
Administrative burden for the company	4	As majority of the factors are fixed, the administrative burden is rather low. However, to compensate hedged risks the company has to keep the regulator constantly informed during the regulatory period and therefore the level of administrative burden is higher compared to Price Cap method.
Risk of un-controllable costs and sales volume	3	All uncontrollable risks are borne by the company, sales volume risk is hedged.
Objective regulatory lag	2	The price is fixed for a long period on the basis of the historical data: the regulator sets the price for the following 5 years on the basis of the data from the previous full year.
Subjective regulatory lag	5	Minimal, fixed regularity for adjustments.
Underinvestment risk	3	Strong pressure to lower costs may lead to a decrease in the required investments. Still, the risk is somewhat lower compared to Price cap method as far as some operating cost risks are hedged.
Overinvestment risk	5	Constant requirement to reduce the costs limits the capability to invest, the risk is low.

TABLE 6. ASSESSMENT OF IMPACTS OF RATE OF RETURN METHOD

Criteria	Score	Rationale for Score
Level of Security of Supply	4	Cost based price guarantees the changes of security of supply at the agreed pace.
Quality of Customer service	5	As long as company must reduce its costs, the quality of customer service remains the same (if there is some inefficiency in the management) or decreases (by curtailing of existing services). Lower risk due to hedging of associated risks.
Readiness to disruption crises	4	Reserves are kept as agreed with the regulator.
Interest of the network company to carry out long-term investments	4	Cost based price guarantees the development of the network at the agreed pace. The agreement on the allowed rate of return is the key to succeed.
Stability of construction market	5	Regular fixing of prices keeps the construction market stable.
Price level to consumers	3	In accordance with the agreed level of security of supply and customer service.
Attractiveness of the country to investors	3	As the company covers partly the costs associated with connecting to the network, the cost for connection is average and attractiveness for investors medium.
Administrative burden for the company	3	Regular adjustments (subject to the company's initiative for the price adjustment) make a medium administrative burden.
Risk of un-controllable costs and sales volume	4	Delays in adjustments are possible both by the regulator and the company.
Objective regulatory lag	4	As the price is not fixed for a long period (a potential 2-3 years' time lag still remains, as the price is set on the basis of the previous full year data), the risk is substantially lower compared to the other methods.
Subjective regulatory lag	2	Unlike the other methods there is no agreed time set – a company can apply for price adjustments any time. Possible delays by the regulator due to the bureaucracy or unwillingness to make unpopular decisions.
Underinvestment risk	4	As the regulation is strictly cost based, the risk of underinvestment is fairly low.
Overinvestment risk	3	Depends on the owner: if the owner is the state or a municipality, then the owner is also interested in the quality of the service; that is not always the case with private owners.

TABLE 7. ASSESSMENT OF IMPACTS OF LRAIC BU METHOD

Criteria	Score	Rationale for Score
Level of Security of Supply	1	If the modelled price is too low, then the company retrenches to survive. If the price is higher, then the company can maximise its short term profits by cutting the costs. This has a long-term negative impact to all selected indicators.
Quality of Customer service	1	
Readiness to disruption crises	1	
Interest of the network company to carry out long-term investments	1	
Stability of construction market	1	No stability as due to the cost-cutting only indispensable investments are made.
Price level to consumers	3	Stable as an ideal network does not change much, adjustments are only due to inflation.
Attractiveness of the country to investors	2	As long as the company covers all the costs associated with connecting to the network, the cost for connection is high and attractiveness for investors low.
Administrative burden for the company	1	Very complicated and demanding calculations. Ideal network requires permanent adjustments due to the changes in the network configuration.

Risk of un-controllable costs and sales volume	1	All uncontrollable costs and the sales volume risks are borne by the company.
Objective regulatory lag	1	Computing model calculates the theoretical costs required and the difference with the actual costs can be substantial.
Subjective regulatory lag	5	Fixed regularity, the risk is low.
Underinvestment risk	1	High risk of underinvestment as the company lacks a motivation to improve security of supply.
Overinvestment risk	5	Computing model defines the limits for investments, the risk is minimal.

IV. Selection of the Preferred Regulatory Method

Selection of a regulatory method depends on the priorities of the government. Depending on the development stage of the electricity network, the priorities of the state may be either increasing the network quality, aiming for the lowest network tariffs to society, or providing low risks for the owners and lenders. Table 8 below describes overall results of the assessment carried out in Chapter 3; it can be as a basis for the selection of the regulatory method for policymakers.

TABLE 8. AVERAGE SCORES OF THE ASSESSMENT PER METHOD

	Price cap	Revenue cap	Rate of Return	LRAIC bottom up
Quality of Network Service	2.4	3.4	4.4	1
Cost of Network Service to Society	4.3	3.7	3	2
Risk of Owners and Lenders	2.8	3.6	3.4	2.6

The data in Table 8 provide grounds for a number of important conclusions:

- If the priority is to raise the quality of network, then the Rate of Return method appears to be the most suitable approach;
- In order to prioritise the low network tariffs to society, policymakers should select Price Cap method;
- In order to attract new owners and lenders to the network business, Rate of Return and Revenue Cap methods appear to be equally attractive approaches;
- To balance all these aspects, the Rate of Return method seems to be the most appropriate solution for a long term policy selection for the electrical networks regulation;
- LRAIC regulatory method seems not to be an attractive solution for the power distribution businesses.

However, it should also be noted that for the sake of a long term stable investment climate of the network business, it is advisable to avoid frequent changes of the regulatory methods. Frequent changes of regulatory methods may ruin the attractiveness of any investment in the energy sector [27]. Therefore the Rate of Return method has a clear advantage also in terms of the stable investment climate.

In order to double-check the outcome of the analysis we have also audited the impact of the Rate of Return method on Elektrilevi OÜ, the largest electricity network company in Estonia. The company is 100% owned by Eesti Energia AS, which in turn is 100% owned by the Estonian Government. The main objective of the government has been to maintain stability of the price of the network services while increasing the quality of the network. The increase of the value or attractiveness of the company has not been a priority for the government.

Figure 2 presents the changes of the electricity supply security indicator SAIDI[3] in Elektrilevi OÜ from 2007 to 2013. The calculations of SAIDI do not take into account the impact of occasional weather impacts.

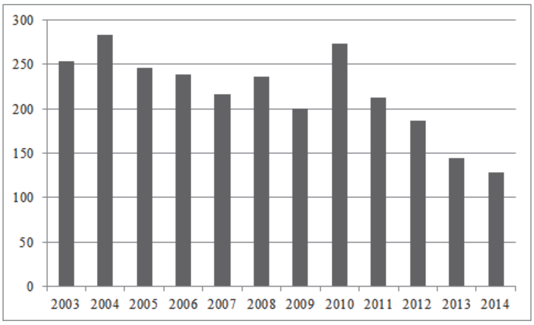

Figure 2. Changes in network quality indicator SAIDI in Elektrilevi OÜ

Graph 3 presents the network tariff and the rate on capital of Elektrilevi OÜ[4] in the timeframe of 2005-2014, adjusted to the changes of Consumer Price Index [28].

As it can be seen from Graph 2 and 3, the Rate of Return method has enabled improvements in the quality of the network services while the network tariff has remained stable for the customers and the company has earned reasonable returns on their investments. So the main objectives of the government as the owner of the utility and developer of the attractive utility services have been achieved.

[3] System Average Interruption Duration Index - the average outage duration for each customer served

[4] The network tariff of Elektrilevi OÜ is excluding the costs for transmission. The cost of transmission is excluded due to the fact, that this is a non-controllable cost for the company.

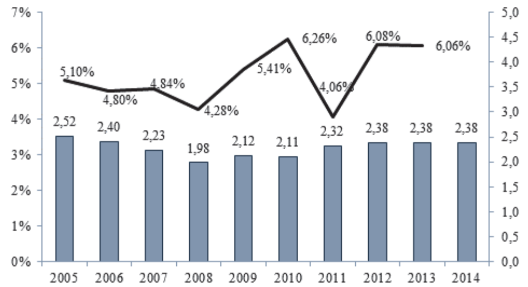

Figure 3. CPI adjusted price and return on capital of Elektrilevi OÜ services during from 2005 to 2014

V. Conclusions

The aim of the article was to analyse the impact of different regulatory methods of the electricity network companies on their strategic managerial decisions and to provide some advice for finding the most efficient method to reach the objectives of the network business. The analyses have been made by using the experience of regulation of distribution networks in Estonia. Four regulatory methods were analysed: price cap, revenue cap, rate of return and LRAIC BU. The managerial decisions analysed were divided into the network quality, cost of network service to society and the risk level for the owners and lenders.

As a result of the analysis and based on Estonian experience the Rate of Return method was assessed to be the best method for long term objectives. The impact of Rate of Return method was also controlled against the overall results of the activities of Elektrilevi OÜ, the largest distribution company of Estonia, where one can observe improvements in the quality of the network services while the price of the network service remained stable and its profit of the utilities was in an expected range.

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