Analysis of distribution network balanced reliability level on the basis of total society production in Estonia

Overview and Background
Results

entellgenio

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Table of content

1 Overview and background of the project

According to the Estonian Long-term Power Scenario 2030 (Energiamajanduse Arengukava Aastani 2030) “the average total duration of interruptions in the distribution network in minutes and consumption point per year shall not exceed 90 minutes”.

In the previous project it was analysed what amount of investments in the electricity network is necessary for Elektrilevi to reach $SAIDI_{total}$ 90 min by 2030. The outcome of the project was that the goal of $SAIDI_{total}$ 90 min cannot be achieved by Elektrilevi with the current budget by 2030. The significant investments in the electricity network that are necessary to reach this quality goal, lead to the question, if it is economically reasonable to continue to pursue this goal. Therefore two additional questions were analysed during this project for Estonia (not only Elektrilevi):

1) How can the costs for society and the investments in the electricity network (incl. stock loss value) for Estonia be balanced? What is the resulting $SAIDI_{total}$ value for Estonia and Elektrilevi in 2030?
   What is the split between companies and reliability areas?
2) How do the results compare to the required budget for $SAIDI_{total}$ 90 min?

The following two scenarios are defined to answer these questions.

1.1 Scenario 1: Minimizing Total Expenses

To calculate a balanced level for costs for society, investments in the electricity network and stock loss value, an optimization scenario was set up: the target function is the overall expenses that consist of these three costs that are minimized. The first two years (2018 and 2019) are fixed, because the budget for these years is already finalized. Changes to budget allocations can therefore only be realized starting in 2020. A technical restriction had to be set to ensure the stability of the network. Based on experience by Elektrilevi the maximum value of assets that are allowed over lifetime was set to 25 percent. This limit is fairly high and has to be validated further.

1.2 Scenario 2: Reaching SAIDI total 90 min for Estonia

The results from the previous project on how to reach $SAIDI_{total}$ 90 min for Elektrilevi were used as a starting point for the optimization for all electricity utilities of Estonia. The restrictions on minimum budgets, the maximum amount of measures and asset value in condition 4 were taken from scenario 1. The budget for the first two years was also set as fixed, making changes only possible in the years 2020-2030.

2 Methods and model description

2.1 Methods

The simulation model that is built is based on the principles of System Dynamics. This in an approach to model the behaviour of complex systems with stocks, flows and feedback between the elements. For details about the used methods see (Sterman 2000).

The solution finder is based on the methodology of evolution strategies a subdomain of evolutionary algorithms which are based on ideas of adaptation and evolution. It belongs to the general class of evolutionary computation. Evolutionary algorithms are most suitable for optimizing systems including: nonlinear relations, step functions, many influencing variables, many restrictions, fast and dynamical (adaptive optimization) and produce robust results.

A more detailed description of the methodology can be found in the previous analysis for Elektrilevi (Hopfensitz/Spitzer 2017).

2.2 Model description and assumptions

2.2.1 Model extension to include all of Estonia's distribution network

One objective of this analysis is to find an overall best solution for the electricity network of Estonia. It was necessary to add other DSOs to the simulation model in addition to Elektrilevi. This was done by extending the existing simulation model. A new level was added to the asset tree to differentiate between Elektrilevi and other DSOs of Estonia. Below that level the differentiation between the reliability areas and the asset trees are taken from the previous simulation model (see Hopfensitz/Spitzer 2017 for more details). 35 kV overhead lines and cables were moved to separate asset groups, the remaining tree was used without any further changes. The overall structure of the extended model can be seen in Figure 1.

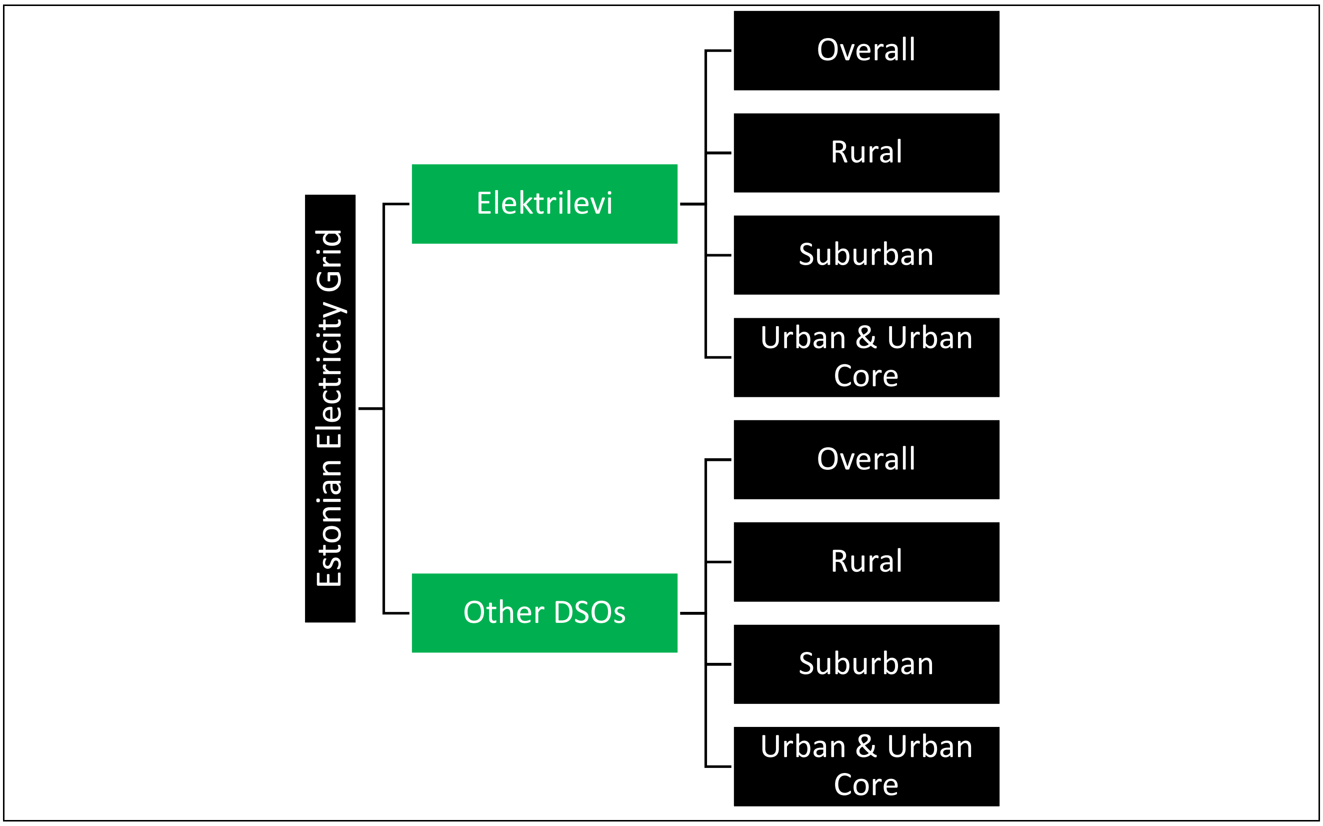

Figure 1: Structure of simulation model

2.2.2 Assumptions for other DSOs

Required data for other DSOs were put together by collecting data from other DSOs (in cooperation with Tallinn Technical University) and making assumptions based on the network of Elektrilevi:

- Asset stock

  The amount per asset group was provided by other DSOs. In cases where the level of detail was not enough to calculate the amount per element in the asset tree, assumptions based on the proportions for Elektrilevi were made. Since the simulation model is based on age and condition the amount was converted to amount per year based on the percentage age distribution of Elektrilevi. This was done separately per reliability area.

- Faults and Quality

  The total number of faults per voltage level was given by other DSOs. These numbers were used to calculate damage rates per asset group and reliability area by using the percentage fault distribution of Elektrilevi. Other quality parameters like average interruption duration and average number of interrupted customers were taken from the model of Elektrilevi. The model was calibrated and the calculated results for SAIDI in 2018 were compared to the values that were provided.
  The percentage reduction of planned SAIDI was also set according to the assumed reduction for Elektrilevi

- Budget for 2018 & 2019

  Budget for 2018 and 2019 is fixed and already planned. Therefore it is not changeable and for the first two simulation years fixed in the simulation model. This was done by using some information that was provided by other DSOs and assumptions from Elektrilevi. The budget split to asset groups and measures was done based on the percentage budget split of Elektrilevi in 2018. For decommissioning the percentage per year was used from Elektrilevi. The budget for other DSOs is fixed at 2.5 Mil. € per year for 2018 and 2019.
  Split of number of customers to reliability areas according to the relations from Elektrilevi

- Further parameters

  Costs per measure, maintenance and inspection intervals as well as technical lifetime and aging behaviour were taken from Elektrilevi.

2.2.3 Assumptions for Elektrilevi

For Elektrilevi most of the simulation parameters were used from the previous project. The CAPEX budgets for 2018 and 2019 were used and split according to the planned budget allocation to asset groups. Based on the given costs per measure, the CAPEX budget was converted into measure amounts. The OPEX budget was used to calculate the costs for operational measures like repair and maintenance. The asset stock data was updated based on the measures that were defined in the previous model for 2017 leading to the starting point for the simulation in 2018.

2.2.4 Results of data validation

Based on these assumptions the simulation model was filled and three steps of data validation were done for the simulation model: grid length, SAIDI and CAPEX/OPEX. SAIDI was compared to the 3-year average to exclude singular external events like storms.
The overall network length is 64,032 km which is split between Elektrilevi and the other DSOs by 60,122 km to 3,911 km.

Cost per rel. area	CAPEX [€]		OPEX [€]	
	Elektrilevi	Other DSOs	Elektrilevi	Other DSOs
Grid	**51,368,899**	**2,521,541**	**12,146,902**	**576,288**
Overall	8,830,392	333,729	1,398,466	44,995
Rural	14,078,698	717,657	6,969,492	326,520
Suburban	19,099,736	920,635	2,717,207	152,303
Urban	9,360,074	549,520	1,061,737	52,470

Table 1: Validation of budget allocation

Quality per reliability area	Number of faults	Number of faults	SAIDI unpl. [min/a]	SAIDI unpl. [min/a]
	Elektrilevi	Other DSOs	Elektrilevi	Other DSOs
Grid	**16,673**	**247**	**134.8**	**24.8**
Overall	73	0	1.5	0.0
Rural	10,684	185	600.0	113.4
Suburban	4,873	44	108.8	19.8
Urban	1,043	18	39.3	7.2

Table 2: Validation of quality calculations

2.2.5 Technology considered in the model

There are several technologies that have to be considered when modelling the development of SAIDI over the next 10 to 20 years. The following technologies were considered during the project:

- Insulated Overhead Lines

  In medium and low voltage a high percentage of SAIDI is generated by non-insulated overhead lines. These overhead lines are not only often old and therefore in a bad condition, but also very susceptible to external influences like storms. Converting these overhead lines to insulated overhead lines or cables can improve SAIDI values significantly.

- Automation

  Automation can be added to the network to improve SAIDI by adding switches that can isolate interruptions after a fault has occurred. It requires two separate supply sources from the area substations. Minimum three switches with short circuit current commutation capability located in the main line are necessary to localize the fault and switch the supply to another substation. Automation is only allowed, if the localizing time with automation is shorter than the localizing time using crews.
  Therefore the field of application is limited for automation and it has to be combined with other measures to achieve better SAIDI values.
  Automation has been modelled by adding separate asset types to the asset tree that reflect OHL or cables with added automation. They have the same set of parameters than the asset types without automation apart from the quality parameters (average duration of interruption and average affected customers). A transition between OHL (or cables) to OHL (or cables) with automation converts standard assets from condition 1-3 to assets with automation without changing their age or condition. Therefore, the cost of this conversion is the average cost per km to add automation to the network. Assets from condition 4 are not converted to automation assets, because they have to be completely replaced or taken out of the network.

- Cable Tubes

  Besides the automation, MV cables in tubes were added to the asset tree for the urban reliability areas. The construction costs of this asset type are significantly lower compared to regular MV cables because there are no costs for digging and resurfacing. The amount MV cables and/or MV OHL that can be converted to MV cables in tubes has to be limited by restrictions in the solution finder to reflect the actual availability of these tubes.

- Decommissioning

  Due to network redesign and demographic changes it was estimated that the current network will decrease until 2030. This is reflected in the model in decommissioning amounts that are defined for several asset types (mostly LV and MV). The total decommissioning amount in the model is 1950 km until 2030, which is approximately 3% of the current grid length. After 2030 there is no more decommissioning in the model. Decommissioning was only done on assets in condition 4.

2.2.6 Interruption costs for society

The interruption costs for society are calculated for each reliability area. The basis of the calculations are society loss cost rates in different reliability areas per kWh energy that is not supplied (CENS; Raesaar 2018). In this analysis the costs for SAIDI unplanned are higher than the costs for SAIDI planned, which makes it necessary to do the following calculations separately for unplanned and planned SAIDI. To calculate the society costs per minute interruption assumptions and transformations were made by Tallinn University of Technology for this project:

The following simplified formula for energy not supplied was defined:

$$\text{Energy not supplied} = P_{average} * SAIDI$$

with $P_{average}$ being defined as the average load per reliability area and SAIDI the total SAIDI per reliability area.

$$P_{average} = \text{Sold Energy} \;/\; 8760$$

Cost per interrupted minute (CIM) can therefore be calculated with the following formula:

$$CIM = CENS * P_{average} / 60 = CENS * \text{Sold Energy} \;/\; 8760 / 60$$

Indirect interrupted power costs (CD) have to be added to these costs as well as predicted load and consumption adjustments during the timeframe of this analysis:

$$CIM_{corr} = CIM * (1+CD/CENS)$$

$$P_{max} = P_{max,0} * (1+\alpha)^n$$

with

P_{ma} *starting year peak load;*

a *peak load growth rate;*

n *half the length of the planning period (set to 10 in this analysis)*

As a result the expected costs per interrupted minute (ECIM) can be calculated with the following formula:

$$ECIM = CIM_{corr} * (1+\alpha)^n$$

Based on these findings ECIM was calculated for the reliability areas urban, suburban and rural for Elektrilevi and the Other DSOs. The results already include the differences in total power supplied between the reliability areas and the DSOs. Therefore the range of the results is between over 165 000 €/minute (Elektrilevi, urban) and around 330 €/min (Other DSOs, rural).

		Urban	Suburban	Rural
CENS unplanned	€/kWh	15.96	15.19	9.23
CENS planned	€/kWh	10.71	9.65	4.48
CD unplanned	€/kW	1.58	1.53	0.83
CD planned	€/kW	0.22	0.30	0.20
Elektrilevi				
$P_{average}$	kW	430077	307429	36500
CIM unplanned	€/min	114401	77841	5616
CIM planned	€/min	76769	49462	2728
CIM_{corr} unplanned	€/min	125726	85679	6123
CIM_{corr} planned	€/min	78346	50975	2850
$(1+\alpha)^n$	-	1.32	0.97	0.89
ECIM unplanned	**€/min**	**165713**	**83143**	**5426**
ECIM planned	**€/min**	**103263**	**49466**	**2526**
Other DSOs				
$P_{average}$	kW	26480	18928	2247
CIM unplanned	€/min	7044	4793	346
CIM planned	€/min	4727	3045	168
CIM_{corr} unplanned	€/min	7741	5275	377
CIM_{corr} planned	€/min	4824	3139	175
$(1+\alpha)^n$	-	1.32	0.97	0.89
ECIM unplanned	**€/min**	**10203**	**5119**	**334**
ECIM planned	**€/min**	**6358**	**3046**	**155**

The results for the costs for society were compared to the results of the 2013 report about costs for society based on energy not served by TTÜ (Raesaar 2013). In the last 5 years SAIDI has changed significantly in Estonia making a direct comparison impossible, but the costs are in a similar range (between 20 and 30 Mil. € per year for Elektrilevi).

2.2.7 Stock Loss

Stock loss value (SLV) is defined as the remaining value of assets that are removed from the networked (by decommissioning, renewal or conversion) before the end of the technical lifetime.

$$\begin{aligned} SLV &= \sum\nolimits_{age \leq lifetime} amount\ of\ assets\ scrapped_{age} * remaining\ lifetime * amortisation\ rate \\ &= \sum\nolimits_{age \leq lifetime} amount\ of\ assets\ scrapped_{age} * (lifetime - age) * \frac{Replacement\ Value}{lifetime} \end{aligned}$$

High stock loss value therefore indicates overinvestments that lead to scrapping of assets before the end of lifetime.

2.2.8 Overall Expenses

The Overall Expenses are calculated as the sum of investments (CAPEX), the costs for society and the stock loss value:

Overall Expenses = CAPEX + Interruption Costs for Society + Stock Loss Value

Overall expenses therefore include the costs that are connected to the management and use of the infrastructure and can be used as a target function to find the best strategy considering all these components.

Note: OPEX is not included in the overall expenses since the assumption was made that it can be seen as a constant that is added to the overall expenses. Further analysis can be done to detail the effects of an increase or decrease of faults on OPEX.

2.2.9 Budget, technical and asset service requirements

The solution was set up with restrictions to reflect several requirements from different areas that have to be considered.

2.2.10 Investment budget requirements

Elektrilevi wants to reduce the technical risk in the MV primary substations asset group by investing in renewal measures over the next years. Because the fault statistics for that asset group are not very detailed, they cannot reflect the effect of one significant failure in a primary substation on the overall SAIDI. Therefore, a minimum amount of money has to be spent on primary stations to ensure that enough money is available to reduce the risk. Other minimum reliability investment budget restrictions were set for high voltage OHL and cables as well as stations. The total sum of budget that is reserved for these measures is 12.2 Mil. €. It has to be noted that the restriction in the previous analysis amounted to 17.5 Mil. €. Further analysis showed that this lead to over-investments in several asset groups, so the restrictions have been lowered accordingly. This also has an effect on the results for the necessary budget to reach $SAIDI_{total}$ 90 min.

2.2.10.1 Technical requirements

It is assumed that 5 % of meters that are in condition 4 have to be replaced per year. The assumption for the remaining 95 % of meters that are over the technical lifetime is that they can be used longer by doing maintenance to prolong the lifetime.

2.2.10.2 Asset Construction requirements

Furthermore, the solution space is restricted because the amount of measures that can be carried out per year are limited by the available resources and the supply security of the network. Therefore, maximum values were set for the amount of achievable constructions per year. These numbers are based on the available resources for Elektrilevi and adjusted for the overall network:

	Max amount
6 - 20 kV bay	208
110/35 - 6 kV power transformer	4
20 - 6/20 - 6 kV transformer	4
35/6 - 20 kV power transformer	24
35 kV bay	54
35/6 - 20 kV area substation	13
6 - 20/6 - 20 kV distribution substation	10
35 kV cable	4
6 - 110 kV sea cable	5
MV cable	213
35 kV overhead line	95
35 - 110 kV pole	97
MV insulated OHL	2582
MV non-insulated OHL	0
MV pole	5362
Building station	21
Compact station (new type)	437
Compact station (old type)	0
Kiosk substation (brick)	0
MV / LV transformer	1075
Pole-mounted station	537
LV cable	321

Table 3: Maximum amount of construction (km or pcs. per year)

3 Main Results of the analysis

3.1 Minimizing the overall expenses of the electricity network in Estonia consisting of costs for society, investments and stock loss value

In 2018 CAPEX accounts for two thirds of the overall expenses at 54 Mil. €. The second largest contributor are the costs for society at 25 Mil. €, followed by the stock loss value at only 3 % of the overall expenses. While CAPEX is higher than the costs for society in all reliability areas, the relation is especially unbalanced in the rural area where CAPEX is at 15 Mil. € while costs for society are only at around 4 Mil. €. This indicates that from an economic perspective the current investment budget in the electricity network, the costs for society and the stock loss value are neither balanced nor minimized.

In the project two very different strategies on how to manage the electricity network in Estonia were calculated: the first scenario minimized the overall expenses, whereas the second scenario aimed to reach the $SAIDI_{total}$ 90 min goal by 2030. Figure 2 shows how costs for society, investments in the electricity network of Estonia and stock loss value differ for these scenarios:
In the Min expenses scenario the investments are reduced drastically after 2019 to reach values at around 30 Mil. until 2030. At the same time the costs for society are not increasing, but even leads to a small decrease to 21 Mil. € in 2030. This means that the reduced budget is allocated efficiently to still manage to decrease the number of interruptions in the electricity network. The stock loss value stays on a very low level at around 2-3 Mil. €. This shows that with this strategy mostly assets over their technical lifetime are replaced.

The SAIDI 90 scenario in contrast increases investments after 2019 to a level at around 60 Mil. € per year. This investment strategy leads to a quality improvement to reach the SAIDI goal. As a result the costs for society decrease to 15 Mil. € in 2030. Compared to the values from 2018 the necessary cumulated increase in investments outweighs the reduction of costs for society by factor 5. In addition this leads to an severe increase in stock loss, because 90 minutes can only be achieved by replacing assets that are within their lifetime, but still contribute a high number of minutes to SAIDI. This effect can especially be seen for overhead lines.

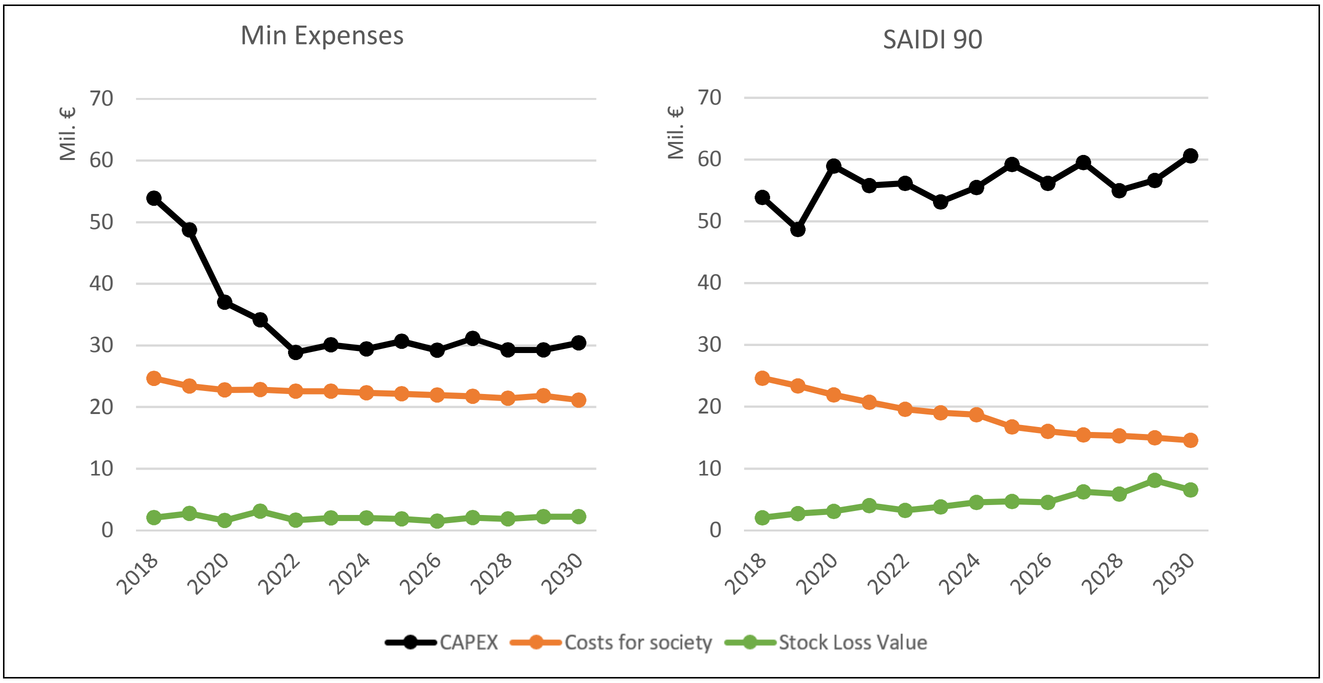

Figure 2: Costs for society, investments and stock loss value comparison

3.2 SAIDI$_{total}$ for Estonian distribution networks and Elektrilevi in 2030

The Min Expenses scenario reaches a SAIDI total of 152 min in 2030. This is only a slight decrease compared to the current level. With the additional investments in the SAIDI 90 scenario, SAIDI minutes in rural is cut in half by 2030 (280 min instead of 630 min) compared to the Min Expenses (SAIDI 152 min) scenario - as it is shown in Figure 3. This validates the previous findings that 90 minutes can only be achieved, if the quality in the rural reliability area is improved substantially. The SAIDI levels in suburban, urban and overall are lower in the SAIDI 90 scenarios as well. The SAIDI 90 goal can be achieved with a combination of 95 min for Elektrilevi and 33 min for the other Estonian DSOs. Further analysis showed that additional reduction from 95 min to 90 min just for Elektrilevi would lead to very high additional investments and a substantial increase in stock loss value.

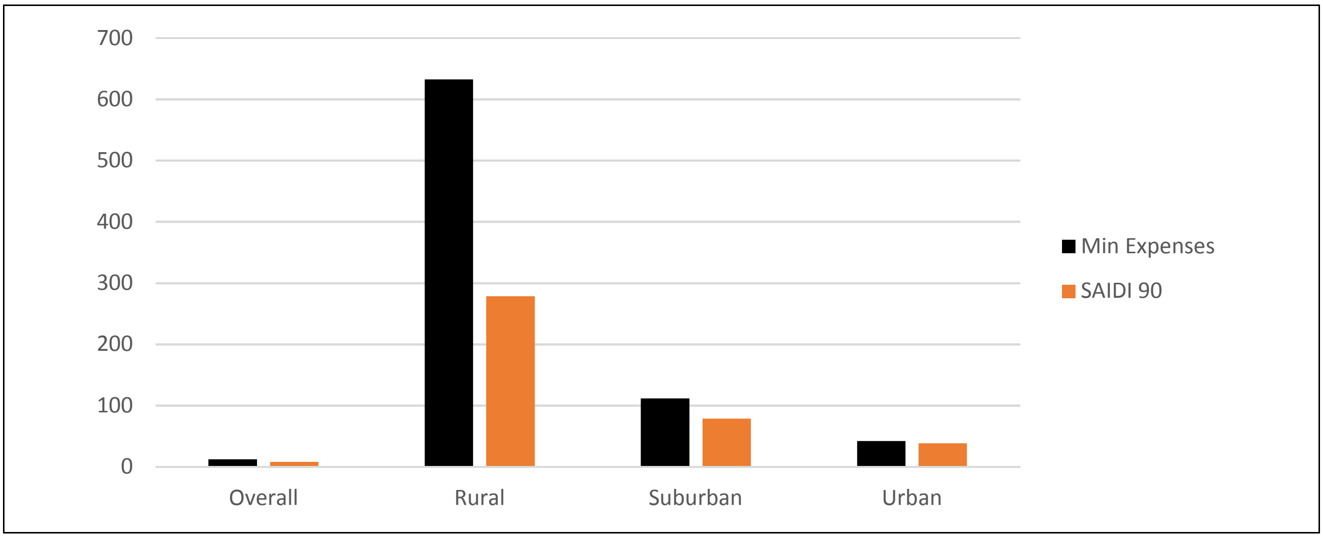

Figure 3: SAIDI total min per reliability area and scenarios Min Expenses (SAIDI 152 min) and SAIDI 90 in 2030

3.3 Split of investments among companies and reliability areas

To make the investment level between Elektrilevi and the other DSOs comparable, the investments per company can be divided by the size of the network. In the SAIDI 90 scenario these investments per km network for Elektrilevi are at 854 €/km in 2018 and increase slightly until 2030 (912 €/km on average). For the other DSOs the investments per km are at 645 € in 2018 and increase to reach a similar level compared Elektrilevi (803 €/km on average). This shows that the result allocates the investments more equally across the DSOs. The majority of these additional investments is necessary for the medium voltage level confirming that a massive shift in budget allocation from low voltage is necessary over the coming years to improve the quality of the network.

The SAIDI 90 scenario confirms the findings of the previous analysis that massive investments are necessary to achieve the given quality target in the short period of time until 2030. Compared to the Min Expenses scenario the cumulated additional investments amount to 287 Mil. € (see Figure 4). Most of these additional investments are necessary in rural (47 %), followed by suburban (30 %) and urban (21%). This contradicts the findings that the rural reliability area already has the biggest imbalance between investments and costs for society. Achieving $SAIDI_{total}$ 90 min will increase this imbalance. As the increase in owner revenue is also outweighed by the additional investments that are necessary, the $SAIDI_{total}$ 90 min goal cannot be justified from an purely economic perspective in the simulation model.

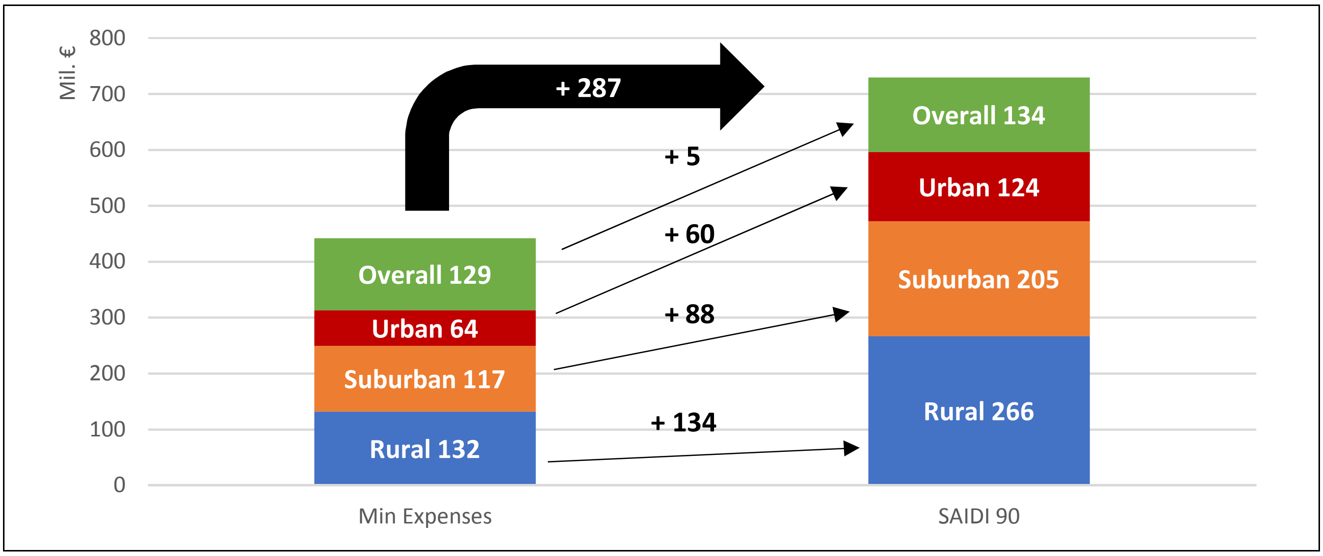

Figure 4: Cumulated investments for both scenarios

4 Conclusion, insights and recommendations

On a technical level it was confirmed that weatherproofing the network has a very high effect on the quality. After the completion in low voltage in the coming years this makes a massive shift in investments necessary to continue the work for medium voltage networks. The feasibility of this shift has to be analysed further to confirm the practicability of the results. Setting the $SAIDI_{total}$ 90 goal for all of Estonia and not only for Elektrilevi's network leads to proposed a split of SAIDI goals between Elektrilevi and the other DSOs of 95 to 33 min. This will lead to a decrease of required investments for Elektrilevi compared to the findings in the previous analysis.

The network in the rural area is most in need of additional investments to reduce the technical risk and improve quality. There are many kilometres of non-insulated lines and poles that are over their technical lifetime. Not investing in these assets will lead to a massive increase in interruptions over the next years and will ultimately pose a high risk to the overall stability of the network. Therefore a restriction in the scenario to minimize the total expenses had to be set to limit the amount of assets that are allowed over the technical lifetime.

Despite the low population density and therefore lower effect of individual faults on the total SAIDI minutes in rural, the SAIDI 90 scenario shows that better quality in the overall network can only be achieved with additional investments in rural. Since this is however neither economically reasonable for Elektrilevi nor Estonia, as the allowed owner revenue does not increase in the same way as the necessary investments in the network and the additional investments and stock losses outweigh the reduction in costs for society, it has to be discussed, if the 90 min overall goal poses a reasonable goal for the rural areas and how the necessary costs of around 300 Mil. € compared to the Min Expenses scenario can be covered.

At the moment the customers in urban and suburban areas are also paying for the rural connections since the tariff is fixed for all customers. This cross subsidization is expected to increase massively if the $SAIDI_{total}$ 90 min goal has to be achieved by 2030. It is recommended to conduct further analysis on the effect on the tariffs in both scenarios.

Furthermore it is recommended to consider setting more nuanced goals that consider not only $SAID_{total}$ for all of Estonia. The concept of reliability areas should be included in these goals to allow to set individual limits and targets that are adapted to the individual structural characteristics. An overall goal can then be deducted based on these individual goals. Besides setting SAIDI goals it might be necessary to also set goals for other factors like amount of assets that are allowed over

their technical lifetime or targets about removing old technology like non insulated overhead lines from the network to ensure that investments are made in a meaningful way.
The guidelines that are set do not match the current state of the electricity network in Estonia.
The results also conform the findings from the previous analysis that current guidelines, state of the electricity network and regulation methods (e.g. use market replacement costs) are not balanced at the moment and need to be adjusted.

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