# INVESTING IN THE FUTURE

# LONG-TERM OPTIMIZATION OF ASSET REPLACEMENT IN THE COLLECTIVE REGIONAL ELECTRICITY GRIDS OF THE NETHERLANDS

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## *ABSTRACT*

*In this paper we present the results of a study on the effects of asset ageing on the reliability and affordability of the collective regional electricity grids of The Netherlands.*

## INTRODUCTION

A challenge for DNOs is the realization of a socially optimal trade-off between reliability and customer costs. After all, a perfectly reliable grid comes at a prohibitive price. As a result of ageing of grid components, or *assets*, postponement of replacement investments can lead to a deterioration of reliability. At the same time, early replacements will have adverse consequences for the (short-term) affordability for customers. It is the challenge for a DNO to replace aged parts of the grid at the right time, in order to achieve the desired future-proof quality of service and low customer costs.

This has given rise to a study, conducted under the flag of *Netbeheer Nederland*, the association of Dutch electricity and gas grid companies, by a delegation of experts from all Dutch DNOs for electricity. In alphabetical order, these are: *Cogas*, *DNWB*, *Endinet*, *Enexis*, *Liander*, *Rendo*, *Stedin*, and *Westland Infra*. Its objective: to obtain a collective view on the effects of asset ageing on reliability and affordability, and to provide insight into replacement policies to anticipate these effects.

## APPROACH

The following phases were completed:

1. Determination of the current structure, asset populations and age distributions of the collective Dutch regional electricity grids.
2. Determination of the current and estimation of the expected future failure behaviour of assets.
3. Development of a numerical model which predicts future asset failures and their effects on reliability and affordability, and which calculates the theoretically optimal replacement policy.
4. Determination and evaluation of common scenarios.

The study adopts an umbrella approach, in which different types of electricity components, or asset *types*, are combined in one model, which forms an outline representation of the current grid. The central question is what the optimal replacement policy is for these asset types during the next decades. The optimization problem has been formulated as a Linear Program. The objective function is the net present value (NPV) of a weighted sum of expected risk costs and preventive replacement costs, minimized over a planning horizon of up to 100 years. The discount factor used in the NPV calculations is based on the weighted average cost of capital (WACC) as determined by the Dutch energy regulator for the current regulation period for the DNOs. The model input comprises the following elements.

### Grid structure

The structure of the collective Dutch regional electricity grids has been determined by means of a collection of asset types. In total, 24 asset types are distinguished, distributed over various asset categories, e.g., transformers, switchgear, protection and cables. Each asset type has a current age distribution. By way of illustration, Figure 1 shows the cumulative amounts, per year of construction, of MV/LV transformers that are currently (still) present in the grid.

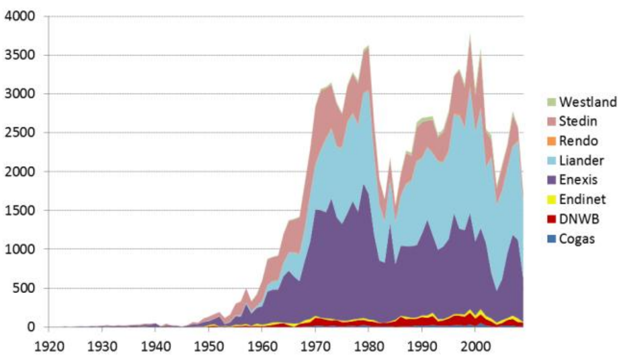


**Figure 1** Age distribution of MV/LV transformers

Because of new customers the size of the grid will grow in coming years. This impacts the asset age distributions as well as the SAIDI, which is based on the number of connections. The model anticipates this effect. In our study the expected growth of the grid is based on the future growth of the number of households in The Netherlands as predicted by the national central bureau of statistics [1].

## Reliability

In accordance with the international PAS-55 framework, all Dutch DNOs have adopted a Risk Based Asset Management system, covering a collection of company values, which are mutually weighed by means of a monetary conversion. This leads to a quantitative valuation of each company value. The valuation of reliability is expressed as € per customer minute lost, or €/CML.

Furthermore, the model follows the Dutch methodology of *Nestor Registration*, used by the collective DNOs to assure a univocal reporting of failure data and common statistics, in particular the SAIDI and SAIFI. Nestor is based on the number of failures on the one hand and the risk per failure on the other; all asset failures are logged and broken down to characteristics such as the corresponding asset type, failure cause and resulting number of CML. All this data is gathered nationwide since 1975 and comprises a large, ever-growing amount of failures and interruptions.

## Failure curves

Ideally, the decision if and when to replace assets is taken on the basis of as much information as possible, preferring factual observations to assumptions. In our study we have subdivided the determination of the failure behaviour of assets into historical failure behaviour on the one hand and expected future failure behaviour on the other. Although future failing will manifest itself only with the lapse of time, it can be estimated by means of available historical failure data and expert judgement. The model considers *age-dependent* failures, e.g., as a result of corrosion or wear, and *age-independent* failures, e.g., as a result of third party interference, in particular excavation work. Furthermore, failures are considered to be either *fatal* or *non-fatal*. Fatal means the asset is beyond repair and must be replaced correctively; non-fatal means the asset is still repairable.

For each asset type we have defined a failure curve, which incorporates both age-dependent and age-independent failure behaviour, and a fatality curve. For each age the failure curve indicates the failure probability in the next year and the fatality curve indicates the probability that such a failure is fatal. The model is flexible to such an extent that both curves can take arbitrary shapes. Besides simulating the physical failure behaviour of components, the fatality curve can be used to simulate a deficiency of spare parts or knowledge of obsolete components.

Using extensive failure data from Nestor, the failure curves have been constructed and calibrated such that for each asset type the number of failures in the coming year as projected by the model equals the actual average yearly number of failures. For MV cables, divided into PILC and XLPE, a remaining life model developed by KEMA [2] was used to construct the failure curves. For transformers and switchgear, Weibull distributions as modelled in [3] were adopted.

## Failure costs

Depending on the asset type and failure cause, failures lead to a number of CML. Using Nestor, for each asset type the expected number of CML per failure was determined. Besides interruption, failures lead to costs. Non-fatal failures lead to costs of repair, whereas fatal failures lead irrevocably to corrective replacement costs. The expected costs of non-fatal failures and preventive replacements have been determined using index prices and subsequent calculations for real, finished projects.

## Policy constraints

The model allows for a variety of constraints, which can be used to enforce certain replacement policies. For the purpose of our study we have implemented two constraints in particular. The first concerns minimum and maximum numbers of preventive replacements, which can be specified per year and per asset type (or group of asset types). Minimum amounts can be used to effectuate replacements commissioned by supervisory authorities, maximum amounts to model capacity or budget constraints, and fixed amounts to evaluate existing replacement programmes.

The second constraint concerns a reliability risk tolerance. For each year in the future a maximum SAIDI can be specified. The optimization routine will then determine the most favourable replacement policy that obeys this condition, or indicate that such a policy does not exist.

# RESULTS

In this section we discuss the numerical results obtained from our model, based on scenarios collectively agreed on.

## Common scenarios

We consider the scenarios listed in Table 1.

| replacement policy | valuation CML |
|---|---|
| 0 - None | |
| 1 - Plans issued in 2009 | |
| 2 - Theoretically optimal | a - € 0.50 / b - € 1 / c - € 5 |
| 3 - Theoretically optimal | SAIDI target: 24 minutes |

**Table 1** Common scenarios

Scenario 0 is a (fictitious) base scenario, which evaluates the consequences of not carrying out any preventive replacements at all. In this scenario, assets are only replaced after a fatal failure.

Scenario 1 evaluates the consequences of the replacement plans for the 5-year planning horizon 2010-2014 that were issued by the respective DNOs to the Dutch energy regulator in 2009. Table 2 outlines these plans in terms of the weighted average annual replacement percentages of the existing populations.

| asset type | annual replacements |
|---|---|
| HV/MV transformers | 0,6% |
| HV/MV switchgear | 1,1% |
| MV cables | 0,3% |
| MV (transport) switchgear | 0,4% |
| MV (distribution) switchgear | 0,7% |
| LV cables | 0,2% |
| Customer supply cables | 0,5% |

**Table 2** Annual replacement plans dated 2009

As part of scenario 1, these percentages are considered to be "structural", i.e., they are considered to apply to the further future as well. For non-mentioned asset types, such as MV/LV transformers, protection and LV switchgear, structural annual replacements of 0.2% are assumed.

Scenario 2 considers the theoretically optimal replacement policy, based on two different valuations of reliability used by Dutch DNOs, namely 0.50 €/CML and 1 €/CML, and in addition a substantially higher valuation of 5 €/CML.

Finally, scenario 3 considers the effect of a SAIDI target. This embodies the strategic objective to maintain the current reliability towards the future. In this scenario the optimal replacement policy is computed under the explicit condition that each year the expected SAIDI does not exceed 24 minutes, which is the current reliability.

## Comparison of future SAIDI

Below we discuss the numerical results obtained for the scenarios described above, focusing on the implication for the reliability and the level of replacement investments. The main result is captured by Figure 2, which shows the expected development of the SAIDI over the next 50 years.

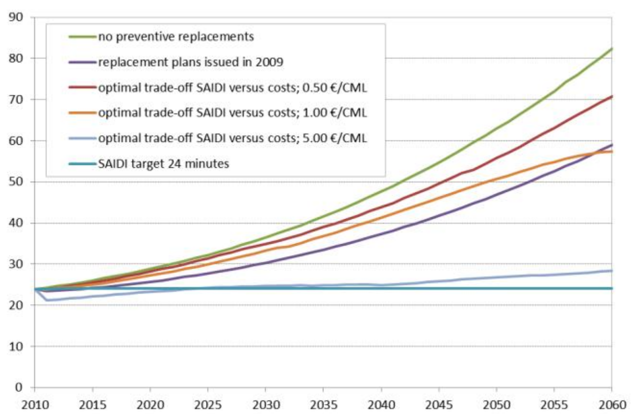


**Figure 2** Projected development of the SAIDI

**Scenario 0: No preventive replacements**
The green curve in Figure 2 shows that only replacing assets correctively will lead to an accelerating increase in the SAIDI, reaching 80 minutes by 2060. This illustrates the importance of timely replacements.

**Scenario 1: Plans issues in 2009**
We see from the purple curve in Figure 2 that the current 5-year plans suffice to maintain the current reliability for the planning horizon it was issued for. With a prolongation of these plans, the current reliability can be maintained until around 2020. Thereafter, the SAIDI will start to increase steadily, reaching 30 minutes around 2030 and subsequently by roughly 10 minutes per decade. Hence, a structural continuation of the replacement percentages as recorded from the 2009 plans will be insufficient to achieve a long-term continuation of the current reliability.

**Scenario 2: Theoretically optimal replacement policy**
By not imposing any fixed replacement numbers, we enable the model to compute the theoretically optimal replacement policy. We see from Figure 2 that valuations of 0.50 €/CML and 1 €/CML both result in a gradual increase in the SAIDI. Apparently, these valuations, in combination with the failure behaviour and age distribution of the grid, do not outweigh the cost of preventive replacement. As a result of the optimal trade-off between reliability and affordability, a much higher SAIDI is accepted. Furthermore, it appears from Figure 2 that the current replacement plans correspond to a valuation of roughly 1 €/CML and that a valuation of at least 5 €/CML is required to maintain the current reliability in the distant future.

**Scenario 3: Theoretically optimal replacement policy**
By imposing a maximum annual SAIDI of 24 minutes, we can assess the feasibility of the strategic objective to maintain the current reliability towards the future. We can see from Figure 2 that in expectation this is indeed possible. The other side of the coin is that this will inevitably require higher replacement investments. These consequences are discussed below.

## Comparison of future replacement investments

For scenarios 1-3, Table 3 summarizes the financial consequences for the next 50 years of the resulting replacement programmes.

| | scenario | | | |
|---|---|---|---|---|
| 50 years | 1 | 2a | 2b | 3 |
| Absolute replacement investments (M€) | 7,820 | 623 | 2,758 | 20,304 |
| Average per year (M€) | 156 | 12 | 55 | 406 |
| NPV (M€) | 2,465 | 91 | 401 | 4,500 |

**Table 3** Summary of projected replacement investments

We see that in the existing replacement plans, an average of around 150 M€ is spent annually on replacements. The theoretically optimal policy spends an annual average of only 12 M€ (at 0.50 €/CML) or 55 M€ (at 1 €/CML). Furthermore, we see that the optimal policy with a SAIDI target of 24 minutes spends around 400 M€ annually. This means an increase of 160% compared to a prolongation of the existing 5-year replacement plans. The net present value increases from 2.5 bn € to 4.5 bn €. The corresponding average annual replacement percentages for selected asset categories are shown in Table 4. The percentages are based on the current asset populations.

| annual replacements | 2010-2020 | 2010-2060 |
|---|---|---|
| Transformers | 0,02% | 1,11% |
| Switchgear | 0,09% | 0,84% |
| MV cables | 0,98% | 1,87% |
| LV cables | 0,24% | 0,75% |
| Customer supply cables | 0,00% | 0,37% |

**Table 4** Average annual replacements for scenario 3

In particular for MV and LV cables, the replacement percentages prescribed by the optimal policy with SAIDI target are considerably higher than in the current 5-year plans. In terms of capital, it turns out that two thirds of the replacement investments involve (underground) cables and one third involves all other (i.e., overground) components. For illustration, Figure 3 shows the projected development of the remaining population of MV and LV PILC.

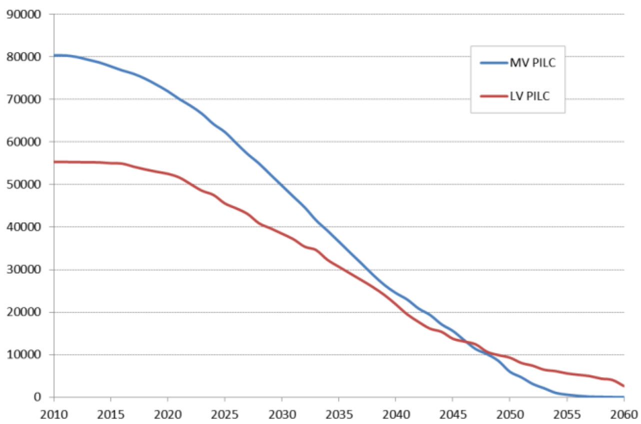


**Figure 3** Remaining population (in km) of PILC

## AUXILIARY MEASURES

Besides preventive replacement of components, the reliability of an ageing electricity network can be maintained by several other approaches:

- **Distribution automation**: Increasing the part of the network where the control center can restore power with remotely controlled switches and disconnectors will greatly enhance the reliability.
- **Intensified maintenance**: Increasing the knowledge of failure modes of components can lead to preventive maintenance measures to avoid failures.
- **Prevention of failures due to excavations**: A vast part of outages is caused by digging incidents. Measures to decrease the number of incidents, e.g., better maps and increased knowledge of secure digging, will prevent a lot of outages.
- **Larger workforce for emergency shift**: Assigning more workforce to emergency shifts will decrease outage recovery times.

Our model calculations have shown that the reliability of the Dutch regional electricity grids maintains its high level for the next ten years. After that period, additional measures are required, which will consist of a mix of preventive replacements of components and some or all of the measures mentioned above. Furthermore, when preventive replacement of components is the most favourable measure to maintain a high level of reliability in the future, it is recommendable to replace these components at natural moments, e.g., in case of extra capacity requirements, new functional requirements, or reconstructions carried out together with other network owners, such as waterworks.

## RECOMMENDATIONS

Based on the results and scope of our study, we make the following recommendations for further research and consultation:

- Determine at a strategic level which (long-term) SAIDI the DNOs aim for.
- Further in-depth research into failure modes, failure behaviour and failure curves of components, in particular MV and LV cables.
- Biennial evaluation and recalibration of the study, where model assumptions and estimations are adopted to advancing knowledge.

## REFERENCES

[1] CBS (*Statistics Netherlands*), 2011, *Huishoudensprognose 2011-2060*, in Dutch

[2] E.F. Steennis, 2011, *Kabeldegradatie, een toelichting bij een methode voor het bepalen van de restlevensduur*, in Dutch

[3] R.A. Jongen, 2012, *Statistical lifetime management for energy network components*, PhD thesis, Delft University of Technology, The Netherlands