DEVELOPMENT OF A BOTTOM-UP SCENARIO ANALYSIS NETWORK PLANNING TOOL

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ABSTRACT

The technical and societal changes brought forth by the energy transition require distribution system operators to be able to swiftly simulate and assess the impact of multiple future scenarios on the networks. A bottom-up scenario analysis tool was developed to be able to automate this impact assessment for the electricity distribution networks. The scenario tool diversifies high-level scenarios to local specific scenarios, and subsequently uses stochastic models to evaluate the loading and voltages in the network. Load profiles are built up from individual connections and aggregated up, to achieve a consistent simulation from the LV cable level up to the high voltage substations. Using the proposed methodology forecasts can be made on the timing, location and probability of bottlenecks, for a given scenario.

INTRODUCTION

The increasing renewable energy generation and the expected electrification of demand caused by the energy transition will have a large impact on the electricity networks [1]. As both the tempo and spread in development of the energy transition is highly uncertain it is necessary to evaluate the impact of different future scenarios, to ensure the distribution networks are able to cope with the changing power flows [2]. Additionally, an increasing number of connection requests for medium to large scale solar and wind farms occur, and municipalities are developing and carrying out sustainability plans to make the built environment more sustainable at an increased speed. This necessitates even more network analyses in an environment that expects increasingly rapid answers. To be able to deal with this growing number of requests for analysis and results, distribution system operators (DSOs) need to be able to swiftly simulate and assess the impact of multiple future scenarios on the networks. This requires the use of automated simulation and analysis tools.

This work discusses the development of a bottom-up scenario analysis tool for network impact studies. The tool is designed to be able to automatically simulate the impact of multiple future scenarios for small to large scale networks (several millions of connections), for low- and medium voltage networks up to the high voltage substations. The remainder of the paper is organised as follows. First, we discuss the modelling methodology applied in the tool, and describe the way the scenarios are built up and calculated. Next the implementation of the methodology in the software tool is described, along with the developed user interface to initiate the calculations and access results. Then simulation results are shown for a specified scenario, and the paper finalizes with several conclusions and recommendations for further work.

MODELLING METHODOLOGY

Process framework

To assess the impact of different energy scenarios on the electricity network a bottom-up load forecasting methodology is developed. Using a three-step process (see Figure 1), the expected loading and voltage levels of network components are calculated for national scenarios describing the expected penetration levels of for instance photovoltaics (PV), electric vehicles (EV) and heat pumps (HP). From this data, insight is obtained on when and where bottlenecks in the network are likely to occur, as well as their probability of occurrence.

Scenario diversification

The penetration of the aforementioned energy technologies may differ from region to region, as a result of differences in spatial and sociodemographic factors. Therefore, high-level scenarios are first diversified to locally specific scenarios using a logistic regression model trained with historical data, based on the methodology

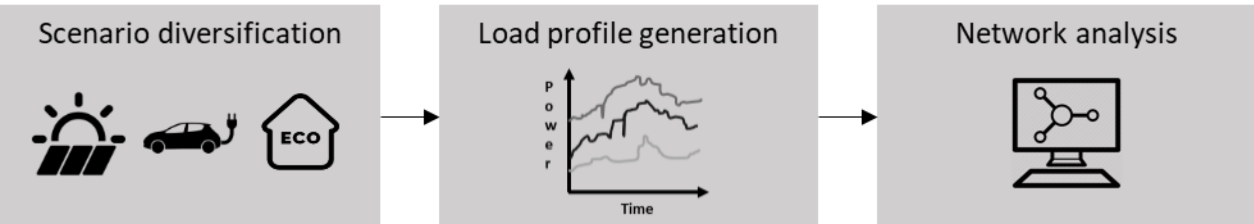

Figure 1. The three-step scenario analysis approach.

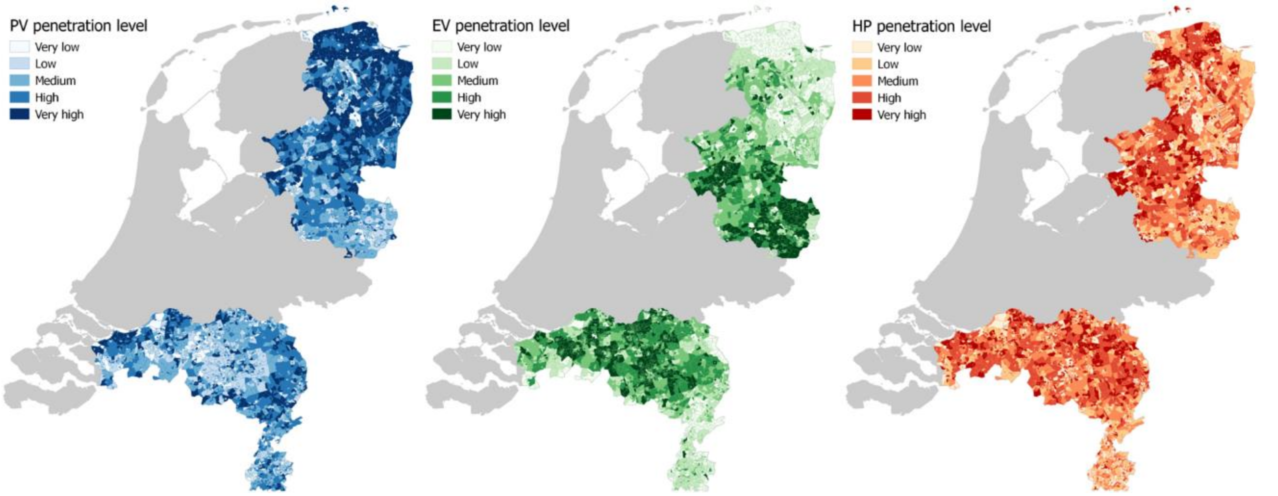

Figure 2. Relative local expected penetration levels per neighbourhood in the supply area of Dutch DSO Enexis.

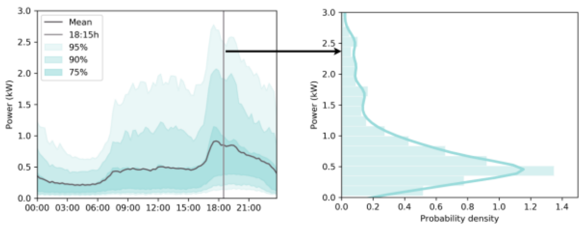

Figure 3. Visualization of the modelling of probability distributions for residential load measurements.

proposed in [3]. By linking the local characteristics and socio-demographic factors to the currently known penetration levels of different technologies an estimate of local adoption probabilities can be obtained. After calculating a technology adoption probability for each household, the high-level scenario expectations can be scaled according to their local characteristics. This yields a forecast of the local differences in the expected penetration levels, as visualized in Figure 2.

Load profile generation

Subsequently individual load profiles per household are determined based on the local scenario parameters and stochastic load and generation models [4]. Depending on the local scenario, a household may have one or more technologies installed, which each have their own characteristic load profile. The load profile of an electric vehicle is dependent on the battery charging time and duration, which is modelled from Dutch residents' mobility data. The load profile of photovoltaic panels is modelled by converting irradiance measurements to power generation based on the position of the sun relative to the PV panels. Heat pump load is modelled from measured heat pump consumption profiles in a pilot project, and linked to the outdoor temperature profile.

Each individual technology is modelled by fitting Gaussian mixture distributions to the aforementioned datasets and correlations in the dataset are modelled using copula functions [5]. Hence, correlated probability distributions are created for each 15-minute value of a day (see Figure 3), clustered per month. Daily load profiles are sampled from these distributions, for the different technologies based on the scenario expectations.

The load profile per customer is subsequently created by aggregating the sampled load profiles of the installed technologies, and the base load profile of lighting and electric appliances. The individual customers are then aggregated per network asset (cable or transformer), to yield load profiles at asset level. Because of the stochastic nature of energy consumption and, in the case of solar PV, energy generation, the output of this step is a range of aggregated load profiles, from which a set of five characteristic confidence intervals are determined.

Network analysis

Next, the individual load profiles are used in a large scale network analysis starting at the low voltage level, moving up to the high voltage substations. This way all cables and transformers in the distribution network are included, which form the components of interest for our analysis. The network analysis method for the low-voltage (LV) network differs from that of the medium-voltage (MV) network in that for LV a simplified load flow calculation is used, whereas for MV a full AC load flow is calculated.

As the vast majority of the LV networks in the Netherlands are radially operated a reduced model can be used for their assessment. From a planning perspective we are mainly interested in the occurrence of bottlenecks in the network. Focusing on loading and voltage bottlenecks, in radial networks the focal points are the loading of the first feeder section from the feeding transformer and the voltage level at the end of the longest (electric) path. For each LV feeder this longest path is determined, and per connection the fraction of the longest path through which its consumption or generation needs to flow is calculated. Then the loading and voltage level of the bottleneck points can be estimated with a single calculation step. This significantly reduces the necessary calculation time for the Enexis' supply area consisting of over 35.000 LV networks and serving over 2.5 million LV customers. This technique also works for radial LV networks with branches, however for meshed networks still a full load flow is required for a proper analysis.

The outputs of the network analysis describe the load and voltage of network components over time, allowing for validation against the DSO's network design criteria. This analysis reveals the expected probability, timing and location of system bottlenecks for a scenario, which is used to determine the required network investments and estimate associated costs.

IMPLEMENTATION

To be able to quickly assess multiple different energy scenarios the methodology is automated in a network analysis tool. Running multiple scenarios for large scale networks with bottom-up stochastic load models requires substantial computational power. The tool will therefore be operated in a cloud environment running multiple parallel processes, so detailed simulations can be executed while maintaining calculation times acceptable.

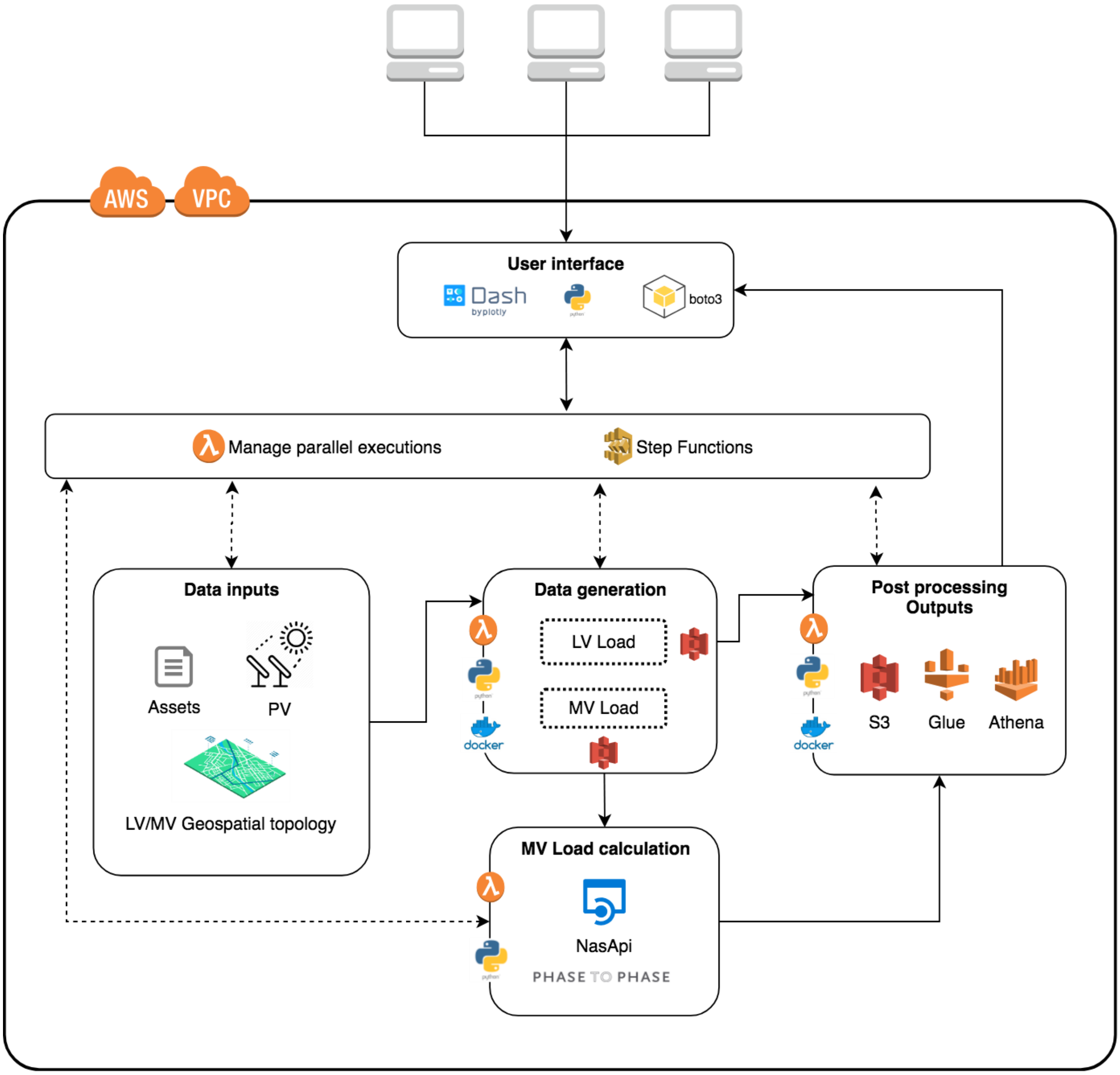

Figure 4. Architecture of the scenario tool, detailing the different process steps and platforms on which they are implemented.

Architecture

The IT architecture of the scenario tool is shown in Figure 4. The tool consists of two main parts, i.e. the core calculation module, which contains the models and handles the simulations, and the user interface, which provides users with the options to interact with the calculation module. The entire scenario tool is implemented on the Amazon Web Services (AWS) cloud platform. Plotly Dash is used for the front-end dashboard to manage user inputs and show calculated results. Dash is a Python framework for building web applications, built on top of Flask, Plotly.js and React Js. After user input selection of specific parameters, e.g. network, stations and scenario penetration levels, the preferred calculation job is placed in a queue to be processed. AWS Lambda executes the code when needed and scales automatically. AWS Step Functions are used to coordinate the different workflows and stitch together services such as Lambda and the calculation task in Docker containers. The data generation is split up in two different streams for LV and MV load. The LV load stream generates load profiles on the LV cables and MV/LV transformers, of which the latter is used as input for the MV load. The MV/LV transformer loads are fed to the NasAPI (load flow calculation service software developed by Phase to Phase) which calculates loading and voltages on substations and MV cables. Afterwards, resulting data from both streams are being post-processed and made available using AWS Glue and Athena. AWS Glue is an extract, transform, and load (ETL) service, while Athena is a query service that makes it easy to analyze data directly using standard SQL. The dash front-end uses the python library boto3 to fetch the processed data and show it to the user.

Demonstration

To demonstrate the operation of the scenario tool, in this section we show several sample inputs/outputs by means of screenshots of the user interface. In Figure 5 a section of the input tab is shown. The left half of the figure shows the part where users can adapt the desired scenario to be simulated, e.g. which network area they are interested in, what penetration level of different technologies they foresee and how many years in the future should be simulated. The right half of the figure shows visualizations of the user input, to provide the user with a feeling of the scenario. The left graph shows the average load profile for an aggregation of a hundred residential customers, given the selected penetration levels at the end of the scenario. The right graph shows the growth of the penetration level of PV, EV and HP over the course of the scenario.

Figure 6 shows some of the results of a simulated scenario for a selected section of the MV network. Here the MV

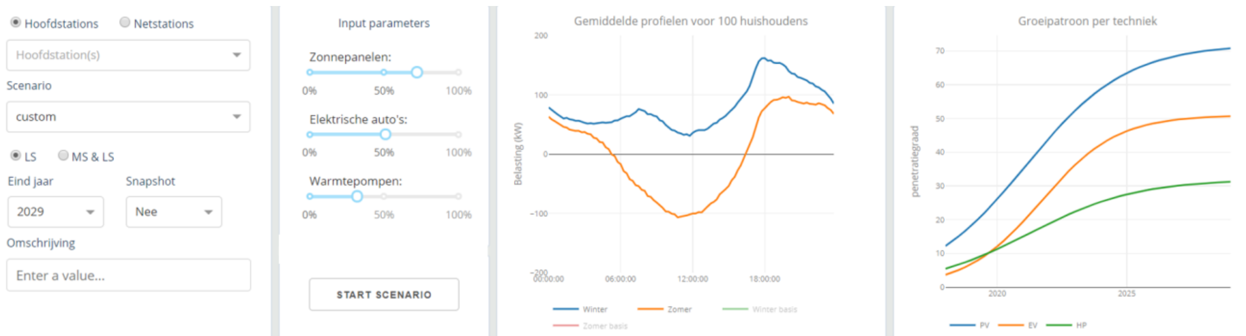

Figure 5. Screenshot of a section of the input tab of the scenario tool.

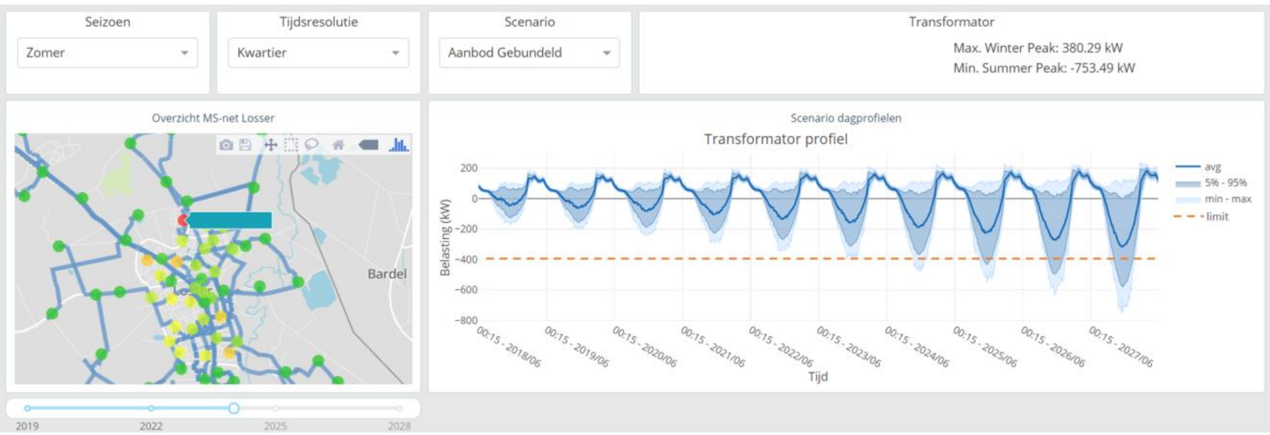

Figure 6. Screenshot of a section of the output tab of the scenario tool, showing results for a simulated scenario.

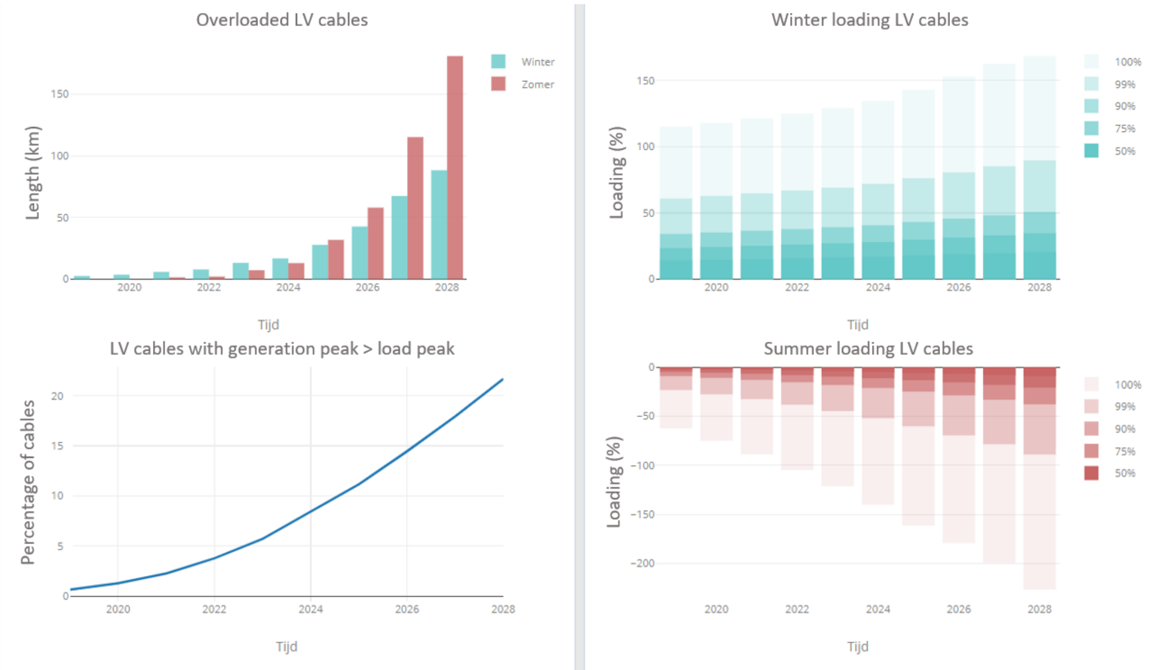

Figure 7. Screenshot of a section of the scenario tool, showing summary results for a simulated scenario.

cables and MV/LV transformer stations are shown geographically. The relative loading of the transformers (in percentages of nominal capacity) are shown by colour, ranging from green (<50% loaded) to red (>120% loaded). By clicking on one of the transformer stations the user can gain insight in the estimated load profile on that transformer. In the figure the profile of one summer day is shown for each scenario year, showing both the aggregated profile and several confidence bands around it. This also highlights the added value of the stochastic models, as these allow the creation of these confidence bands. This yields more insight in the actual expected load profiles than only peak loads or aggregated (averaged) profiles can give.

Furthermore, the scenario tool can also be used to generate summary statistics for the simulated scenario, as shown in Figure 7. Shown here are for instance the total length of overloaded LV cables in a simulation, the percentage of LV cables where the generation peak (from PV) exceeds the load peak, and the distributions of the loading of the LV cables in each scenario year. The summary statistics can be used to identify how much investments would be necessary and what

CONCLUSIONS AND FUTURE WORK

A bottom-up scenario analysis methodology was developed and is currently implemented as an automated tool. The use of stochastic models allows for an accurate modelling of load behaviour, while the increased computational effort is handled by parallelizing the simulations.

The tool is under further active development to adapt to future desired needs and be able to cope with the changing demand from users and external parties.

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