Integrated topology optimisation of multi-energy networks

Hybrid Networks

Integrated Topology Optimisation of Multi-Energy Networks

Multi-carrier hybrid energy distribution networks provide flexibility in case of network malfunctions, energy shortages and price fluctuations through energy conversion and storage. Therefore hybrid networks can cope with large-scale integration of distributed and intermittent renewable energy sources. In this article an optimisation approach is proposed which determines the optimal topology of hybrid networks.

The transition towards a renewable energy system requires a distribution network that is able to cope with distributed production units, with units simultaneously or alternately both producing and consuming energy and with fluctuations in energy availability and energy prices. Hybrid energy networks provide such flexibility. Unlike conventional energy distribution networks, which operate independently, a hybrid energy network consists of multiple energy carriers between which conversion is possible. When one of the energy carriers suddenly becomes unavailable – in case of price fluctuations or in case of a malfunction – a hybrid energy network is able to adapt.

This article presents the ongoing research project in which an approach is developed to determine the optimal layout of a hybrid energy distribution network. This approach determines the location of energy distribution lines, conversion and storage units, given the location of producers and consumers in order to find the optimal balance between capital, operational and maintenance costs on the one hand and revenue on the other hand.

Wiet Mazairac, Eindhoven University of Technology, Eindhoven/the Netherlands, and Vito – Flemish Institute for Technological Research NV, Mol/Belgium, *Robbe Salenbien*, *Dirk Vanhoudt*, *Johan Desmedt*, Vito – Flemish Institute for Technological Research NV, Mol/Belgium, *Bauke de Vries*, Eindhoven University of Technology, Eindhoven/the Netherlands

The first part of this article describes the topology optimisation of single-carrier energy distribution networks. The second part describes the topology optimisation of multi-carrier networks. Algorithms described in the first part are extended in order to support more than one carrier and in order to support conversion between different carriers. The last part briefly describes future developments.

Single-carrier optimisation

Although the goal of this research project is to optimise the topology of multi-carrier energy networks, first the topology optimisation of single-carrier networks was addressed. Two different optimisation methods were applied, the cross-entropy method, which is a heuristic optimisation method and the LP-method, which requires all equations to be linear.

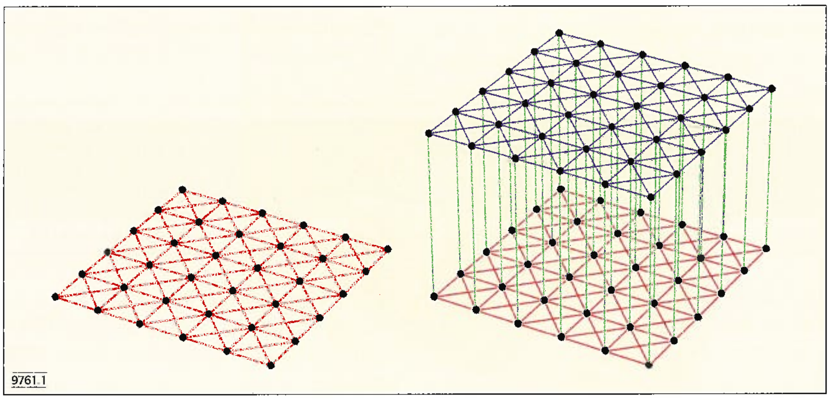

Figure 1. The solution space of a single- (left) and a multi-carrier network (right)

Cross-entropy

The CE-method [1] relies on the consecutive generation of collections of random data samples or in this case, collections of random district heating networks. The quality of each randomly generated network is evaluated and the parameters of the random generation mechanism are updated based on the outcome of that evaluation. Therefore the quality of the last collection is most likely higher than the quality of any of the preceding collections.

The CE-method allows for separation between the optimisation algorithm itself and the algorithms that determine the quality of a solution generated by this heuristic method. This separation provides the opportunity to apply more detailed, non-linear physical and economical equations to determine the quality of a randomly generated network. These are equations to determine investment costs, operational costs, thermal losses, heat generation costs and heat revenue. For each randomly generated network, costs and revenues are added to determine the quality of the network in order to generate a higher quality collection in the next iteration. Here quality is related to costs, however quality can also be related to any other objective, e.g. environmental impact or comfort. The CE-method is stopped when the quality of the generated network no longer increases.

Linear programming

The LP-method relies on the optimisation of a linear objective function, subject to linear equality and linear inequality constraints, which means that the non-linear equations described in the cross-entropy section need to be linearised. Compared to the CE-method in which a clear separation between the optimisation algorithm and the model is observed, which provides flexibility during development of the model, this separation is less clear in the case of linear programming.

Dorfner and Hamacher [2] describe how the LP-method is applied to find the optimal layout of a district heating network. Investment costs, operational costs and thermal losses vary with the thermal capacity of a distribution line. For each specific scenario supply temperature, return temperature, maximum pressure drop, thermal properties of the distribution pipe and the relation between the diameter and the costs of the distribution pipe are approximated by linear equations.

Comparison

Both the CE- as well as the LP-method return plausible results, however validation is required to confirm these and also to determine the error as a result of the linear approximation. Although the CE-method allows for the optimisation of a more detailed model, process time increases exponentially with the size of problem. Also, a heuristic optimisation approach, in contrast to the LP-method, can not guarantee to find the optimal solution. For these reasons the linear optimisation approach will be applied to find the optimal topology of multi-carrier networks.

Multi-carrier optimisation

The algorithms applied to find the optimal topology of single-carrier networks can be applied to find the optimal topology of multi-carrier networks. In order to do so, these algorithms are expanded to cope with multiple energy carriers and energy conversion, which results in an increased solution space.

The solution space of a single-carrier network consists of a single set of edges (*figure 1*). Each edge represents a possible location for an energy distribution line. The solution space of a multi-carrier network, with in this example two carriers, consists of three sets of edges. Each red edge represents a possible location for an energy line, which distributes the first energy carrier. Each blue edge represents a possible location for an energy line, which distributes the second energy carrier. Each green line represents a possible location for an energy converter, which transfers energy between carriers.

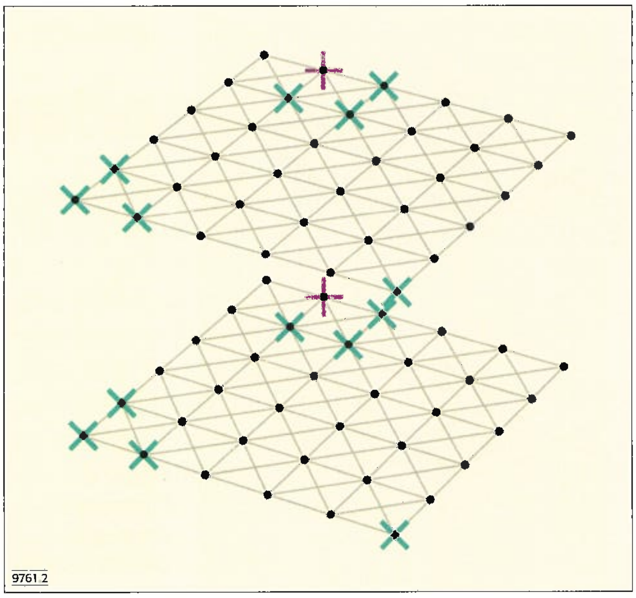

Figure 2. Multi-carrier topology problem with producers (+) and consumers (×)

Cross-entropy

First the CE-method is applied to find the optimal topology of a multi-carrier energy system. Although process time increases exponentially with the size of the problem, this method is applicable to smaller problems.

In [2] equations relating to investment costs, operational costs, thermal losses, heat generation costs and heat revenue were introduced. These equations apply to district heating networks. Similar equations are required for the second network, in this case the electricity grid. These equations relate to investment costs, operational costs, energy losses to resistance, generation of electricity costs and electricity revenue. Finally, similar equations are required for the conversion units. These equations relate to investment costs, operational costs and energy conversion losses.

Figure 2 represents a problem that can be solved by applying the CE-method. The edges part of the upper half represent possible locations for heat distribution lines. The

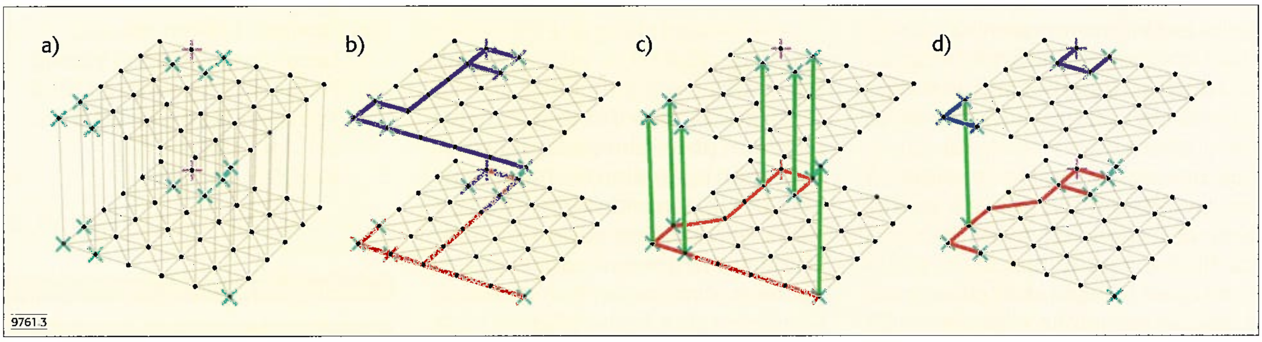

Figure 3. Optimal topologies for scenarios a), b), c) and d)

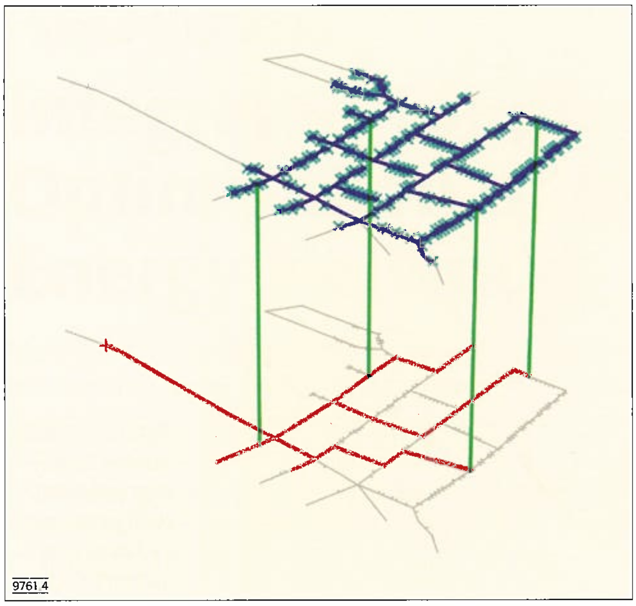

Figure 4. Optimised multi-stage district heating network

edges part of the lower half represent possible location for electric power lines. The vertical lines represent possible locations for conversion units.

The violet colored node (+) part of the upper mesh represents an electric energy production unit. The turquoise colored nodes (×) part of the upper mesh represent electric energy customers.

Four hypothetical scenarios were examined by the cross-entropy method. In scenario a) conversion units are relatively expensive and energy revenues are high. In scenario b) conversion units are relatively inexpensive and energy revenues are high. In scenario c) energy revenues are low. In scenario d) conversion units are reasonably priced compared to energy revenues.

Figure 3 shows the multi-carrier networks generated by the CE-method for the four scenarios. In scenario a) expensive energy units and high energy revenues result in two separate, fully connected networks. In scenario b) inexpensive conversion units and high revenues result in one fully connected network. Instead of constructing a second network, conversion units provide the second form of energy. In scenario c) energy revenues are too low to make an energy distribution network profitable. In scenario d) customers close to the production unit are directly connected to both production units. A distant group of consumers is directly connected to one production unit. The other form of energy is obtained through conversion. The single, distant consumer is not connected; that connection would not be profitable.

Linear programming

A district heating network with a high-temperature, high-pressure primary network and a low-temperature, low-pressure secondary network can be regarded as a multi-carrier network. Area substations transfer energy between the primary and the secondary network. The multi-carrier topology optimisation algorithms described in this article can be applied to any combination of carriers, including a multi-stage district heating network. In *figure 4*, which shows the result of the optimisation process, analogous to previous examples, the violet node (+) represents the heat production units, the turquoise nodes (×) represent the heat customers, the red lines represent the primary network, the blue lines represent the secondary network and the green lines represent the area substations.

Conclusions

Both the CE- as well as the LP-method return plausible results, however validation is required to confirm this and also to determine the error as a result of the linear approximation. The solution space of a multi-carrier problem increases with the number of carriers and is therefore at least twice as large as the solutions space of a single carrier problem. Accordingly, as a result of better performance, the LP-method is more applicable than the CE-method when dealing with multi-carrier problems.

Outlook

The optimisation methods described in this article return plausible results. The introduction of other carriers, e.g. natural or hydrogen gas, requires collecting data on those carriers and related conversion techniques. Introduction of many distributed renewable energy production units, e.g. rooftop PV-panels, requires collecting data on the location and power of those techniques.

Intermittent renewable energy sources are inseparable from energy storage. Dynamic modelling and optimisation over time is required to determine the location, capacity and power of potential storage units. To make this possible, first, the existing optimisation method needs to be extended in order to remember a storage unit's state. Second, consumption and production profiles need to be added to the optimisation model.

These extensions provide the possibility to determine the optimal topology of a future multi-carrier hybrid energy network, taking into account distributed generation with the possibility to decide between local and central storage.

References

[1] Rubenstein, R. Y.; Kroese, D. P.: The Cross-Entropy Method: A Unified Approach to Combinatorial Optimization, Monte-Carlo Simulation and Machine Learning. Springer-Verlag, 2004.

[2] Dorfner, J.; Hamacher, T.: Large-Scale District Heating Network Optimization. IEEE Transactions on Smart Grid, 5(4), pp. 1884 – 1891, July 2014.

l.a.j.mazairac@tue.nl

www.tue.nl

www.vito.be