ene.field project

Grant agreement No: 303462

ene.field

Benefits of Widespread Deployment of Fuel Cell Micro CHP in Securing and Decarbonising the Future European Electricity System

Status: F- 04/10/2017

(D-Draft, FD-Final Draft, F-Final)

Dissemination level: PU

(PU – Public, PP – Restricted to other programme participants,
RE – Restricted to a group specified by the consortium, CO – Confidential)

The ene.field project has received funding from the European Union's Seventh Framework Programme (FP7/2007-2013) for the Fuel Cells and Hydrogen Joint Undertaking (FCH-JU) under grant agreement n° 303462.

Authors: Imperial College London

Danny Pudjianto

Email: d.pudjianto@imperial.ac.uk

Mobile: +44(0)79 89 44 33 98

Predrag Djapic

Email: p.djapic@imperial.ac.uk

Tel: +44 (0) 20 7589 5111 ext: 59755

Goran Strbac

Email: g.strbac@imperial.ac.uk

Tel: +44 (0)20 7594 6169

1 Executive Summary

This report is part of the ene.field project, i.e. European-wide field trials for residential fuel cell micro combined heat and power (micro-CHP), the Europe's largest demonstration project for the fuel cell based micro-CHP systems. During this project, up to 1,000 residential fuel cell micro-CHP installations will be deployed across 11 key European countries. It represents a step change in the volume of fuel cell micro-CHP deployment in Europe and a meaningful step towards commercialisation of the technology and rolling out the technologies.

In that context, the aim of the study is to provide a definitive result on the overall macro-economic and macro-environmental implication of a widespread rollout of fuel cell micro-CHP technology for Europe's electricity systems. The use of micro-CHP systems is appealing due to two fundamental reasons: (i) the efficiency of energy conversion is above 90%, much higher than the efficiency of Combined-Cycle Gas Turbine (i.e. around 60%), (ii) the systems are installed at the end-use premises reducing the need for energy transport infrastructure and losses. The micro-CHP can also provide a local peaking capacity (back-up), and it can become an alternative to the conventional boiler in a smart home environment where the electricity and heat demand can be managed more efficiency. The study involves analyses on the impact of micro-CHP on the capacity and operation of the electricity systems across Europe and the impact on CO_2, gas consumption across different uptake scenarios and system backgrounds.

In order to evaluate the system benefits of micro-CHP, a range of simulation studies has been carried out to examine the impact of micro-CHP on the European electricity systems (generation, main transmission, and distribution systems) for different future scenarios. The analysis considers today's grid mix and the impact of likely changes in the future, based on national energy plans and their central projections for the change in the generation mix through time. *The benefits of micro-CHP are quantified by finding the performance differences between two systems*, i.e. : (i) a system without micro-CHP, called the Reference scenario, where the electricity was supplied by a portfolio of generation with no micro-CHP and the heat demand was met using electricity-heat pump, (ii) a system with micro-CHP, called the micro-CHP scenario, where the electricity demand was supplied by a portfolio of generation including micro-CHP which also supplied the heat demand. It is important to note that the heat output of the micro-CHP only supplies part of the domestic heat demand (space heating and hot water); and therefore, in practice, other means of heating, e.g. gas boiler, heat pumps and resistive heating also exist.

The economic and carbon performance of these two systems were evaluated using a set of analysis tools developed by Imperial College London, i.e. WeSIM.The key feature of the tools (WeSIM) is in its capability to simultaneously consider system operation decisions and infrastructure additions to the system, with the ability to quantify trade-offs of using alternative technologies, for real-time balancing and transmission network and/or generation reinforcement management. The model is based on the whole-system approach able to capture all the energy system interactions of CHP, heat, electricity capacity and network services. Thus, the model enables a spectrum of holistic analysis at a system level to quantify the multiple system benefits of micro-CHP. The performance differences between the two systems, i.e. with and without micro-CHP determine the whole-system costs or benefits of micro-CHP on the system.

In order to capture the range of whole-system implication of integrating micro-CHP in Europe, two uptake scenarios, i.e. low (minimum) and high (maximum) scenarios, developed by Element Energy considering different support policies are used in the studies[1]. The average hourly profiles of heat generated by micro-CHP in the ene.field trial[2] are applied in the study to reflect the actual average load factor of the micro-CHP.

The values of micro-CHP in reducing the infrastructure cost (generation [G CAPEX], transmission networks [T CAPEX], distribution networks [D CAPEX], and Heat Pumps [HP CAPEX]) and operating cost [OPEX] are presented in Figure 1, expressed in €/kW electrical capacity of micro-CHP[3]. These values reflect the cost-saving of the system with micro-CHP in comparison to the cost of a system without micro-CHP, i.e. heat demand is supplied by HP. It is important to note that the CAPEX of micro-CHP is not included in the results; the OPEX of micro-CHP has been included.

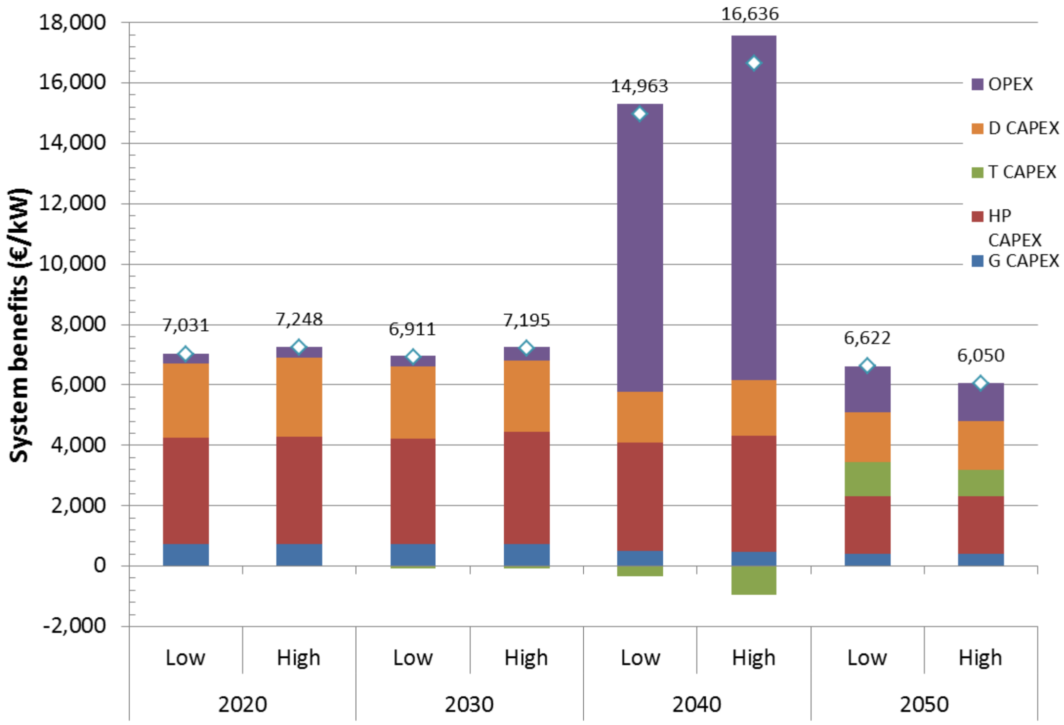


Figure 1. Overall system benefits of micro-CHP

[1] Element Energy, Cost and market projections, ene.field report for WP5.1, 2017
[2] Data are provided by DBI - Gastechnologisches Institut gGmbH Freiberg and Gas- und Wärme-Institut Essen e.V.
[3] Unless otherwise stated, the kW rating of the micro-CHP refers to the power rating of the mCHP

The total (gross) benefits are around €6000 - €7300/kW, with the 2040 cases as an exception[4]. While the magnitude of the benefits is relatively similar, the savings may come from different sources. In the short and medium term, the savings are dominated by the savings in displacing the capacity of HP, power generation, and distribution network capacity. In the long run, the OPEX savings become higher. The OPEX savings can also become higher when the firm generating capacity in the system is scarce, as illustrated in the cases for 2040.

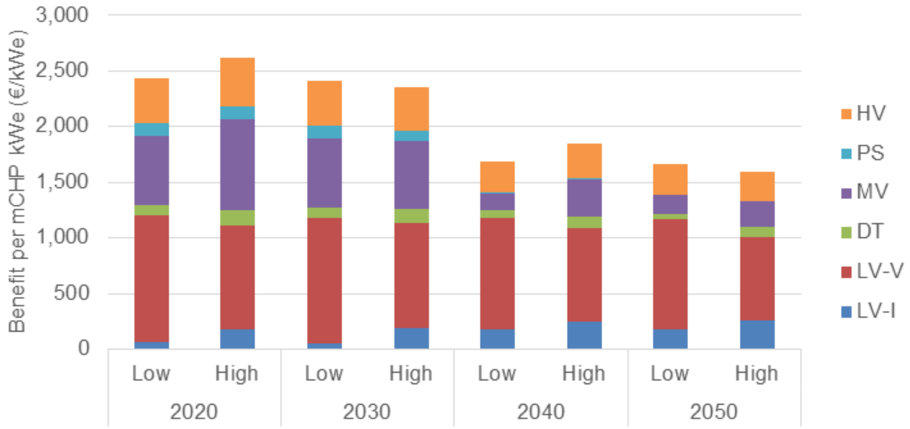
The results show that micro-CHP can:

- Displace capacity of central generators. The capacity value of micro-CHP is comparable to traditional gas-fired plant providing it can be dispatched as back-up,
- Displace the capacity of alternative heat sources,
- Reduce operating costs. Net energy consumption is reduced indicating higher energy efficiency,
- Release network capacity / postpone reinforcement at distribution and transmission networks.

Some of the benefits can only be realised if the micro-CHP can provide grid services; this has implications for the design and control of the micro-CHP, for example: enabling remote operation capabilities for the system operator to access and use micro-CHP to support the grid. While the remote control technologies exist and can be integrated into the micro-CHP easily, it also requires stronger control coordination between transmission and distribution system operators if they are operated by separate entities.

Figure 2 shows the average benefits of micro-CHP on the European distribution networks. The average benefits for the low and high uptake scenarios are estimated between €1660 - €2400/kW and €1600 - €2600/kW respectively. The results show that the largest benefit comes from deferring the investment cost at LV especially investment driven by voltage issues and the second/third largest savings come from the cost reduction at Medium Voltage feeders to the HV feeders. It is important to note that the deployment of HP, as an alternative to micro-CHP, will lead to higher electricity loads and may trigger some network reinforcement due to voltage drop issues. Therefore, deployment of micro-CHP brings benefits in this context. Other benefits are obtained from the savings in the LV feeders, distribution transformers, and primary substations.

[4] The OPEX savings for the 2040 cases are much higher as the generation backgrounds used in the scenario, simulate the transition condition where there is not enough low carbon and low marginal cost plant built to accommodate load growth and decommissioning of fossil fuel plants. As a result, expensive peaking plants operate longer. This should be considered as a plausible scenario in order to identify the drivers of the value of micro-CHP and should not be treated as a forecast of the future system.



HV: High Voltage, PS: Primary Substation, MV: Medium Voltage, DT: Distribution Transformer, LV-V: Voltage driven LV network reinforcement, LV-I: Thermal driven LV network reinforcement

Figure 2. Estimated average value of micro-CHP in reducing distribution network cost in Europe in different scenarios

As anticipated, the benefits are system specific and driven by the opportunity of the micro-CHP to reduce the overall costs; thus, the ratio of the saving components varies across different scenarios. However, it is observed that the benefits (per kW) are not too sensitive to the penetration levels of micro-CHP projected which indicate that there is no significant barrier for the micro-CHP at the levels being studied.

In the short term, based on the to-date level of renewables and efficiency of the micro-CHP, it is sufficient if micro-CHP operates in heat-led mode. Combined electrical and heat-led is required when micro-CHP can be a least-cost alternative source to displace high marginal cost generators such as peaking plant (e.g. when the efficiency of micro-CHP is high, or when the generation mixes are not optimal). The studies also find that micro-CHP is competitive against HP in the short and medium term; however, when the renewable penetration in the system is sufficiently high (>70%), a combination of micro-CHP and HP may form an optimal portfolio.

Wide deployment of micro-CHP is not only improving the efficiency of the overall system but also reducing carbon emissions. The magnitude of the carbon saving per kW installed micro-CHP in Europe is estimated between 370 – 1100 kg CO_2 per year[5]. In the short and medium term, at least when the use of conventional coal/gas/oil-fired plant is still dominant, the impact of micro-CHP in reducing carbon emissions is expected to be relatively significant. The results are shown in Figure 3.

[5] The carbon reduction refers to the saving in carbon emissions due to electricity production. This analysis does not cover the full Life Cycle Analysis which is reported in D3.4, “Environmental life cycle assessments”.

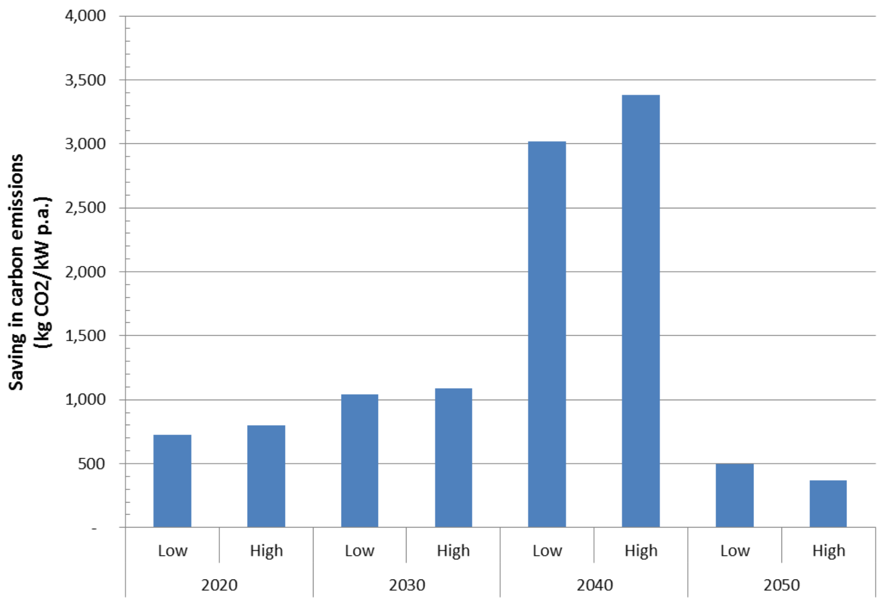


Figure 3. Contribution of micro-CHP in reducing carbon emissions

In the long term, when the supply of electricity is mainly from low-carbon generation sources, the use of natural-gas fuel cell micro-CHP becomes less attractive, in the context of carbon reduction. Alternative fuel for micro-CHP, especially from sustainable and low-carbon sources will be needed.

Based on these results and the analysis, it can be concluded that micro-CHP technologies are important for the future European energy system development in both short and long run. The micro-CHP can also complement the operation of other low-carbon technologies such as HP.

As the system benefits of micro-CHP are now clear, it is important that *appropriate mechanisms are put in place to encourage wide deployment of this technology in the European system*. Without acknowledgement of its system benefits, the micro-CHP may not be able to compete with other low-carbon technologies, and this may lead to a sub-optimal development of this technology.

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Acronyms

AT	Austria
BE	Belgium
CAPEX	Capital expenditure
CCGT	Combined Cycle Gas Turbine
CCS	Carbon Capture and Storage
CHP	Combined Heat and Power
CZ	Czech Republic
D CAPEX	Distribution network capital expenditure (reinforcement cost)
DK	Denmark
DT	Distribution transformer
ENTSO-E	European Network of Transmission system Operators for Electricity
ES	Spain
FC	Fuel Cell
FC CHP	Fuel cell CHP
FiT	Feed-in tariff
FR	France
G CAPEX	Power generation capital expenditure
GB	Great Britain
HP	Heat pump
HU	Hungary
HV	High voltage
IE	Ireland
IT	Italy
LCC	Life Cycle Cost
LV	Low voltage
LV-I	Thermal driven LV network reinforcement
LV-V	Voltage driven LV network reinforcement
micro-CHP	Micro Combined Heat and Power
MS	Member state
MV	Medium voltage
NL	Netherlands
OCGT	Open Cycle Gas Turbine
PL	Poland
PS	Primary substation
PT	Portugal
PV	Photovoltaic
RHI	Renewable Heat Incentive
RO	Romania
SK	Slovakia
T CAPEX	Transmission network capital expenditure (reinforcement cost)
WeSIM	Whole electricity System Investment Model

2 Introduction

2.1 Context

A fuel cell micro-CHP system consists of a small fuel cell or a heat engine driving a generator which produces electric power and heat for an individual building's heating, ventilation, and air conditioning. A micro-CHP may primarily follow heat demand, delivering electricity as the byproduct. Alternatively, its operation could also be driven by electrical demand especially as a mid-merit/peaking plant when a high marginal cost of generators needs to operate, or the capacity of electrical generation is scarce. The micro-CHP system may also include a thermal energy storage system enabling a smoother micro-CHP operation as the heat can be stored or released according to the temporal system requirement.

The use of micro-CHP systems is appealing due to two fundamental reasons: (i) the overall efficiency of energy conversion is above 90%, much higher than the efficiency of combined-cycle gas turbine (CCGT) around 60%, (ii) the systems are installed at the end-use premises reducing the need for energy transport infrastructure and losses. The system can also provide a local backup capacity, improving the energy security at the local level. The micro-CHP system can become an alternative or supplement to the conventional gas boiler in a smart home environment where the electricity and heat demand can be managed more efficiently.

However, the issue of the environmental and economic value of micro-CHP, particularly when fuelled by natural gas, is the subject of much debate. It is unclear whether the use of natural gas fuel cell micro-CHP is of limited value, as the grid is likely to decarbonise so fast that CHP-generated electricity based on natural gas will become part of a problem rather than a solution before the technology has matured. Others argue that the nature of the generation from CHP is such that it will displace high polluting central power generation plant for many decades to come and hence has huge environmental benefits in the long term. Moreover, in the long term, biogas or hydrogen at volume could provide an alternative renewable gas to natural gas; which makes a case for the fuel cell micro-CHP more appealing.

In addition, it is also unclear how the roll out of fuel cell micro-CHP will benefit the power system in Europe. There is a view that micro-CHP may reduce the peak demand for electricity hence it reduces the system capacity (generation, transmission, and distribution) requirement while at the same time, it improves the efficiency and reduces the operating cost. On the other hand, high penetration of distributed generation may trigger voltage rises or reverse power flow problems in distribution networks, especially during off-peak demand. Therefore, it is important to understand the net benefit of the micro-CHP in this context.

Another important issue that needs to be understood is the interactions between the micro-CHP and other heat decarbonisation technologies such as heat pumps (HP). An Electric HP produces heat with an “efficiency” of more than 200%, and it is expected to be the technology that can most significantly decarbonise the heating sector. However, high penetration of HPs will increase the electricity peak demand, and therefore, the system integration cost of this technology should be considered when optimising the design of the future system. It is important to understand whether micro-CHP competes with HPs, or both technologies can work supplementing each other?

In this context, the work presented in this report is an attempt to gain a better understanding of the aforementioned issues. In order to do so, European electricity system models have been developed, and a range of simulation studies have been carried out to examine the impact of micro-CHP on the electricity system for different future scenarios. The analysis considers today's grid mix and the impact of likely changes in the future, based on national energy plans and their central projections for the change in the generation mix through time. The studies also explore the impact of micro-CHP on future investment requirements (positive and negative) for electricity distribution.

2.2 Objectives

The aim of the analysis is to provide definitive results and a set of analyses on the overall macroeconomics, in the power system context, and the macro environmental implications of a widespread rollout of fuel cell micro-CHP technology for Europe's electricity systems. This involves analyses on the impact of micro-CHP on the capacity (power generation, main interconnection, distribution) and the operation of the electricity systems across Europe and the impact on CO_2 across different uptake scenarios and system backgrounds taking into account how the generation mixes in Europe will evolve to a low-carbon and sustainable energy system. The insight obtained from these studies can facilitate informed discussions on how micro-CHP will play its roles in the future European energy systems.

2.3 Structure of the report

Chapter 3 describes the approach used to derive and analyse the system benefits of the micro-CHP. Chapter 4 and 5 present system benefits of fuel cell micro-CHP in a generation, transmission, and distribution respectively. In chapter 5, the results discussed in chapter 3 and 4 will be combined to provide a full overview of the benefits of micro-CHP. Finally, the last chapter consists of the key conclusions obtained from the analyses discussed in the previous chapters. Overview of the numerical approaches and the distribution network models used in these studies can be found in the Appendix.

3 Methodology

3.1 Overall approaches

In order to evaluate the system benefits of micro-CHP, two systems were developed: (i) a system without micro-CHP, called the Reference scenario, where the electricity was supplied by a portfolio of generation with no micro-CHP and the heat demand was met using electricity-heat pump, (ii) a system with micro-CHP, called the micro-CHP scenario, where the electricity demand was supplied by a portfolio of generation with micro-CHP which also supplied the heat demand. The economic and carbon performance of these two systems were evaluated using Imperial's analysis tools, i.e. WeSIM[6] (Section 3.5) and European distribution network analysis tool (Chapter 5). The performance differences between these two systems determine the costs or benefits of micro-CHP on the system. This approach is illustrated in Figure 4 below.

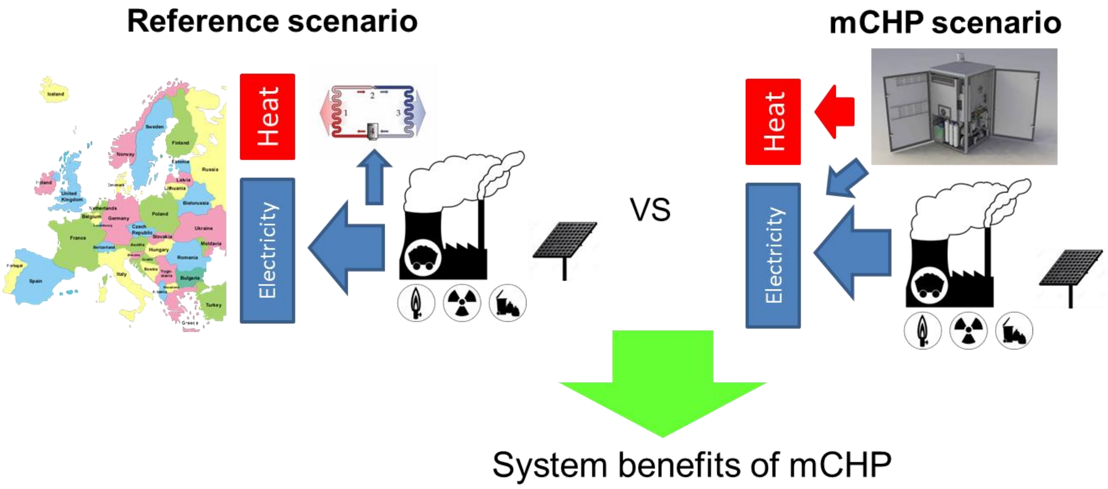


Figure 4. Quantifying the benefits of micro-CHP by comparing the performance of the system with and without micro-CHP

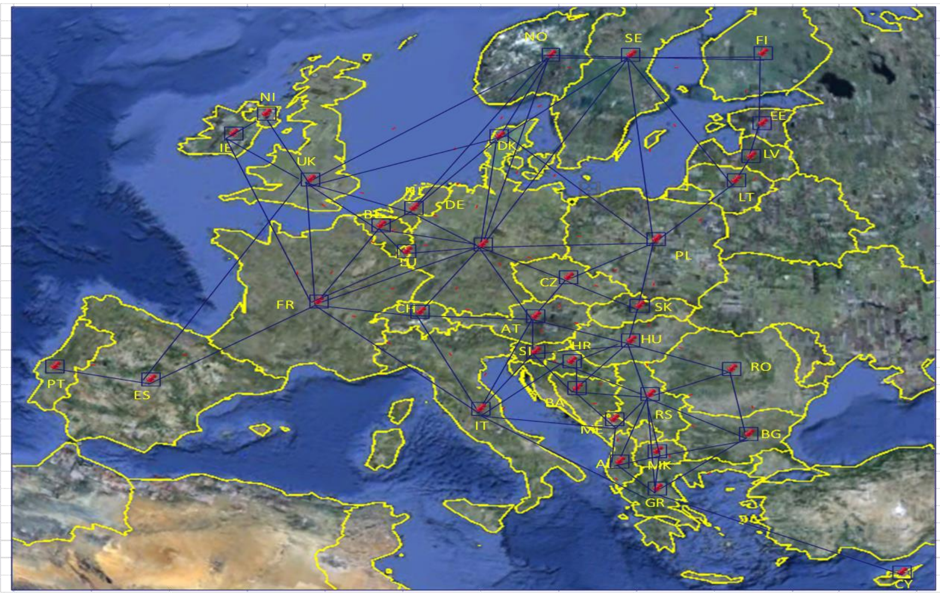
3.2 Test systems

Simulations were carried out on the European electricity system model illustrated in Figure 5. Each Member State (MS) is represented as a node. The connections between each MS are presented as lines with finite capacity. The capacity of all interconnectors is optimised in all cases

[6] D. Pudjianto, M. Castro, G. Strbac, and E. Gaxiola, "Transmission Infrastructure Investment Requirements in the Future European Low-Carbon Electricity System", Proc. 10th International Conference on European Energy Market Conference, Stockholm, 27-31 May 2013.

to ensure that sufficient capacity is provided to ensure both operational and investment efficiency of the system.

Demand and generation backgrounds for each MS were based on various resources. Data for 2020 are based on the ENTSO-E Ten Years Network Development Plan 2016, market modelling data for 2020. Data for 2030 are based on the same source, Vision 3 2030 scenario. Data for 2040, and 2050 are obtained by extrapolating the data for 2030 to 2050 data based on the e-Storage project[7].



Code	Country
AL	Albania
AT	Austria
BA	Bosnia and Herzegovina
BE	Belgium
BG	Bulgaria
CH	Switzerland
CY	Cyprus
CZ	Czech Republic
DE	Germany
DK	Denmark
EE	Estonia
ES	Spain
FI	Finland
FR	France
UK	UK
GR	Greece
HR	Croatia
HU	Hungary
IE	Ireland
IT	Italy
LT	Lithuania
LU	Luxembourg
LV	Latvia
ME	Montenegro
MK	Macedonia
NI	Northern Ireland
NL	Netherlands
NO	Norway
PL	Poland
PT	Portugal
RO	Romania
RS	Serbia
SE	Sweden
SI	Slovenia
SK	Slovakia

Figure 5. European grid model

Figure 6 shows the total Europe portfolio of generation systems used in the study for different year snapshots from 2020 to 2050. The use of different generation backgrounds, and also demand, broadens the spectrum of the analysis as the impact of micro-CHP on different generation system characteristics can be investigated and studied.

For the 2020 and 2030 scenario, the share of conventional thermal generators such as gas and the coal-fired plant is still relatively large although the installed capacity of wind farms and solar PV continues to increase. By 2040, the share of coal and conventional gas-fired power plants decreases significantly; at a certain extent, those capacities are substituted by gas CCS and the peaking plant OCGT. The capacity of renewables continues to increase till 2050 as the renewables are expected to supply 75% of electricity demand by 2050.

[7] http://www.estorage-project.eu/

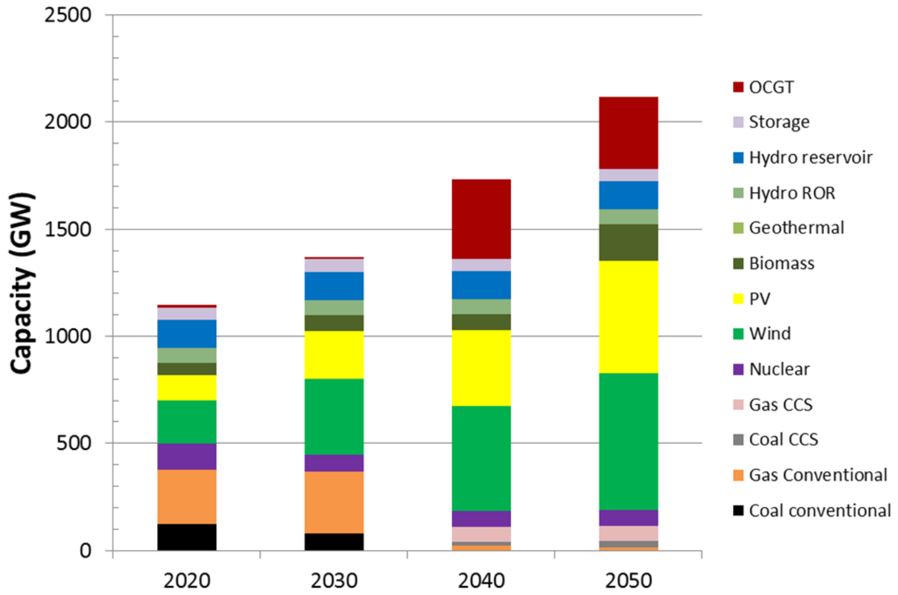


Figure 6. Generation background

3.3 Market projections

Market projections of the micro-CHP uptake in Europe for different policy scenarios are obtained from the task enefield project task 5.1 carried out by Element Energy. Data include the market projection for single and multi-family homes with the generic micro-CHP capacity of 0.7 kW and 5 kW per building respectively. Based on that study, the total installed power capacity of micro-CHP in Europe between 2015 and 2050 for different policy scenarios can be derived, as shown in Figure 7.

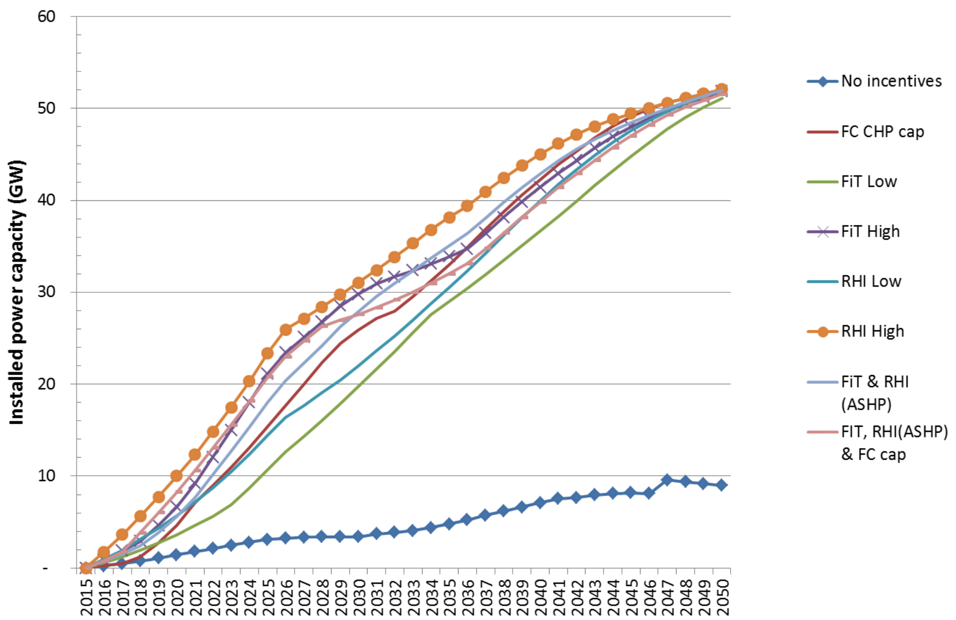


Figure 7. Market projection of micro-CHP for various incentive schemes

Description of the policy scenarios can be found in the ene.field report D5.1 entitle "Cost and Market Projection", produced by Element Energy. Based on this market projection, the "No incentive" scenario in combination with the "uncapped potential" yields the lowest uptake of mCHP; nevertheless, the capacity of micro-CHP still increases and reaches around 9 GW by 2050. The uptake of micro-CHP based on the "No incentive" scenario is used to create the minimum micro-CHP uptake trajectory between 2015 and 2050.

On the other hand, the maximum uptake trajectory is determined by the combination of the "RHI High" policy and "distributed systems" scenario. This scenario is represented by a rapid growth in the installed capacity of micro-CHP which will reach around 10 GW in 2020 and 31 GW in 2030[8]. Beyond 2030, the projection also shows a continuous promising uptake of micro-CHP and the capacity is projected to reach around 52 GW by 2050.

The approach and analysis on how different incentive policies have been modelled and affect the uptake of micro-CHP in Europe can be found in the report made by Element Energy[9].

Using both the low (minimum) and high (maximum) uptake scenarios of micro-CHP across Europe, the study aims to capture the range of implication for integrating micro-CHP in the European system. Based on the selected two uptake scenarios, i.e. the low and high scenarios, the installed capacities of micro-CHP for each MS in the year 2020, 2030, 2040, and 2050 are determined. The projected installed capacities of micro-CHP across Europe used in the studies are shown in Figure 8.

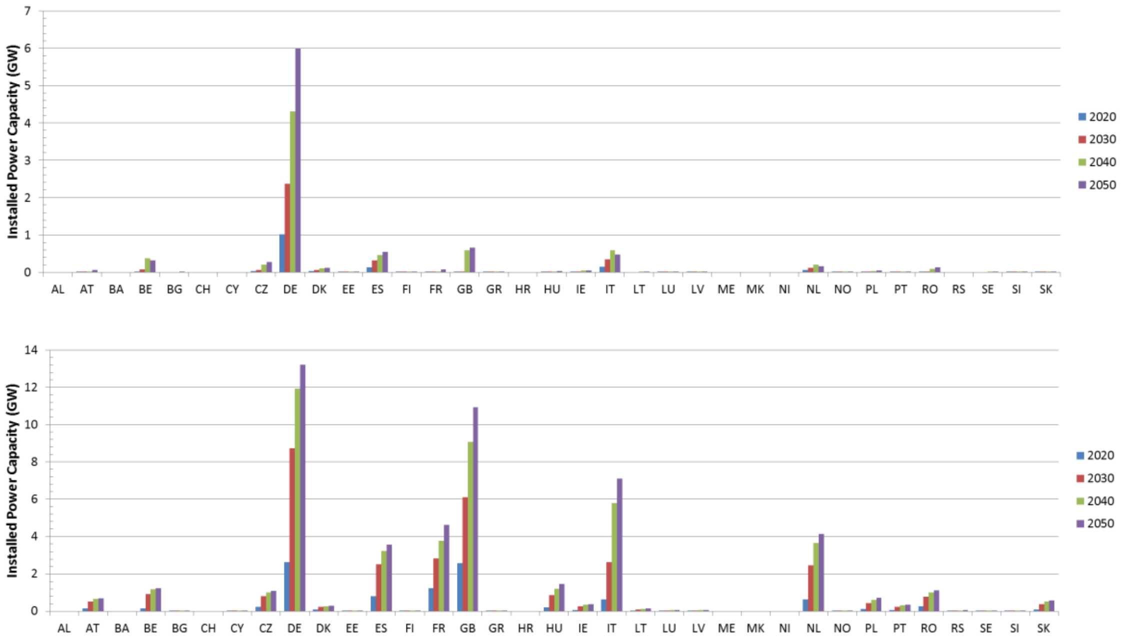


Figure 8. Low and high uptake scenario of micro CHP installed capacity across Europe

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[8] By 2020, it is projected that there will be around 10 million units (both large and small) and by 2030, 30 million units installed.

[9] I.Walker and S.van Limpt,"Cost and market projection", a report by Element Energy for the enefield project, 2017.

It is observed that in the low uptake scenario, the majority of the micro-CHP capacity is installed in Germany while some visible capacities can be found in Spain (ES), Great Britain (GB) and Italy (IT). In the high uptake scenario, the installed capacity of micro-CHP in Germany is still the highest in Europe, but more visible capacities of micro-CHP can be observed in Austria (AT), Belgium (BE), Czech (CZ), Spain (ES), France (FR), Great Britain (GB), Hungary (HU), Ireland (IE), Italy (IT), Netherlands (NL), Poland (PL), Portugal (PT), Romania (RO), and Slovakia (SK).

3.4 Heat production profile of mCHP

Data obtained from the field trials are used to determine the average hourly profile of the heat production output of the micro-CHP for one year. The data we obtained from ene.field WP 2 were from the 1st October 2014 until the end of March 2016; the data are shown in Figure 9. It is observed that the data obtained during the period between Oct 2014 and April 2015 were relatively unstable due to the low number of samples and monitoring issues. Smoother and more stable data were obtained after 1st April 2015 as the number of samples increased, and the data acquisition and monitoring processes had been improved. Thus, only data after the 1st April 2015 are used in this study.

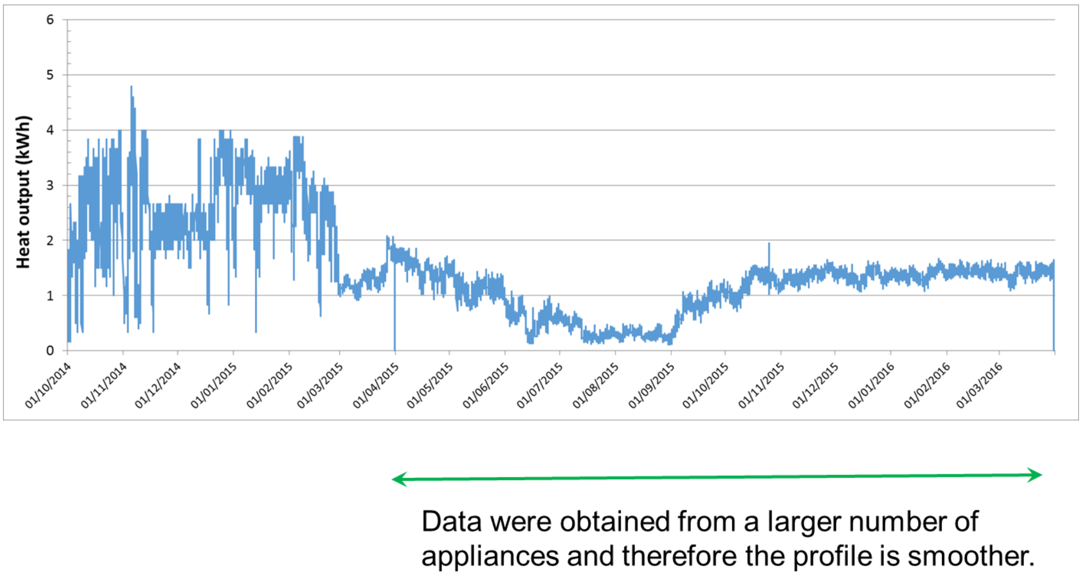


Figure 9. Heat output produced by micro-CHP in the trial

The profile shows a strong seasonal pattern of the micro-CHP where the utilisation during summer period is significantly lower than the utilisation during other seasons. There are also volatilities in daily and hourly profiles, which are reduced where thermal storage is used.

It is important to note that the studies in this report only consider the heat demand which is supplied by the micro-CHP in the micro-CHP scenario. There are other heat demands which are supplied by other means of heating (gas boiler, heat pumps, resistive heating, etc.) but as they will be the same in the two systems (i.e. with and without micro-CHP) and therefore, they have no impact, they are excluded from the studies.

3.5 Overview of the Whole-electricity System Investment Model

WeSIM is a comprehensive electricity system analysis model that simultaneously balances long-term investment decisions against short-term operation decisions, across generation, and transmission systems, in an integrated fashion. When considering the development of future low-carbon electricity systems, including the application of micro-CHP, it is important to consider two key aspects electricity system operation as illustrated in Figure 10 below.

- **Different time horizons of investment when considering infrastructure behaviour and operational behaviour** : there is a long-term investment-related time horizon for optimising capacity margins to meet security of supply requirements, and a real-time demand-supply balancing on a second-by-second scale (Figure 10); Meeting the requirements for both time horizons is important as, for example, micro-CHP can impact both system investment and operation cost (and carbon) performance simultaneously.

- **The interaction of different assets and their location in the electricity system**: generation assets (from large-scale to distributed small-scale), and transmission network (national and interconnections have an impact on system operation. This is important as alternative technologies may be located at different locations in the system and in different capacities.

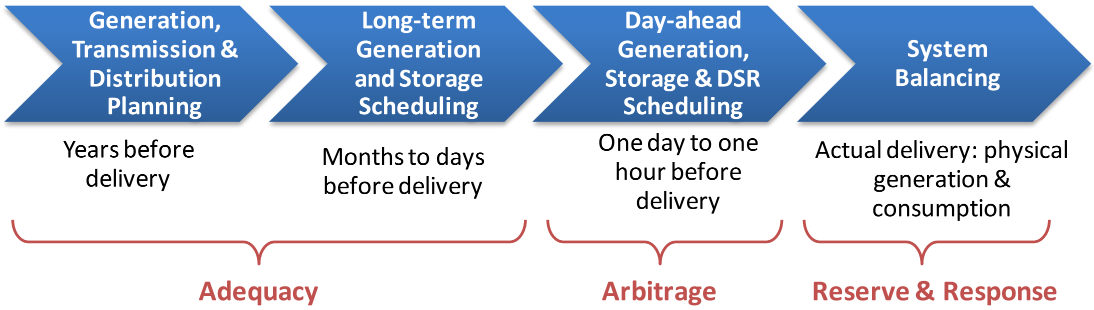


Figure 10. Balancing electricity supply and demand across different time horizons

In this context, WeSIM is a holistic model that enables optimal decisions for investing into generation, network and/or storage capacity (both in terms of volume and location), in order to satisfy the real-time supply-demand balance (including the impact of inertia effects) in an economically optimal way, while at the same time ensuring efficient levels of security of supply. A key feature of WeSIM is in its capability to simultaneously consider system operation decisions and infrastructure additions to the system, with the ability to quantify trade-offs of using alternative technologies, for real-time balancing and transmission network and/or generation reinforcement management.

The key input data for WeSIM are:

- Generation data which include the capacity, operational cost, production profile and technical characteristics of different generation technologies such as conventional coal and gas-fired power generation, coal/gas CCS, nuclear, wind, solar PV, Concentrated Solar Power, various hydro technologies, geothermal, biomass, micro-CHP (based on the high and low scenarios), and peaking plant such as oil or gas-fired Open Cycle Gas Turbine (OCGT). In this study, the capacity of each generation technology including micro-CHP is given except the capacity of OCGT which is optimised by the model to ensure the supply reliability.
- Electricity demand and heat demand data. The latter only comprises the heat demand which is supplied by the micro-CHP in the micro-CHP scenario. The heat demand is obtained from the derived data submitted by WP2. Demand flexibilities can also be modelled in this tool allowing flexible demand to be time-shifted for peak-load reduction or energy arbitrage and to provide balancing services such as frequency regulation and reserve services.
- Network data that include the topology and capacity of interconnectors and the cost of reinforcing the capacity. The capacity is optimised to ensure that merit generators are not constrained sub-optimally.

Based on those data, WeSIM determines the optimal investment in generation peaking, heat pump, and network capacity and the optimal allocation of resources across the system in order to minimise the overall investment and operational costs. Figure 11 illustrates the input and output data flows from WeSIM.

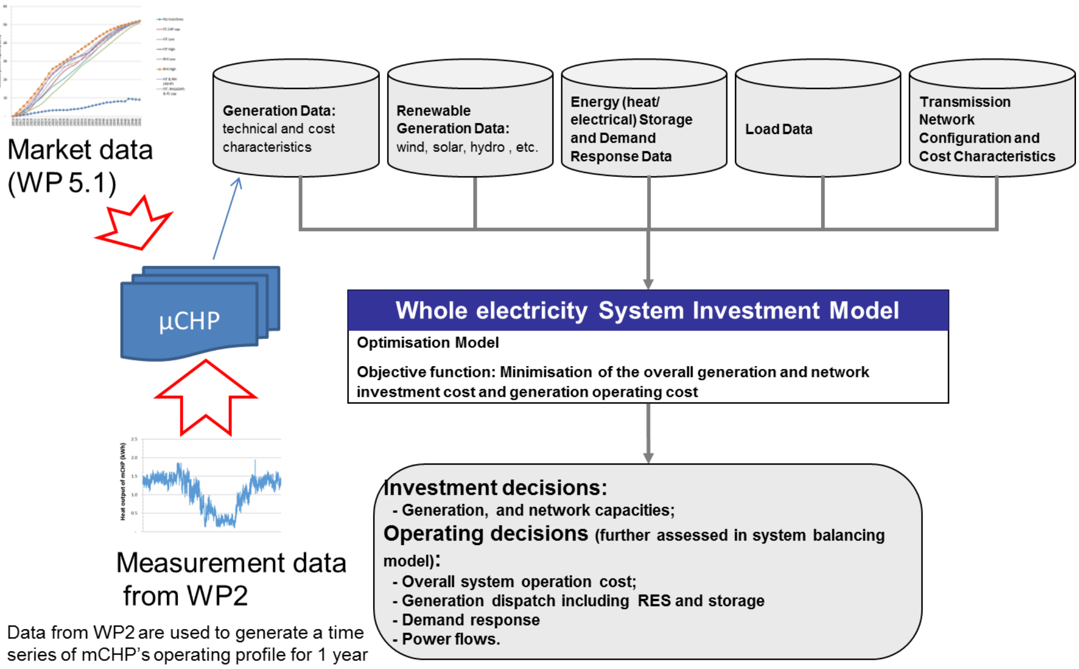


Figure 11. Overview of the WeSIM tool

The key output data of WeSIM that are used in the study are the following:

- Generation capacity and the associated capital costs;
- Capacity of heat pump and the associated capital costs;
- Network capacity and the associated capital costs;
- Electricity production from different technologies and the operation costs;
- Carbon emissions.

3.6 Assumptions

There are a number of assumptions used in the study as listed below.

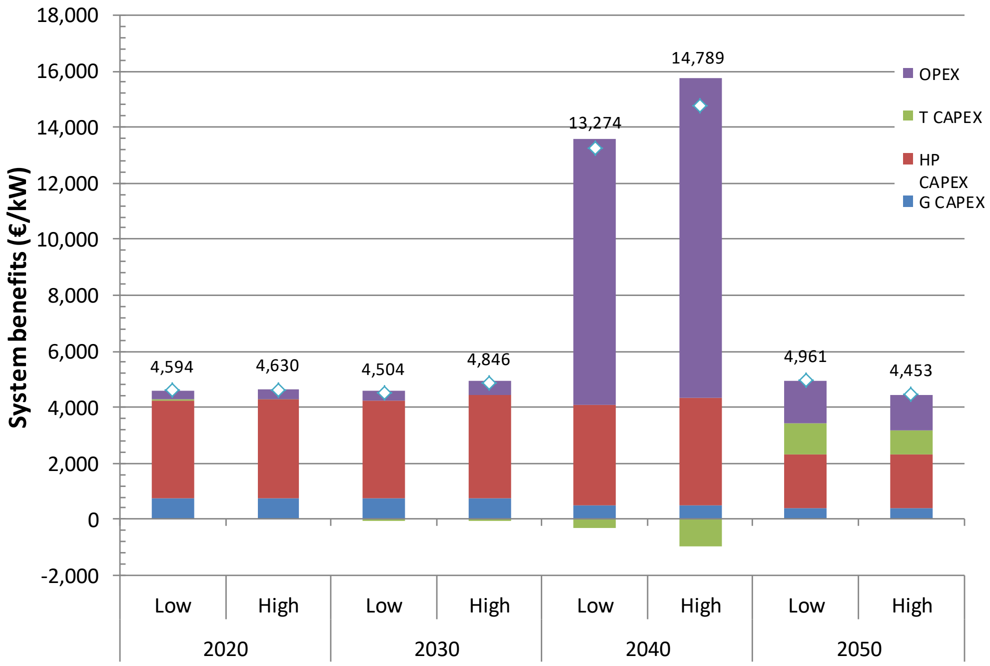
- micro-CHP can be dispatched when its capacity is needed by the system for example as a peaking/backup capacity when there is shortage in the system capacity;
- The cost of natural gas used by micro-CHP is the same as the cost of gas used in the CCGT;
- micro-CHP is also exposed to the same carbon price (€/tonne) as applied to large-scale generators; the impact of the carbon prices is also a function of the level of emissions.

4 System benefits of fuel cell micro CHP: Generation and Transmission

The focus of this chapter is on quantifying the system benefits of micro-CHP in the context of power generation and transmission. Due to the complexity of the problems, the benefits of micro-CHP on distribution networks will be analysed separately in the next chapter.

4.1 System benefits

The results are presented in Figure 12, expressed in €/kW electrical capacity of micro-CHP.



Carbon prices (€/tonne CO2)	11	11	71	71	151	151	224	224
Capacity factor of mCHP	55%	55%	55%	55%	90%	90%	39%	30%

Figure 12. Overall system benefits (exclude distribution network) of micro-CHP

The system benefits are obtained from the following:

- The reduction in generation CAPEX as the micro-CHP reduces the capacity of CCGT or OCGT or the combination of both. It is important to note that the cost of micro-CHP itself is not accounted, and therefore the figures shown below represent the gross value of the micro-CHP.
- The savings from not using HP to supply the heat demand; the savings represent the avoided capital cost of HP as the heat demand is met by micro-CHP.

- The savings in transmission cost (T CAPEX); the changes in the system capacity due to micro-CHP may increase or reduce the transmission capacity requirements;
- The reduction in the operating cost (OPEX).

It is important to note that the CAPEX of micro-CHP is not included in the results, but the OPEX of micro-CHP has been included.

The results provide the following insight:

- In 2020 and 2030, the savings come from three different sources:
    - Savings in HP CAPEX; as the largest saving component. This indicates that in the short-term, micro-CHP can efficiently displace HP as an alternative heat source;
    - Savings in G CAPEX, indicating that micro-CHP provides firm capacity to the system;
    - Savings in OPEX
- There is no large variation in the system benefits of storage for 2020, 2030 and the 2050 scenarios. The range of benefits of micro-CHP from those aforementioned factors is between 4,504 and 4,961 €/kW. These indicate that micro-CHP can benefit the European system in the short, medium, and long term.
- The savings per kW of micro-CHP are not affected significantly by the penetration of micro-CHP considered in the low and high scenarios indicating that there is no significant system barrier to incorporate micro-CHP at the levels being studied. It is important to note that even in the maximum scenario used in the study, the installed capacity of the micro-CHP is still less than 3% of the total generation capacity.
- The OPEX savings are relatively modest in 2020, 2030 but there is a significant increase in the value of micro-CHP in 2040 dominated by a significant increase in the OPEX savings; this is caused by the use of micro-CHP to reduce the utilisation of expensive OCGT as the share of peaking capacity in the overall generation portfolio increases together with increased penetration of renewables[10]. This is indicated by the increased utilisation of micro-CHP from 55% in the 2020 and 2030 scenarios to 90% (the upper limit) in 2040.

[10] The OPEX savings for the 2040 cases are much higher as the generation backgrounds used in the scenario, simulate the transition condition where there is not enough low carbon and low marginal cost plant built to accommodate load growth and decommissioning of fossil fuel plants. As a result, expensive peaking plants operate longer. This should only be considered as a plausible scenario in order to identify the drivers of the value of micro-CHP and should not be treated as a forecast of the future system.

- In the 2050 scenario, the utilisation of micro-CHP drops to 30% - 39% as there is a shift of using HP during high renewable output instead of burning gas. This reduces the benefits of micro-CHP to 4,453 – 4,961 €/kW.

In the following sections, the changes in the system caused by micro-CHP are analysed.

4.2 Impact on the capacity of primary sources

The micro-CHP can provide firm capacity as long as they can be dispatched when it is needed by the TSO to improve the capacity margin, especially during peak demand periods. However, this requires new control infrastructure which, to date, is not present; in the absence of this control capability, the capacity value of micro-CHP is less, and its related benefit cannot be included in the value of micro-CHP to the grid. In this study, it is assumed that the micro-CHP can be dispatched when the system needs it, and therefore it can provide firm capacity to the system.

Figure 13 shows the impact of micro-CHP on the generation system. It can be observed that the micro-CHP displaces by one to one ratio the capacity of other gas-fired technologies such as CCGT and OCGT. It is economical to displace first the capacity of CCGT which has higher capital cost than OCGT. So in the short and medium term, micro-CHP can displace the capacity of CCGT as the trend to use gas, while displacing high content carbon generation such as coal, increases until 2030. Beyond 2030, the capacity of CCGT that can be displaced becomes less, but micro-CHP can still reduce the demand for back-up or peaking plant by displacing the capacity of OCGT.

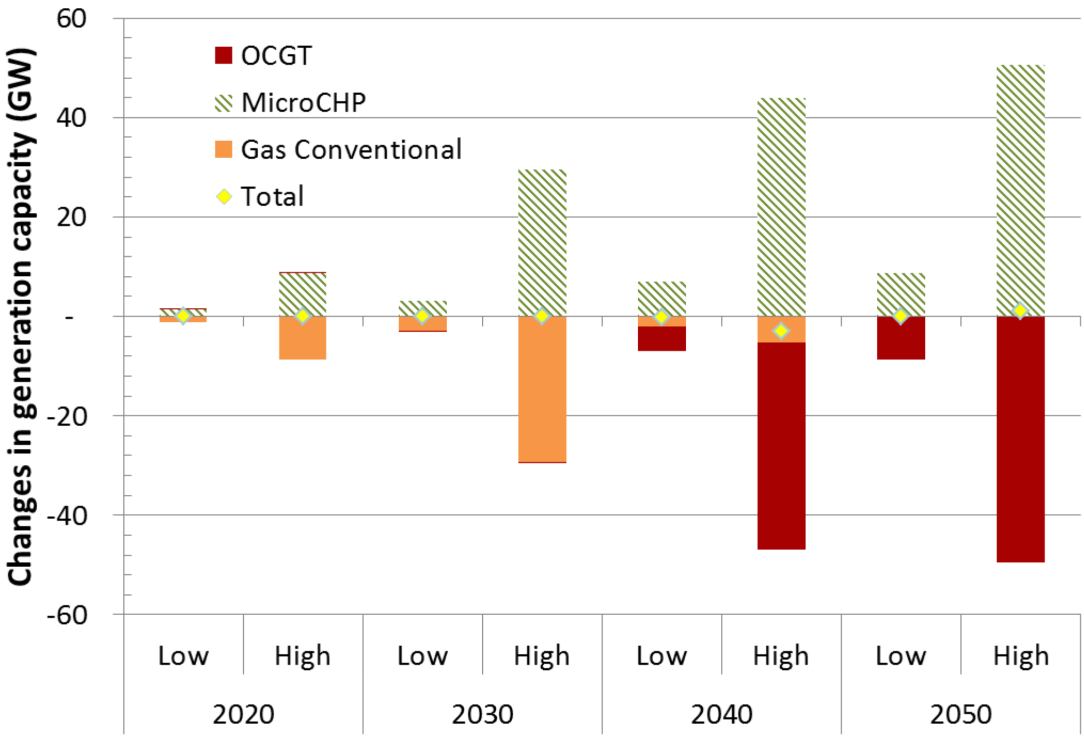


Figure 13. Impact of micro-CHP on the generation capacity

As a consequence, the value of micro-CHP in the context of displacing the capacity of primary sources is higher in short/medium term as the CAPEX of CCGT is considerably higher than the CAPEX of OCGT. This is shown in Figure 12.

4.3 Impact on electricity production

It is expected that micro-CHP will reduce the operating cost of electricity production as the overall energy efficiency of micro-CHP, operated in a combined heat and power mode (90%), is higher compared to the efficiency of conventional coal/gas/oil-fired thermal generators. The total of electricity production in the micro-CHP scenario is lower as the heat produced by micro-CHP is used to supply the heat demand directly. In the alternative scenario, the heat is supplied by HP which requires electricity that needs to be produced by power generation. The changes in the electricity production of the two scenarios ("reference" and "micro-CHP" scenarios) are shown in Figure 14.

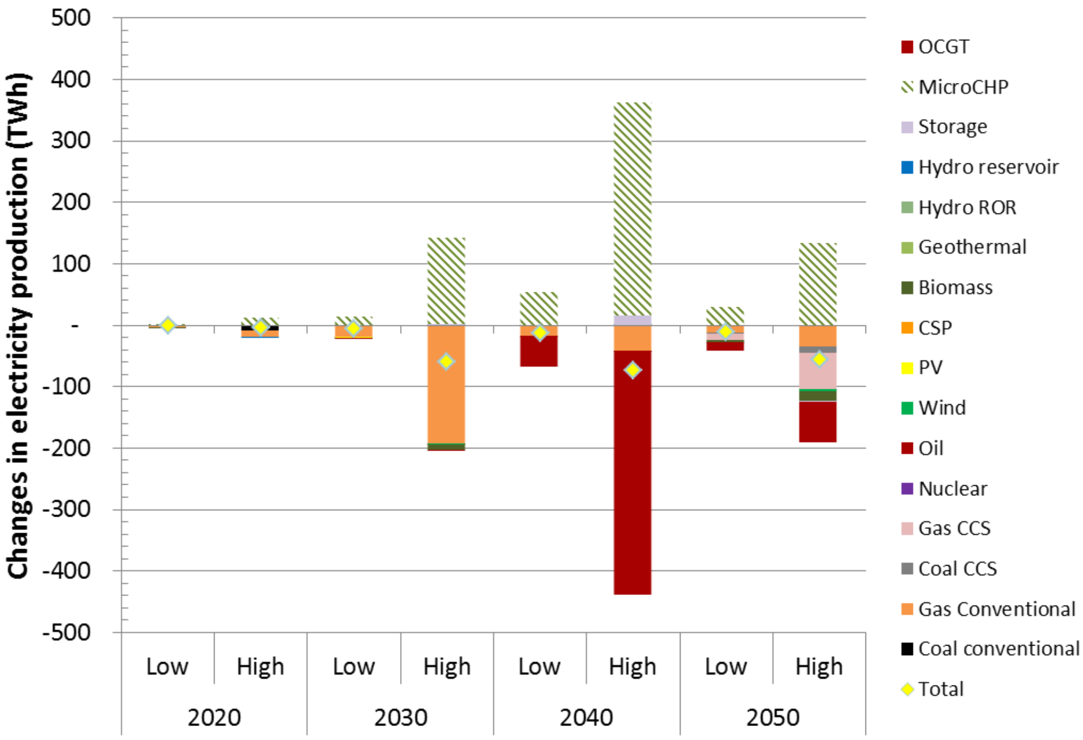


Figure 14. Impact of micro-CHP on the electricity production of other generating technologies

The results provide the following insight:

- In the short and medium term, additional electricity that is used to power HPs is mainly produced from mid-merit and/or peaking capacity. Therefore, one can observe that the energy being displaced by micro-CHP comes from coal-fired or peaking gas plant, only a small proportion comes from the output of low-carbon technologies until 2050.

- The net changes in electricity production are negative, that means that there is a reduction of electricity needed to supply the energy demand in the system with micro-CHP compared to the electricity production in the system without micro-CHP. This also indicates that the efficiency of the system, in terms of meeting the electricity and heat demand, is higher with micro-CHP compared with the efficiency of the system with HP.
- The impact on the operating cost will vary depending on the production cost of energy that is displaced by the micro-CHP. In 2040, the OPEX savings increase significantly as the micro-CHP, in this case, displaces energy mostly from peaking plant with the highest marginal cost. The savings become less when the micro-CHP energy starts to displace energy from low marginal cost plants.
- Impact on the increased carbon prices on the opex savings is also important. With much higher carbon prices in future, the benefit of displacing the output of high carbon content generators becomes higher.

4.4 Contribution of micro-CHP in reducing carbon emissions

In the short and medium term, at least when the use of conventional coal/gas/oil-fired plant is still dominant (at least until 2030), the impact of micro-CHP in reducing carbon emissions is expected to be relatively significant. This is quantified by calculating the difference in the emissions of the “Reference” and “micro-CHP” system. The results are shown in Figure 15.

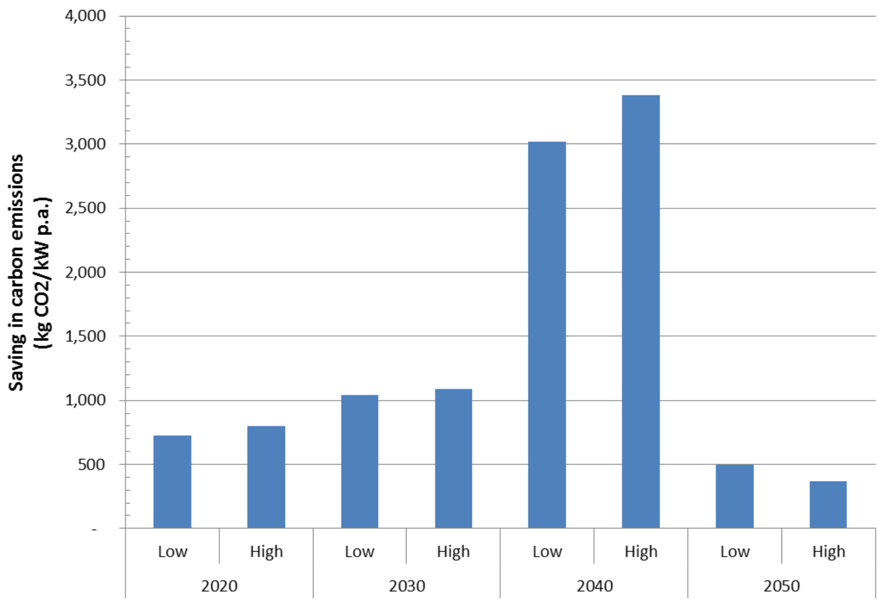


Figure 15. Contribution of micro-CHP in reducing carbon emissions

The reduction in carbon emissions depends on the sources of energy that is being displaced by the micro-CHP. In 2020 and 2030, the reduction in the emissions is contributed by the micro-CHP in displacing the energy from coal and gas-fired plants. The emission reduction is larger in 2040, as micro-CHP displaces the energy from gas or high carbon content oil-fired OCGT. In 2050, as the micro-CHP starts to displace the energy from low carbon technology, the benefits become less.

Therefore, it can be concluded that the natural-gas fuel cell micro-CHP can play a role in reducing the carbon emissions particularly within the timeframe between 2020-2040; when high carbon content generators such as coal/gas/oil-fired generators still have considerable shares in the generation mixes. In the long term, when the supply of electricity is mainly from low-carbon generation sources, the use of natural-gas fuel cell micro-CHP becomes less attractive, in the context of carbon reduction. Alternative fuel for micro-CHP, especially from sustainable and low-carbon sources will be needed.

Figure 16 shows the carbon emission reduction that can be achieved in the selected MS with considerable micro-CHP capacity by 2030. Given that Germany has the largest installed capacity, it is expected that the carbon emission reduction is the highest.

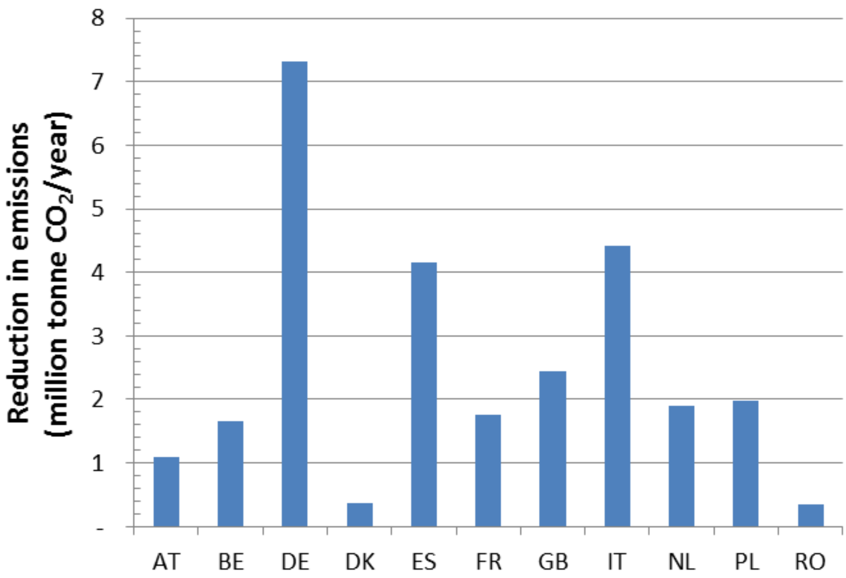


Figure 16. Contribution of micro-CHP in reducing carbon emissions by 2030 (maximum uptake scenario)

The extent of the emissions that can be reduced is also system specific. Countries with a significant share of low-carbon generators will have less reduction compared to the countries which still depend largely on fossil fuel based plants.

4.5 Operational driver for micro-CHP

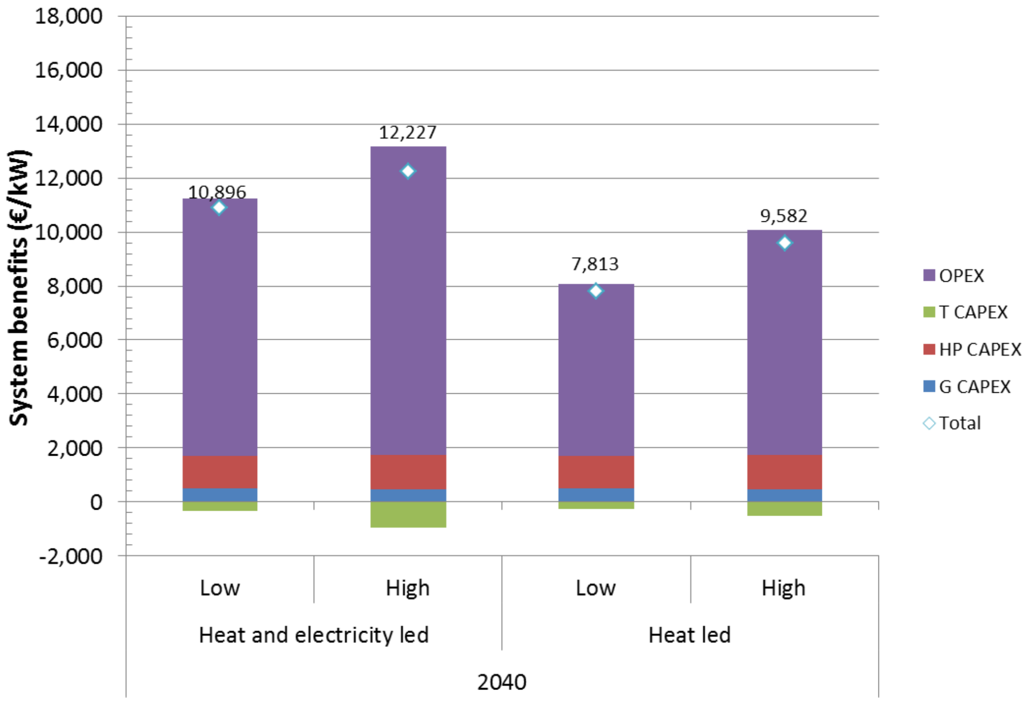
In order to gain from its high efficiency, micro-CHP should operate when it can provide heat and electricity simultaneously. The use of storage can help to balance temporarily supply and demand of energy. In this study, the profile of heat output of the micro-CHP indicates the use of thermal storage which flattens the operational profile of micro-CHP while managing the variability in heat demand. However, there is a question whether the micro-CHP should be allowed to operate driven by electricity demand only.

In order to address this question, the simulation was carried out allowing the micro-CHP to be operated in two modes: electricity led or heat led. The results of the studies shown previously in Figure 12 suggests that in 2020 and 2030, the optimal operation of micro-CHP is heat-led (however, in the case of system scarcity, the micro-CHP can be dispatched). This is indicated by the capacity factor of micro-CHP, i.e. 55% in 2020 and 2030. However, in 2040 due to the suboptimal capacity of mid-merit and baseload plant in the system, micro-CHP is required to displace the energy from peaking plant (i.e. OCGT). The simulation shows that the capacity factor of micro-CHP reaches 90% which is the maximum annual capacity factor set for micro-CHP in this study. The capacity factor drops to below 55% in 2050 as the capacity of renewables is sufficient to reduce the utilisation of natural gas micro-CHP.

It can be concluded that in general, the heat-led operation mode for micro-CHP is sufficient except in the situation where there is scarcity in the central generation system that requires micro-CHP to operate in both modes. With the heat-led operation, there is no need for complex dispatch infrastructure needed to allow micro-CHP to be operated in electricity-led mode.

In order to understand the impact of constraining the micro-CHP to be operated only in heat mode, an additional study was carried out using the 2040 scenario with a setup that forced micro-CHP to operate only when there was heat demand. The results are shown in Figure 17 below.

With the constraints, the results show that the capacity factor of micro-CHP drops from 90% to 55% indicating heat-led operation only. The results also indicate that the opex savings obtained by constraining the operation mode of the micro-CHP are less; this is expected as the electricity production of micro-CHP is less than its production in the previous case.



Capacity factor of mCHP	90%	90%	55%	55%

Figure 17. The benefits of combined heat and electricity led compared with heat led micro-CHP operation

The difference in the benefits may provide additional insight on how much the cost of the control and communication infrastructure that can be justified to allow the micro-CHP to be operated in electricity-led mode. In this case, the difference is around 3 thousand euros per kW. It is important to highlight that the results are conditional; it means that the generation background used in the 2040 scenario drives the need for electricity-led operation. In other situations, such as in 2020, and 2030 the results indicate that only heat-led operation mode is already optimal.

4.6 System benefits of micro-CHP with high electrical efficiency

The studies described in the previous section are based on the micro-CHP which is operated with 35% electrical efficiency and 60% thermal efficiency. As an alternative, for a certain micro-CHP technology, it is plausible to design the fuel cell micro-CHP to have a different characteristic, e.g. 60% electrical efficiency and 35% thermal efficiency. In this context, the objective of this exercise is to understand and compare the performance of these two designs in the context of the power system. The results will provide useful insight on how different micro-CHP technologies will perform.

Two scenarios are used: (i) low electrical efficiency scenario, i.e. the cases that have been discussed previously, (ii) high electrical efficiency scenario, i.e. new cases where the electrical efficiency of micro-CHP is 60% but with 35% thermal efficiency. In both cases, the overall micro-

CHP efficiency to around 95%. The impact of improving the electrical efficiency of the fuel cell micro-CHP is shown in Figure 18.

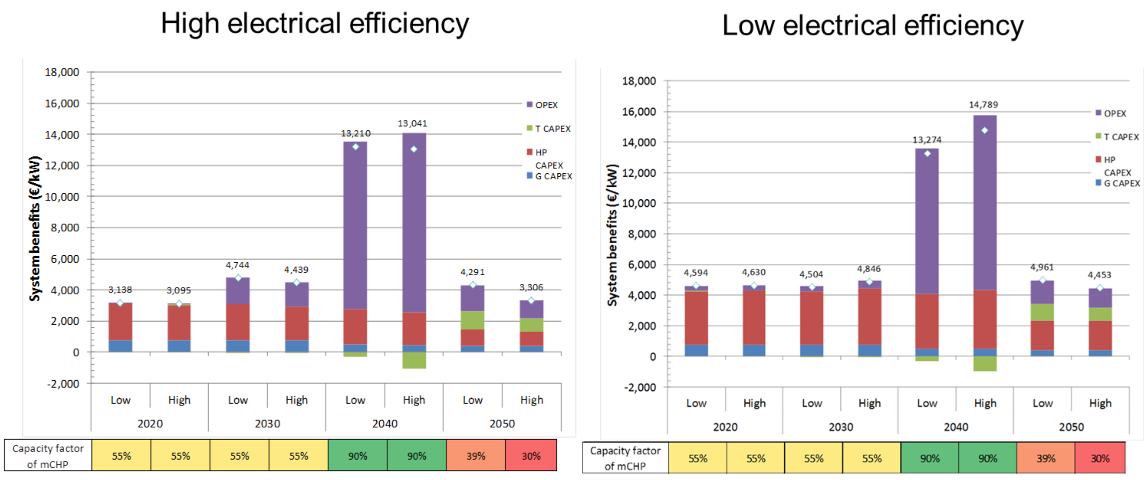


Figure 18. The benefits of different micro-CHP designs

The results demonstrate the following:

- The benefits of micro-CHP with higher electrical efficiency but lower thermal efficiency (Figure 18 right) is slightly lower compared to the benefits of the micro-CHP which is designed with lower electrical efficiency but higher thermal efficiency (Figure 18 left).
- The results show that by improving the electrical efficiency, it can increase the OPEX savings but at the expense of smaller savings in the HP CAPEX as the thermal efficiency is lower.
- In terms of the capacity value of these two technologies, they are the same. So this particular design does not affect the capacity value of the micro-CHP.
- There is no significant change in other savings, e.g. transmission CAPEX.
- There is no evidence, at least from the simulation studies being carried out, that the improvement of the electrical efficiency affects how the micro-CHP is utilised. The capacity factor of micro-CHP remains the same in both cases. It is still important that micro-CHP can provide both electricity and heat at the same time to maximise its energy efficiency. Only when the capacity is scarce, micro-CHP needs to be electricity-led.

4.7 Heat pump as a competing or complementing technology?

HP and micro-CHP are often proposed as a combined solution for providing heat while improving the overall efficiency of the energy (electricity and heat) systems. However, it is unclear whether the combination of micro-CHP and HP is really necessary considering that both technologies can supply heat. Thus, a set of additional studies has been performed to identify the conditions when HP is competing or complementing the micro-CHP. In the studies, HP is allowed to be added to the system in order to minimise the overall system cost.

The results (Figure 19) suggest that no HP is necessary to complement the micro-CHP in the system until 2050. This is demonstrated by virtually zero capacity of HP proposed for 2020 to 2040. By 2050, the level of renewables, or low-marginal cost generation is sufficient to drive the investment in HP.

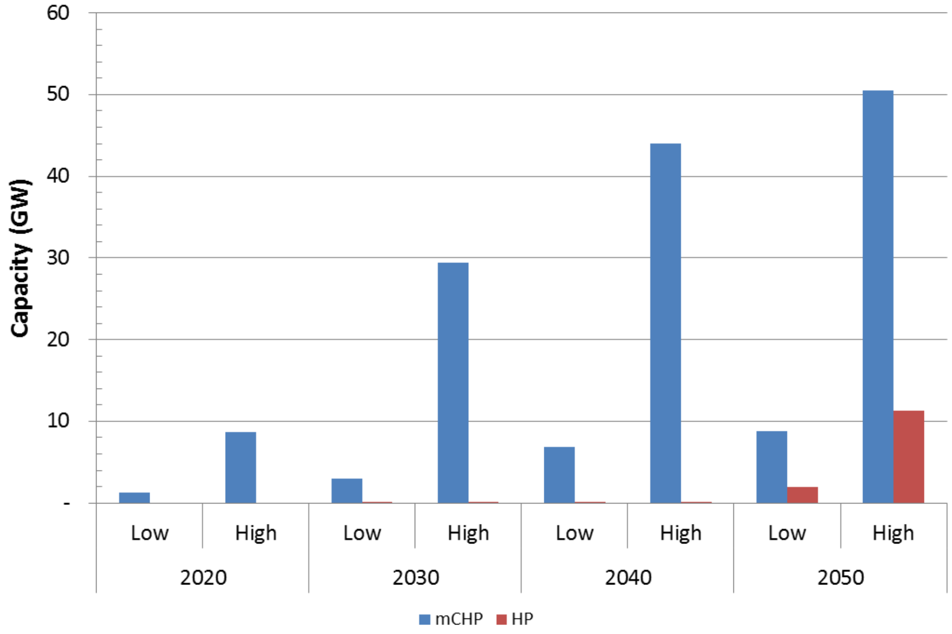


Figure 19. Analysing the need of HP in the presence of micro-CHP

It is important to highlight that the study only considers the amount of heat demand that can be supplied by micro-CHP. In reality, a combination of micro-CHP with other heat sources such as HP or conventional boilers may be required; but this is out of the scope of the study. What can be concluded in the study is that at a certain degree, the micro-CHP competes with HP and in the case where the micro-CHP is already present in the system, at least in the short and medium term, there is no need for additional HP that competes with the micro-CHP.

However, in the system with high level of renewables such as wind or solar, the combination of HP and micro-CHP may become an optimal solution; this is indicated by the results for the 2050 scenario. The illustrative diagram[11] below (Figure 20) describes how the HP can complement the operation of micro-CHP.

[11] Source: Delta-ee and COGEN Europe, the benefits of mCHP

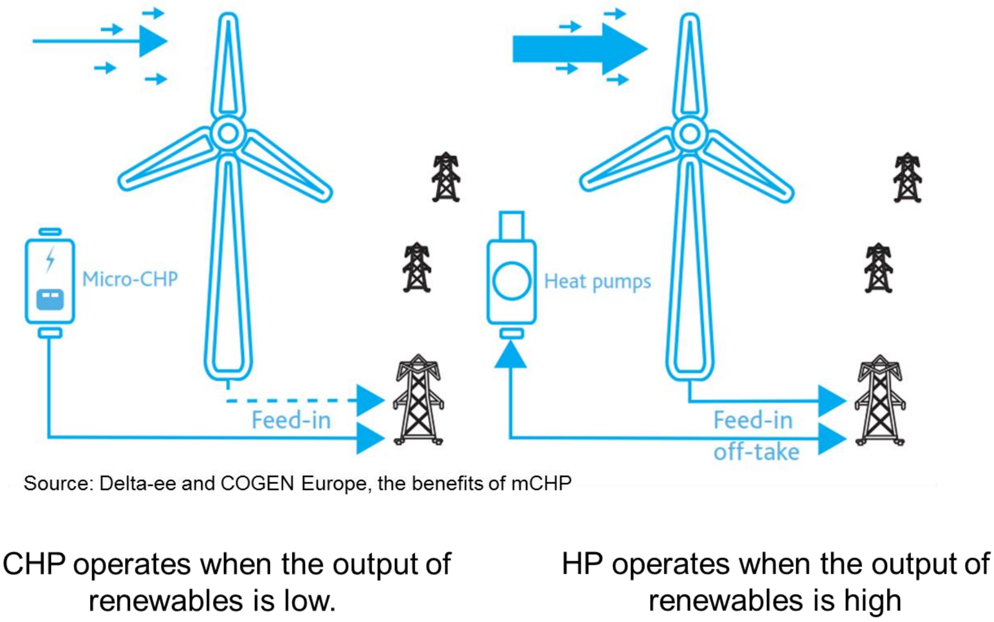


Figure 20. Synergy between HP and micro-CHP in systems with high renewable energy

In periods when the output of wind farm is low, micro-CHP produces electricity and heat to meet the local heat and electricity demand. The excess electricity can be exported to the grid. In periods when the output of wind farm is high, instead of burning gas and using micro-CHP to generate heat, HP can be used as an alternative heat source supplied by the electricity from renewable sources.

This phenomenon was observed in one of the simulation studies using the 2050 scenario. This is illustrated in Figure 21 which shows the output of renewable sources (wind + PV) and the dispatch for micro-CHP and HP in Germany for more than 2 days.

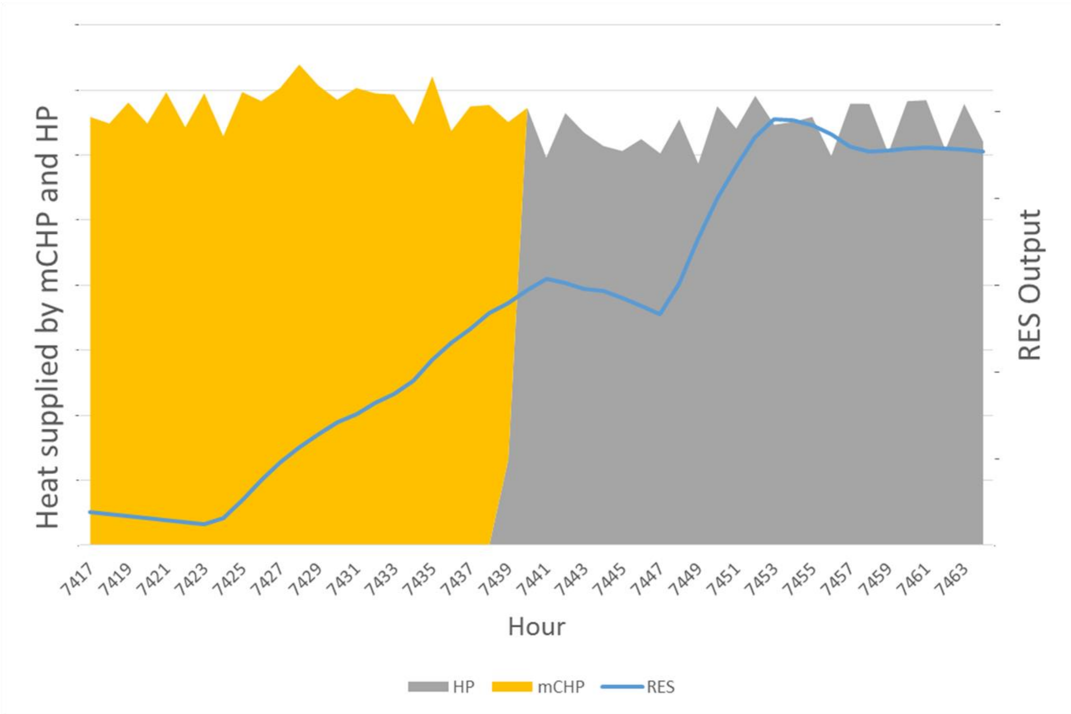


Figure 21. Synergy between HP and micro-CHP following the availability of renewables

On the first day, the output from renewable sources in Germany is relatively low, and the simulation shows that micro-CHP is used in this period. On the second day, the output of renewables is relatively high, and the HP is used in this period. This demonstrates the synergy between the operation and investment in micro-CHP and HP.

The synergy occurs when the penetration of renewables is already high, either in European scale or on the national scale. Thus, it can be concluded that in the long run there are benefits of having two complementary technologies such as micro-CHP and HP.

5 Benefits of fuel cell micro-CHP for distribution network

5.1 Approach

In this chapter, we discuss the approach and the results of the studies analysing the impact and the benefits of the micro-CHP on the electrical distribution systems across Europe. The studies complement the previous analyses and enable the impact of micro-CHP on the electrical system to be analysed in a holistic manner.

In order to enable the studies, a set of representative network models has been developed by Imperial College. The models resemble the characteristics of distribution systems across Europe in terms of the load density, network length, number of substations, number and type of transformers, etc. Details of the models can be found in the Appendix A.3.

Studies were carried out to determine the required reinforcement measures and estimate the reinforcement cost for different network classes (rural, urban, semi-rural/urban) for a given HP or micro-CHP deployment level and control approaches. The integration of HP or micro-CHP may trigger thermal and/or voltage driven problems in the network; in order to solve the problems, the network will need to be reinforced. If the problems are voltages, there may be possibilities to solve by optimising the position of tap-changing transformers. The studies consider some discrete reinforcement options, which may create some headroom in the network. By aggregating the reinforcement costs across all network classes, it is possible to determine accurately the impact of HP or micro-CHP on different network classes and estimate the total distribution reinforcement costs at the national level. Figure 22 depicts the approach aforementioned above.

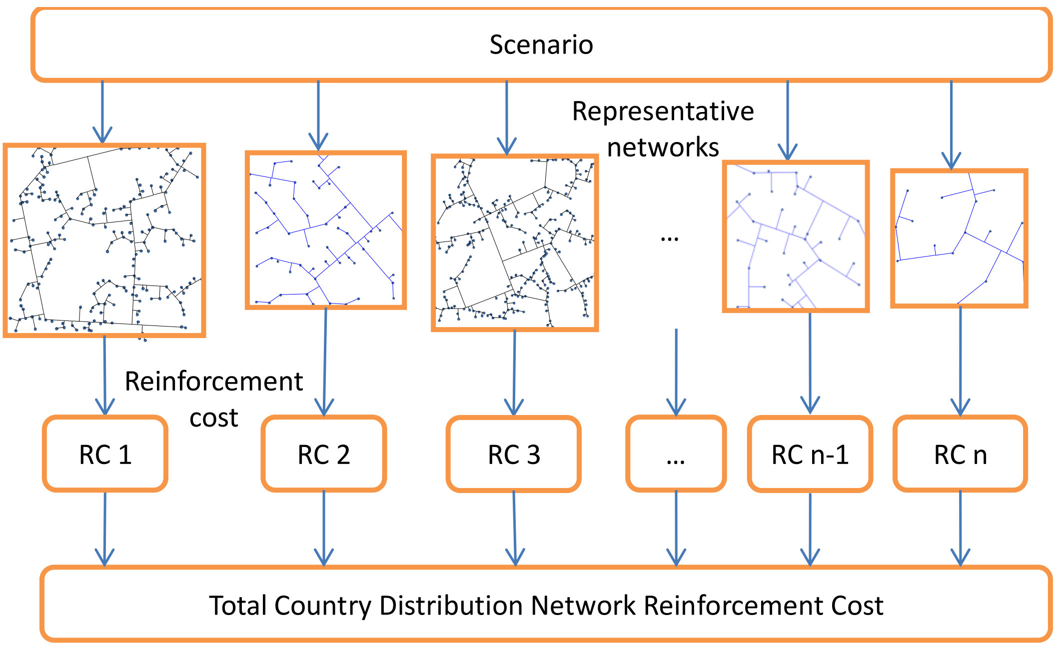


Figure 22. Estimating distribution reinforcement cost for a given scenario

In order to quantify the impact of the micro-CHP, the same approach as described in section 2.1 is applied. Two market uptake projection scenarios of micro-CHP (min and max) as described in section 3.3 are used in the studies. For each scenario, a reference case is created by having HP to supply the heat demand, which is supposed to be supplied by the micro-CHP in the second case. The benefit of micro-CHP is derived by calculating the cost difference between the two cases. The results are as follow:

5.2 Country-specific benefit of micro-CHP on distribution networks

Figure 23 and Figure 24 show the potential benefit per micro-CHP kW (electricity) installed in 2020 per country for the low (minimum) and high (maximum) uptake scenarios, respectively. The benefits are broken down to the savings obtained in different classes such as: HV: High Voltage, PS: Primary Substation, MV: Medium Voltage, DT: Distribution Transformer, LV-V: Voltage driven LV network reinforcement, LV-I: Thermal driven LV network reinforcement. The savings are relative to the system with HP.

Overall, the benefit of micro-CHP on distribution networks is considerable. The maximum benefit, i.e. about €4000/kW is found for Denmark (DK) and the Netherlands (NL), primarily achieved by deferring voltage driven investment in LV distribution networks (LV-V). Another visible saving is at the Medium Voltage (MV) feeders as the micro-CHP can release some capacity and defer the future network investment requirement due to load growth.

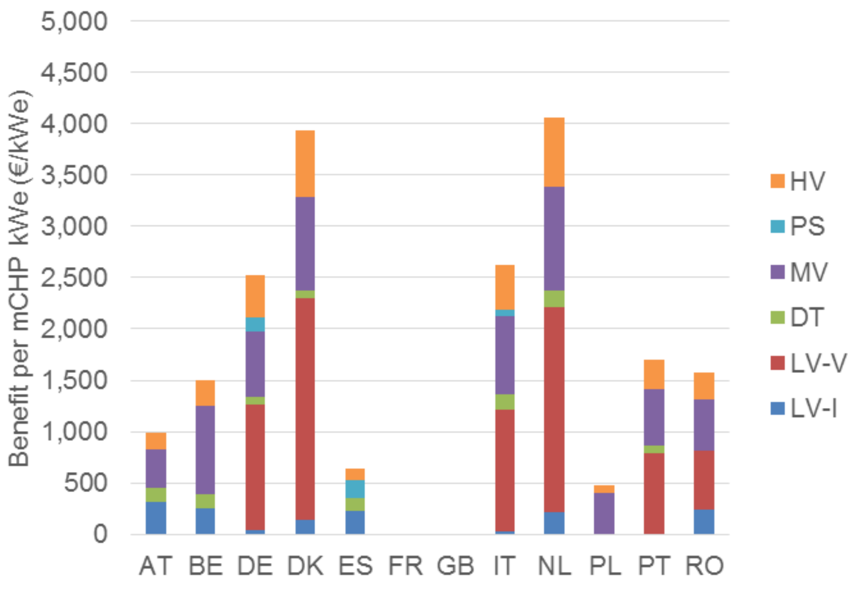


Figure 23. Estimated value of micro-CHP in reducing distribution network cost in Europe [2020: low uptake scenario]

It is important to highlight that the reinforcement at distribution network considered in the analysis tool is discrete and lumpy. As a consequence, the temporal value of the micro-CHP becomes lumpy and may fluctuate according to the system conditions. The benefit of micro-CHP varies in a relatively wide range depending on many factors such as the capacity of micro-CHP, load profiles, network costs, network configurations, etc. Therefore, it is not surprising that the results for different countries are different.

Figure 24 shows the benefits of the micro-CHP when the high uptake scenario is used. The maximum benefit, circa. €4700/kW is found in Denmark. The benefits are still dominated by the savings in the voltage-driven low-voltage network and medium voltage systems. Other savings are obtained by deferring the cost of High Voltage (HV), Primary Substation(PS) and Distribution Transformers (DT).

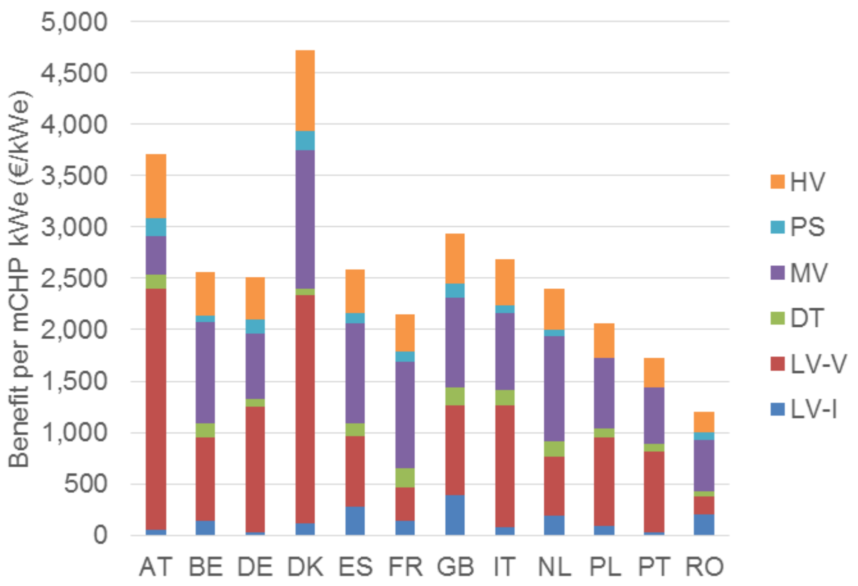


Figure 24. Estimated value of micro-CHP in reducing distribution network cost in Europe [2020: high uptake scenario]

Considering the installed capacity projected in the low uptake scenario is relatively low, in practice, the impact may be absorbed by the headroom available in the system. For this reason, the rest of the discussions will focus on the results of the high uptake scenario.

For 2030 - 2050, the benefit of micro-CHP in reducing distribution network cost per country is depicted in Figure 25 - Figure 27 respectively. Depending on the projected capacity of micro-CHP, HP and load growth for some countries, like Austria and Great Britain, the benefit of micro-CHP varies. As shown in those figures, the benefits can go up or down within the 2020 – 2050 period depending on the headroom available in the distribution network.

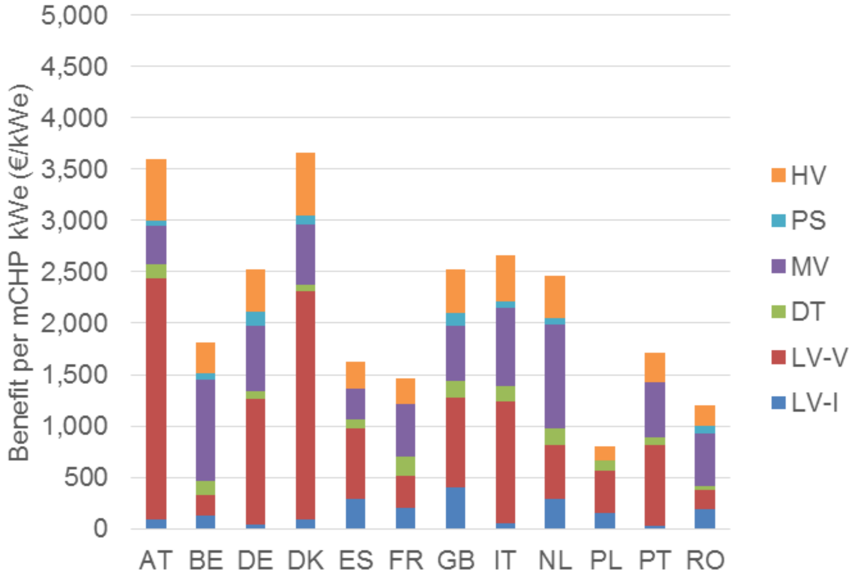


Figure 25. Estimated value of micro-CHP in reducing distribution network cost in Europe [2030: high uptake scenario]

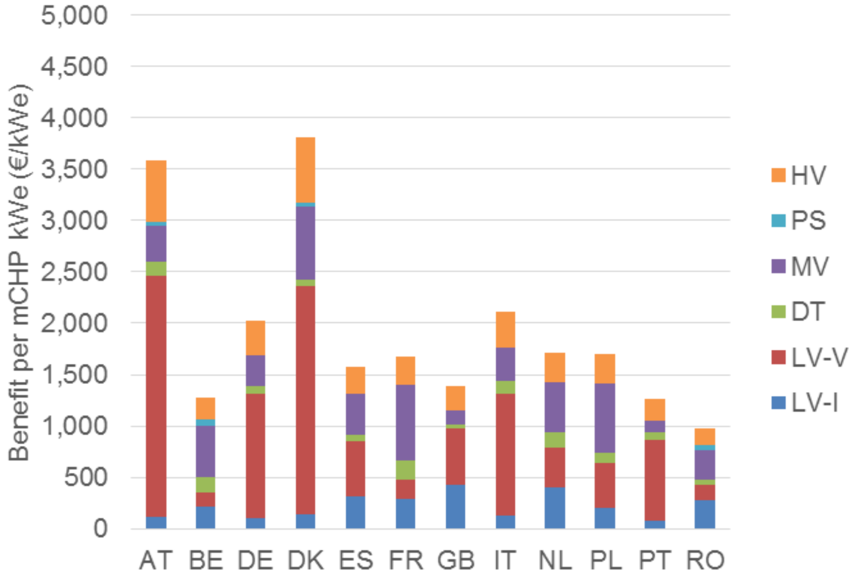


Figure 26. Estimated value of micro-CHP in reducing distribution network cost in Europe [2040: high uptake scenario]

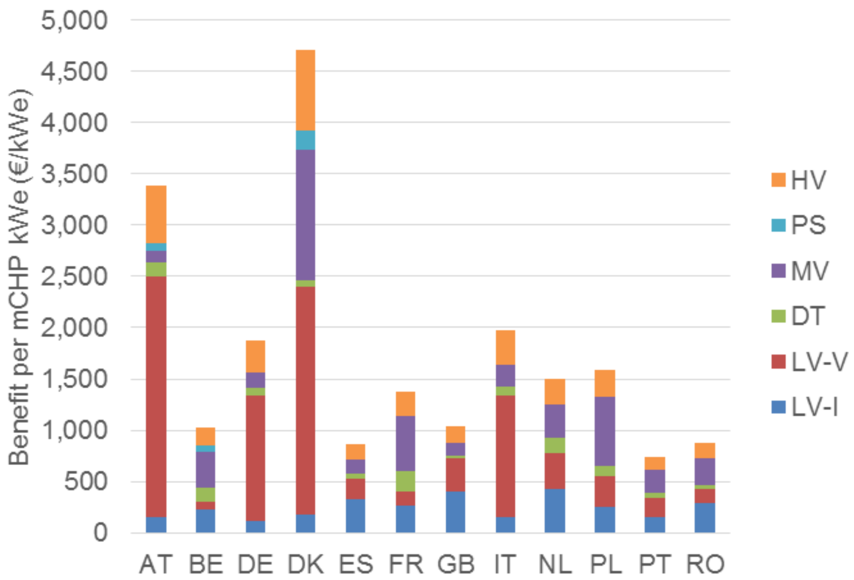


Figure 27. Estimated value of micro-CHP in reducing distribution network cost in Europe [2050: high uptake scenario]

Using the maximum uptake scenario, the benefit can be up to €4700/kW but the benefits are system specific. It is interesting to note that the benefits of micro-CHP are likely to become less in the future, especially in 2050. As the electrical load is expected to increase in future driven by increased electrification in the system, distribution networks in Europe will need to be reinforced. This will make some headroom in the system to absorb the impact of micro-CHP. This trend can be observed more clearly in Figure 28.

5.3 Average benefits of micro-CHP on distribution networks

Figure 28 shows the average benefits of micro-CHP on the European distribution networks. The value is derived by calculating the total savings divided by the total installed capacity (electricity). The average benefits for the minimum and maximum uptake scenarios are estimated between €1660 - €2400/kW and €1600 - €2600/kW respectively.

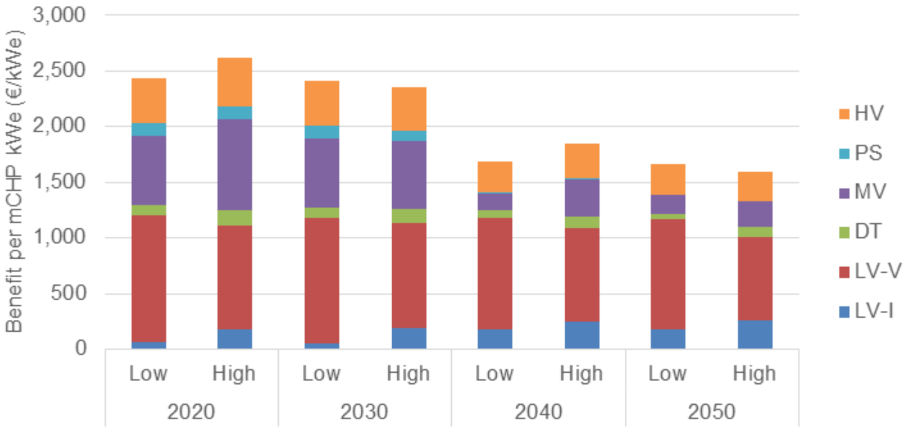


Figure 28. Estimated average value of micro-CHP in reducing distribution network cost in Europe in different scenarios

The results indicate the following:

- The largest benefit comes from deferring the investment cost at LV especially investment driven by voltage issues.
- The second/third largest savings come from the cost reduction at Medium Voltage feeders or the HV feeders.
- Other benefits are obtained from the savings in the LV feeders, distribution transformers, and primary substations.
- The savings between the low and high uptake scenario are relatively similar. Again, this suggests that there is no significant barrier in integrating micro-CHP with low or high uptake scenarios.

The results also demonstrate that there are benefits, in the context of reducing the distribution network capacity requirement, of deploying micro-CHP technologies. This emphasises that micro-CHP can play a role in the future development of European energy system, and particularly on distribution network development.

6 Conclusions

In this chapter, the benefits of micro-CHP on generation, transmission, and distribution are combined to give a complete overview of the system benefits of micro-CHP. The results discussed in section 4.1 are combined with the average savings in distribution network (section 5.3); the total system benefits are presented in Figure 29.

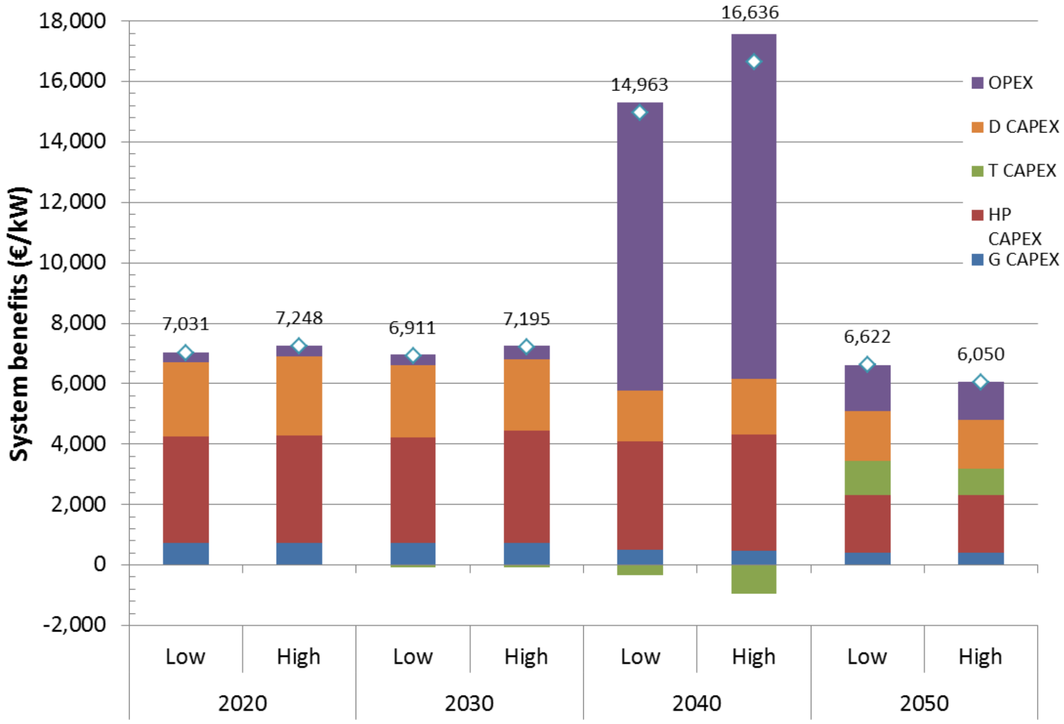


Figure 29. Estimated average value of micro-CHP in reducing distribution network cost in Europe in different scenarios

The total system benefits are around €6050 - €7248/kW, with the 2040 cases as an exception. While the magnitude of the benefits is relatively similar, the savings may come from different sources. In the short and medium term, the savings are dominated by the savings in displacing the capacity of HP, power generation, and distribution network capacity. In the long run, the OPEX savings become higher.

Based on the results of the studies and the analyses that have been carried out, a set of conclusions can be derived as follows:

- micro-CHP can bring the following benefits:
  a. Displace capacity of central generators. The capacity value of micro-CHP is comparable to traditional gas-fired plant providing it can be dispatched as back-up;
  b. Displace the capacity of alternative heat sources;

c. Reduce operating costs. Net energy consumption is reduced indicating higher energy efficiency;

d. Release network capacity / postpone reinforcement at distribution and transmission networks;

e. Reduce carbon emissions.

Some of the benefits can only be realised if the micro-CHP can provide grid services; this has implications for the design and control of the micro-CHP, for example: enabling remote operation capabilities for the system operator to access and use micro-CHP to support the grid.

- The benefits are system specific and driven by the opportunity of the micro-CHP to reduce the overall costs; thus, the ratio of those components vary across different scenarios.
- The benefits (per kW) are not too sensitive to the penetration level of micro-CHP projected which indicate that there is no significant barrier for the micro-CHP at the levels being studied.
- In the short term, based on the to-date level of renewables and efficiency of the micro-CHP, it is sufficient if micro-CHP operates in heat-led mode. Combined electrical and heat-led is required when micro-CHP can be a least-cost alternative source to displace high marginal cost generators such as peaking plant (e.g. when the capacity is scarce). This can also be triggered by having higher electrical efficiency.
- A micro-CHP with higher electrical efficiency but lower thermal efficiency has similar system benefits to the benefits of a micro-CHP with lower electrical efficiency but higher thermal efficiency. The former can bring more efficiency to the electrical system operation but its value in displacing alternative heat supply such as HP is lower.
- micro-CHP is competitive against HP in the short and medium term; however, when the renewable penetration in the system is sufficiently high (>70%), a combination of micro-CHP and HP may form an optimal portfolio.

Based on these results and the analysis, it can be concluded that micro-CHP technologies are important for the future European energy system development in both short and long run. The micro-CHP can also complement the operation of other low-carbon technologies such as HP.

The grid system benefits of micro-CHP arising from this analysis suggest that appropriate mechanisms should be put in place including removal of barriers and a framework in ancillary services markets to enable wide deployment of this technology in the European system. Acknowledgement of its system benefits and a full framework for participation in the ancillary services market, will allow the micro-CHP to fully participate in the power and heat sectors and to compete with other low-carbon technologies.

7 Appendix

A.1. Description of WeSIM

When considering system benefits of enabling technologies such as storage, Demand-Side Response (DSR), interconnection and flexible generation, it is important to consider two key aspects:

- **Different time horizons**: from long-term investment-related time horizon to real-time balancing on a second-by-second scale (Figure 30); this is important as the alternative balancing technologies can both contribute to savings in generation and network investment as well as increasing the efficiency of system operation.

- **Different assets in the electricity system**: generation assets (from large-scale to distributed small-scale), transmission network (national and interconnections), and local distribution network operating at various voltage levels. This is important as alternative balancing technologies may be placed at different locations in the system and at different scales. For example, bulk storage is normally connected to the national transmission network, while highly distributed technologies may be connected to local low-voltage distribution networks.

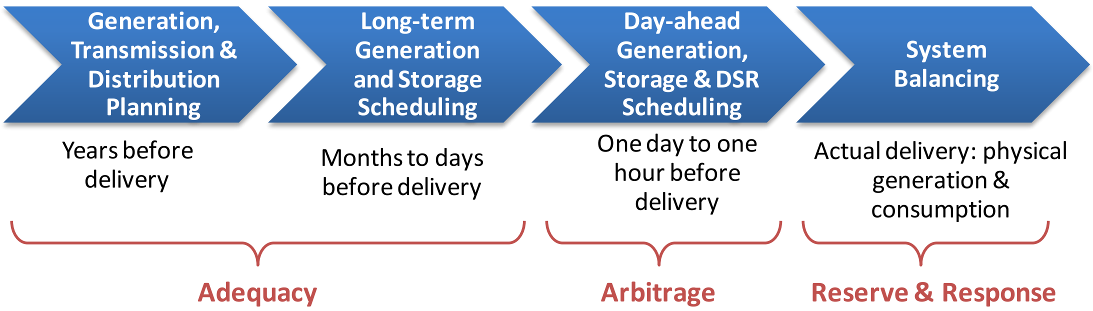


Figure 30. Balancing electricity supply and demand across different time horizons

Capturing the interactions across different time scales and across different asset types is essential for the analysis of future low-carbon electricity systems that includes alternative balancing technologies such as storage and demand side response. Clearly, applications of those technologies may improve not only the economics of real time system operation, but they can also reduce the investment into generation and network capacity in the long-run.

In order to capture these effects and in particular trade-offs between different flexible technologies, it is critical that they are all modelled in a single integrated modelling framework. In order to meet this requirement we have developed *WeSIM*, a comprehensive system analysis model that is able to simultaneously balance long-term investment decisions against short-term operation decisions, across generation, transmission and distribution systems, in an integrated fashion.

This holistic model provides optimal decisions for investing into generation, network and/or storage capacity (both in terms of volume and location), in order to satisfy the real-time supply-demand balance in an economically optimal way, while at the same time ensuring efficient levels of security of supply. The WeSIM has been extensively tested in previous projects studying the interconnected electricity systems of the UK and the rest of Europe.[12] An advantage of WeSIM over most traditional models is that it is able to simultaneously consider system operation decisions and capacity additions to the system, with the ability to quantify trade-offs of using alternative mitigation measures, such as DSR and storage, for real-time balancing and transmission and distribution network and/or generation reinforcement management. For example, the model captures potential conflicts and synergies between different applications of distributed storage in supporting intermittency management at the national level and reducing necessary reinforcements in the local distribution network.

A.2. WeSIM problem formulation

WeSIM carries out an integrated optimisation of electricity system investment and operation and considers two different time horizons: (i) short-term operation with a typical resolution of one hour or half an hour (while also taking into account frequency regulation requirements), which is coupled with (ii) long-term investment i.e. planning decisions with the time horizon of multiple years (e.g. 2015-2050). All investment decisions and operation decisions are determined simultaneously in order to achieve an overall optimality of the solution. An overview of the WeSIM model structure is given in Figure 31.

[12] WeSIM model, in various forms, has been used in a number of recent European projects to quantify the system infrastructure requirements and operation cost of integrating large amounts of renewable electricity in Europe. The projects include: (i) “Roadmap 2050: A Practical Guide to a Prosperous, Low Carbon Europe” and (ii)“Power Perspective 2030: On the Road to a Decarbonised Power Sector”, both funded by European Climate Foundation (ECF); (iii) “The revision of the Trans-European Energy Network Policy (TEN-E)” funded by the European Commission; and (iv) “Infrastructure Roadmap for Energy Networks in Europe (IRENE-40)” funded by the European Commission within the FP7 programme.

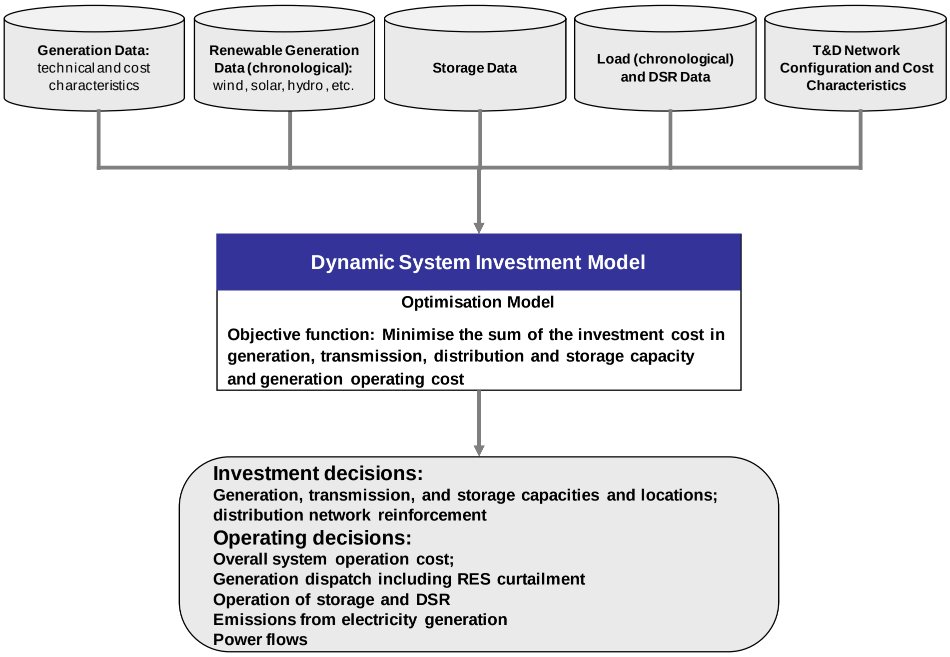


Figure 31. Structure of the Whole-electricity System Investment Model (WeSIM)

The objective function of WeSIM is to minimise the overall system cost, which consists of investment and operating cost:

- The investment cost includes (annualised) capital cost of new generating and storage units, capital cost of new interconnection capacity, and the reinforcement cost of transmission and distribution networks. In the case of storage, the capital cost can also include the capital cost of storage energy capacity, which determines the amount of energy that can be stored in the storage. Various types of investment costs are annualised by using the appropriate Weighted-Average Cost of Capital (WACC) and the estimated economic life of the asset. Both of these parameters are provided as inputs to the model, and their values can vary significantly between different technologies.

- System operating cost consists of the annual generation operating cost and the cost of energy not served (load-shedding). Generation operating cost consists of: (i) variable cost which is a function of electricity output, (ii) no-load cost (driven by efficiency), and (iii) start-up cost. Generation operating cost is determined by two input parameters: fuel prices and carbon prices (for technologies which are carbon emitters).

There are a number of equality and inequality constraints that need to be respected by the model while minimising the overall cost. These include:

- *Power balance constraints*, which ensure that supply and demand are balanced at all times.

- *Operating reserve constraints* include various forms of fast and slow reserve constraints. The amount of operating reserve requirement is calculated as a function of uncertainty in generation and demand across various time horizons. The model distinguishes between two key types of balancing services: (i) frequency regulation (response), which is delivered in the timeframe of a few seconds to 30 minutes; and (ii) reserves, typically split between spinning and standing reserve, with delivery occurring within the timeframe of tens of minutes to several hours after the request (this is also linked with need to re-establish frequency regulation services following outage of a generating plant). The need for these services is also driven by wind output forecasting errors and this will significantly affect the ability of the system to absorb wind energy. It is expected that the 4 hour ahead[13] forecasting error of wind, being at present at about 15% of installed wind capacity, may reduce to 10% post-2020 and then further to less than 6%, may have a material impact of the value of flexibility options. Calculation of reserve and response requirements for a given level of intermittent renewable generation is carried out exogenously and provided as an input into the model. WeSIM then schedules the optimal provision of reserve and response services, taking into account the capabilities and costs of potential providers of these services (response slopes, efficiency losses of part loaded plant etc.) and finding the optimal trade-off between the cost of generating electricity to supply a given demand profile, and the cost of procuring sufficient levels of reserve and response (this also includes alternative balancing technologies such as storage and DSR as appropriate).

In order to take into account the impact of having less inertia during low demand and high renewable output conditions, the WeSIM's formulation has been enhanced by including additional constraints that dictate the minimum response requirements to meet the RoCOF specification, the minimum frequency at the nadir point, and the steady state frequency deviation from the nominal frequency as illustrated in Figure 32.

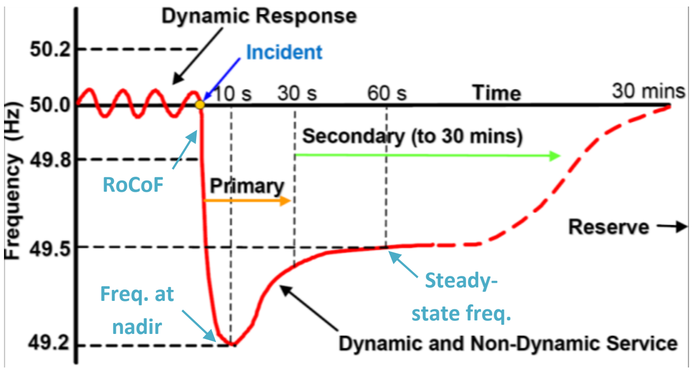


Figure 32. System frequency evolution after a contingency (source: National Grid)

In WeSIM, frequency response can be provided by:

- Synchronised part-loaded generating units;
- I&C flexible demand;

[13] 4 hours is generally the maximum time needed to synchronize a large CCGT plant.

- Interruptible charging of electric vehicles;
- Smart domestic appliances;
- Interruptible heat storage when charging;
- A proportion of electricity storage when charging;
- Interconnections.

While reserve services can be provided by:

- Synchronised generators;
- Wind power or solar power being curtailed;
- Stand-by fast generating units (OCGT);
- Electricity storage.

The amount of spinning and standing reserve and response is optimized ex-ante to minimise the expected cost of providing these services, and we use our advanced stochastic generation scheduling models to calibrate the amount of reserve and response scheduled in WeSIM.[14,15] These models find the cost-optimal levels of reserve and response by performing a probabilistic simulation of the actual utilisation of these services. Stochastic scheduling is particularly important when allocating storage resources between energy arbitrage and reserve as this may vary dynamically depending on the system conditions.

- *Generator operating constraints* include: (i) Minimum Stable Generation (MSG) and maximum output constraints; (ii) ramp-up and ramp-down constraints; (ii) minimum up and down time constraints; and (iv) available frequency response and reserve constraints. In order to keep the size of the problem manageable, we group generators according to technologies, and assume a generic size of a thermal unit of 500 MW (the model can however commit response services to deal with larger losses, e.g. 1,800 MW as used in the model). The model captures the fact that the provision of frequency response is more demanding than providing operating reserve. Only a proportion of the headroom created by part-loaded operation, as indicated in Figure 33.

- Given that the functional relationship between the available response and the reduced generation output has a slope with an absolute value considerably lower than 1, the maximum amount of frequency regulation that a generator can provide (R_{max}) is generally lower than the headroom created from part-loaded operation ($P_{max} – MSG$).

[14] A. Sturt, G. Strbac, "Efficient Stochastic Scheduling for Simulation of Wind-Integrated Power Systems", *IEEE Transactions on Power Systems*, Vol: 27, pp. 323-334, Feb 2012.
[15] A. Sturt, G. Strbac, "Value of stochastic reserve policies in low-carbon power systems", *Proceedings of the Institution of Mechanical Engineers: Part O-Journal of Risk and Reliability*, Vol: 226, pp. 51-64, Feb 2012.

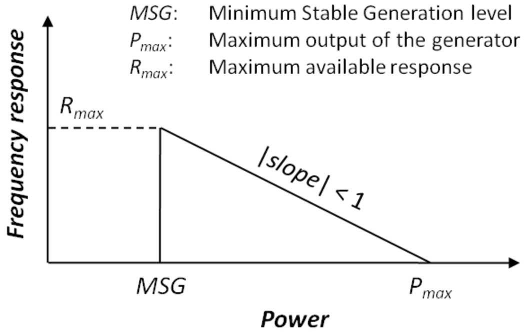


Figure 33. Provision of frequency regulation from conventional generation

- *Generation:* WeSIM optimises the investment in new generation capacity while considering the generators' operation costs and CO_2 emission constraints, and maintaining the required levels of security of supply. WeSIM optimises both the quantity and the location of new generation capacity as a part of the overall cost minimisation. If required, the model can limit the investment in particular generation technologies at given locations.

- *Annual load factor constraints* can be used to limit the utilisation level of thermal generating units, e.g. to account for the effect of planned annual maintenance on plant utilisation.

- For *wind, solar, marine, and hydro run-of-river* generators, the maximum electricity production is limited by the available energy profile, which is specified as part of the input data. The model will maximise the utilisation of these units (given zero or low marginal cost). In certain conditions when there is oversupply of electricity in the system or reserve/response requirements limit the amount of renewable generation that can be accommodated, it might become necessary to curtail their electricity output in order to balance the system, and the model accounts for this.

- For *hydro generators with reservoirs and pumped-storage units*, the electricity production is limited not only by their maximum power output, but also by the energy available in the reservoir at a particular time (while optimising the operation of storage). The amount of energy in the reservoir at any given time is limited by the size of the reservoir. It is also possible to apply minimum energy constraints in WeSIM to ensure that a minimum amount of energy is maintained in the reservoir, for example to ensure the stability of the plant. For storage technologies, WeSIM takes into account efficiency losses.

- *Demand-side response constraints* include constraints for various specific types of loads. WeSIM broadly distinguishes between the following electricity demand categories: (i) weather-independent demand, such as lighting and industrial demand, (ii) heat-driven electricity demand (space heating / cooling and hot water), (iii) demand for charging electric vehicles, and (iv) smart appliances' demand. Different demand categories are associated with different levels of flexibility. Losses due to temporal shifting of demand are modelled as appropriate. Flexibility parameters associated with various forms of DSR are obtained using detailed bottom-up modelling of different types of flexible demand.

- *Power flow constraints* limit the energy flowing through the lines between the areas in the system, respecting the installed capacity of network as the upper bound (WeSIM can handle different flow constraints in each flow direction). The model can also invest in enhancing network capacity if this is cost efficient. Expanding transmission and interconnection capacity is generally found to be vital for facilitating efficient integration of large intermittent renewable resources, given their location. Interconnectors provide access to renewable energy and improve the diversity of demand and renewable output on both sides of the interconnector, thus reducing the short-term reserve requirement. Interconnection also allows for sharing of reserves, which reduces the long-term capacity requirements.

- *Distribution network constraints* are devised to determine the level of distribution network reinforcement cost, as informed by detailed modelling of representative UK networks. WeSIM can model different types of distribution networks, e.g. urban, rural, etc. with their respective reinforcement cost (more details on the modelling of distribution networks are provided in the section "Distribution network investment modelling").

- *Emission constraints* limit the amount of carbon emissions within one year. Depending on the severity of these constraints, they will have an effect of reducing the electricity production of plants with high emission factors such as oil or coal-fired power plants. Emission constraints may also result in additional investment in low-carbon technologies such as renewables (wind and PV), nuclear or CCS in order to meet the constraints.

- *Security constraints* ensure that there is sufficient generating capacity in the system to supply the demand with a given level of security.[16] If there is storage in the system, WeSIM may make use its capacity for security purposes if it can contribute to reducing peak demand, given the energy constraints.

  WeSIM allows for the security-related benefits of interconnection to be adequately quantified.[17] Conversely, it is possible to specify in WeSIM that no contribution to security is allowed from other regions, which will clearly increase the system cost, but will also provide an estimate of the value of allowing the interconnection to be used for sharing security between regions.

[16] Historical level of security supply are achieved by setting VOLL at around 10,000£/MWh.
[17] M. Castro, D. Pudjianto, P. Djapic, G. Strbac, "Reliability-driven transmission investment in systems with wind generation", *IET Generation Transmission & Distribution*, Vol: 5, pp. 850-859, Aug 2011.

A.3. Description of distribution network analysis methodology

The purpose of distribution network modelling approach is to understand and quantify the impact of future load growth, including impact of electrification of heat and transport sectors, on necessary distribution network reinforcements and to assess the benefits of smart control of network and load in avoiding or postponing network investments. The approach to distribution network modelling is based on analysing statistically representative networks rather than actual networks. This method allows formulation of computationally feasible analytical models with only a minor sacrifice in terms of the accuracy of estimating reinforcement cost.

The use of statistically representative networks is motivated by the fact that the reinforcement cost in distribution networks tends to be driven by the network length, which can be expressed as a function of customer density. Using a limited number of these statistically representative network types, although not representing any particular physical networks, results in very accurate estimates of reinforcement costs in larger areas such as countries and regions.

Figure 34 shows the block diagram of the proposed methodology. The impact assessment of alternative network control strategies ("Business as Usual" and "Smart") involving heat pumps, electric vehicles, and smart appliances on het investment in network reinforcement and emissions will be assessed. The investment needed to reinforce the network will be determined considering a range of reinforcement strategies under different penetration levels of responsive demand technologies. The difference between the control strategies will give benefits of Smart Grid based solutions in terms of investment cost and emissions savings.

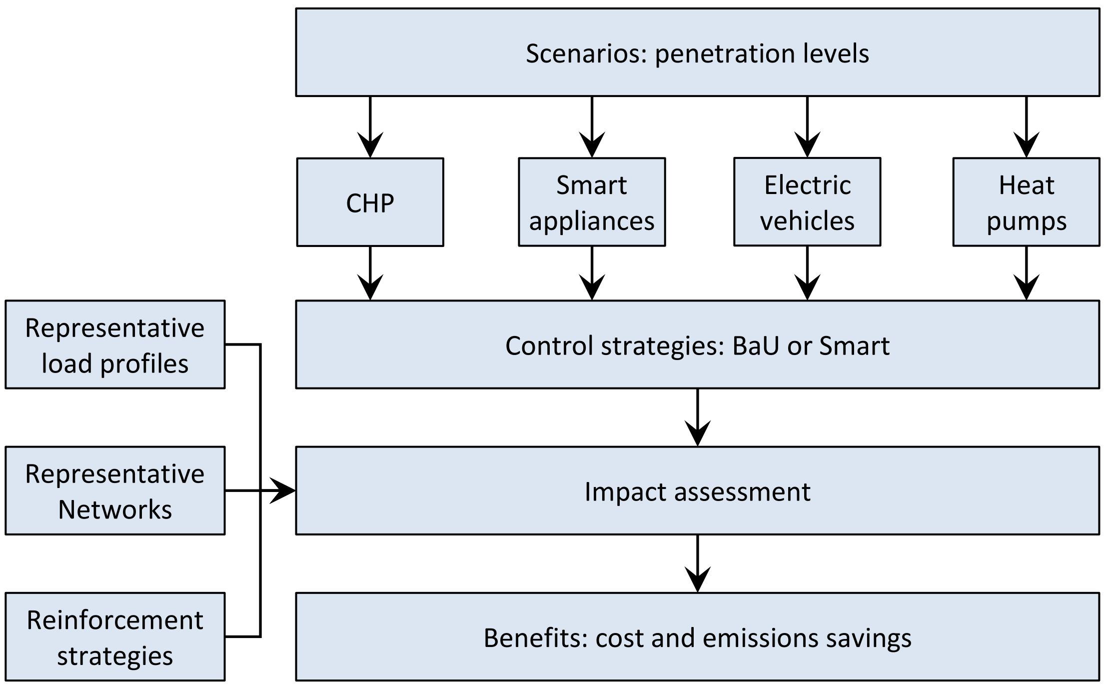


Figure 34: Methodology block diagram

In order to deal with overloads of feeders and transformers and inadequate network voltages network caused by the uptake of transport and heat demand, two network reinforcement strategies are investigated. One is based on reinforcing feeders with inadequate voltage profiles or feeder sections with thermal overloads, while maintaining the original structure of the network. This like-with-like reinforcement strategy would correspond to an upper bound on network reinforcement cost. The other network reinforcement strategy involves injecting additional distribution transformers that split the existing LV network hence reducing the length and loading of the feeders. Given that the total distribution network reinforcement cost are dominated by LV network reinforcement, this would correspond to a lower bound on network reinforcement costs.

A.3.1. Statistically representative networks

The applied distribution investment model tests whether thermal or voltage constraints are violated and proposes appropriate upgrades of assets based on a defined reinforcement strategy. The associated upgrade cost for a given scenario and control strategy (resulting in a given level of peak demand) is used to build reinforcement cost characteristics. The model can also include alternative network reinforcement and design strategies, quantifying the potential benefits of alternative mitigation measures such as demand response and other active network management techniques.

The developed modelling approach includes three distribution network models:

- Low Voltage (LV) network model;
- Medium Voltage (MV); and
- High Voltage (HV).

The LV network model is based on representative fractal networks with the parameters that represent the key characteristics of typical LV networks supplied from individual distribution transformers. The MV network model contains feeders with a voltage of approximately 6-20 kV starting from secondary busbars in the HV/MV substations and finishing with distribution substations. The HV network finally contains assets from the Grid Supply Point, i.e. the connection to transmission (220-400 kV) or sub-transmission grids (72-132 kV) down to HV/MV transformers in primary substations.

A.3.2. Fractal network models

The consumer distribution pattern varies greatly from one area to another. The Inner city area would have very different consumer distribution pattern than the rural area. Furthermore, the consumers are not normally distributed uniformly along the feeder. The conventional geometric model, which assumes equal spacing between the consumers, is not adequate to represent the consumer distribution realistically. In order to capture the consumer position and hence the network length more realistically, the statistically similar network models which based on fractal science are used[18].

The key element of the distribution network analysis is the Fractal Distribution Networks Model (Fractal Model). The Fractal Model can create representative LV, HV and EHV distribution networks that capture statistical properties of typical network topologies that range from high-load density city/town networks to low-density rural networks. The design parameters of the representative networks represent those of real distribution networks of similar topologies, e.g. the number and type of consumers and load density, ratings of feeders and transformers used, associated network lengths and costs, etc.

Due to the lack of detailed information and the large degree of diversity in distribution network planning and design, it is not feasible to perform a detailed assessment of the existing distribution networks in different countries or regions within relatively short timeframe. Nevertheless, experience has shown that it is possible to represent real networks through a limited number of typical networks with statistically similar network configurations. This approach allows for a number of design policies to be tested on a network with the same statistical properties as the network of interest, with only a minor sacrifice in terms of accuracy of reinforcement cost estimates. Moreover, any conclusions reached are applicable to other areas with similar characteristics.

For this purpose, we rely on a limited number of typical representative LV networks, such as those typical for urban, semi-urban, semi-rural, or rural areas. Our fractal LV network models have the capability to generate many statistically similar networks (in terms of key network parameters) that resemble different area types, thus allowing statistically significant conclusions to be drawn. These models can reproduce realistic network topologies and particularly network lengths, which represent one of the main drivers for the cost of network reinforcement.

The procedure of generating representative networks consists of the following steps: (i) creation of consumer layouts, (ii) generation of supply networks, and (iii) supply network design.

A.1.1.1. Consumer point generation

Consumers' position plays the most critical role in terms of network design, as together with the specific demand load patterns it affects the design and the length of the network. In this respect, previous researches have shown that typical consumer positions characteristic for different areas, such as urban or rural, can be modelled through spatial distributions of fractional dimension[19]. The number of consumer points in a given squared area and the area itself are inputs to the developed tool. Examples of the different consumer patterns / layouts that can be created by specifying desired capacity dimension of a fractal (i.e. Fractal Dimension or FD) are shown in

[18] J.P. Green, S.A. Smith and G. Strbac (1999), Evaluation of electricity distribution system design strategies, IEE Proc. Generation, Transmission and Distribution, vol.146, no.1, pp.53-60, Jan 1999

[19] Barnsley et al. (1988), Fractal Everywhere

Figure 35 for different (typical) urban, rural and intermediate layouts. These consumer patterns are characterised by different FDs, ranging from 1.9 for urban areas to 1.4 for rural ones. If all consumers were located along a single line, the FD of this layout would be equal to one (minimum value), while if the consumers fill the space uniformly, the FD would be two (maximum value). Clearly, in an urban situation (a) the consumers are distributed almost evenly across the area, while in a rural situation (d) consumers grouped into distinct clusters, with significant parts of the area that are empty.

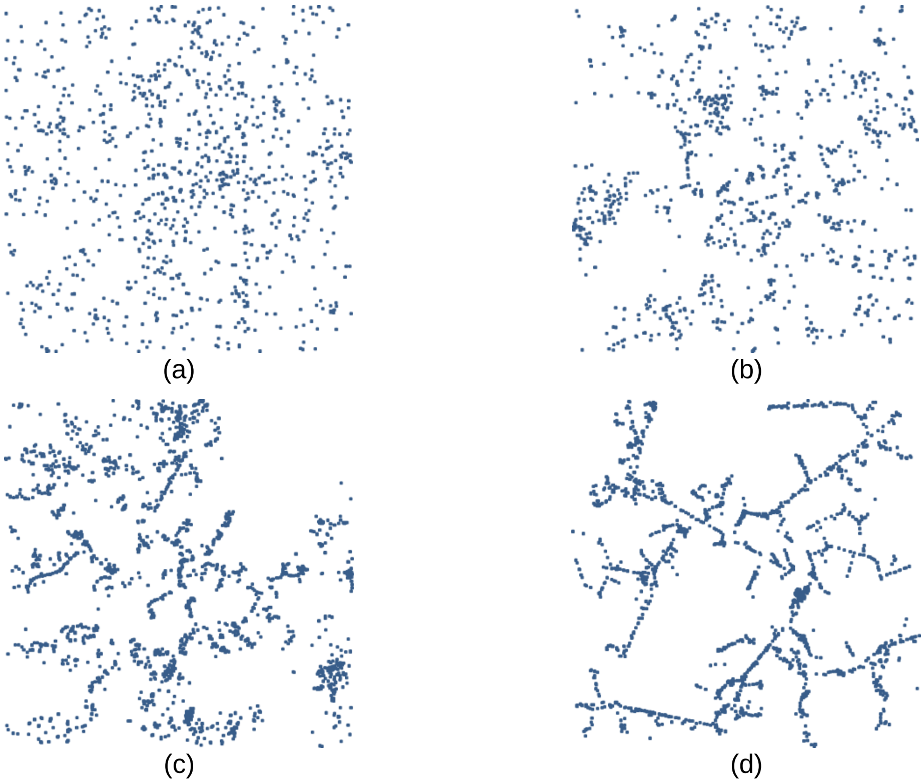


Figure 35: Examples of generated consumer layouts: (a) urban area (FD = 1.9); b) semi-urban area (FD = 1.75); c) semi-rural area (FD = 1.55); and d) rural area (FD = 1.4)

A.1.1.2. Network branch connections

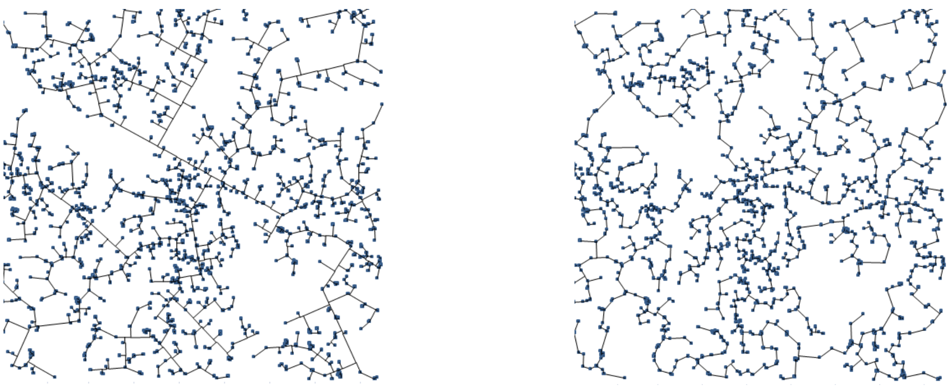
Once the consumer points are generated, they are connected with number of connections can be identified by using the concept of branching rate (BR), that is, the ratio of the number of (T-points) to the total number of consumers' nodes of the generated network. In practice, a lower BR means that the network tends to follow the consumer base as normally encountered in the LV network. On the other hand, a MV network path is influenced more by the other factors such as the avoiding of lakes and parks, which in turn leads to a higher network BR. The developed tool combines two algorithms for connecting consumers to the network:

- In the first algorithm, the next consumer to be dynamically connected to the network is chosen randomly. This algorithm leads to networks with higher BR.

- In the second algorithm, the next consumer to be connected is always the nearest one to the previous one connected to the existing network. This approach produces a much lower *BR* than the previous algorithm.

Combining these two approaches, it is possible to control the branching rate (that is an input to the model) and to generate networks with BR in the range 0.2÷0.6. Typical branching rates for different areas have been estimated through empirical calculations as shown in Green et al. (1999). Examples of two networks with different BR for the same consumer set are shown in Figure 36 for BR = 0.6 (a) and BR = 0.2 (b), indicative of high and low branching rates, respectively. Despite the same consumer layout, the resulting network topologies are visibly different – the network layout on the left has frequent branch splitting, whereas the one on the right contains far fewer branching points.

The network generated is weakly meshed. However, further adjustments are carried out (see below) to transform the network into a number of radial ones.



(a) High branching rate (b) Low branching rate

Figure 36: Impact of branching rate in LV networks with 1500 consumers for urban area with a) high branching rate (BR = 0.6) and b) low branching rate (BR = 0.2)

A.1.1.3. Statistical network creation algorithm

The final network topology information is the input data to the LV network design module. The complete network creation algorithm is shown in Figure 37.

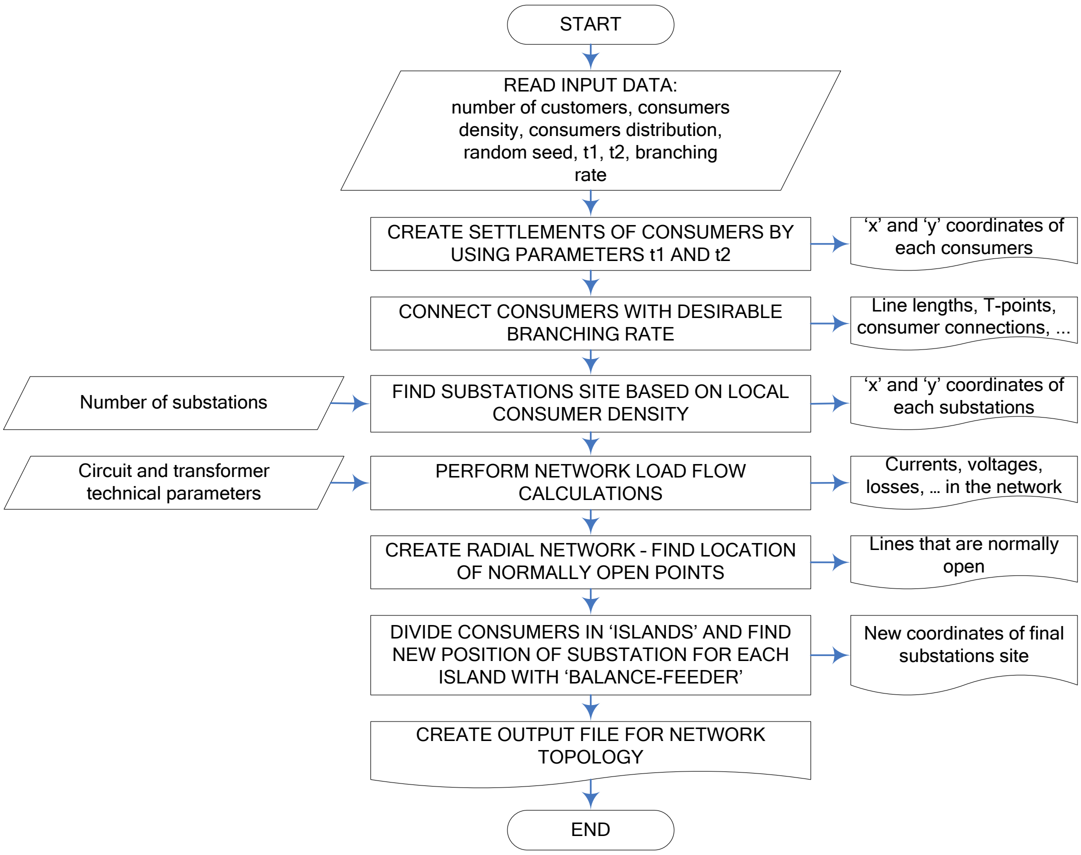


Figure 37: Representative network creation flow chart

The statistically similar networks can be generated by manipulating the input parameter *seed*. With different seed number, a completely new set of random numbers (representing consumer load points) can be generated. These random numbers, under the continued influence of fractal and economic interaction with other points generate a new set of realistic consumer positions, which have similar network characteristics (consumer distribution, load density, substation density, etc.), as shown in Figure 38. The capability to generate many statistical similar network sets would allow a number of design policies to be tested on a network with the same specific characteristics. Nevertheless, these networks are statistically similar as they are characterised by the same FD, same number of customers and the similar network length. Thus, the conclusion reached is applicable to all areas with the similar characteristics and not only to a specific or particular area.

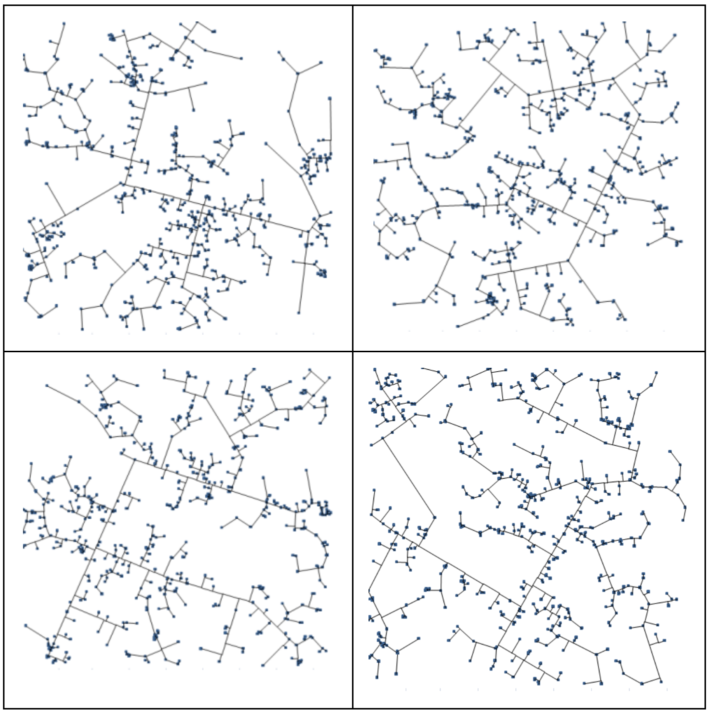


Figure 38: Example of four statistically similar LV networks

The obtained network lengths for statistically similar networks are shown in Figure 39, which suggests a very strong correlation between different consumer patterns (characterised by the appropriate FD) and the network length density. The error bars in the figure indicate the minimum and maximum network density values obtained in a large number of model runs.

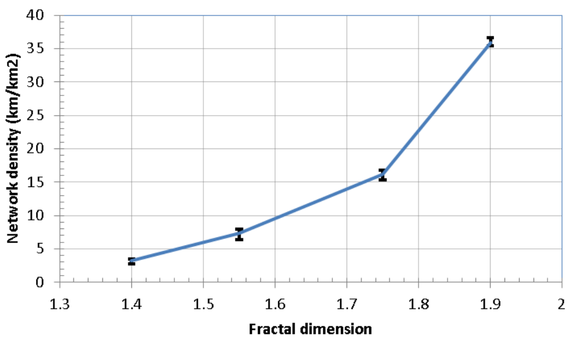


Figure 39: Relationship between length density of LV network and FD

The functional relationship between the network length density (total length of LV cables and lines per square kilometre) and the total LV network cost is illustrated in Figure 40, suggesting an almost linear relationship. In other words, network length density represents a key driver for the LV network cost, which also applies to the cost of reinforcing existing LV networks.

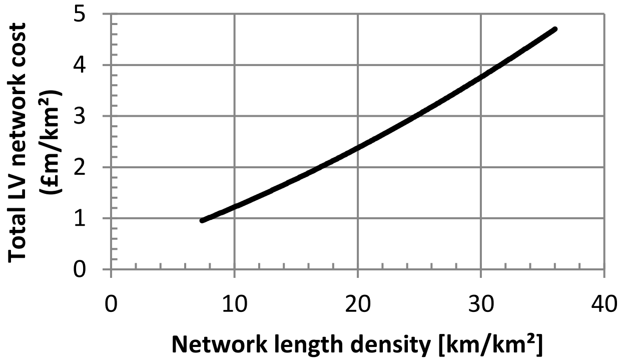
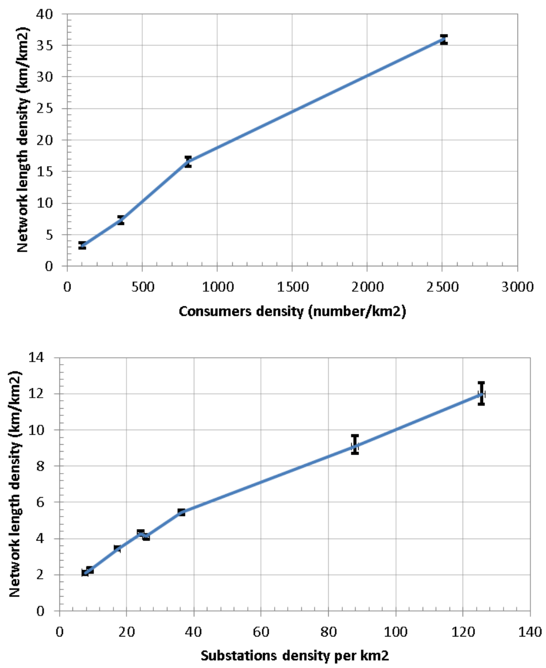


Figure 40: Total LV network cost as function of length density

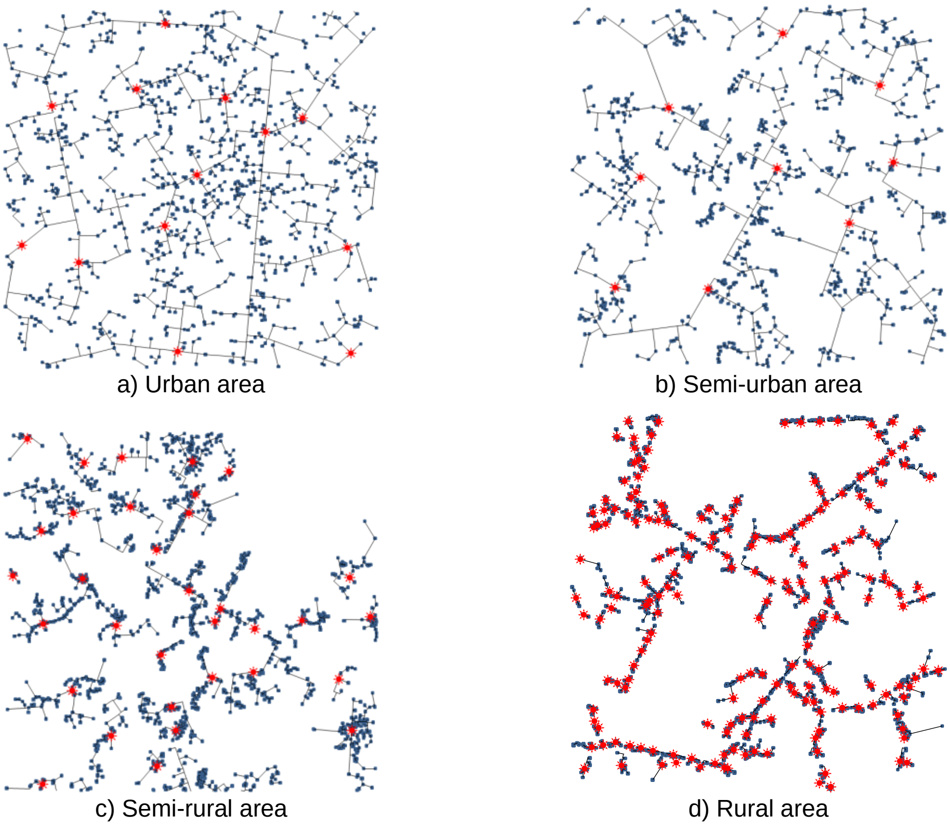
Given the observed correlation between the FD and consumer density (Figure 39), it is possible to establish the correlation between consumer density and network length density illustrated in Figure 41a (the error bars show the minimum and maximum values observed). Our analysis has further revealed that similar to the close correlation between the LV network length density and consumer density, there is also a strong link between the HV network length density and the distribution substation density, as illustrated in Figure 41b. This demonstrates that HV distribution network lengths can be reasonably well estimated from the number of distribution substations (the estimation is more accurate for rural areas where the number of substations is higher). These correlations suggest that if realistic networks with actual consumer i.e. substation density could be generated, they would be representative of actual networks in terms of network length density, and consequently in terms of total network cost.



(a) LV network *(b) HV network*

Figure 41: Correlation between network length density and: (a) consumer density in LV networks; (b) substation density in HV networks

Examples of different network topologies that can be created by specifying the desired layout parameters are shown in Figure 42 for urban, rural and mixed areas, characterised by different consumer densities, areas and branching rates. In this procedure, the parameters of representative networks are chosen to calibrate them against the actual distribution networks of the analysed system.



Note: Blue dots represent consumers and red stars represent distribution substations.

Figure 42. Different examples of consumer layouts generated using the fractal model

A.3.3. Representative HV Distribution Network Creation Methodology

The key network characteristics of HV networks are driven by LV networks. The HV network will supply the HV/LV transformers as well as some industrial customers. It is also important to note that the load density of LV networks within the HV network vary from region to region. Thus, to address this situation, the HV network was modelled by inputting different sets of LV networks, which can have different load and substation density, into a grid-matrix. The location of HV/LV transformers and their annual loading profiles for each of the HV/LV transformers are recorded in the LV networks and become the input parameter of the HV distribution network. By doing so, the loading characteristics and the distances between the HV/LV transformers were kept on the HV distribution network. Figure 43 shows how different LV networks can be ‘entered’ into a HV distribution network.

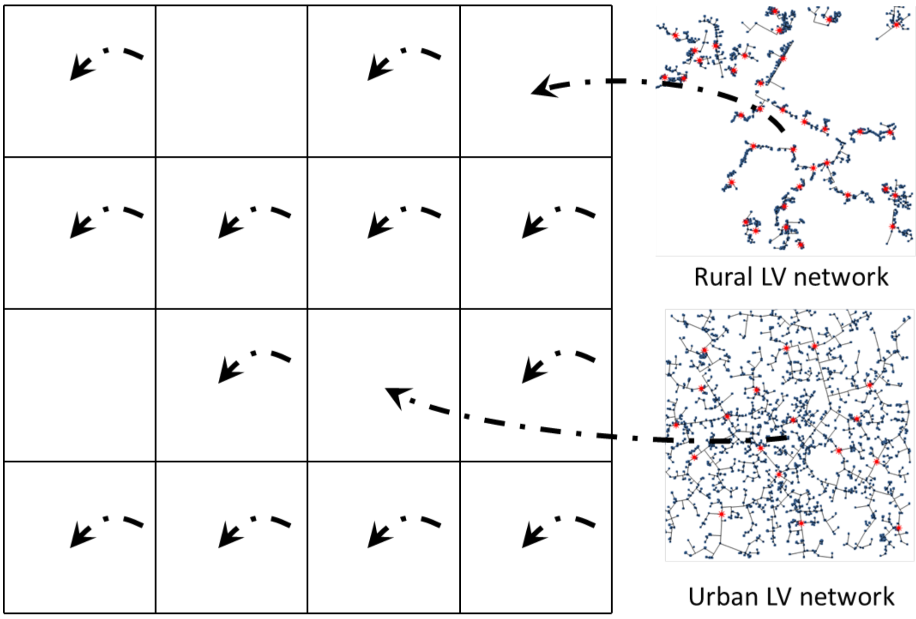


Figure 43: HV network ***grid-matrix***

The HV customers are then connected with a controllable branching rate. Figure 44 shows a representative HV distribution network which supplies 65 representative LV networks. It is then connected with a 69 % branching rate. The input LV networks have load density ranging from 5MVA/km^2 to 25MVA/km^2. The small 'dots' are HV/LV transformers and the 'red stars' being HV network substations.

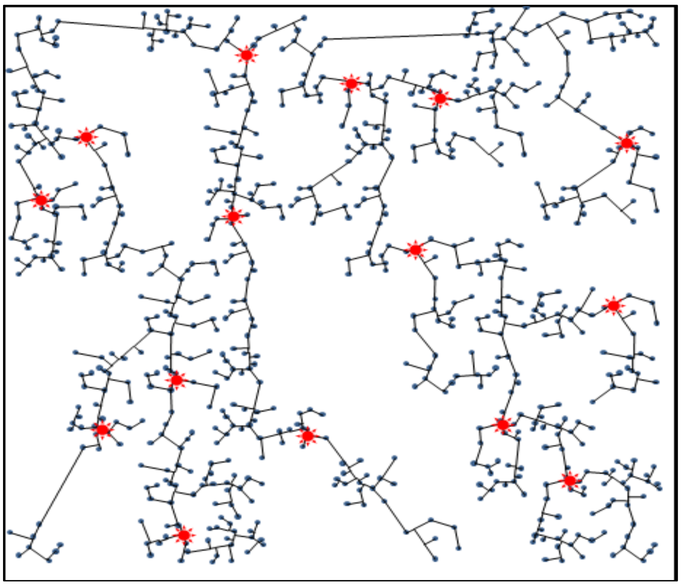


Figure 44: Representative HV distribution network (200,000 LV consumers, 300MVA-peak, 6MVA/km^2, 0.3 sub/km^2) supplying 65 representative LV networks

An important feature of this model is the capability to *mix* both LV rural networks and LV urban networks and supply them with OHL/Cable or Indoor/Outdoor substations according to LV network type.

A.3.4. Mapping representative distribution networks to European statistical data

As mentioned earlier, European distribution networks are characterised by different planning and design standards. Moreover, for most countries there is very limited information publicly available on the actual design of existing networks, which could potentially support a highly detailed analysis. To cope with these issues, we have used a combination of statistical analysis of the distribution supply areas in each Member State on one hand, and the application of representative networks in the Fractal Model on the other.

The overall approach can be summarised as follows:

- In a first step, we collected information on population density and land use for close to 100,000 administrative units (municipalities, districts, provinces etc.)[20] in the EU-27.
- In a second step, the administrative areas were clustered into different population classes in each country, and mapped against a limited number of representative networks.
- In a third step, the design parameters of the representative networks in a given country were adjusted such that the sum of the individual networks corresponds to the overall size and structure of the distribution networks in that country.
- Finally, we assigned a set of generation and load profiles to different network classes, based on the assumed load and penetration of decentralised generation in each country.

As mentioned above, the first two steps were based on a comprehensive data set for close to 100,000 administrative units in the EU-27.[21] The administrative areas in a given country were then grouped into different density classes, which can be associated with different types of distribution networks. For illustration, Table 1 shows an example from Germany. The table shows how some 11,000 municipalities in four German regions used in the study are grouped into five different density classes. Unsurprisingly, the table suggests there are major differences between regions, with a large share of scarcely populated areas in Northern Germany, and more densely populated areas in the areas in the South (DE_S) and West (DE_W). Consequently, the share of rural and semi-rural areas is much higher in the first two regions (DE_NE and DE_NW), whilst the other two include a much higher share of urban and semi-urban areas.[22]

[20] The level of detail varies by country, subject to the quality of publicly available data.
[21] The corresponding data has been collected from Eurostat, national statistical offices and other sources.
[22] Please note that the individual administrative units cannot be directly equated to different networks. In fact, most administrative units cover different types of distribution supply areas themselves. For instance, in rural areas there will

Table 1. Example of mapping of local areas to density classes for Germany

Density class (people/km^2)	DE_NE	DE_NW	DE_W	DE_S
Number of regions				
< 50	1,269	699	537	255
50-100	793	681	732	1,024
100-250	535	636	1,008	1,065
250-1000	209	415	460	712
> 1000	20	93	48	101
Total	**2,826**	**2,524**	**2,785**	**3,157**
Aggregate area (km^2)				
< 50	50,812	15,242	5,300	11,354
50-100	26,748	21,563	10,182	36,755
100-250	19,892	32,108	16,381	33,789
250-1000	8,662	20,811	9,418	18,214
> 1000	2,490	7,611	2,043	3,647
Total	**108,604**	**97,335**	**43,324**	**103,760**
Aggregate population				
< 50	1,501,556	506,620	188,557	433,683
50-100	1,889,187	1,590,516	748,545	2,740,615
100-250	3,066,271	5,137,881	2,656,371	5,239,721
250-1000	4,153,253	9,874,573	4,515,818	8,140,647
> 1000	5,715,566	13,771,151	3,143,161	6,737,910
Total	**16,325,833**	**30,880,741**	**11,252,452**	**23,292,576**

Using the number of different network classes and assumptions on their typical design (such as network length, number of connections or installed transformation capacity per km^2), we have then derived an estimate of the overall distribution infrastructure in a given country. This information was then compared against available evidence from each country, in order to calibrate the resulting assumptions.

A.3.5. Validation of network mapping

The mapping of representative networks to actual statistical information in various European countries and regions is carried out in such a way as to minimise deviations in terms of:

- Regional area
- Regional number of domestic consumers
- Country's distribution network statistics:
  - Network length (overhead lines, cables and total)
  - Number of substations/transformers (GMTs, PMTs and total)

typically be smaller parts of the network with a higher population density. Similarly, even larger towns will usually comprise of some areas with much lower load density, such as in parks or the areas outside the inner city.

The mapping process and the illustration of the accuracy are shown for the example of Spain. For the purpose of the analysis Spain is divided into five regions: North (ES_N), Northeast (ES_NE), Central (ES_C), Southeast (ES_SE) and South (ES_S). Spanish distribution network are approximated using ten representative networks: 4 rural, 3 intermediate and 3 urban networks. The parameters of these networks are given in Table 2.

Table 2. Representative distribution networks for Spain

Network type	Area (km^2)	Consumer density (consumers/km^2)	Substation density (DT/km^2)
Rural 1	400	5	0.35
Rural 2	80	25	1
Rural 3	40	50	1.5
Rural 4	20	100	2
Intermediate 1	12.5	200	2
Intermediate 2	6.3	400	3.2
Intermediate 3	4.9	800	2
Urban 1	2.4	1,600	3.3
Urban 2	1.7	3,200	7.7
Urban 3	0.8	6,400	11.9

In order to maximise mapping accuracy, each density class within each of the five regions is represented by a portfolio of representative models, i.e. by a certain number of each of the ten representative networks. Table 3 shows the comparison of actual statistical data with those approximated using the representative network. The comparison is made with respect to the number of domestic customers, geographical area, total length of the LV network and the total number of distribution transformers. Given that the data on network length and number of transformers is not available for individual regions and density classes, the comparison is only made with the aggregate national values.

The comparison confirms that it is possible to obtain a very close match with national statistical data by using representative distribution networks. In this case, the discrepancy in terms of total area is about -1%, while the deviation in total number of domestic consumers is only about 0.2%. The approximation of key network parameters is also very accurate – the difference is 0.34% for the total network length, and 0.15% for the number of distribution transformers. Given the high level of uncertainty around forecasting the demand, EV penetration, generation capacity evolution etc. in the 2030 horizon, this level of accuracy appears to be more than acceptable.

Similar levels of accuracy are obtained using the same approach to representative network mapping for Italy (Table 4), Germany (Table 5), Denmark and Ireland (Table 6) and Great Britain (Table 7).

Table 3. Accuracy of representative network mapping for Spain

	Statistical data					Representative network data					Discrepancies				
Density class (people/km^2)	**ES_N**	**ES_NE**	**ES_C**	**ES_SE**	**ES_S**	**ES_N**	**ES_NE**	**ES_C**	**ES_SE**	**ES_S**	**ES_N**	**ES_NE**	**ES_C**	**ES_SE**	**ES_S**
Area (km^2)															
< 50	85,593	69,880	144,535	33,123	51,363	85,616	67,225	141,901	33,129	51,386	0.03%	-3.80%	-1.82%	0.02%	0.04%
50-100	14,304	5,422	9,876	4,095	15,360	14,304	5,433	9,877	4,096	15,363	0.00%	0.20%	0.01%	0.02%	0.02%
100-250	8,606	4,364	5,626	4,039	5,633	8,607	4,371	5,625	4,040	5,634	0.01%	0.16%	-0.01%	0.02%	0.02%
250-1000	7,686	3,955	2,038	4,508	5,349	7,693	3,966	2,038	4,513	5,335	0.10%	0.27%	0.02%	0.12%	-0.27%
> 1000	2,895	1,470	279	1,179	1,099	2,890	1,470	278	1,178	1,098	-0.18%	0.03%	-0.18%	-0.08%	-0.08%
Total	**119,083**	**85,091**	**162,353**	**46,943**	**78,804**	**119,109**	**82,464**	**159,719**	**46,955**	**78,815**	**0.02%**	**-3.09%**	**-1.62%**	**0.03%**	**0.01%**
Number of domestic consumers															
< 50	519,697	302,079	659,224	213,915	418,768	519,776	319,653	674,739	213,950	418,832	0.02%	5.82%	2.35%	0.02%	0.02%
50-100	384,153	152,026	247,898	117,056	436,544	384,211	152,020	247,903	117,086	436,606	0.02%	0.00%	0.00%	0.03%	0.01%
100-250	542,186	264,432	315,107	268,632	359,632	542,192	264,407	315,090	268,632	359,620	0.00%	-0.01%	-0.01%	0.00%	0.00%
250-1000	1,407,186	840,776	291,676	848,580	824,042	1,405,925	838,980	291,364	847,726	826,819	-0.09%	-0.21%	-0.11%	-0.10%	0.34%
> 1000	3,541,561	2,223,452	213,068	1,035,395	1,032,535	3,547,610	2,221,531	211,311	1,036,406	1,033,104	0.17%	-0.09%	-0.82%	0.10%	0.06%
Total	**6,394,782**	**3,782,764**	**1,726,973**	**2,483,579**	**3,071,520**	**6,399,713**	**3,796,591**	**1,740,407**	**2,483,799**	**3,074,982**	**0.08%**	**0.37%**	**0.78%**	**0.01%**	**0.11%**
LV network length (km)															
Overhead	402,774					403,703					0.23%				
Cable	62,449					63,117					1.07%				
Total	**465,223**					**466,820**					**0.34%**				
Number of distribution transformers															
DT	**307,936**					**308,401**					**0.15%**				

Table 4. Accuracy of representative network mapping for Italy

	Statistical data			Representative network data			Discrepancies		
Density class (people/km²)	**IT_N**	**IT_M**	**IT_S**	**IT_N**	**IT_M**	**IT_S**	**IT_N**	**IT_M**	**IT_S**
Area (km²)									
< 50	26,550	43,588	24,327	26,549	43,622	24,362	0.00%	0.08%	0.14%
50-100	11,619	21,419	21,255	11,619	21,426	21,279	-0.01%	0.03%	0.12%
100-250	14,871	18,816	22,624	14,870	18,823	22,650	-0.01%	0.04%	0.12%
250-1000	11,747	11,501	12,882	11,741	11,248	12,360	-0.05%	-2.20%	-4.05%
> 1000	1,763	2,347	2,647	1,763	2,346	2,648	-0.01%	0.00%	0.01%
Total	**66,551**	**97,670**	**83,735**	**66,542**	**97,465**	**83,299**	**-0.01%**	**-0.21%**	**-0.52%**
Number of domestic consumers									
< 50	212,643	439,105	300,370	212,627	438,861	300,208	-0.01%	-0.06%	-0.05%
50-100	334,784	604,082	623,962	334,761	603,682	623,368	-0.01%	-0.07%	-0.10%
100-250	957,612	1,175,122	1,414,591	957,498	1,173,563	1,411,592	-0.01%	-0.13%	-0.21%
250-1000	2,168,326	2,000,699	2,164,468	2,168,247	2,039,035	2,240,596	0.00%	1.92%	3.52%
> 1000	1,451,029	1,830,912	2,508,518	1,451,017	1,827,757	2,500,149	0.00%	-0.17%	-0.33%
Total	**5,124,394**	**6,049,920**	**7,011,909**	**5,124,150**	**6,082,897**	**7,075,913**	**0.00%**	**0.55%**	**0.91%**
LV network									
Length (km)	892,220			890,223			-0.22%		
No. of DTs	501,834			501,094			-0.15%		

Table 5. Accuracy of representative network mapping for Germany

	Statistical data				Representative network data				Discrepancies			
Density class (people/km^2)	**DE_NE**	**DE_NW**	**DE_W**	**DE_S**	**DE_NE**	**DE_NW**	**DE_W**	**DE_S**	**DE_NE**	**DE_NW**	**DE_W**	**DE_S**
Area (km^2)												
< 50	50,812	15,242	5,300	11,354	50,801	15,247	5,306	11,359	-0.02%	0.03%	0.11%	0.04%
50-100	26,748	21,563	10,182	36,755	26,756	21,571	10,190	36,805	0.03%	0.04%	0.08%	0.14%
100-250	19,892	32,108	16,381	33,789	19,888	32,129	16,406	33,848	-0.02%	0.07%	0.15%	0.18%
250-1000	8,662	20,811	9,418	18,214	8,658	20,721	9,405	17,549	-0.04%	-0.43%	-0.13%	-3.65%
> 1000	2,490	7,611	2,043	3,647	2,398	7,593	1,852	3,658	-3.71%	-0.24%	-9.33%	0.30%
Total	**108,604**	**97,335**	**43,324**	**103,760**	**108,500**	**97,261**	**43,160**	**103,219**	**-0.09%**	**-0.08%**	**-0.38%**	**-0.52%**
Number of domestic consumers												
< 50	600,622	202,648	75,423	173,473	600,198	202,551	75,414	173,415	-0.07%	-0.05%	-0.01%	-0.03%
50-100	755,675	636,206	299,418	1,096,246	754,484	635,590	299,069	1,094,910	-0.16%	-0.10%	-0.12%	-0.12%
100-250	1,226,508	2,055,152	1,062,548	2,095,888	1,223,392	2,051,358	1,058,305	2,088,509	-0.25%	-0.18%	-0.40%	-0.35%
250-1000	1,661,301	3,949,829	1,806,327	3,256,259	1,656,265	3,958,155	1,798,147	3,331,023	-0.30%	0.21%	-0.45%	2.30%
> 1000	2,286,226	5,508,460	1,257,264	2,695,164	2,333,158	5,520,945	1,343,562	2,689,322	2.05%	0.23%	6.86%	-0.22%
Total	**6,530,333**	**12,352,296**	**4,500,981**	**9,317,030**	**6,567,498**	**12,368,599**	**4,574,496**	**9,377,180**	**0.57%**	**0.13%**	**1.63%**	**0.65%**
LV network length (km)												
Total	1,164,012				1,189,631				2.20%			

Table 6. Accuracy of representative network mapping for Denmark and Ireland[23]

	Statistical data			Representative network data			Discrepancies		
Density class (people/km²)	**DK_W**	**DK_E**	**IE**	**DK_W**	**DK_E**	**IE**	**DK_W**	**DK_E**	**IE**
Area (km²)									
< 50	8,879	0		8,956	0		0.87%	0.00%	
50-100	15,518	4,882		15,858	4,888		2.19%	0.13%	
100-250	7,826	3,353		7,948	3,354		1.55%	0.05%	
250-1000	907	1,209		912	1,216		0.54%	0.56%	
> 1000	0	320		0	321		0.00%	0.27%	
Total	**33,131**	**9,764**	**84,116**	**33,674**	**9,780**	**84,481**	**1.64%**	**0.16%**	**0.43%**
Number of domestic consumers									
< 50	145,538	0		147,020	0		1.02%	0.00%	
50-100	424,238	145,050		429,863	146,444		1.33%	0.96%	
100-250	426,839	191,267		429,658	192,272		0.66%	0.53%	
250-1000	222,289	236,535		223,108	237,647		0.37%	0.47%	
> 1000	0	439,884		0	439,552		0.00%	-0.08%	
Total	**1,218,904**	**1,012,736**	**2,531,269**	**1,229,649**	**1,015,916**	**2,532,185**	**0.88%**	**0.31%**	**0.04%**
LV network length (km)									
Overhead	7,112		79,990	7,102		79,608	-0.13%		-0.48%
Cable	87,343		16,951	87,735		16,962	0.45%		0.07%
Total	**94,455**		**96,940**	**94,837**		**96,569**	**0.40%**		**-0.38%**
Number of distribution transformers									
PMT			320,982			321,529			0.17%
GMT			12,239			12,231			-0.06%
Total			**333,221**			**333,760**			**0.16%**

[23] Ireland here refers to both the Republic of Ireland and Northern Ireland. Some values have been estimated due to lack of available data.

Table 7. Accuracy of representative network mapping for Great Britain

	Statistical data						Representative network data						Discrepancies
	GB_SCO	**GB_N**	**GB_M**	**GB_LON**	**GB_S**	**Total GB**	**GB_SCO**	**GB_N**	**GB_M**	**GB_LON**	**GB_S**	**Total GB**	**Total GB**
Number of domestic consumers													
Total	2,996,192	7,656,576	5,047,743	2,311,841	11,403,761	**29,416,113**	2,996,194	7,656,574	5,047,738	2,310,478	11,403,759	**29,416,238**	**0.0%**
LV network length (km)													
Overhead	8,552	12,160	10,896	0	33,321	**64,929**	8,552	12,160	10,896	0	33,321	**64,929**	0.0%
Cable	36,192	89,863	59,570	22,556	119,428	**327,609**	36,192	89,863	59,570	22,558	119,428	**327,598**	0.0%
Total	**44,744**	**102,023**	**70,466**	**22,556**	**152,749**	**392,538**	**44,744**	**102,023**	**70,466**	**22,558**	**152,749**	**392,527**	**0.0%**
Number of distribution transformers													
PMT	67,823	68,388	57,706	0	149,940	**343,857**	67,823	68,388	57,706	0	149,940	**343,857**	0.0%
GMT	26,175	50,448	35,058	17,145	101,639	**230,465**	26,175	50,448	35,058	17,143	101,639	**230,474**	0.0%
Total	**93,998**	**118,836**	**92,764**	**17,145**	**251,579**	**574,322**	**93,998**	**118,836**	**92,764**	**17,143**	**251,579**	**574,331**	**0.0%**

The purpose of distribution network modelling approach is to understand and quantify the impact of future load growth, including impact of electrification of heat and transport sectors, on necessary distribution network reinforcements and to assess the benefits of smart control of network and load in avoiding or postponing network investments. The approach to distribution network modelling is based on analysing statistically representative networks rather than actual networks. This method allows formulation of computationally feasible analytical models with only a minor sacrifice in terms of the accuracy of estimating reinforcement cost.

The use of statistically representative networks is motivated by the fact that the reinforcement cost in distribution networks tends to be driven by the network length, which can be expressed as a function of customer density. Using a limited number of these statistically representative network types, although not representing any particular physical networks, results in very accurate estimates of reinforcement costs in larger areas such as countries and regions.

The key steps of the overall approach to distribution network modelling can be summarised as follows:

- In the first step, statistical information on population density (serving as proxy for load density) for a large number of smaller administrative units in each country or region as well as data on distribution network lengths in each country or region is collected and processed;
- This information is then used to create a set of typical networks that are representative of actual networks with respect to estimating the reinforcement cost for different countries or regions; and
- These representative networks then provide the basis for the detailed distribution analysis and the quantification of network reinforcement costs as a function of load growth and smart control strategies under different scenarios.