# THERMOS

Thermal Energy Resource Modelling and Optimisation System

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# THERMOS Network Validation Study: A comparison of THERMOS tool outputs to existing district heating network

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|---|---|
| **Deliverable No:** | N/A |
| **Workpackage Title:** | N/A |
| **Date Submitted:** | 07/05/2021 |
| **Dissemination level:** | Public |
| **Document file Name:** | THERMOS_network_validation_study.docx |
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## Contents

# 1 Objective

The purpose of this report is to compare the outputs of the THERMOS tool to a real DH network in a specific locality. In order to make the comparison, two real DH networks were used as benchmark for the outputs of the THERMOS tool. The comparison has been performed for two types of validation. First, a routing validation in the town of Sulsted, and a second validation for pipe dimensioning in Aarhus city, both located in Denmark.

Regarding the timeline of the analyses, routing and dimensioning validation were performed separately in November 2019 and February 2021, using the available THERMOS versions correspondingly. For more information about the THERMOS tool version update, visit the THERMOS changelog available in the tool's help menu. Furthermore, resources and update documentation are available on the tool's website.

For the first validation, the town Sulsted was chosen, as it was recently connected to the larger DH system of the city Aalborg. Thus, the whole distribution network is built around a single connection to the transmission network, which makes it a good routing validation case as the THERMOS tool is built around estimating routes from a source point to demand points.

For the second validation, the city of Aarhus was chosen as it represents a denser and more complex heat supply DH network. The THERMOS tool estimates pipe sizes based on the heat demand peak loads of the buildings it supplies, including diversity factors for connections with multiple buildings. The dimension of each pipe is chosen to be large enough to carry the demands for all buildings it provides connection to. Therefore, in the Aarhus case, the higher connection density enables a validation of the dimensioning capabilities of the THERMOS tool.

The structure of the report describes the methodologies followed by the scenario analyses for both cases. Furthermore, below each methodology section, existing infrastructure, and the parameters used for the THERMOS tools for both validation assessments are explained alongside with the scenario characterization for each city. Through visualization means, the scenario analysis sections depict the results of the validation under the chosen parameters, followed by a summary of the findings section at last. Additional scenario visuals are attached in the Appendix section for further reference of the validation performed.

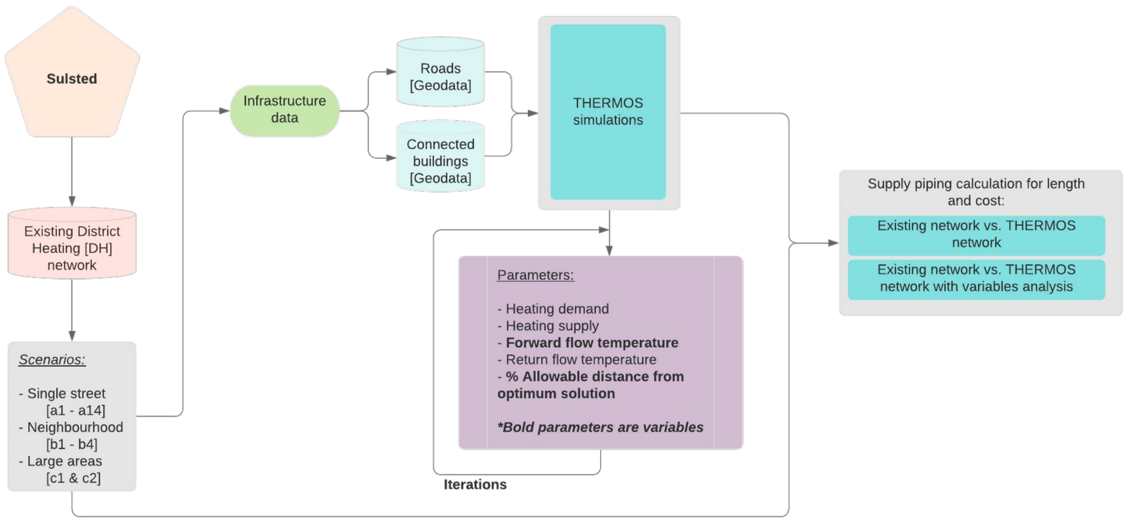
# 2 Methodology

The methodology section is divided into two subchapters where the first focuses on the network routing validation in Sulsted, and the second on the network dimensioning validation in Aarhus. It is important to know that the focus on the validation is on network length for routing and pipe sizing for dimensioning.

## 2.1 Network routing validation - Sulsted

The methodology used for this validation is depicted on Error: Reference source not found. As seen, the main input is the existing infrastructure data – DH network, building and roads - coming on a geospatial format matching compatibility with the THERMOS tool. The city infrastructure is therefore divided into different sized areas as different neighbourhood areas and connector routing analysis are seek. THERMOS GeoJSON [.json] output is converted to shapefile [.shp] in order to proceed with the network characterization – piping length and network costs - using QGIS v.3.8.1 and ArcGIS Desktop v.10.6.13 from ESRI Inc. (Environmental Systems Research Institute). Variables – flow temperature, % allowable distance from top optimization - are altered while running the different scenarios as its influence on the overall results are to be analysed. Optimization iterations outputs are also contemplated for certain scenarios for THERMOS version at the time of the analysis.

Figure 1 Sulsted routing validation methodology




### 2.1.1 Existing DH network

The current existing DH network in Sulsted is characterized in length and inner diameter by distribution, service, branch, as well as transmission pipes. Its individual components can be seen in Table 1, and geographically visualized in Figure 2. The map legend shows the piping diameter classification used in this analysis.

Table 1 Sulsted existing DH infrastructure characterization

| Diameter (mm) | Meters | Diameter (mm) | Meters | Diameter (mm) | Meters |
|---|---|---|---|---|---|
| **Distribution Pipes** | | **Service Pipes** | | **Transmission Pipe** | |
| 20 | 50 | 33.7 | 224 | 168.3 | 2,220 |
| 26 | 196 | 42.4 | 19 | 219.1 | 895 |
| 26.9 | 11 | 48.3 | 34 | | |
| 32 | 23 | **Branch Pipes** | | **Summary** | **Meters** |
| 33.7 | 1,300 | 16 | 3,378 | Distribution Pipes | 24,103 |
| 42.4 | 1,899 | 20 | 1,570 | Service Pipes | 555 |
| 48.3 | 2,065 | 26 | 305 | Branch Pipes | 11,696 |
| 60.3 | 2,702 | 26.9 | 19 | Transmission Pipe | 6,231 |
| 76.1 | 845 | 32 | 212 | **Total** | **42,585** |
| 88.9 | 672 | 33.7 | 2 | | |
| 114.3 | 397 | 42.4 | 45 | | |
| 139.7 | 803 | 48.3 | 151 | | |
| 168.3 | 1,090 | 60.3 | 47 | | |
| | | 76.1 | 118 | | |

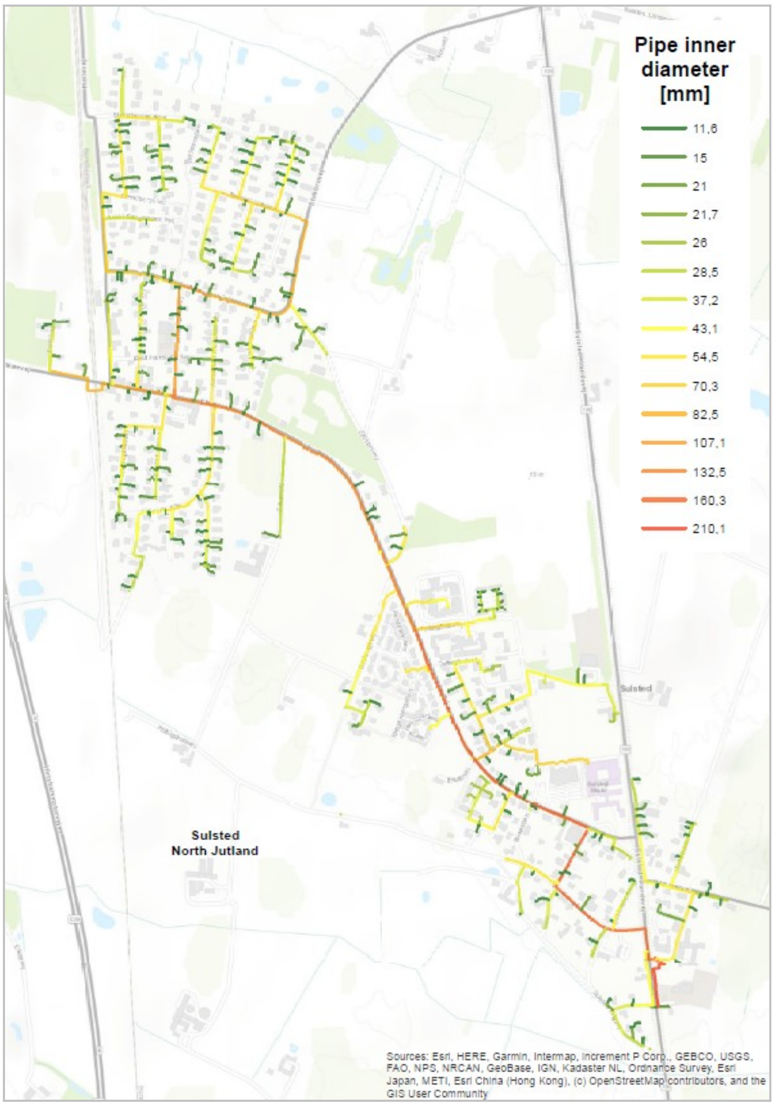



Figure 2 Sulsted existing DH network

### 2.1.2 Input simulation parameters

In the following subsections, parameters, assumptions, and usage of the available data at the moment of the analysis are developed further. Maps are added for a visual representation when possible.

#### *2.1.2.1 Infrastructure*

**Buildings DH connection**

As no data is found on connected buildings to the grid, these are found by selecting building polygons based on the location of the DH pipes. Here, buildings that are within 10 meters of the DH pipes are included as demands. For the available data, a visual manual examination is performed for a more coherent comprehension of the connections. However, connection uncertainty can potentially represent a source of error in the final result. Here, the selected buildings with a potential DH connection are seen in Figure 3.

**Roads**

The Danish topographical data (Styrelsen for Dataforsyning og Effektivisering, 2021)[1] is used as the input for the DH routing in the software. The roads are set to optional type of constrain for the optimization network. Figure 3 and Figure 4 show the roads and the chosen buildings used as input for the simulation.

[1] https://sdfe.dk/


Figure 3 Sulsted buildings connected to the DH network


Figure 4 Sulsted's routing optional roads for DH network

### 2.1.2.2Network properties

**Buildings heat demands**

The measured data from Sulsted is available, however the measurements are from 2010-2015, previous to the town connecting to DH. Therefore, the average measured data for each building that is within the selected building polygons is used as the input for the heat demands. Complementary, estimated demand from the Danish Heat Atlas (AAU Sustainable Energy Planning, 2020)[2] is used for the buildings without measured demand.

Although individual building heat demands were part of THERMOS input, Aalborg's heating degree days taken from BizEE Degree Days (BizEE Software, 2021) were used in parallel, this can be seen in Table 2.

Table 2 Heating degree days in Aalborg - average from years 2014-2018

| | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec | Total |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **HDD** | 458 | 407 | 385 | 265 | 140 | 61 | 30 | 37 | 79 | 192 | 313 | 376 | **2743** |

[2] https://energymaps.plan.aau.dk

### Temperature flow

DH database available do not show flow properties. According to the Aalborg District Heating, the DH water is heated to 75° C in summer and ca. 82-90 °C in winter. After delivering heat, the water returns with a temperature of approximately 40° C (Aalborg Forsyning, 2020). Comparatively, the Knowledge Center for Energy Savings in Buildings dictates a 70°C and 40° C for forward and return flow temperature in direct DH networks, respectively (Videncenter for energibesparelser i bygninger, 2011).

### Heat prices

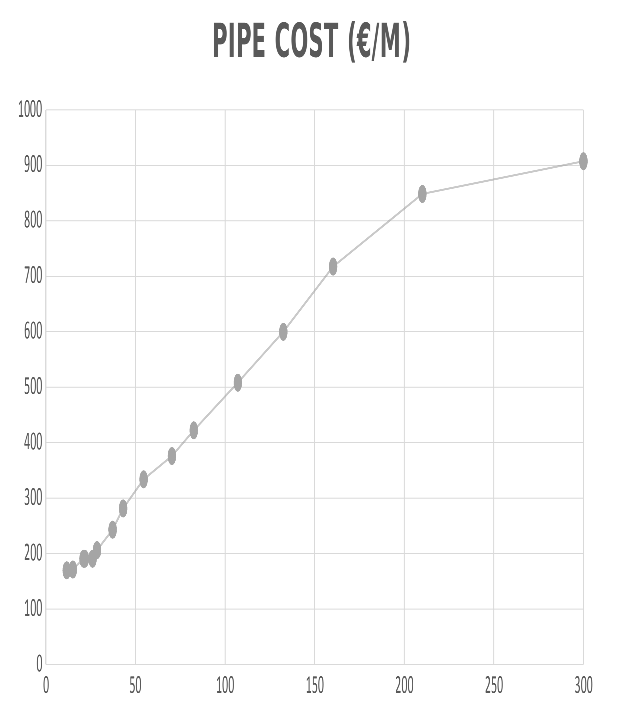
Heat price is not used as a determining factor in the modelling, as the aim of the analysis is to use compare the routing and pipe sizing of the THERMOS tool and not to make an economic feasibility analysis of DH. However, for the purpose of this analysis, the price in THERMOS is set to a low price of 10 c/kWh, to make sure that all buildings are connected.

#### *2.1.2.3Piping characterization*

The piping characterization was made according to the existing DH network as to make it comparable. Piping and network costs are calculated manually from the THERMOS output and the unitary costs are taken from the Swedish district heating pipe cost catalogue (The Swedish District Heating Association, 2013). These costs include materials, pipe work, connector installation and ground digging and were chosen as to make scenarios comparable for both existing and THERMOS networks.

Table 3 Pipe costs by inner diameter

| PIPE COST (Total EUR/m) | PIPE SIZE (INNER MM) | MAPPING COLOUR SCALE |
|---|---|---|
| 169,70 | 11,6 | |
| 171,24 | 15 | |
| 190,65 | 21 | |
| 190,65 | 21,7 | |
| 190,65 | 26 | |
| 206,15 | 28,5 | |
| 243,08 | 37,2 | |
| 281,30 | 43,1 | |
| 333,73 | 54,5 | |
| 375,86 | 70,3 | |
| 422,13 | 82,5 | |
| 508,05 | 107,1 | |
| 599,88 | 132,5 | |
| 717,51 | 160,3 | |
| 848,40 | 210,1 | |
| 907,34 | 300 | |



### 2.1.3 Scenarios

In the analysis, three kind of different sized area were analysed, ranging from small and single streets to large block agglomerated areas within the city of Sulsted. Figure 5 shows geospatial distribution of the areas.

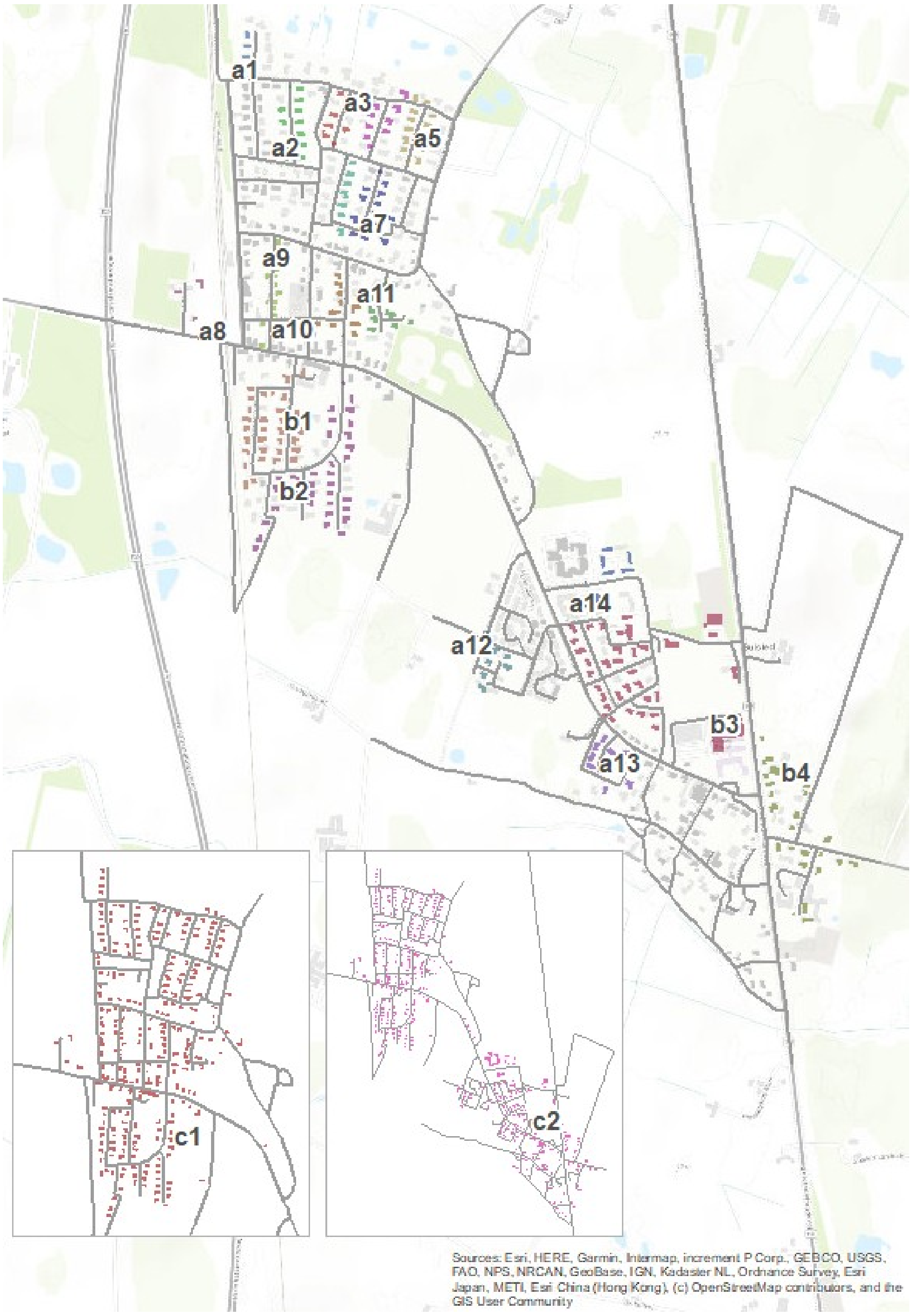


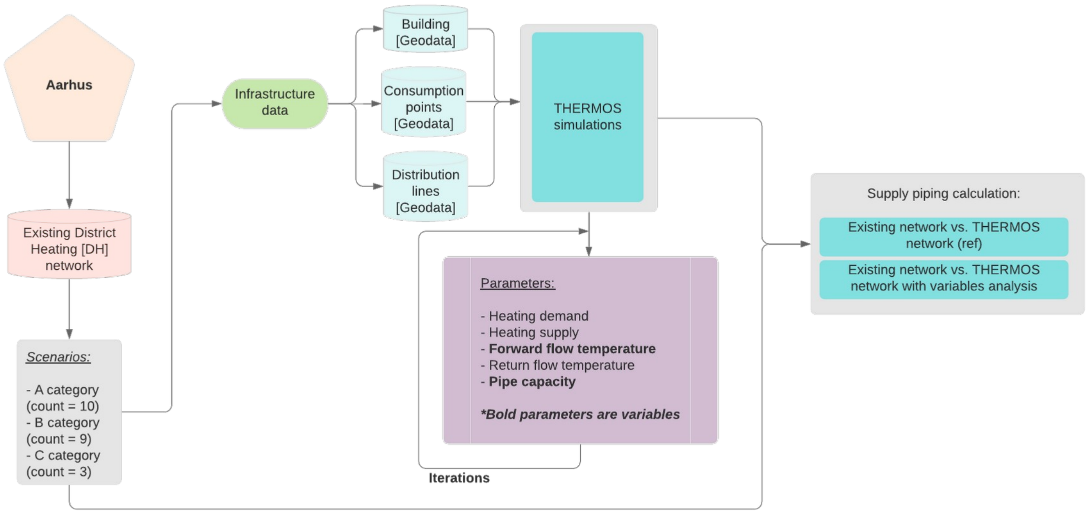

Figure 5 Sulsted validation scenarios

| Size level | Scenarios | Total areas | Number of houses |
|---|---|---|---|
| Single street | a1 to a14 | 14 | Up to 17 |
| Neighbourhood | b1 to b4 | 4 | Up to 36 |
| Large | c1 & c2 | 2 | Up to 250 |

## 2.2 Network dimensioning validation – Aarhus

The methodology used for this validation is depicted in Figure 6. As with the previous methodology, the main input to the model is the geocoded infrastructure data on buildings, consumption points and distribution lines. For scenario selection, several branches belonging to a single distribution line of the network were chosen from the infrastructure data, and then each scenario was categorized according to the number of houses connected to it. Variables – flow temperature and pipe capacity - where altered for the different iterations as its influence is to be analysed, and the output network of the simulations performed was classified pipe bits by diameter and lengths.

Figure 6 Aarhus dimensioning validation methodology




### 2.2.1 Existing DH network

The existing DH network in Aarhus is characterized in length and inner diameter by distribution and branch both single and double pipe type. Its individual components can be seen in Table 4, and geographically visualized in Figure 7. The map legend shows the piping diameter classification used in this analysis.

Table 4 Aarhus existing DH infrastructure characterization

| | Diameter (mm) | Meters |
|---|---|---|
| | **Distribution Pipes** | |
| **Double** | 28.5 | 1,387 |
| | 37.2 | 4,093 |
| | 43.1 | 92 |
| | 54.5 | 13,819 |
| | 70.3 | 8,558 |
| | 82.5 | 4,741 |
| | 107.1 | 4,316 |
| | 132.5 | 3,351 |
| | 160.3 | 1,054 |
| | 210.1 | 159 |
| | 264.0 | 1,064 |
| | 501.7 | 1 |
| **Single** | 21.7 | 135 |
| | 28.5 | 17,763 |
| | 37.2 | 64,032 |
| | 43.1 | 4,869 |
| | 54.5 | 209,575 |
| | 70.3 | 178,839 |
| | 82.5 | 125,589 |
| | 107.1 | 73,247 |
| | 132.5 | 112,245 |
| | 160.3 | 67,352 |
| | 210.1 | 84,010 |
| | 264.0 | 101,170 |
| | 318.3 | 37,706 |
| | 400.1 | 39,705 |
| | 501.7 | 14,072 |
| | 602.9 | 5,821 |
| | 703.2 | 1,015 |

| | Diameter (mm) | Meters |
|---|---|---|
| | **Branch Pipes** | |
| **Double** | 28.5 | 25,568 |
| | 37.2 | 1,702 |
| | 43.1 | 19 |
| | 54.5 | 666 |
| | 70.3 | 1,647 |
| | 82.5 | 1,003 |
| | 107.1 | 466 |
| | 132.5 | 585 |
| | 160.3 | 4 |
| **Single** | 15.0 | 59 |
| | 21.7 | 42,462 |
| | 28.5 | 426,011 |
| | 37.2 | 167,133 |
| | 43.1 | 6,216 |
| | 54.5 | 40,776 |
| | 70.3 | 32,027 |
| | 82.5 | 25,177 |
| | 107.1 | 11,114 |
| | 132.5 | 14,750 |
| | 160.3 | 5,333 |
| | 210.1 | 4,802 |
| | 264.0 | 1,056 |
| | 318.3 | 5 |

| Summary | Meters |
|---|---|
| Distribution Pipes | 1,179,779 |
| Branch Pipes | 808,582 |
| **Total** | **1,988,361** |

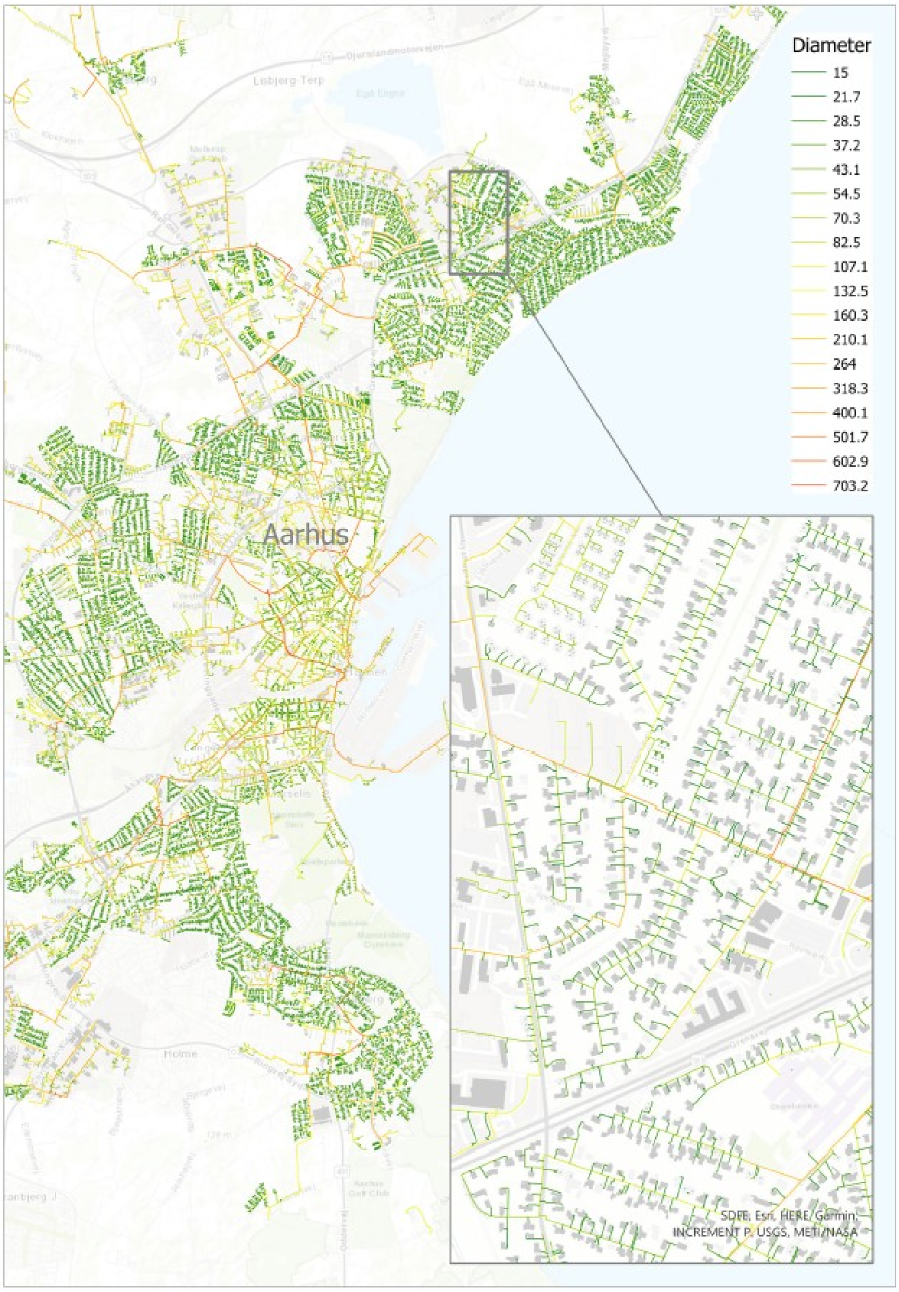



Figure 7 Aarhus existing DH network

### 2.2.2 Input simulation parameters

In the following subsections, parameters, assumptions, and usage of the available data at the moment of the analysis are developed further. Maps are added for a visual representation when possible.

#### *2.2.2.1Infrastructure*

**Buildings DH connection**

Building footprints[3], in a polygon geographical representation is the first dataset used for the identification of buildings connected to the DH network. The buildings layer was spatially joined with heat consumption point source geographic dataset further explained in 2.2.2.2. Where no such geographical

[3] Topographic data from https://www.geodanmark.dk

intersection was found, a generic shaped building was generated as to preserve representation, and for the network to identify the point as heat consumption. Supply points where allocated through dummy buildings on the start of the distribution networks for each scenario.

**DH network**

The existing DH network[4], described in  is used as the unique routing option for the THERMOS tool. The network is then set as constrain required for the network optimization. As with the previous dataset, the proximity of buildings to network was assessed, and when no connection was found, THERMOS generated a branch pipe connection for the building from the distribution pipe nearby. The same principle is followed for pieces of pipes following a certain network that are found not to be connected amongst themselves where a piece of pipeline was generated.

Both data sources manipulations stated, the generic building and branch generation might be the source of slight pipe length difference in the representation on the real network, nevertheless it is considered minor for the dimensioning validation of the network. A map extract showing both the spatially joined and generated infrastructure used in THERMOS is shown in Figure 8.


Figure 8 Aarhus infrastructure used in THERMOS

### *2.2.2.2Network properties*

**Building heat demands**

Aarhus building heat demand data[5] was obtained as a heat consumption point source from the local district heating company. The dataset includes heat demand for circa 51k geocoded consumption points. Building infrastructure dataset provides georeferenced information for approximately 34k features. All consumption points are kept with the help of the generic building generation

[4] Non-public district heating network data from the local district heating company Affaldvarme Aarhus
[5] Non-public consumer data from the local district heating company Affaldvarme Aarhus

stated in 2.2.2.1. Heat demand data is expressed in annual kWh consumption and is shown in Figure 9.

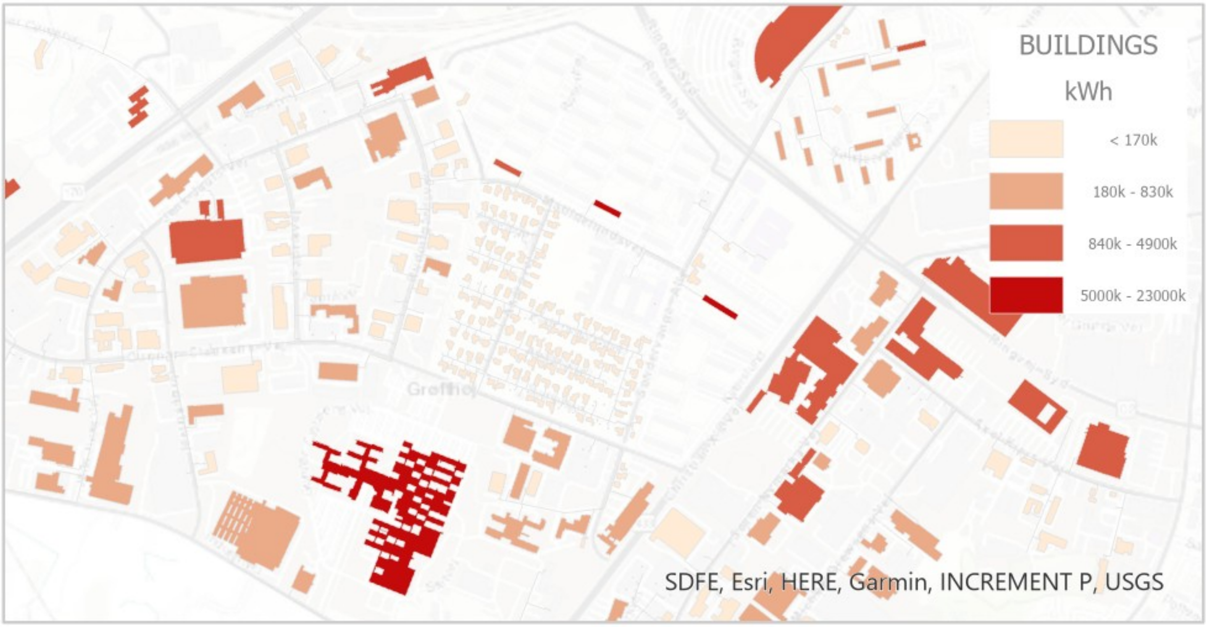



Figure 9 Aarhus building spatially joined annual heat demands

**Delta temperature**

Considering the sources of information for district heating networks included in 2.1.2.2, and since there is no information available in the datasets when it comes to temperature nor flow properties. Delta temperatures where set as variable in order to investigate further their implications in the dimensioning process. Their variation includes 20, 30, and a reference temperature of 40° C.

#### *2.2.2.3Piping characterization*

As to be consistent with both validations, similar piping characterization was utilized. Therefore, refer to 2.1.2.3 for pipe description and unitary costs associated to each pipe size.

### 2.2.3 Scenarios

For this validation, 3 categories of scenarios were included, ranging from small to larger areas distributed in the city of Aarhus. Scenarios were chosen individually, following independent branches of the network so they can be assess individually. Scenarios were named with a letter category followed by the number of houses connected to its network. In such wat, B156 scenario has 156 houses connected on its DH scenario analysis performed by THERMOS. Figure 10 shows the geospatial distribution of the areas.

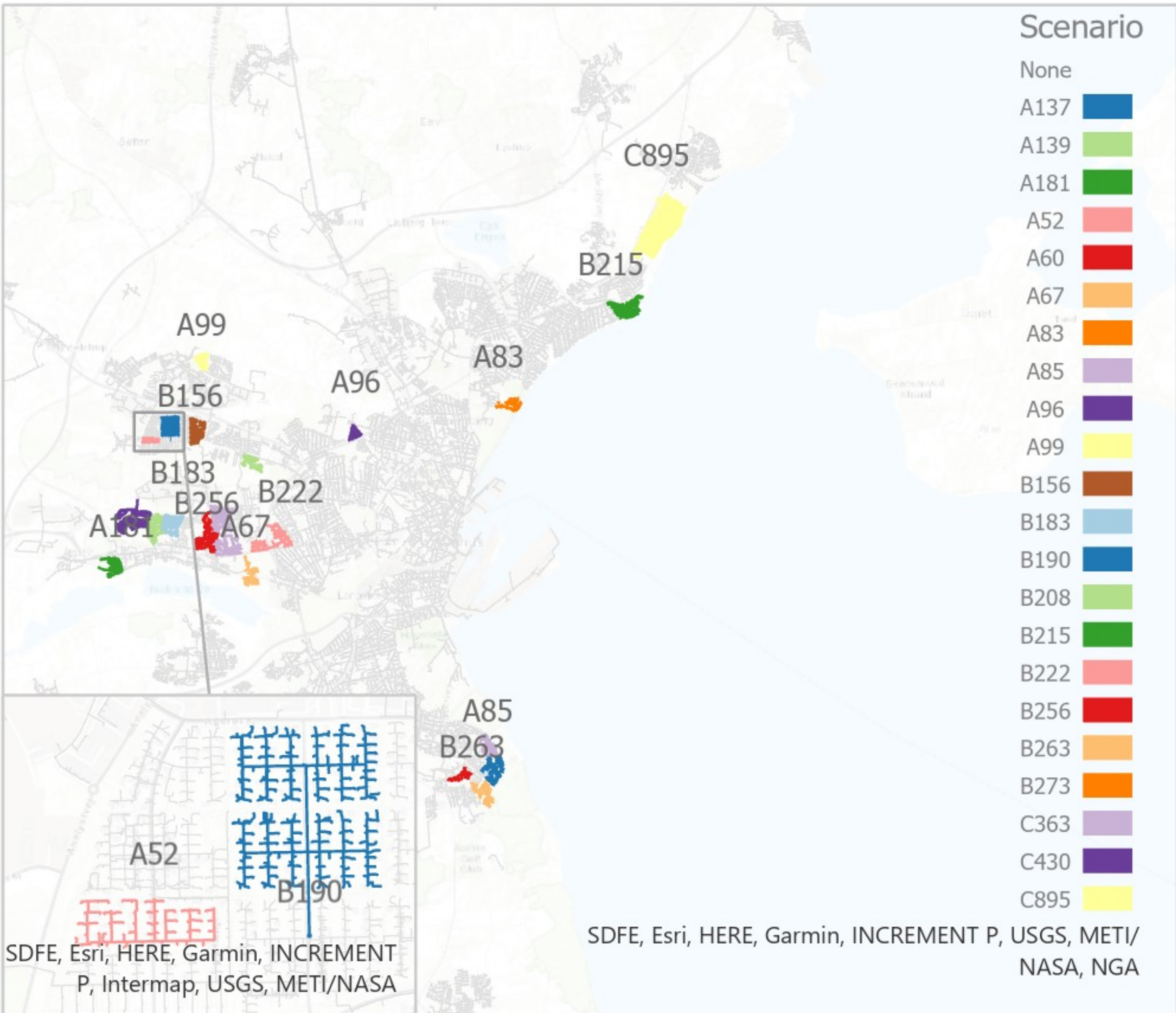



Figure 10 Aarhus validation scenarios

| Category | Total scenarios |
|---|---|
| A | 10 |
| B | 9 |
| C | 3 |

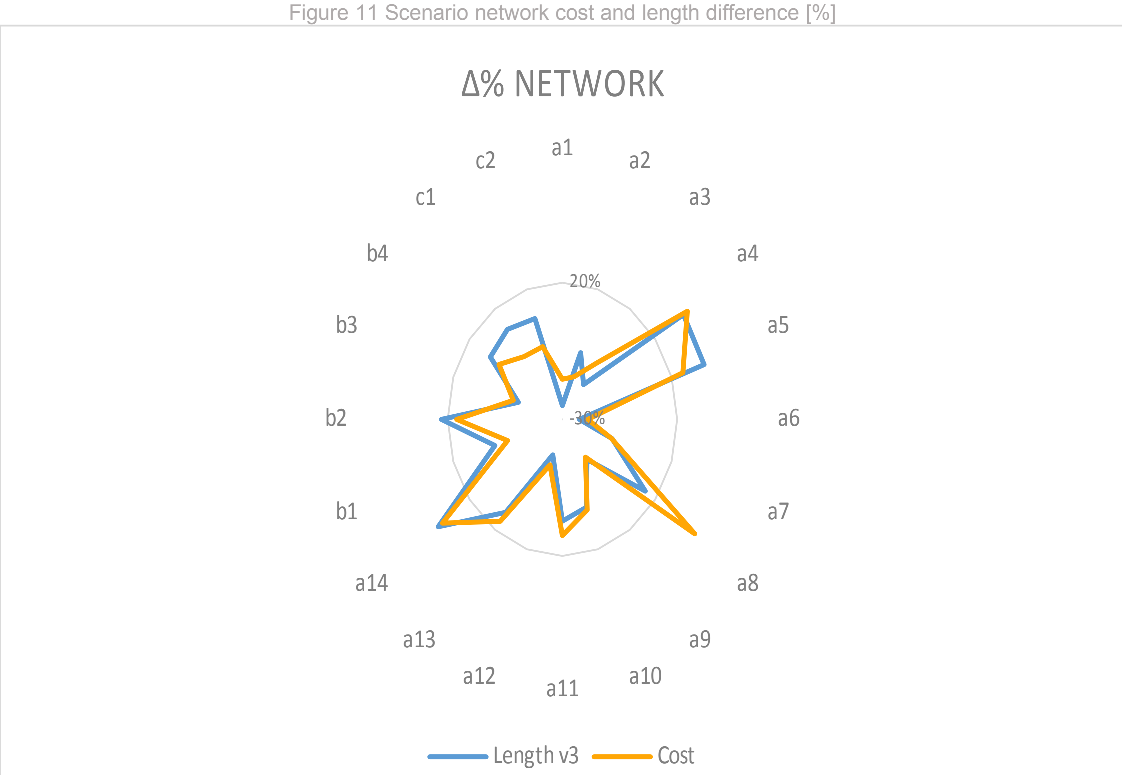
# 3 Scenario analysis

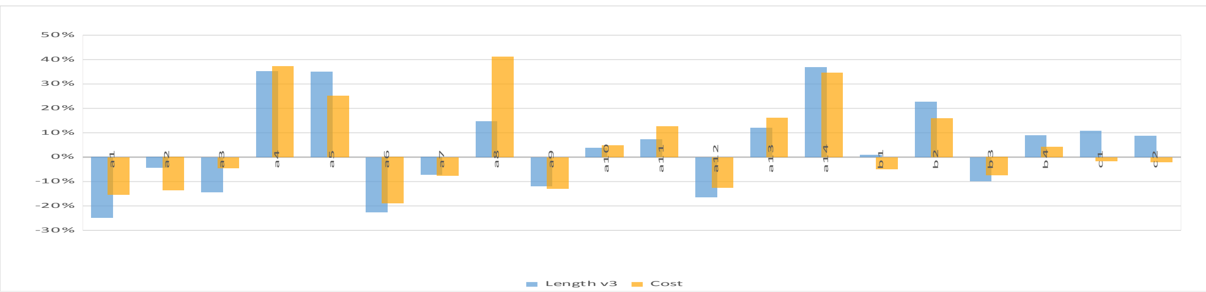
## 3.1 Network routing validation - Sulsted

For the analysis, at first an overview of the results obtained of all scenarios run is presented. Later in the chapter, the specific more detailed scenario analysis is included for certain areas where noteworthy findings are found. All size level scenarios are part of the analysis.

Figure 11 represent the difference in percentage when THERMOS is compared to the existing network for both investment cost and length. In the figure a positive difference represents the difference of THERMOS estimation over existing network. For example, scenario b1 has a difference of +1% on length and -5% in cost. Meaning that THERMOS output a network which compared to the existing network is 1% shorter, and for the cost 5% more costly. Therefore, a positive difference means positive response - lower cost and shorter length - from the THERMOS simulation output.

Figure 11 Scenario network cost and length difference [%]



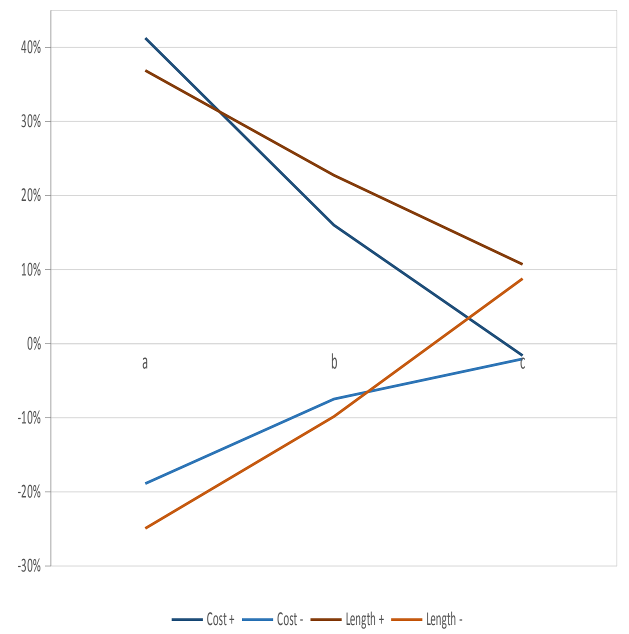



The scenarios in Figure 11, the THERMOS output has an average deviation of 4% in terms of length and 7% in terms of costs, which is quite good. However, one should note that there are large variations in between.

As important differences are noted amongst different scenario sizes, Table 5 aims at portraying the percentages that vary significantly amongst the different sizes analyzed. As seen, the percentages of variation of length and cost tend to get closer to zero with a larger number of houses connected to the DH network. These percentages are the ones acquired when THERMOS scenarios are performed for fixed flow temperature of 70/40 and 10% allowable distance from optimum optimization.

Table 5 % Variation general comparison

| | | THERMOS | |
|---|---|---|---|
| **Size level** | **Number of houses (Up to)** | **Δ% Cost range** | **Δ% Length range** |
| **[a]** | 17 | +41 to -19 | +37 to -25 |
| **[b]** | 36 | +16 to -7 | +23 to -10 |
| **[c]** | 250 | -2 to -2 | +11 to +9 |




* Blue and brown represents cost and length respectively

In the following subchapters, three different analyses are presented for selected interesting scenarios, to illustrate some of the important observation when comparing the THERMOS output to the existing DH network design. The results are depicted in various tables and maps, where the top shows a column chart of the total meters of pipe divided into the different pipe size categories. In the bottom left side, a column chart shows the total investment costs of the network divided into the different pipe size categories. Finally, in the bottom middle and right side, maps of the existing and the THERMOS proposed networks are shown. In addition, to these selected results, the main results of all scenarios are available in .

### 3.1.1 Typical use (70°C /40°C, 0% allowable deviation from optimal)

This subchapter presents what can be considered a typical use of the THERMOS tool, where the same forward and return temperatures and a 10% allowable deviation from the optimal is used. The results of scenario a4, a8, a14, b2, c1 and c2 are presented on the next pages and the main points for each are discussed here.

**Scenario a4:** Comparing the two maps shows that the network layout is very similar for the distribution part, with similar length and pipe sizing. However, for the service pipes for each household there is a difference, as the THERMOS model takes the shortest distance from each building, while the existing network seems to be longer for each building. The reasons behind this could be based on the location of the heat exchanger in the building and the driveway, two things that are typically not part of GIS data. Another observation is that the existing network uses smaller pipe dimensions for the service pipes compared to THERMOS. All this leads to that the THERMOS model underestimates the network investment cost with around 18,000 EUR.

**Scenario a8:** In this scenario, the THERMOS model finds a similar network layout, but again with a shorter routing for the service pipes. What is interesting in this case is, however, that the main pipe is very different in size compared to the existing network, resulting in THERMOS being around 20,000 EUR cheaper, even with a similar network length. The reason for using these large main pipes in the existing network can be assumed to be related to planning reasons, ensuring that the capacity in the main pipe can provide heat if the city is expanded.

**Scenario a14:** The scenario shows another interesting difference, as the existing network uses a completely different layout of a large part of the network, as it does not follow the roads. Instead the network is created as a u-shape between the buildings, as these buildings are attached houses, with two families in each, each building also has two service pipes. This is not something that is only possible to recreate in THERMOS if each building is split into two in external GIS software.

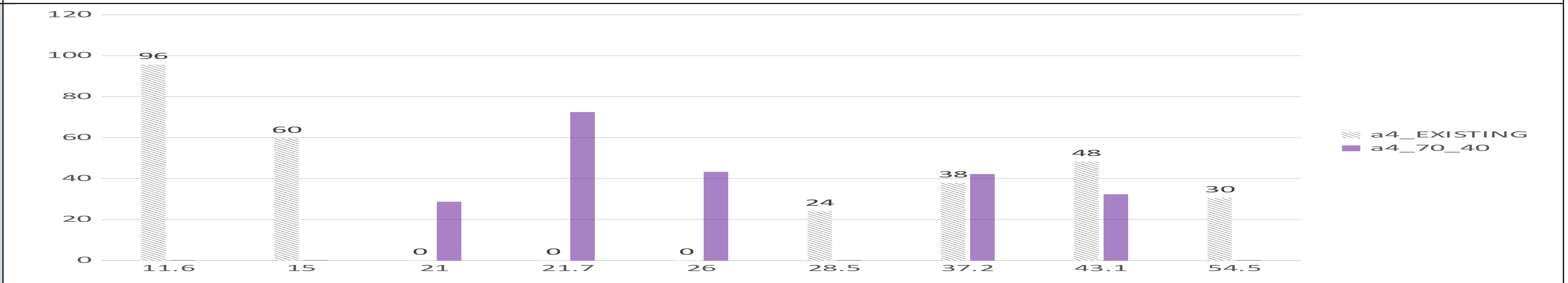
**Scenario b2:** This scenario shows the model in a larger area. Here, network length follows the same routes in both the existing and THERMOS. Again, the THERMOS model uses larger service pipes, but it also shows another trend that the THERMOS model does not use the same length of the larger pipe sizes. However, it only results in a 16% cost difference between the two outputs, in favour of the THERMOS network being cheapest.

**Scenario c1:** This scenario expands even further in size, and is the first that shows a very different routing than the existing. In this case, the THERMOS output actually has more meters of large pipes, than the existing network, which results in the THERMOS output being slightly more expensive, however only 2% difference.

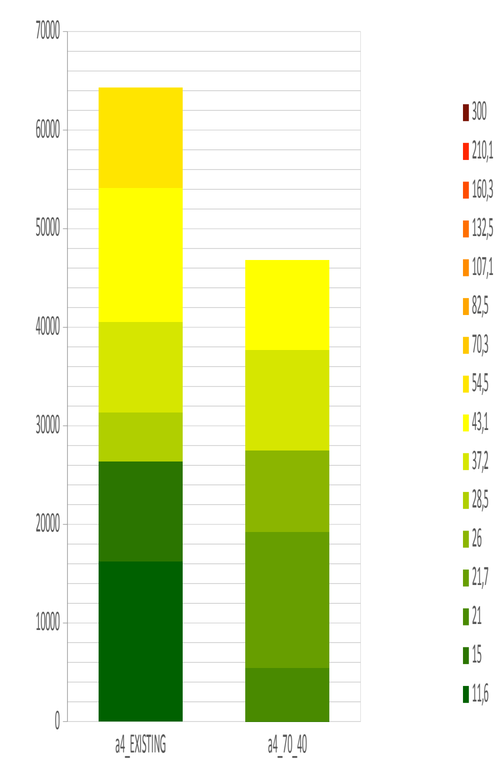
**Scenario c2:** This scenario, is the one with most buildings, the cost difference is around 2%, and the general routing is similar, but with smaller deviances in parts of the system. It shows the same tendencies as the previous scenario, with larger service pipes, and more meters of larger pipes.

## Scenario [a4]

Pipe length [m] vs. Inner diameter [mm]



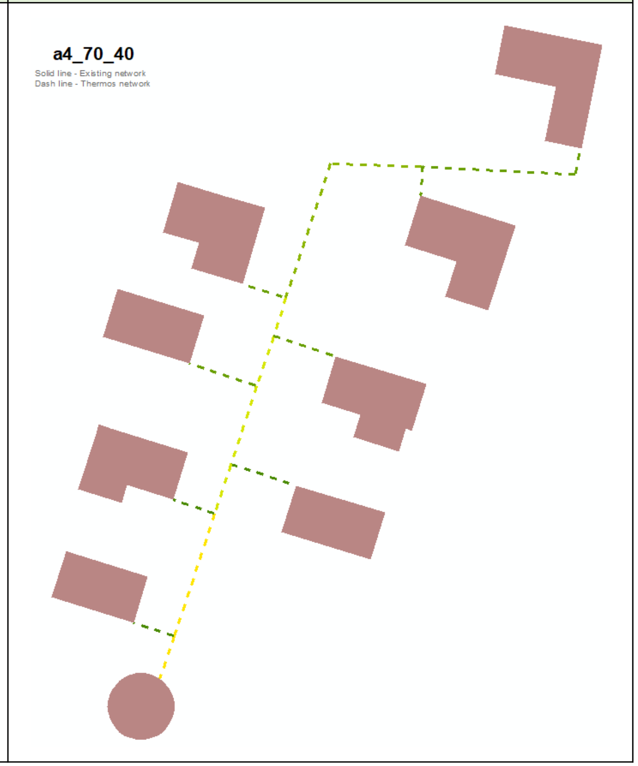

Total network cost [EUR] vs. Scenario




NETWORK (Solid line - Existing network, Dash line - THERMOS network)

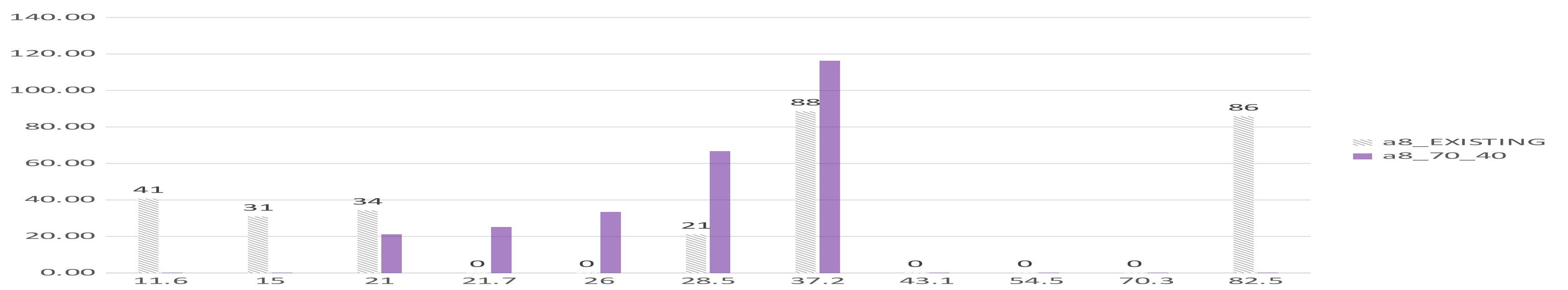
EXISTING


THERMOS

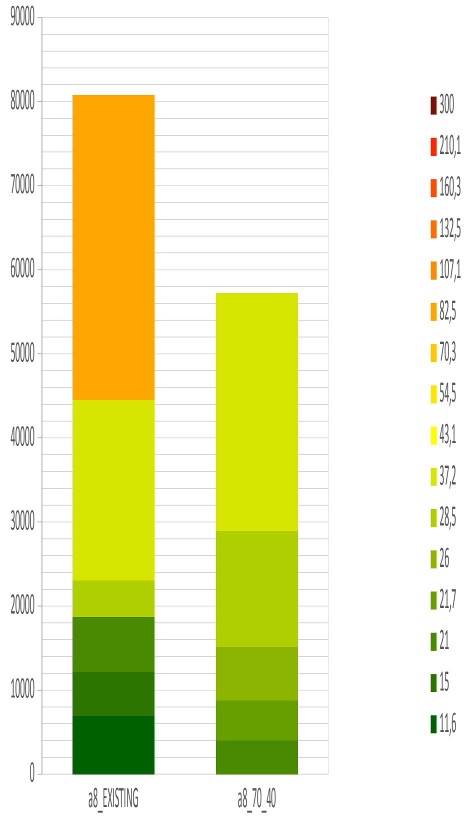


## Scenario [a8]

Pipe length [m] vs. Inner diameter [mm]

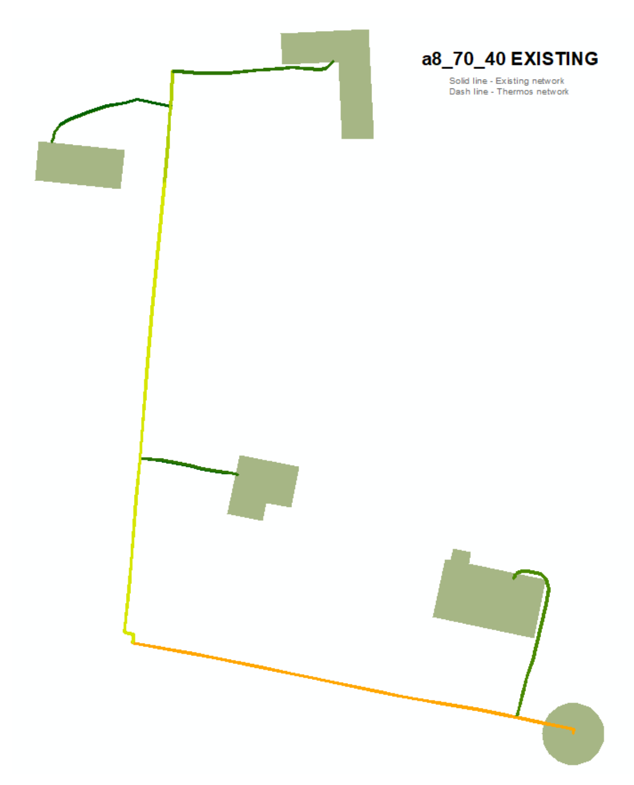



Total network cost [EUR] vs. Scenario

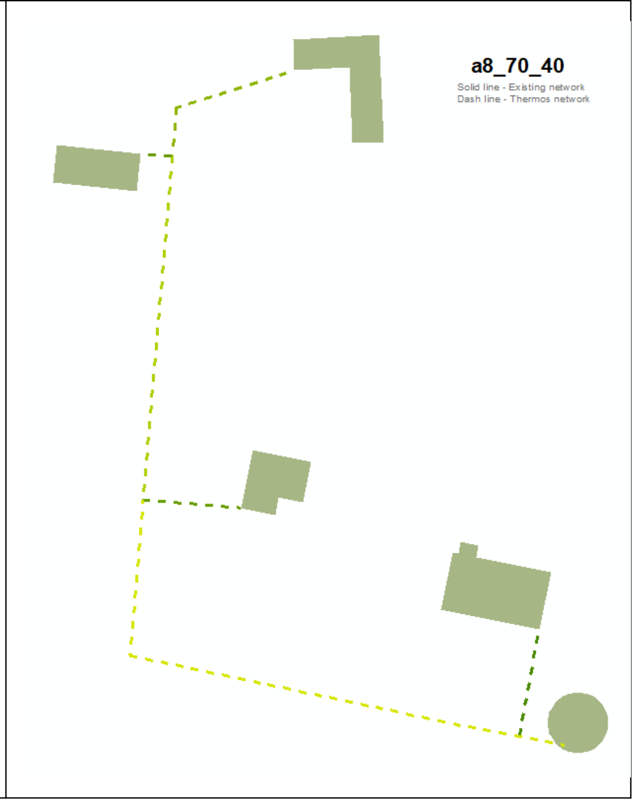



NETWORK (Solid line - Existing network, Dash line - THERMOS network)

EXISTING

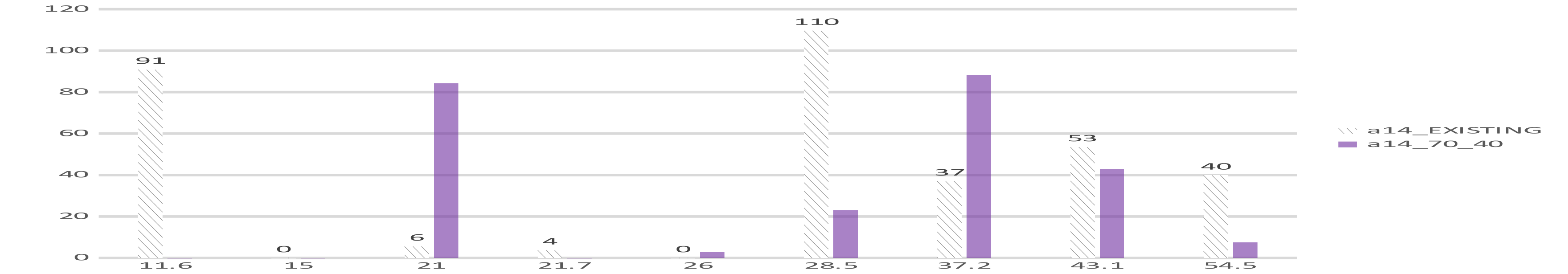



THERMOS

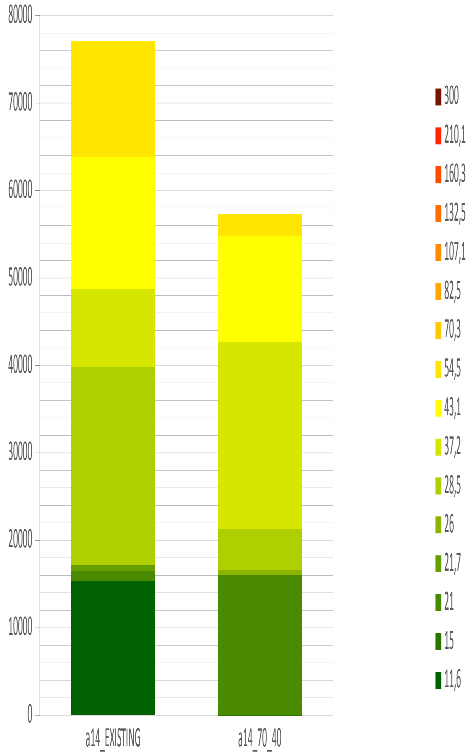


## Scenario [a14]

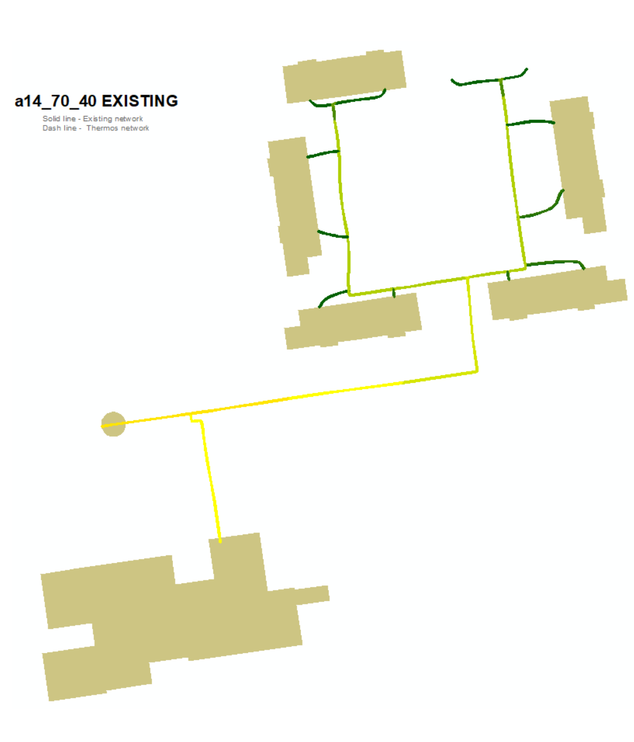
Pipe length [m] vs. Inner diameter [mm]



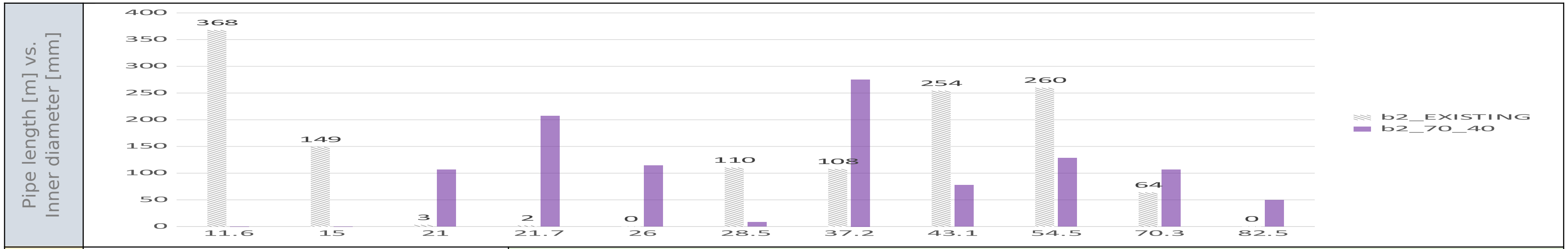

Total network cost [EUR] vs. Scenario

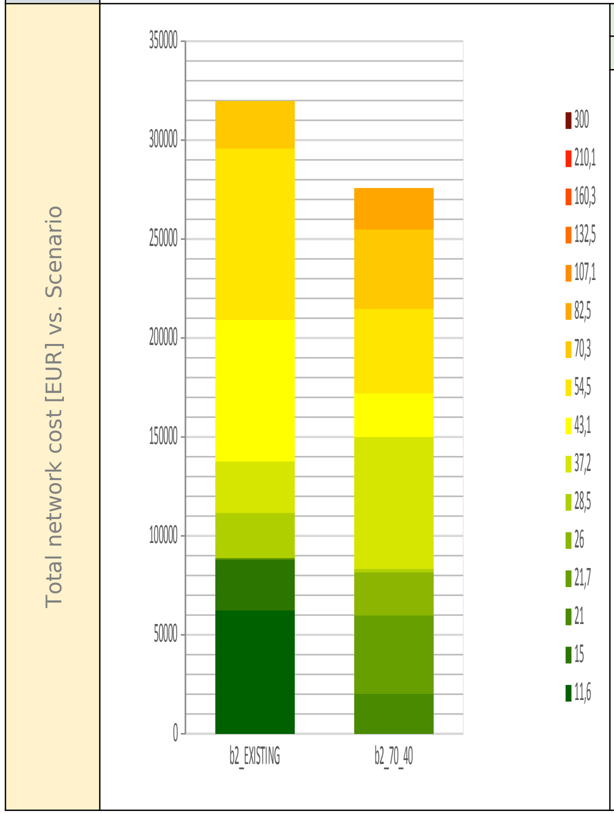



NETWORK (Solid line - Existing network, Dash line - THERMOS network)

| EXISTING | THERMOS |
|---|---|
|   |   |

## Scenario [b2]

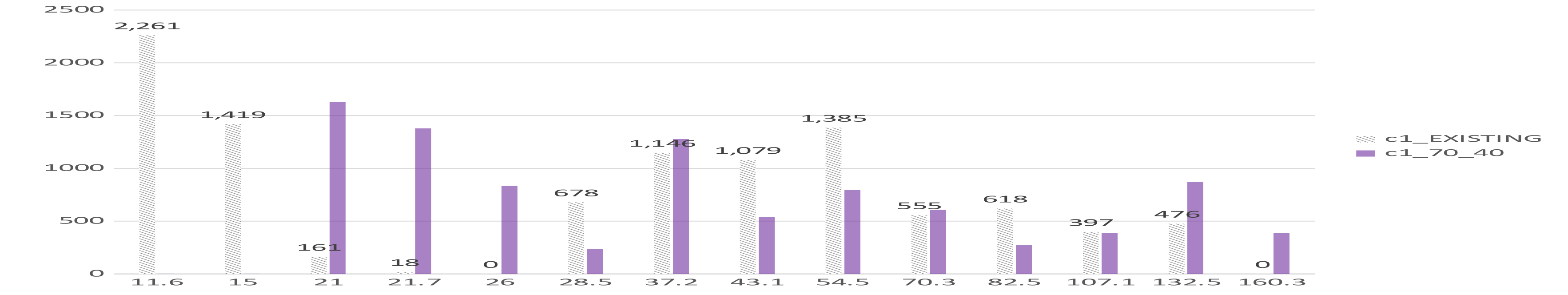

Pipe length [m] vs. Inner diameter [mm]
400
350
300
250
200
150
100
50
0
368
149
3
2
0
110
108
254
260
64
0
11.6
15
21
21.7
26
28.5
37.2
43.1
54.5
70.3
82.5
b2_EXISTING
b2_70_40


Total network cost [EUR] vs. Scenario
350000
300000
250000
200000
150000
100000
50000
0
b2_EXISTING
b2_70_40
300
210,1
160,3
132,5
107,1
82,5
70,3
54,5
43,1
37,2
28,5
26
21,7
21
15
11,6

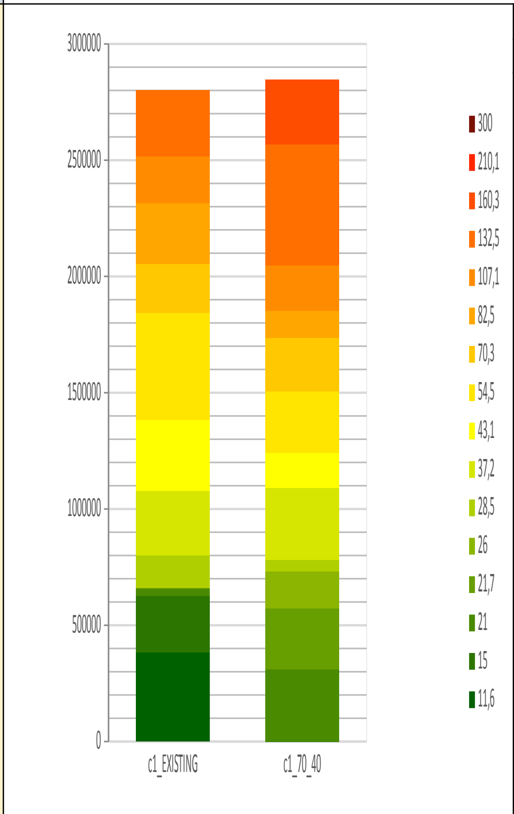

NETWORK (Solid line - Existing network, Dash line - THERMOS network)
EXISTING
THERMOS
b2_70_40 EXISTING
Solid line - Existing network
Dash line - Thermos network
b2_70_40
Solid line - Existing network
Dash line - Thermos network

Scenario [c1]

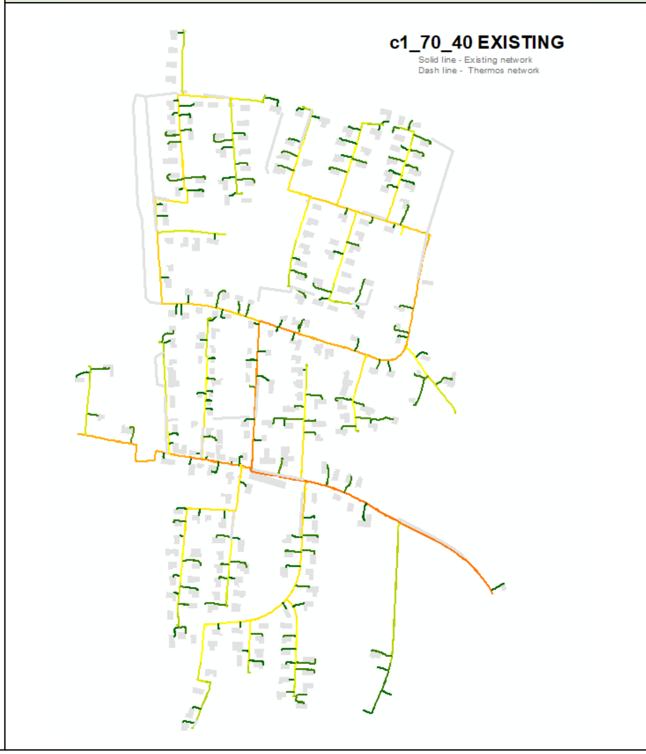
Pipe length [m] vs. Inner diameter [mm]




Total network cost [EUR] vs. Scenario



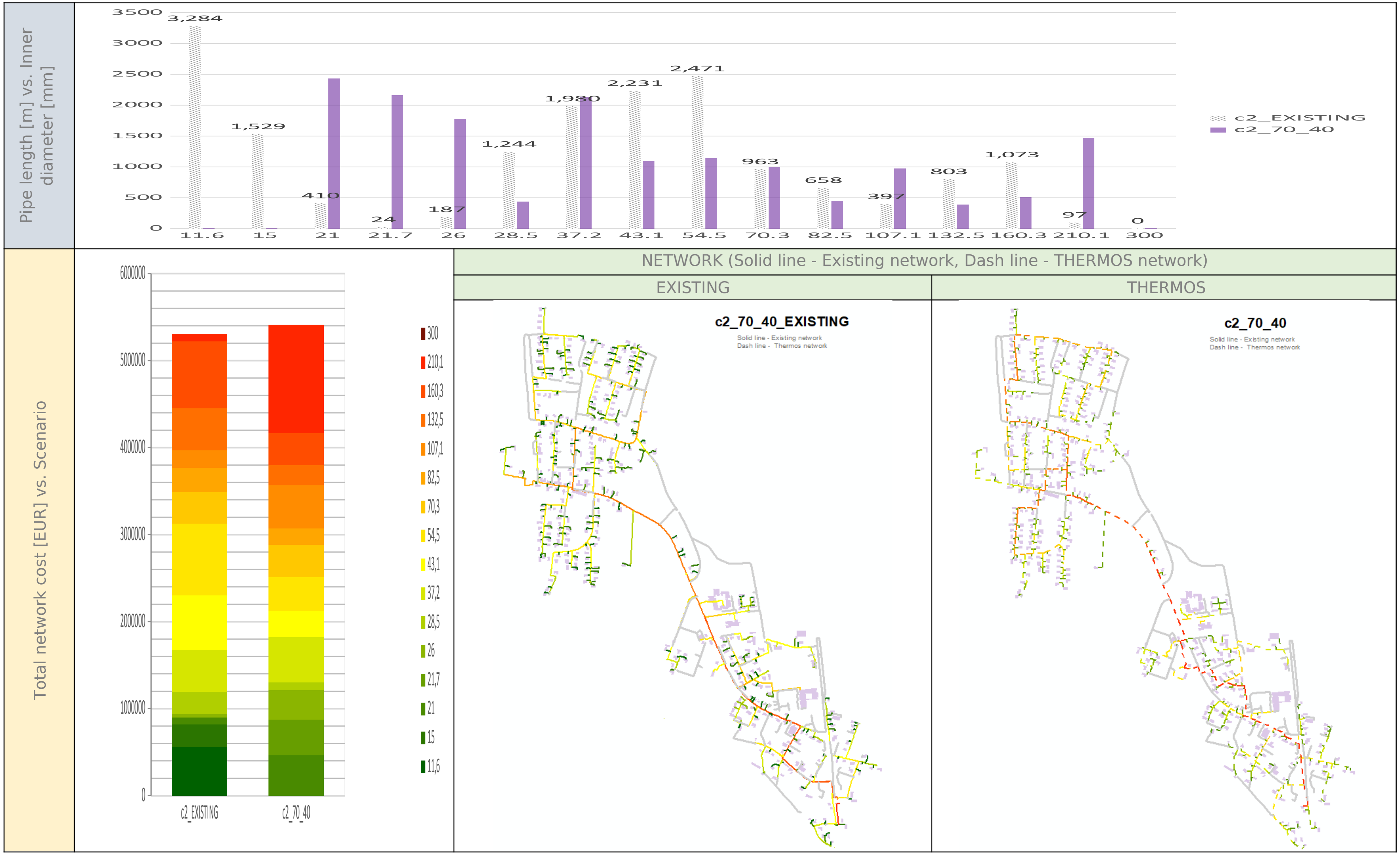

NETWORK (Solid line - Existing network, Dash line - THERMOS network)

| EXISTING | THERMOS |
|---|---|
|  |  |



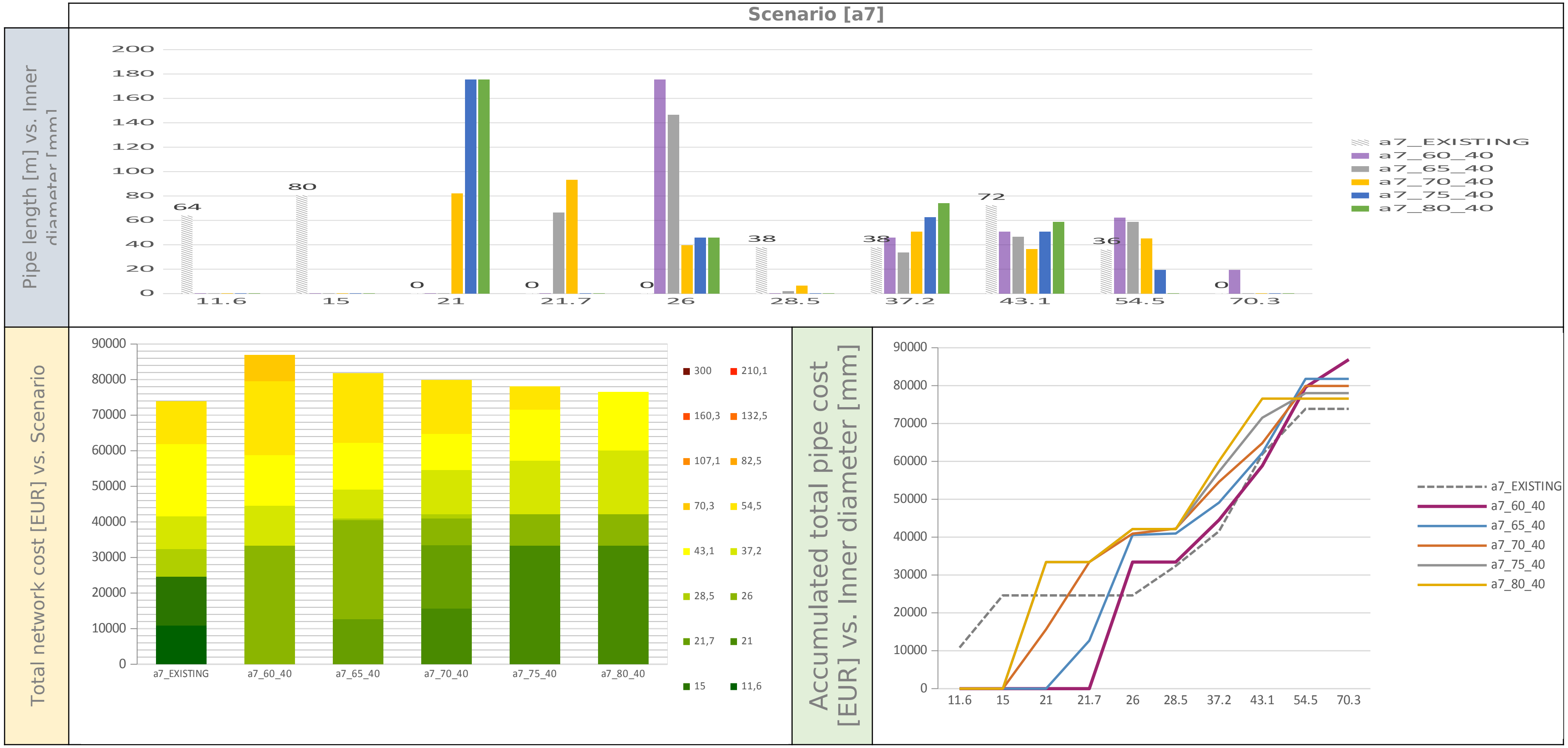


**Scenario [c2]**




### 3.1.2 Variable flow temperature

This Subchapter shows the influence of varying the forward temperature in the THERMOS model with the case of Scenario a7. The forward temperatures that are tested are 60°C, 65°C, 70°C, 75°C and 80°C. Using lower temperatures in general increases the pipe sizes and thus the costs. This means that the costs are highest in the 60°C case with around 86,000 EUR, while the lowest is the 80°C with around 75,000 EUR. When comparing to the existing network, the case with 70°C is most similar in terms of varying between sizes, however the 80°C is closed in terms of investment costs. It should be noted, that the cost difference is only reduced from 8% in the 70°C case to 4% in the 80°C case.

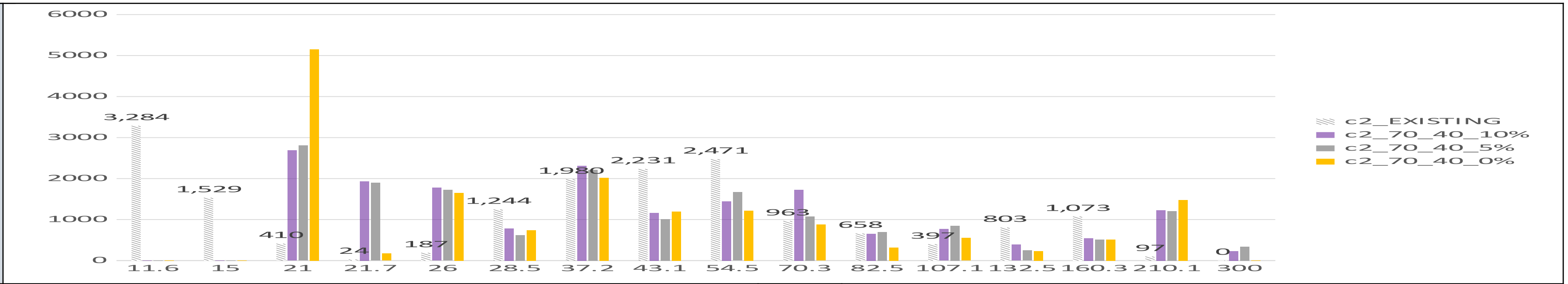



### 3.1.3 Variable allowable distance from top optimization

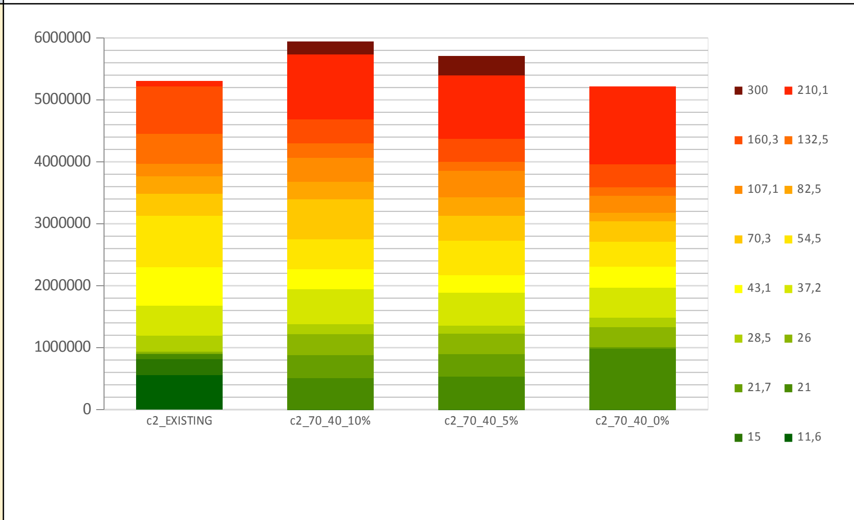
This Subchapter examines the influence of changing the allowable distance from the optimal solutions. The allowable distance is changed between 0%, 5% and 10% in Scenario C2. The results indicate that the costs by using a high allowable distance gives a solution with higher costs than not allowing any distance. In the case of 0% case the cost is only 2% lower, while in the 10% case the cost is 11% higher than the existing network investment.

Scenario [c2]

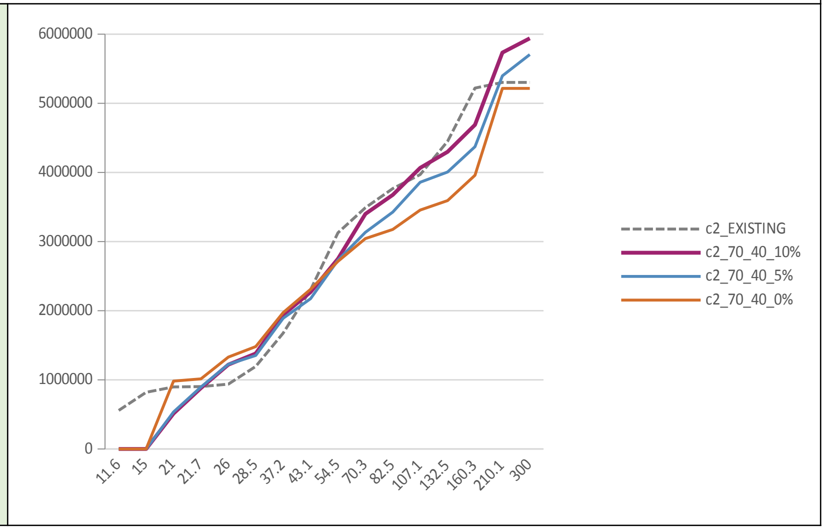
Pipe length [m] vs. Inner diameter [mm]




Total network cost [EUR] vs. Scenario




Accumulated total pipe cost [EUR] vs. Inner diameter [mm]



## 3.2 Network dimensioning validation – Aarhus

This section describes overall and more detailed analysis for certain scenarios where noteworthy findings are present. It is important to note that a reference scenario was pre-stablished for this validation. Each scenario simulated for a 40°C delta temperature and mid-peak capacity will then be referred as the reference scenario for a given case. The different variables such as peak capacity and delta temperatures are modified consequently from the reference scenario conditional parameters. Meaning, that the different peak capacities will be simulated for a 40°C delta temperature, and the different delta temperatures will be simulated for a mid-peak capacity.

Below, an overview of the general results is presented. The overview aims at depicting distance from pipe sizing allocation in THERMOS tool, when compared to the existing one. For each scenario, THERMOS piping estimations and its distance from the existing pipe category were categorized and normalized as to create indicators for this assessment. The partial length associated to each belonging category distance was then calculated and plotted. The figure's symbology in the radar visualization of Figure 12 represent the step distance of THERMOS simulated pipe size e.g. 0 represents no distance and 1 represent one step of distance between THERMOS estimation and the existing network.

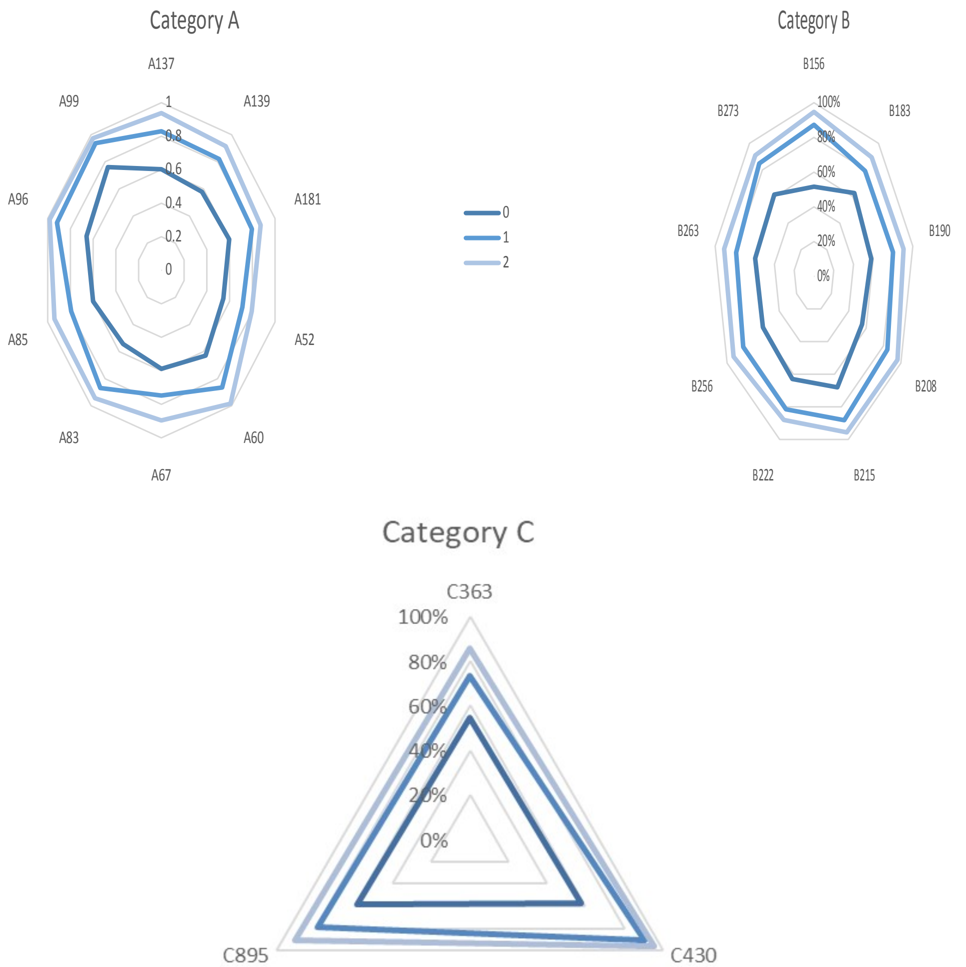



Figure 12 General THERMOS simulated pipe distance

The figure reads the allocated partial length of the network that falls within each distance category. Note that the distance is absolute, meaning that the allocation can be to larger or smaller pipe categories. Each scenario is a data point and the scenario categories are plotted in different figures so to have an overview of the category implication.

For most of the scenarios within each category, more than 60% of the total network falls within no distance – 0. Additionally, the sizing of the network does not seem to influence this tendency when scenarios in Figure 12 are compared. This assessment suggests a general decent sizing allocation and estimate of the THERMOS tool simulations.

In the following subchapters, two analyses for the variables used are presented for selected interesting scenarios, in order to illustrate some of the important observations when comparing the THERMOS output to the existing DH network. Modelled versus existing results are illustrated by visualization means in a table. For Error: Reference source not found, the table top shows column charts, the left one shows pipe lenghts and costs for the reference scenario, whereas the one on the right shows reference scenario dissagregation by various diversity factor ranges. A closer view to the geographical representation of the scenario is included in the bottom part of the table where diameter differences are represented by the map’s symbology. Pipe diameters symbolized with Not a Number (NaN) label represent pipe sections not used in THERMOS, and are understood as drawing inaccuracies or duplications in the network.

For Error: Reference source not found sensitivity analysis graphs are shown, peak capacity in the upper part and delta temperature in the lower. Tables with remaining scenarios are available in Appendix B – Aarhus scenarios.

### 3.2.1 Typical use (delta 40°C, mid-peak capacity, diversity disaggregation)

This subchapter represents the reference scenario analysis used on the THERMOS tool. Scenarios A60, A99, A139, B215, B263, B273, C363, and C895 are presented on the next pages and the main points for each are discussed hereby:

**Scenario A60:** This scenario is considered for its good representation for what is normally seen in a small scale network. The allocation of length varies along the diameter scale, regardless, the existing infrastructure shows significantly larger allocation in 54.5mm. THERMOS dimensioning on the contrary, appears to distribute that length across 43.1mm and 37.2mm dimensions. For the network cost, THERMOS overestimates the investment cost for smaller sizes and grows slowly into the largest ones, it ends up underestimating the total investment cost by 12%. When it comes to diversity factors, smaller diameters show the highest records as expected, since these represent the denser connection branches. Furthermore, the diameters of such diversities are of the smallest denominations as the network represented is the smallest category. Visually, using the map, it can be argued that THERMOS uses smaller pipes for distribution and larger sizes for various branches of the network.

**Scenario A99:** This scenario is similar from the previous one in terms of THERMOS length allocation to the stated diameters. A larger smaller diameter allocation is seen in the existent infrastructure, whereas THERMOS moves towards larger pipe sizing such as 107.1mm and 160.3mm. No allocation is seen in the real network to 43.1mm nor some of the largest pipes, similarly to the previous A-category scenario. Cost wise, slight differences are seen throughout the distribution with a slim to none difference in the total accumulative investment cost of the network. High diversities are also allocated to smaller pipe diameters as this scenario is also of the smallest category. On the maps however, it can be seen that more sections are allocated to larger diameters for both distributions and branches pipes by THERMOS, when compared to the previous A-category scenario.

**Scenario A139:** For this scenario, existing length distribution show a more consistent to the existing distribution in larger pipes whereas THERMOS tendency in smaller pipes is overestimation. No existing pipe denominations to 43.1mm are also seen in this scenario whereas the peaking differences are seen in 54.5mm and 132.5mm with a circa 200% and 350% THERMOS underestimation, correspondingly. Network investment cost remains with relative difference, ending up with a hardly 6% THERMOS underestimation. As a larger network, the diversities appear to be slightly different in this scenario for higher factors are also included in 43.1mm and 54.5mm pipe denominations. On the map, it can be seen that THERMOS chooses smaller diameters for the distribution pipes closer to the heat supply and smaller denominations as the network expands. For the branches however, a general overestimation tendency in THERMOS is visualized.

**Scenario B215:** This network grows in complexity and demand when compared to the ones in the previous category analysed. THERMOS distribution in the small sizing denomination seem closer to the existing network than the ones in the largest diameters where THERMOS tendency is underestimation. Diameters 43.1mm and 107.1mm remain barely used in the existing network, as in the previous category. An underestimated total investment cost of 4% is seen in THERMOS, while its distribution along the sizing denomination present minor differences. Visually, it can be said that smaller pipes are chosen by THERMOS for some of the network distribution fractions whereas general similar pipe denominations are used for the branches.

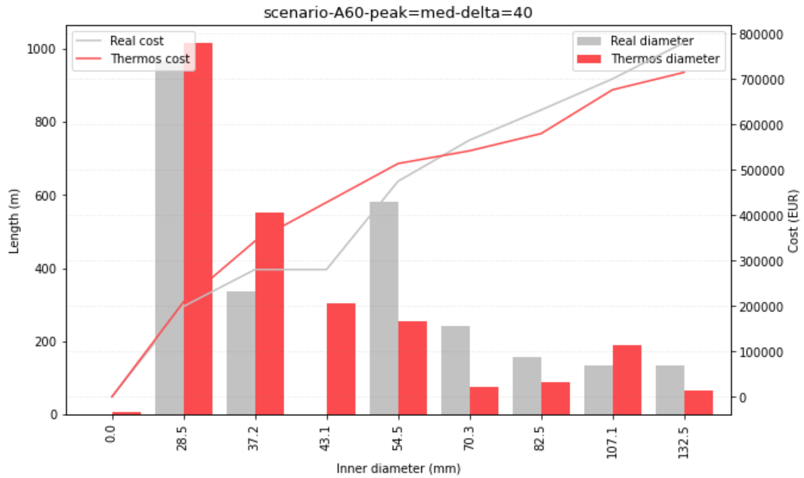
**Scenario B263:** For this scenario, THERMOS allocates its distributions tending to larger pipe denominations. Existing network shows no allocation for pipes larger than and including 210.1mm, whereas the THERMOS estimation goes up to 318.3mm. In this scenario, NaN values start to show in small parts of the network. The tool estimates a higher total investment cost for the network by approximately 8%. High diversity factors are seen also in a small fraction of 70.3mm pipe denomination. According to the map of the network, some smaller denominations are seen in branches and a general overestimation on the distribution pipes of the network.

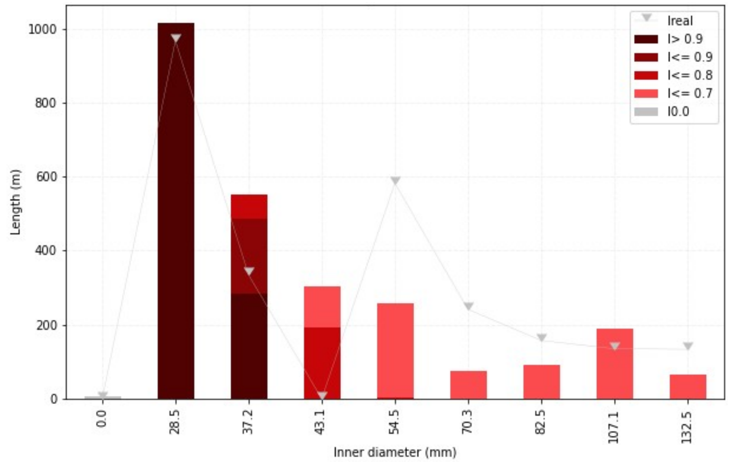
**Scenario B273:** Compared to the previously described B-category scenarios, this network presents similar tendency on its distribution. More allocation is given to larger pipe sizes when compared to the existing one. Peculiarly, THERMOS does not allocate pipe length in the 160.3mm denomination, and the existing network shows no records for the 43.1mm pipe size. For the network, THERMOS underestimated the total investment cost by roughly 4% although showing a relatively consequent distribution across the diameter denominations. High diversity factors start at 82.5mm for this scenario which highlights the extension and density of the network. NaN values are shown to be larger in this scenario, what is also visible in the map along with a general overestimation for the network in smaller branches sizing by THERMOS.

**Scenario C363:** This scenario represents a large network with 363 buildings, and thus is more complex than the scenarios shown previously. Nevertheless, this scenario shows some of the same tendencies, where THERMOS gives similar lengths for the smallest pipe sizes (<28.5mm). In the 37.2-54.5mm categories, THERMOS tends to add more pipe lengths in the smaller diameters, while the real network uses the 54.5mm category more. For the pipe sizes above 54.5mm there is a trend towards THERMOS adding more larger pipes, but not to the same extend. The costs underline this very well, as THERMOS follows the real diameter to around 70.3 mm, then the real network increases more for a period until it is caught up by THERMOS at almost identical accumulated investment cost. As expected, the diversity factors in general follows the pipe sizes, with lower diversity for the larger pipes. From the visual representation on the map, there are more NaN sections in the result for the THERMOS model, which can be expected from a more complex network, but also suggests that THERMOS avoids parallel pipes. This could be one of the reasons why THERMOS uses more pipes above 264mm.

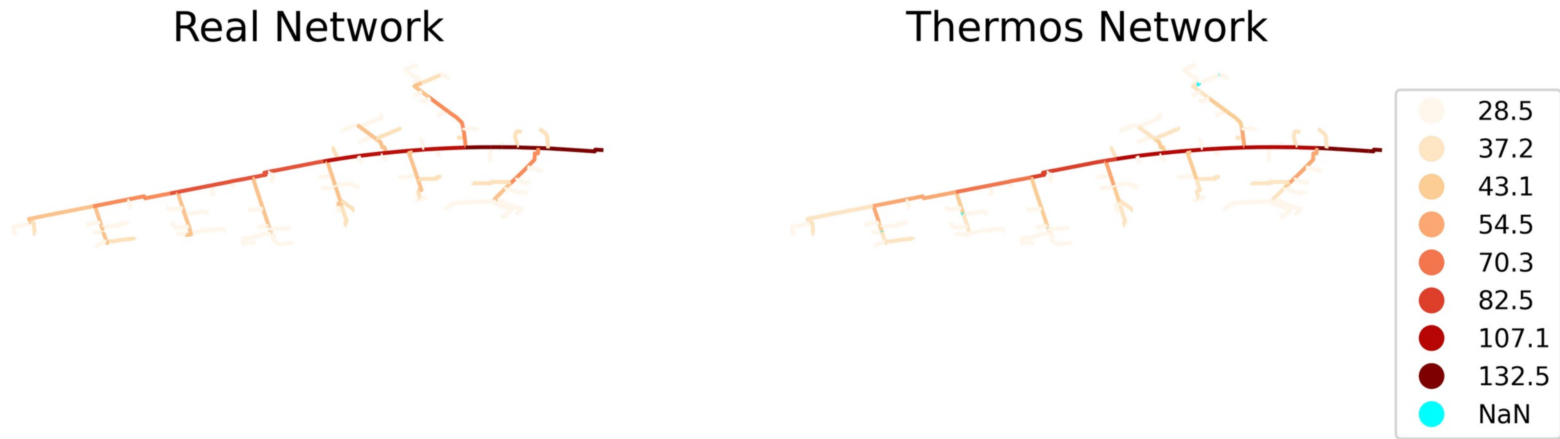
**Scenario C895:** This scenario represents the largest area with 895 buildings and is roughly 2.5 the size of the C363 scenario. The results show the same trend as the previous scenarios. THERMOS adds more pipe meters in the two categories below 54.5mm, while adding more of the larger pipes, due to a more optimized routing. The total accumulated investment cost is very similar, so for pre-feasibility studies the model is very suitable.

| Scenario [A60] | |
|---|---|
| Reference scenario | Diversity disaggregation* |



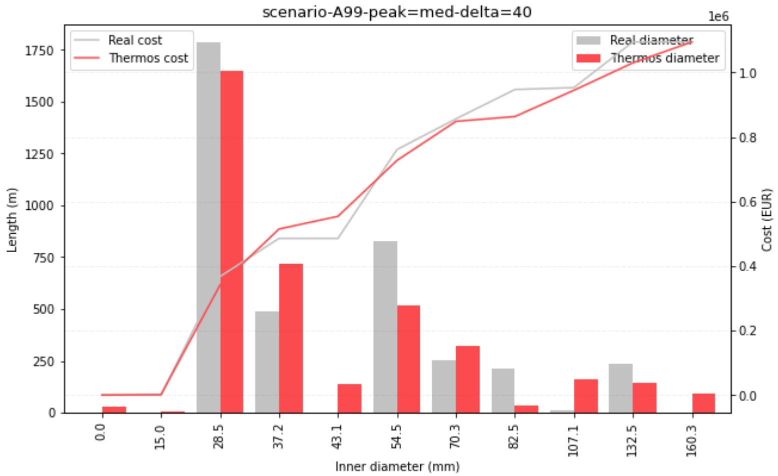
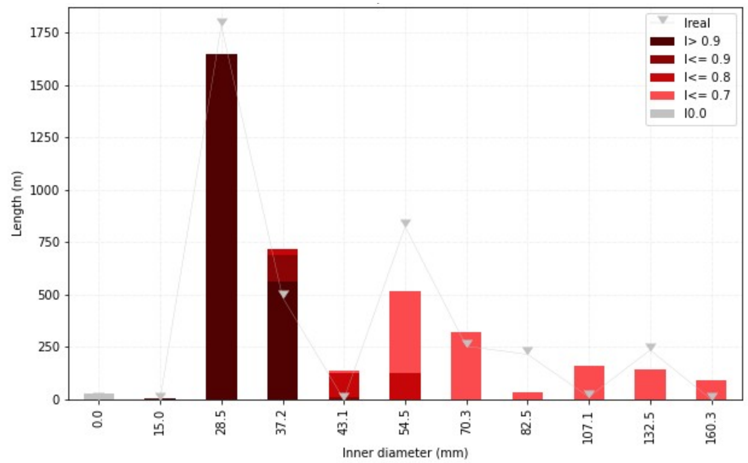




Network comparisson*




*Uses reference scenario

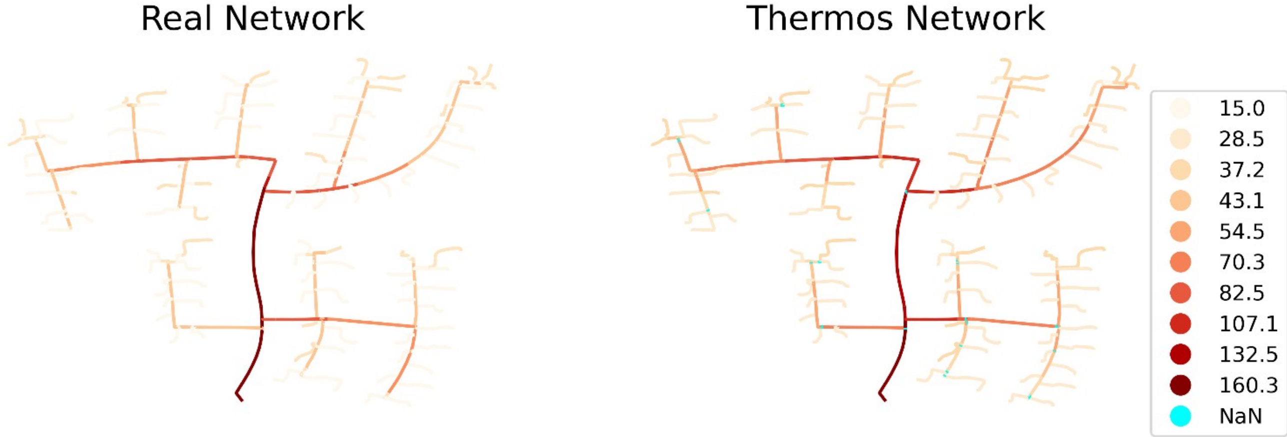
| Scenario [A99] |
|---|

| Reference scenario | Diversity disaggregation* |
|---|---|
|  |  |





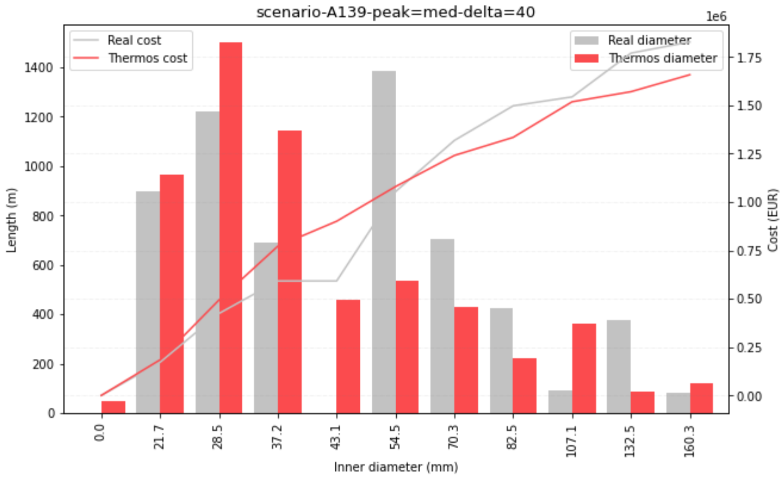
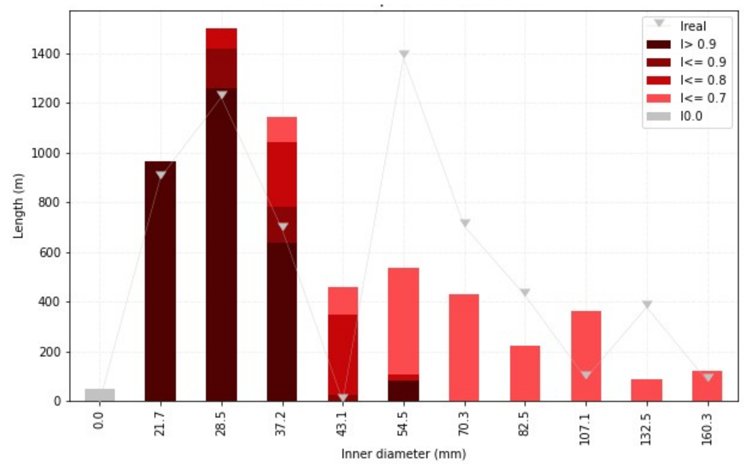
**Network comparisson***



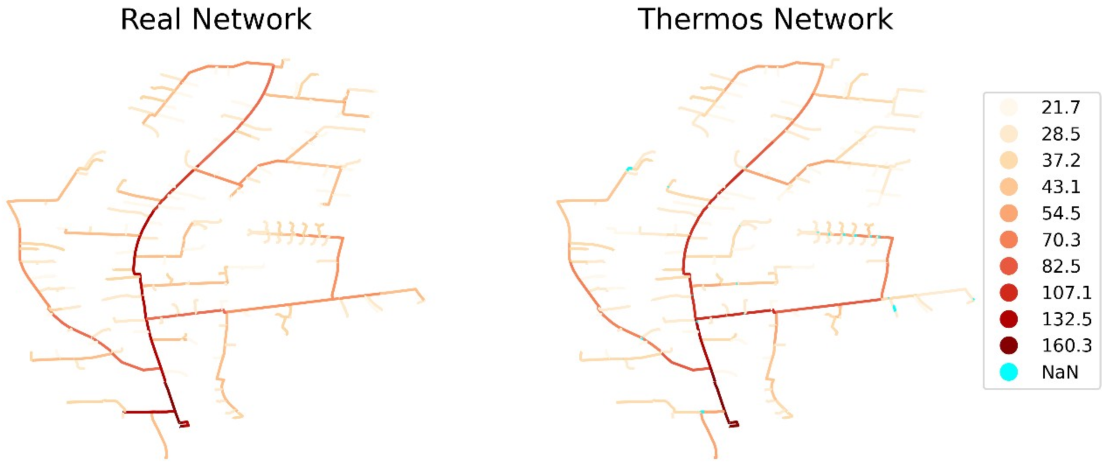


*Uses reference scenario

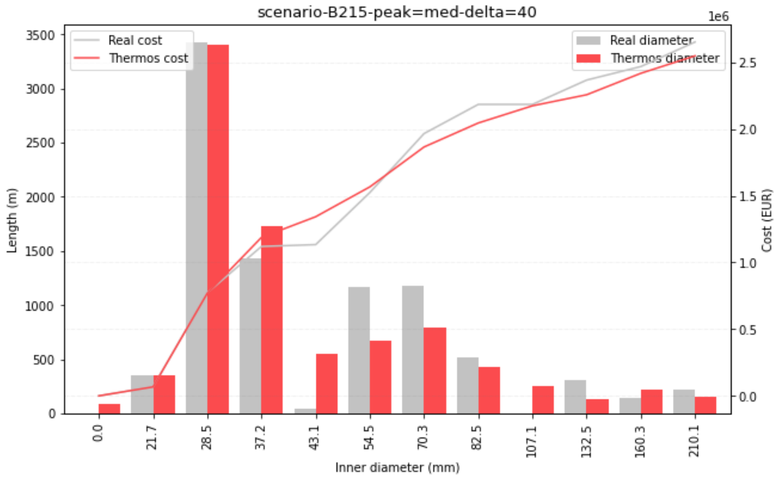
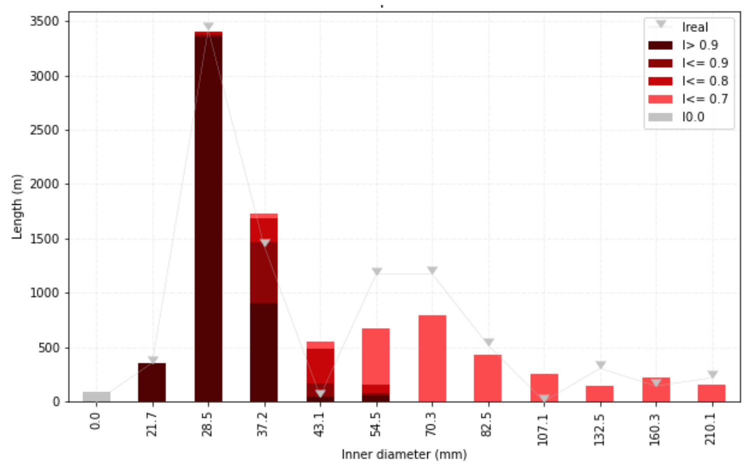
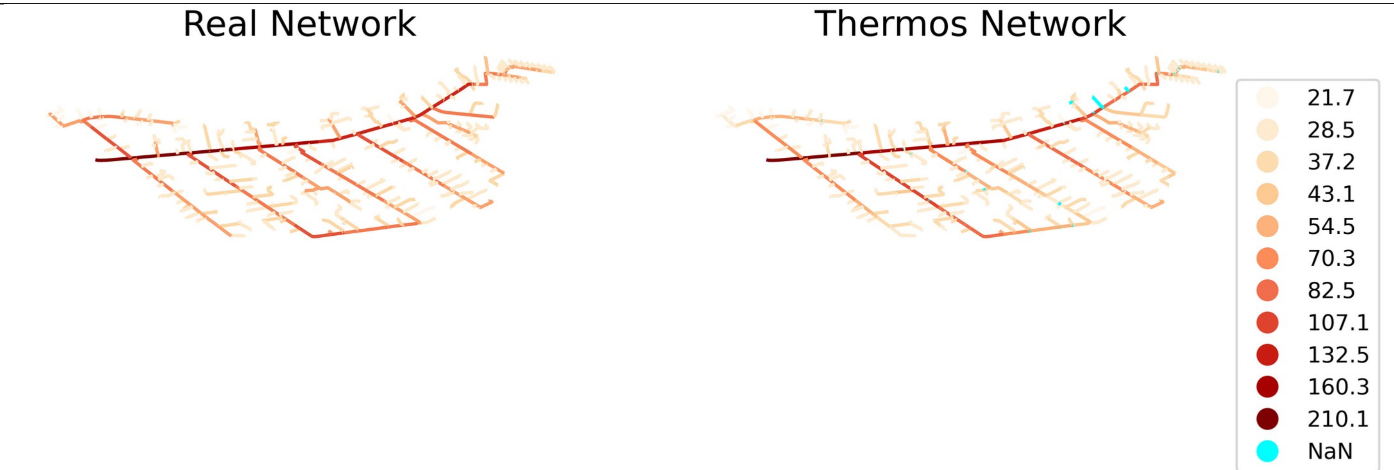
**Scenario [A139]**

| Reference scenario | Diversity disaggregation* |
|---|---|
|  |  |

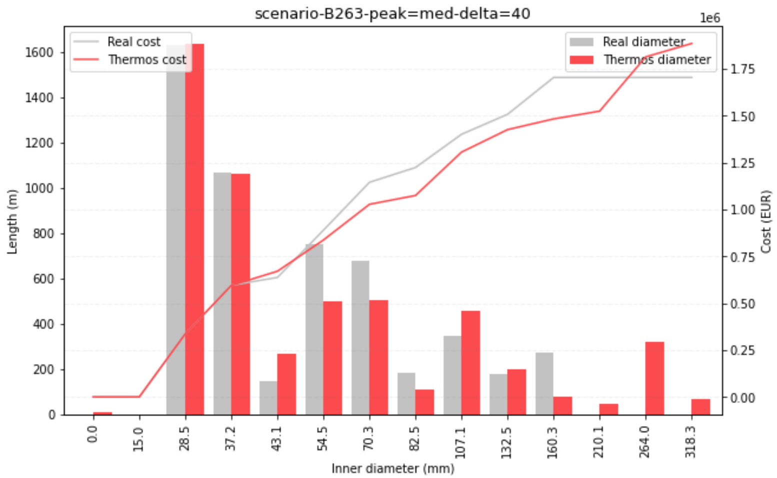
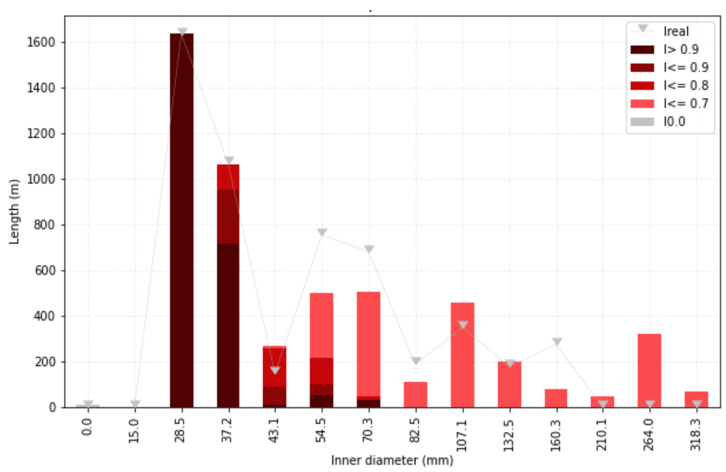
**Network comparisson***




*Uses reference scenario

| Scenario [B215] | |
|---|---|
| Reference scenario | Diversity disaggregation* |
|  |  |
| Network comparisson* | |
|  | |
| *Uses reference scenario | |

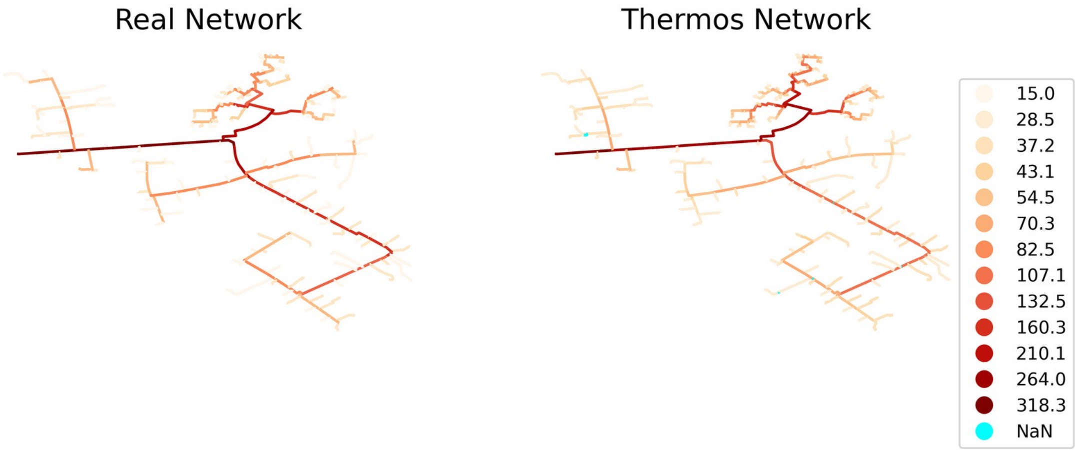
## Scenario [B263]

| Reference scenario | Diversity disaggregation* |
|---|---|
|  |  |





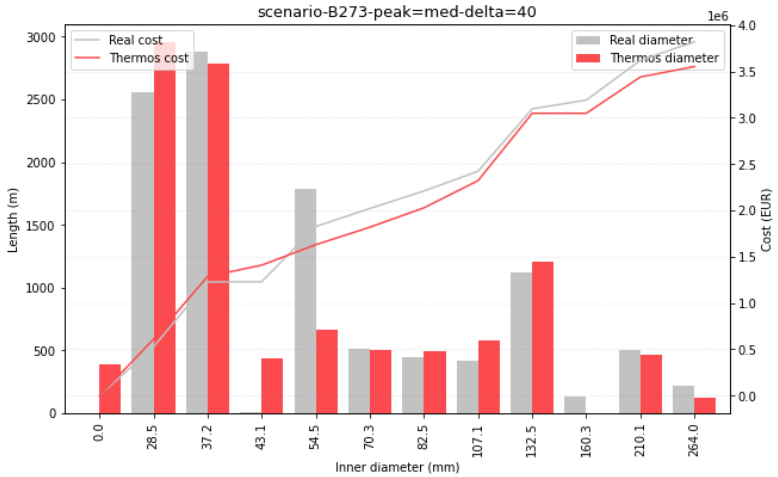
### Network comparisson*



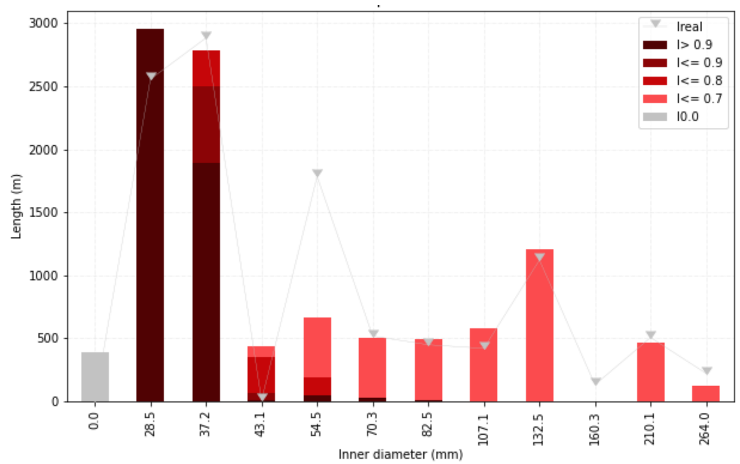

*Uses reference scenario

## Scenario [B273]

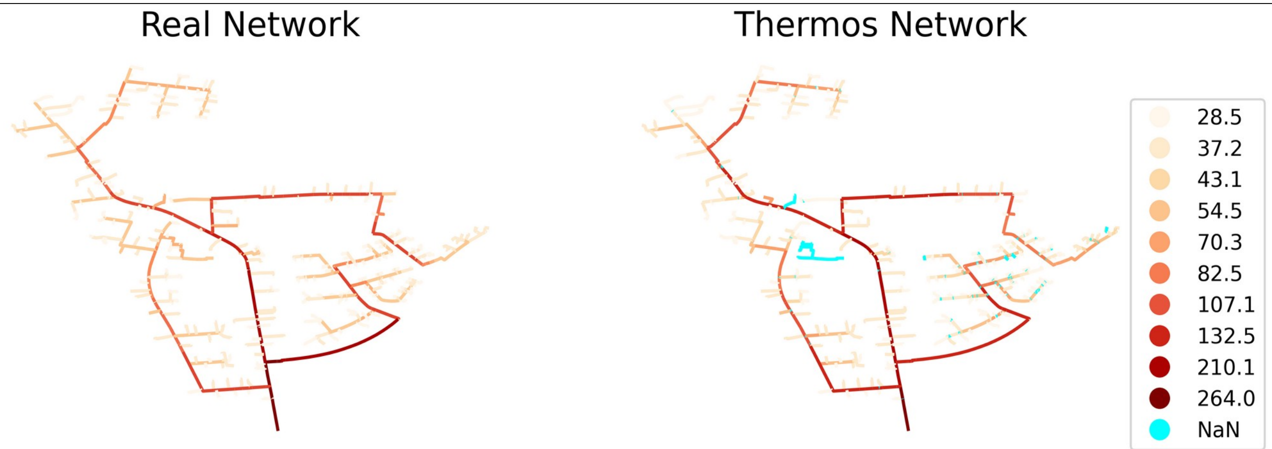
### Reference scenario



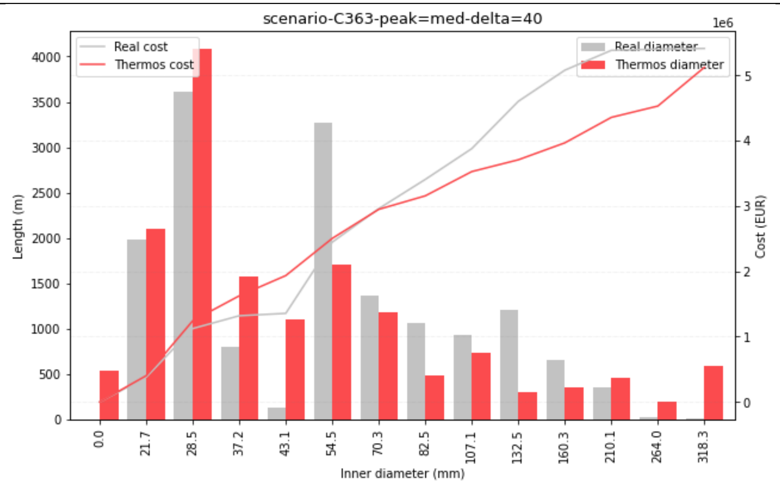
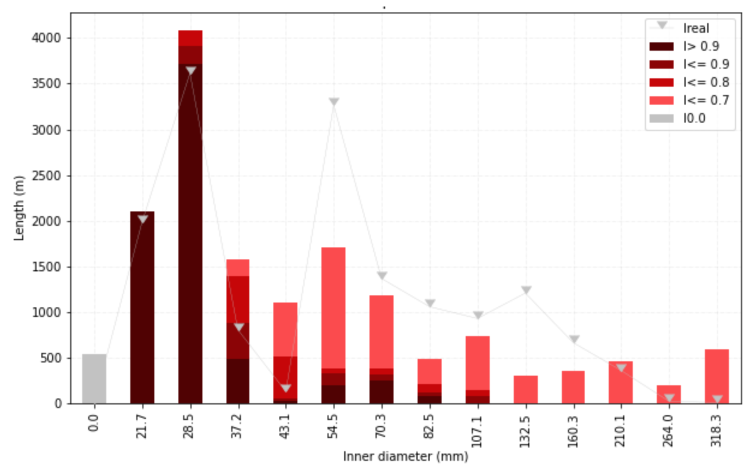
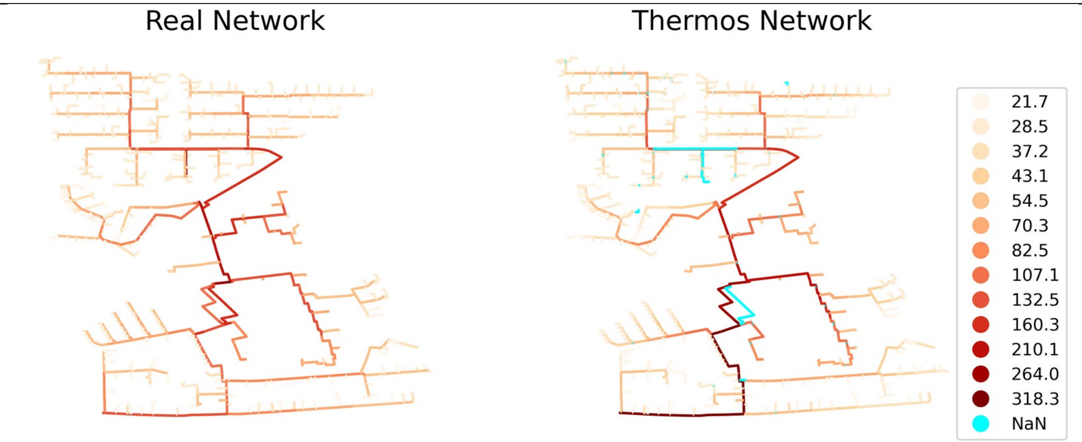

### Diversity disaggregation*

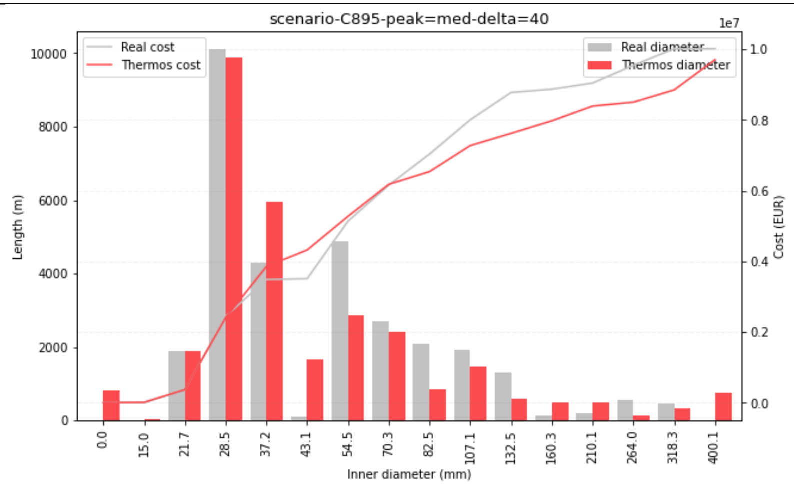
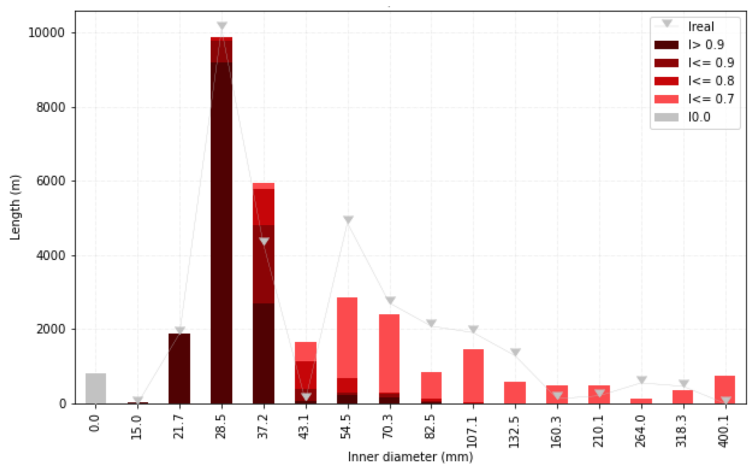
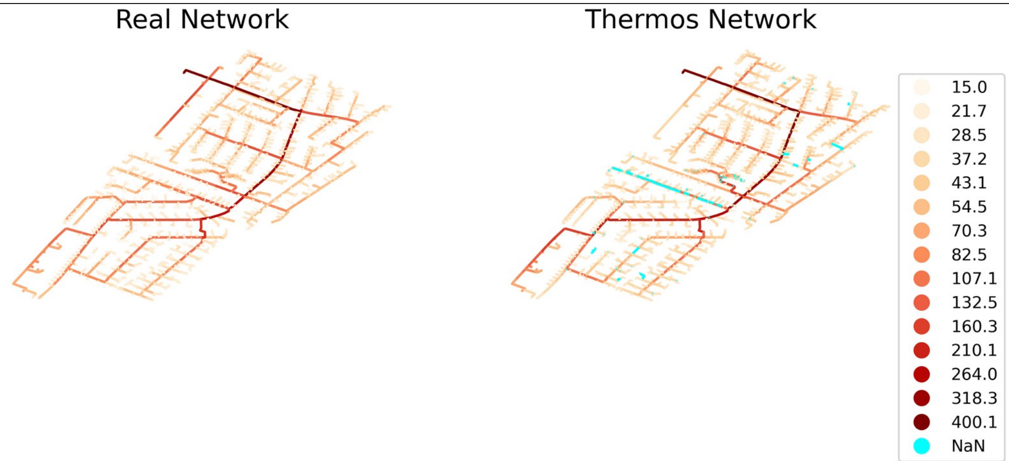



### Network comparisson*




*Uses reference scenario

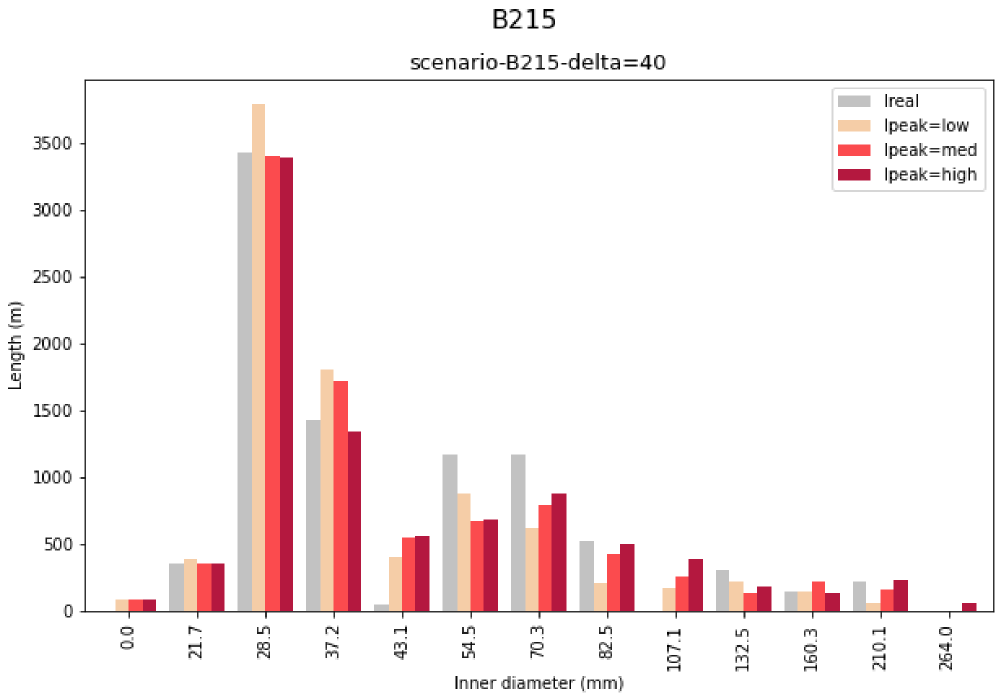
| Scenario [C363] | |
|---|---|
| **Reference scenario** | **Diversity disaggregation*** |
|  |  |
| **Network comparisson*** | |
|  | |
| *Uses reference scenario | |

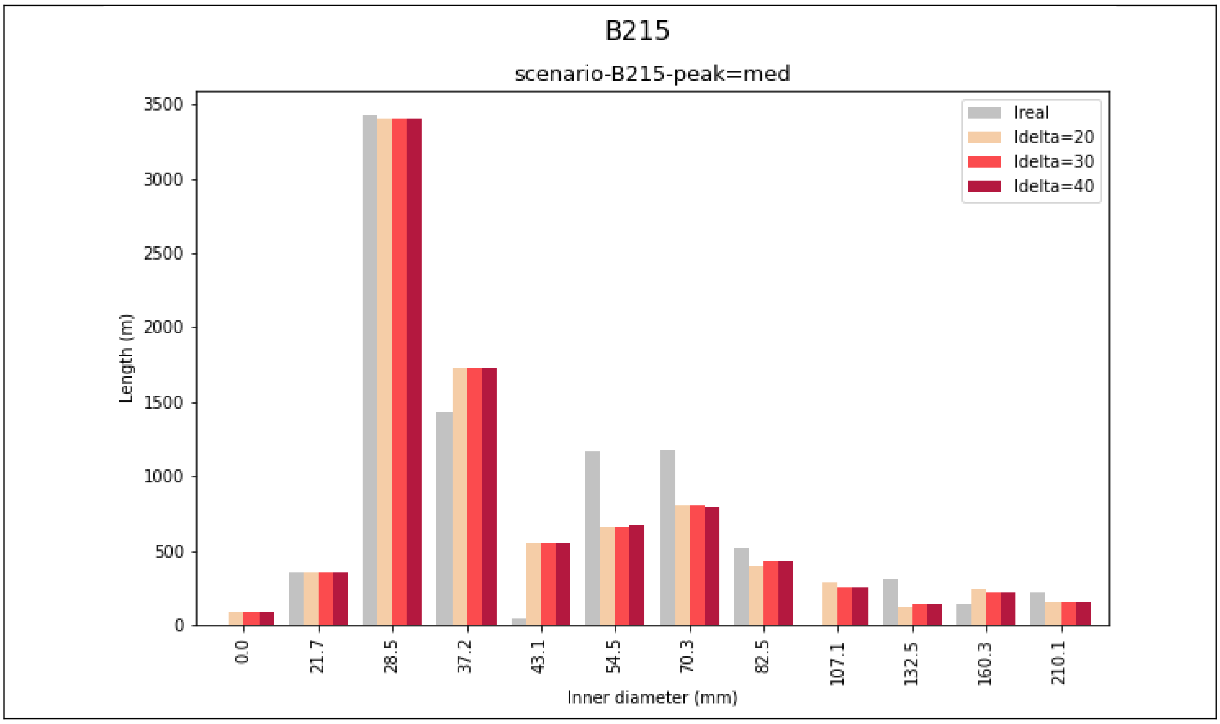
| Scenario [C895] | |
|---|---|
| **Reference scenario** | **Diversity disaggregation*** |
|  |  |
| **Network comparisson*** | |
|  | |
| *Uses reference scenario | |

### 3.2.2 Variable flow temperature and pipe capacity

This subchapter represents the sensitivity analysis made for pipe peak capacity and delta temperature, both variables used on the THERMOS tool. It is worth mentioning that both sensitivities use the reference scenario parameters. Scenario B215 is presented hereby along with its main points:

**Scenario B215:** This scenario is presented as to be the standard scenario for sensitives of both, peak capacity and delta temperature. Although the three sensitivities do not display an extreme difference amongst them, when pipe peak capacities are set to low, THERMOS allocates more length towards smaller sized diameters such as 21.7mm, 28.5mm, or 37.2mm. For larger sizes however, THERMOS seem to underestimate lengths in the network in a bigger proportion than when peak capacity is set to mid. The next two sensitivities, mid and high peak capacity seem overall less distant one to another, the tendency however is that THERMOS overestimates length in larger diameter when pipes are on high peak capacity. These differences however do become more noticeable as the networks grow in both extension and density. This is also true for the delta temperature sensitivity analysis, where overall, scenarios do not show a significant difference and their length remain fairly constant among the different delta parameters considered.

| Scenario [B215] |
|---|
| Capacity sensitivity |
|   |
| Delta temperature sensitivity |




# 4 Delimitations and uncertainties

Some delimitations are noteworthy to be pointed out as potential source of error or omission in the analysis previously mentioned. These can be summarized in the following:

Sections of network - categorized by NaN in the analysis – not included by THERMOS might have led to slight differences in total pipe length. This is explained by THERMOS routing optimization processes when connecting the network and dismissing any alternative unnecessary paths.

Additionally, uncertainties of the existing network geographical dataset used include parts of the network that might not belong to updated versions, or might belong to projected/planned network areas for future and not current heat demands.

# 5 Summary of the findings

This section summarizes that findings of both the network routing analysis and the dimensioning analysis.

**Network routing validation:**

1. In general, the THERMOS model makes good estimates for both network length and pipe sizes with an average deviation of 4% in terms of length and 7% in terms of costs. However, there are a few cases where the estimates deviate up to ~40% from the existing network.

2. The THERMOS tool does not show a tendency to under- or overestimate network lengths. However, the service pipes, between building and distribution network, is often shorter in the THERMOS model output. This is due to the fact that, the THERMOS model uses Euclidean distance to the nearest edge of the building as service pipes, whereas in the existing network the same connection might be up to 200% of the THERMOS estimation due to the inlet location on each residence. In addition, the model adds a single connector per building whereas in the existing network there might be more than a single connection.
3. The largest differences when compared to existing network are seen for smaller single street [a] rather than in large areas [c] network sized scenarios. The distinctions are more visual when the routing is visible in the maps as more road options are found by THERMOS in [c] scenarios. The noticeable difference is seen due to the allocations of piping length to smaller piping dimensioning as the scenarios grow in size. Length-wise networks have null to small difference but cost-wise the difference becomes more tangible. This new classification of piping network is also evident when each scenario is compared in the Scenario analysis section.
4. Temperature flow variations in scenarios show a more distributed tendency along the piping categorization. THERMOS tool did not output any pipes below 21mm in diameter in the majority of scenarios, whereas the existing networks include down to 11.6mm piping diameter.
5. The option to allow the THERMOS tool to deviate from the optimum solution, adds speed to the model, but also impacts the result. The impact in the examined case was around a ~ 9% higher cost with 10% allowed deviation compared to 0%. Thus, it is important that the user is aware of this influence, when using the option.

**Network dimensioning validation:**

The purpose of this analysis was to examine the pipe dimensioning aspect of the THERMOS model. Thus, the existing DH network is used for the routing, instead of a road network, to force THERMOS to use similar routes. Missing branch pipes were added to the network, giving exactly the same network length for most parts of the network. Furthermore, the existing pipe sizes, where used to estimate the kW peak for each building. The results show:

1. Using the existing DH network as routing gives very similar network routes. However, in larger networks THERMOS sometimes uses more optimal routes, leaving out parts of the network as unused. In general, the total length of the network is however very similar.
2. The total accumulated costs in the THERMOS outputs are very close to the actual network for all scenarios. Thus, it can be concluded that the THERMOS gives reasonable results for pre-feasibility studies. Following, the cost curves for different pipe dimensions, there are differences, which mainly is due to more optimal routing for, especially the larger networks.
3. The pipe sizing of THERMOS in general is quite good, with small and large areas showing the same trends. The smallest pipe diameters are very similar in real network and the THERMOS outputs. For the 37.2-54.5mm

categories, THERMOS tends to add more pipe lengths in the smaller diameters, while the real network uses the 54.5mm category more. Another trend, less predominant, where THERMOS tend to use slightly more meters of larger pipes sizes in some scenarios, which could be due to slightly more optimized routing.

Although there are differences in pipe sizing, the differences should only be something that can be expected, as THERMOS is a more simplified model and there are many uncertainties in relation to how the actual network has been designed. The actual DH network has been developed over time and cannot be expected to show the optimized network that the THERMOS model provides. On the other hand, there are also planning aspects, that the THERMOS model does not include, such as e.g. estimated future expansion possibilities, or preferences to specific pipe categories, pressure levels etc.

# 6 References

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The Swedish District Heating Association. (2013). Kulvertkostnadskatalog (The district heating pipe cost catalogue).

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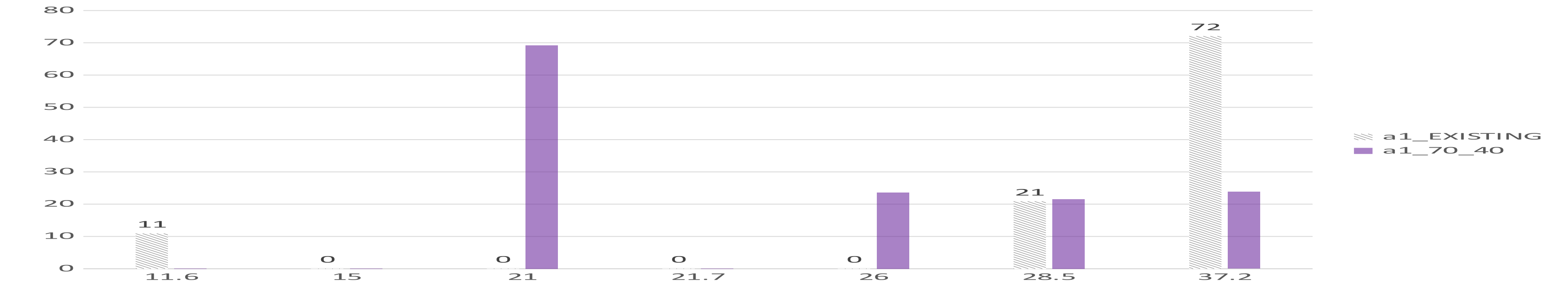
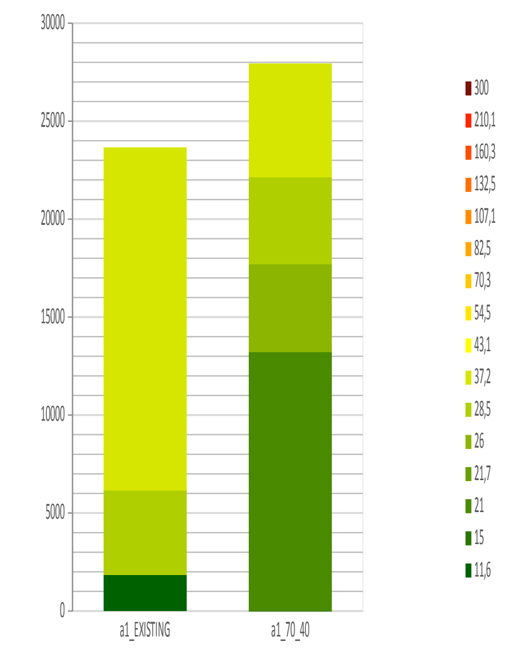
# 7 Appendix A – Sulsted scenarios

**Scenario [a1]**

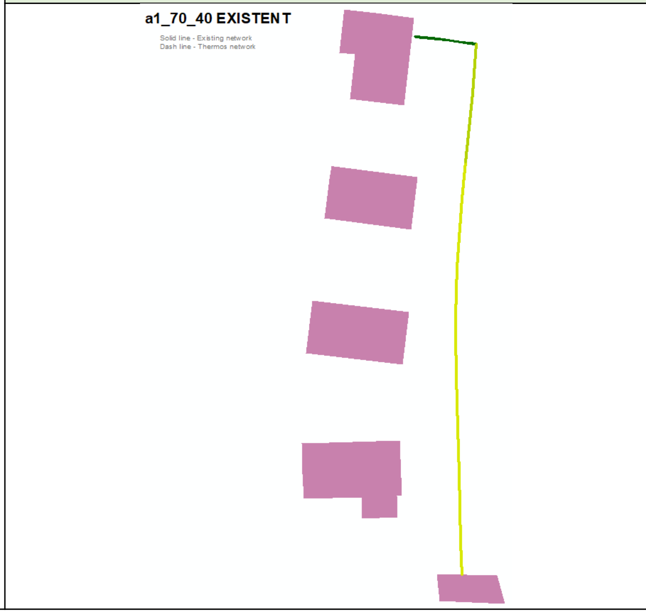
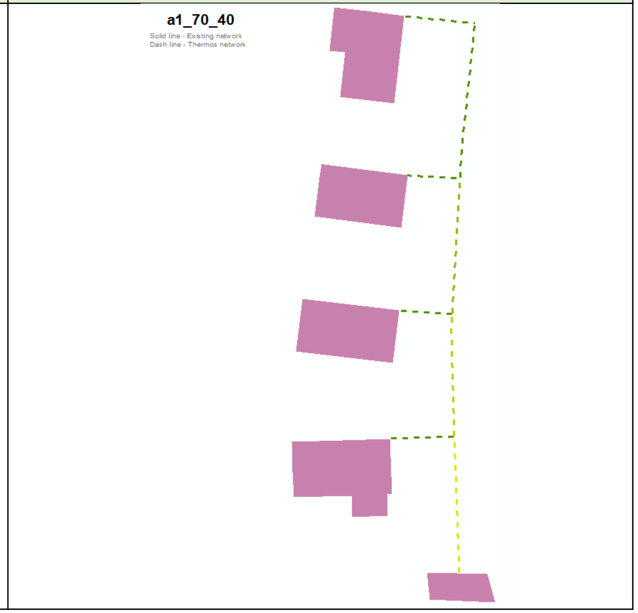
Pipe length [m] vs. Inner diameter [mm]




Total network cost [EUR] vs. Scenario

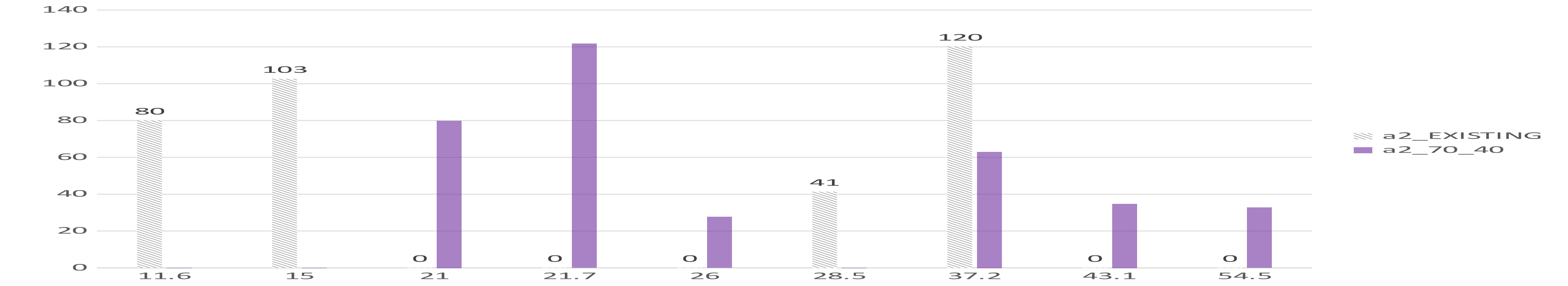



NETWORK (Solid line - Existing network, Dash line - THERMOS network)

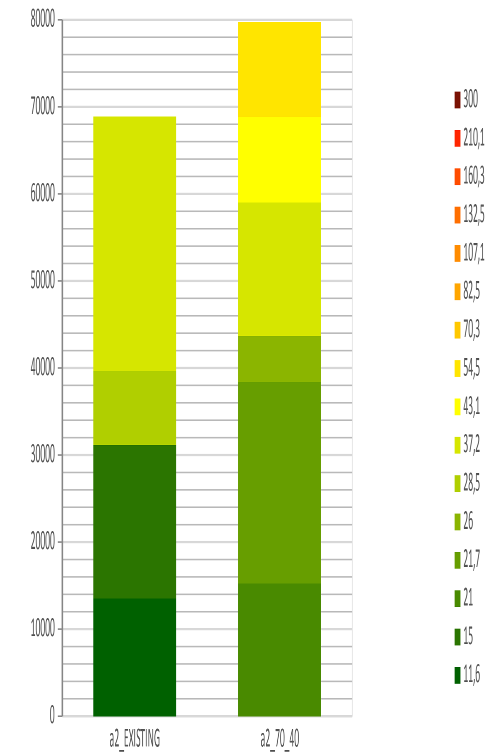
| EXISTING | THERMOS |
|---|---|
|  |  |

## Scenario [a2]

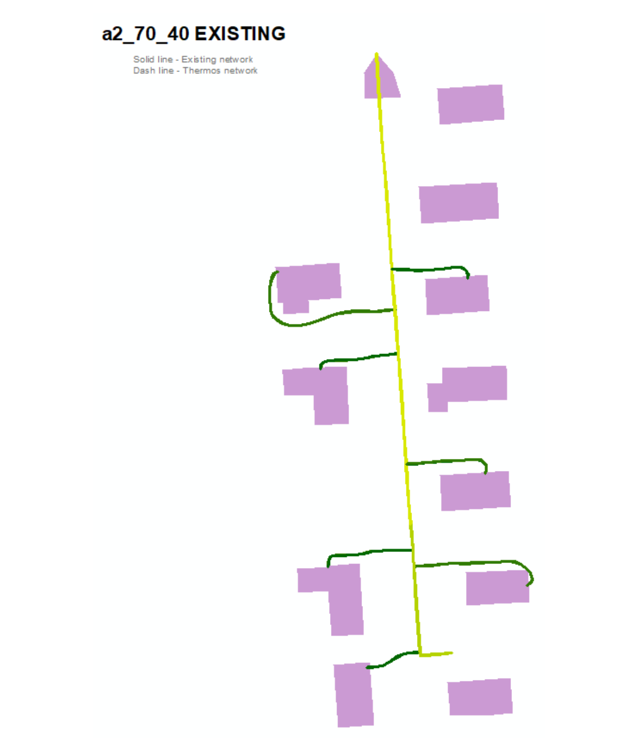
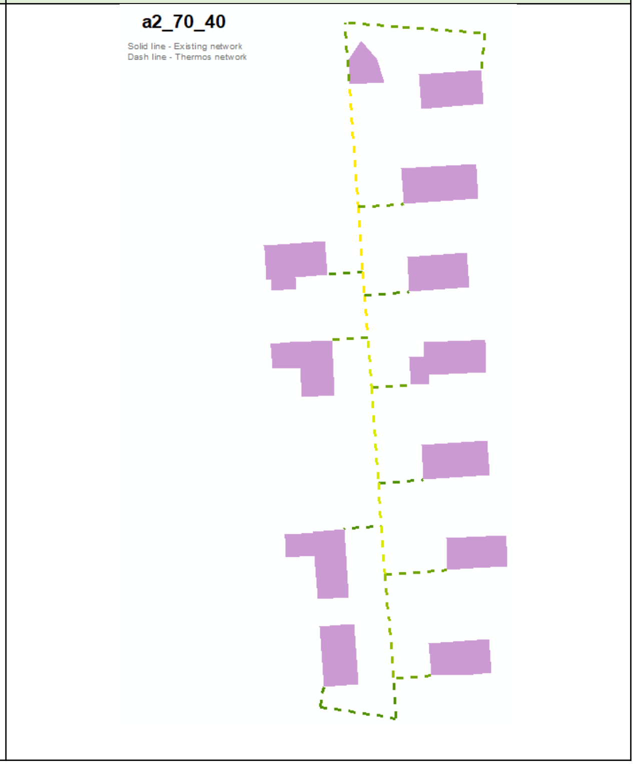
Pipe length [m] vs. Inner diameter [mm]




Total network cost [EUR] vs. Scenario




NETWORK (Solid line - Existing network, Dash line - THERMOS network)

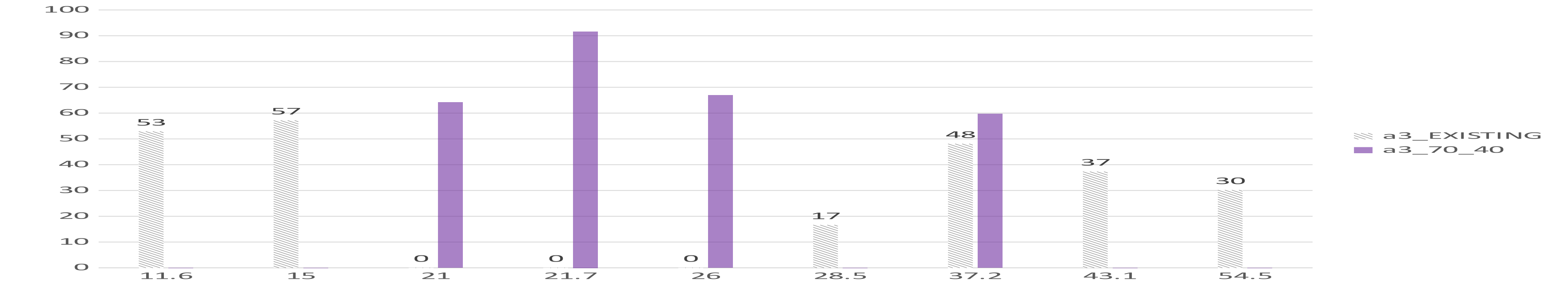
| EXISTING | THERMOS |
|---|---|
|  |  |



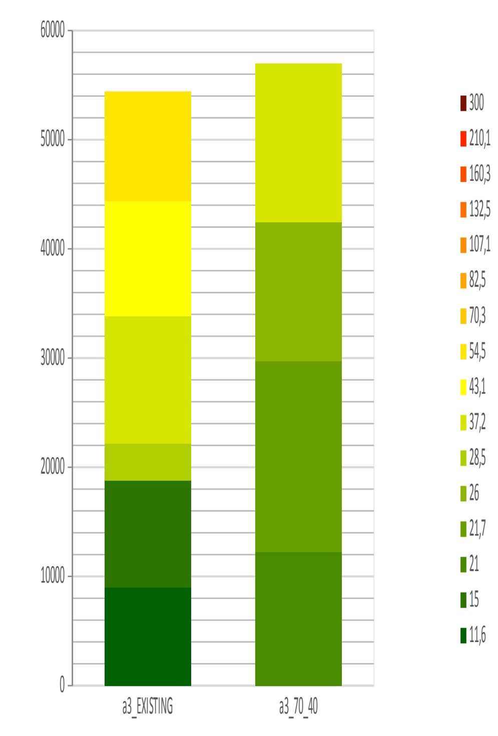


## Scenario [a3]

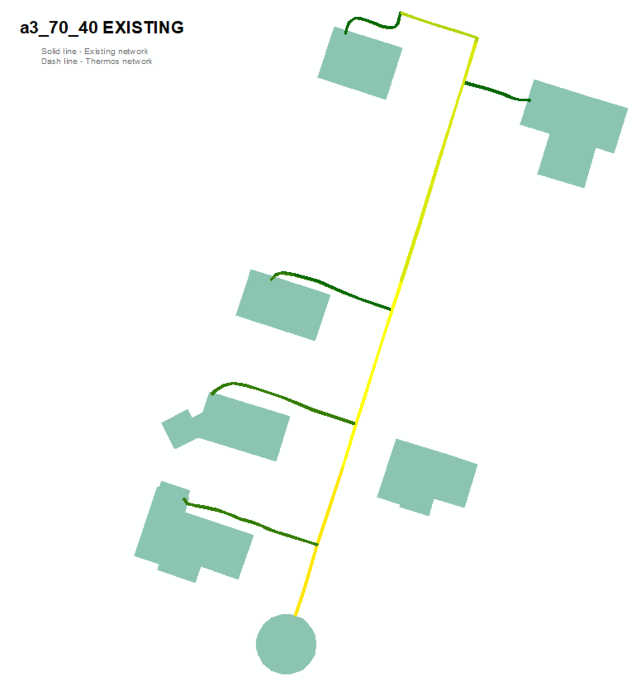
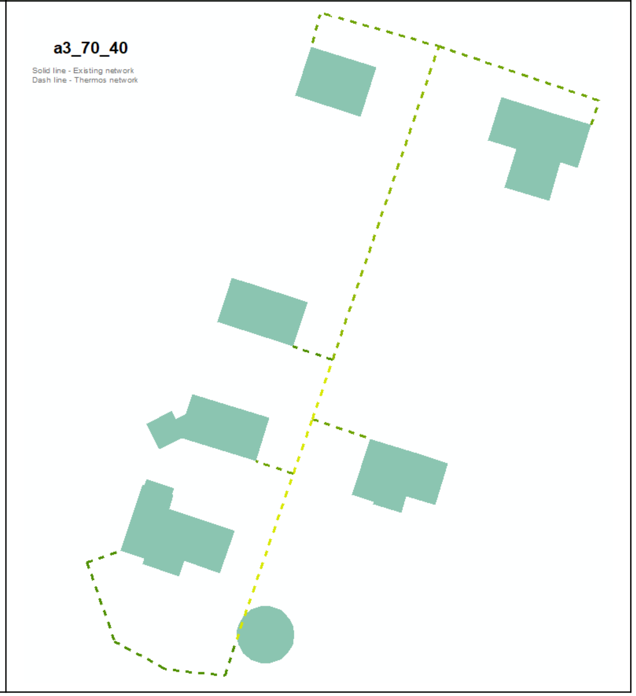
Pipe length [m] vs. Inner diameter [mm]




Total network cost [EUR] vs. Scenario




NETWORK (Solid line - Existing network, Dash line - THERMOS network)

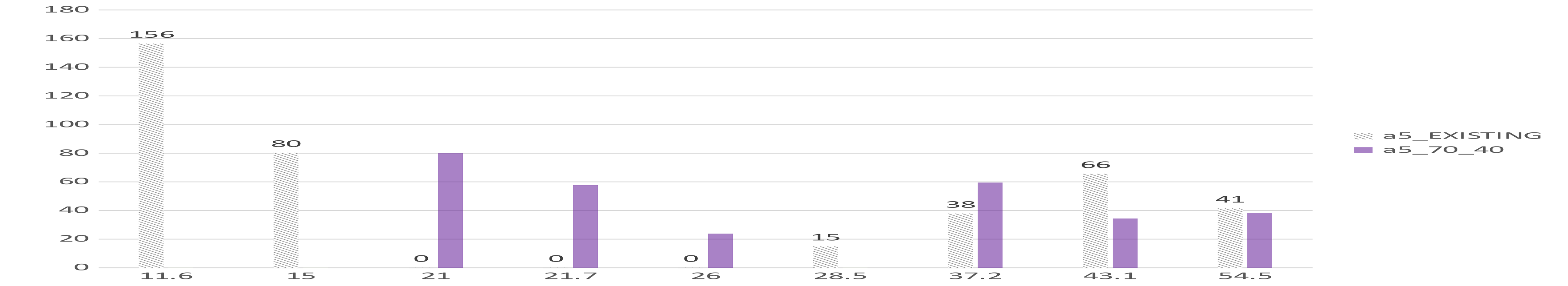
| EXISTING | THERMOS |
|---|---|
|  |  |



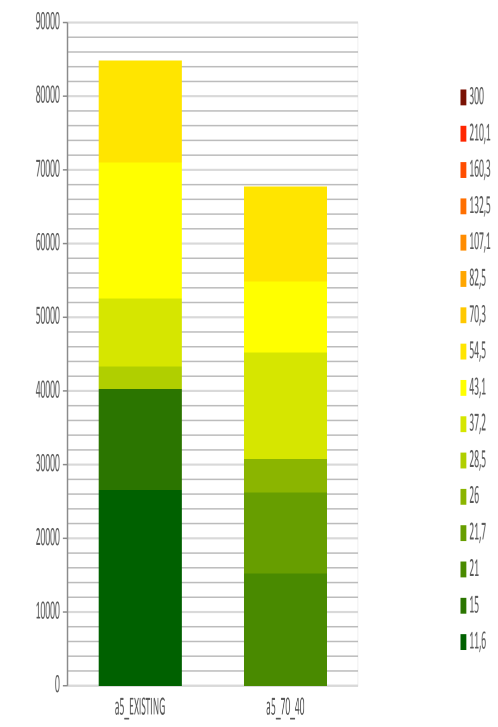


**Scenario [a5]**

Pipe length [m] vs. Inner diameter [mm]

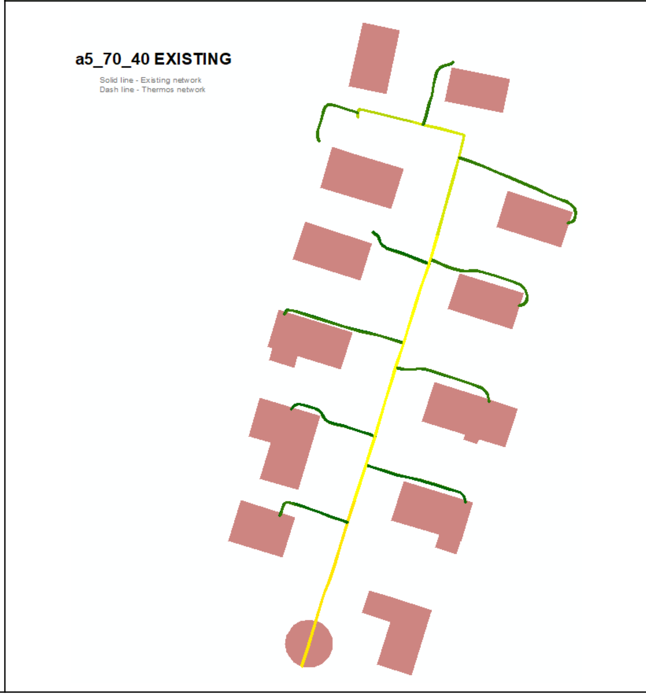



Total network cost [EUR] vs. Scenario

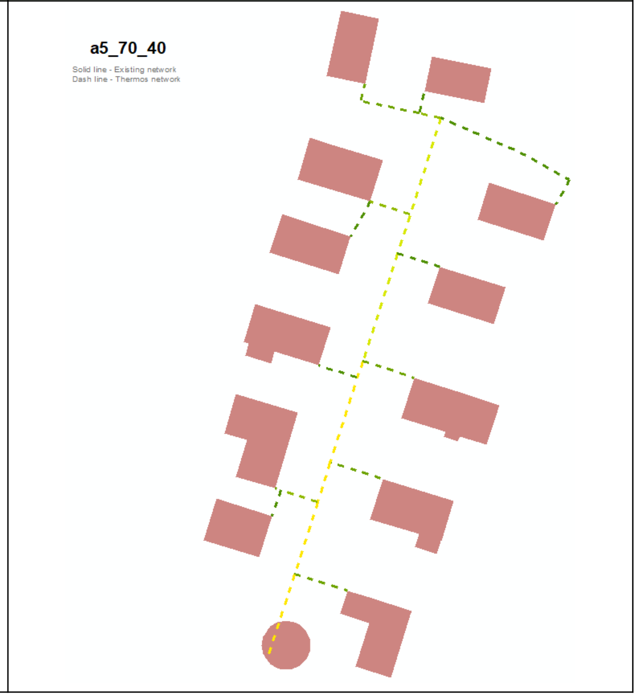



NETWORK (Solid line - Existing network, Dash line - THERMOS network)

EXISTING

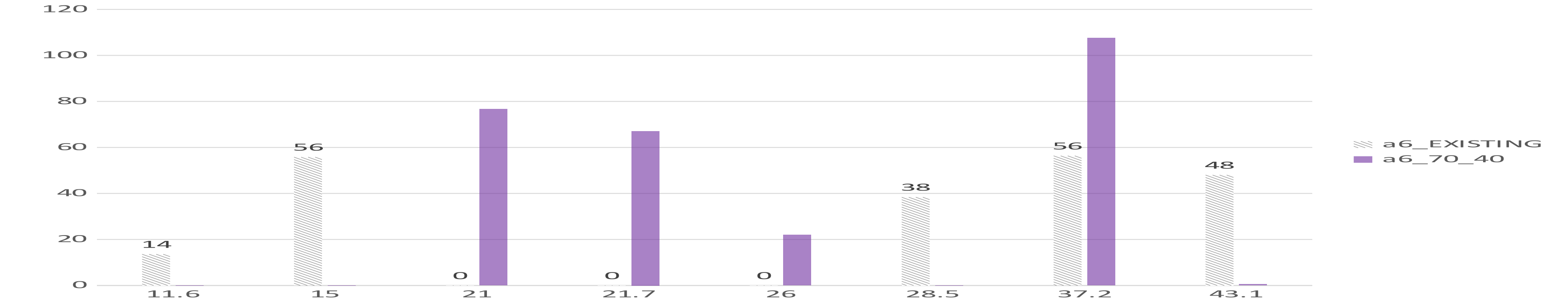



THERMOS

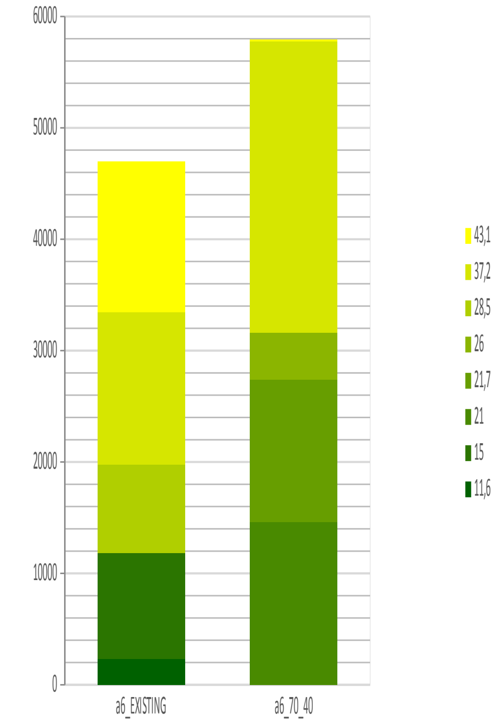



**Scenario [a6]**

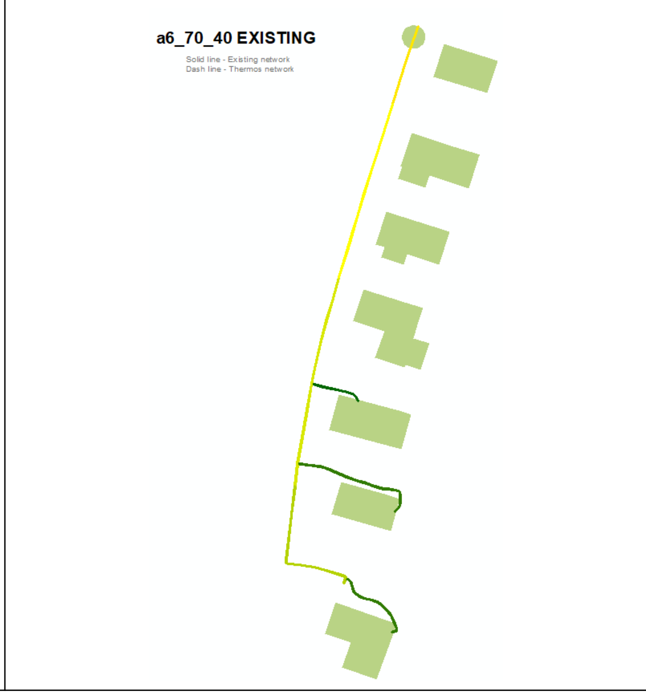
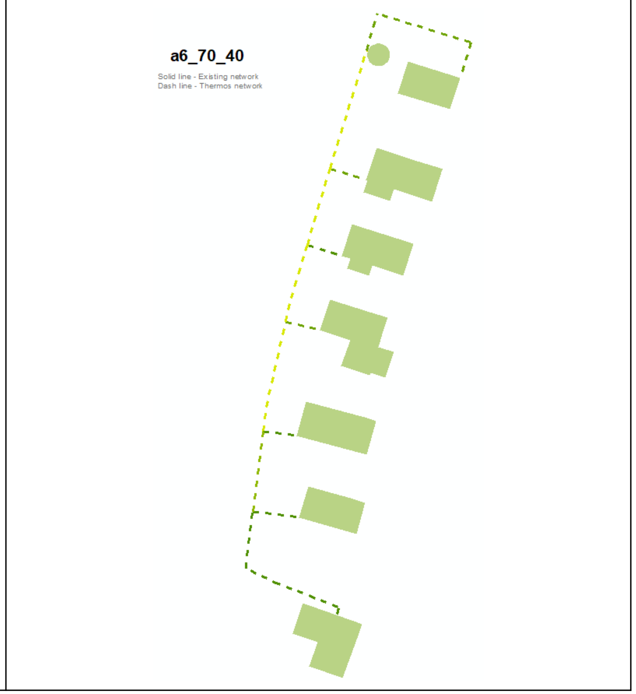
Pipe length [m] vs. Inner diameter [mm]




Total network cost [EUR] vs. Scenario




NETWORK (Solid line - Existing network, Dash line - THERMOS network)

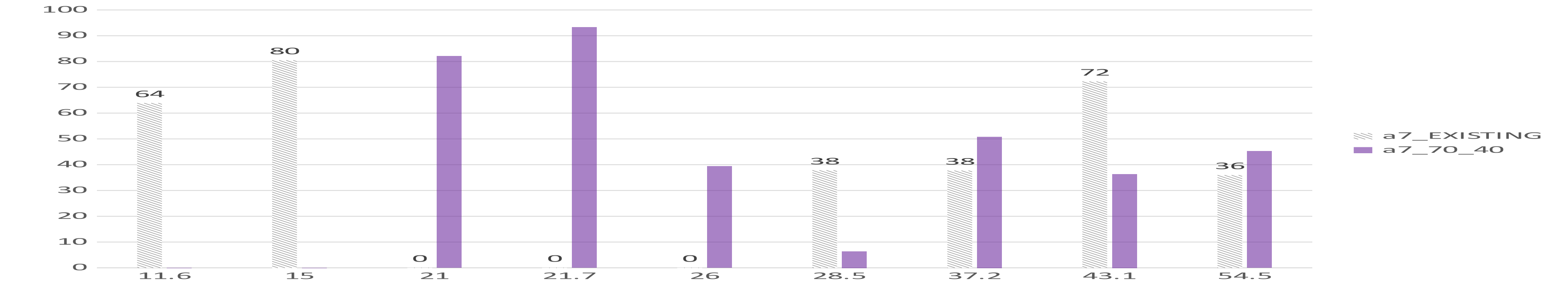
| EXISTING | THERMOS |
|---|---|
|  |  |



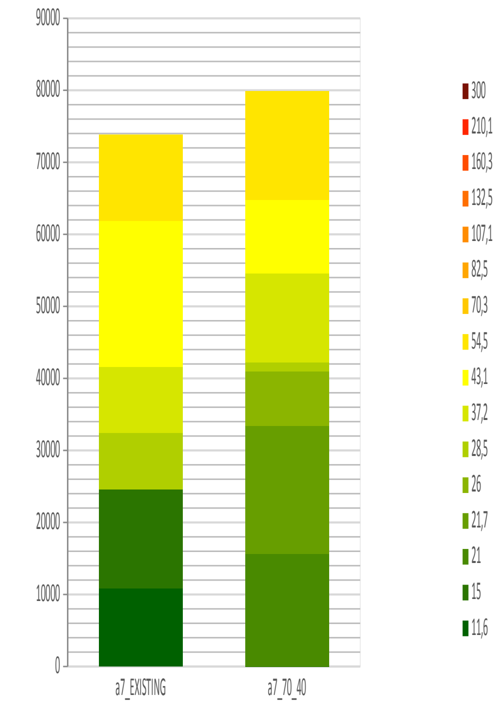


**Scenario [a7]**

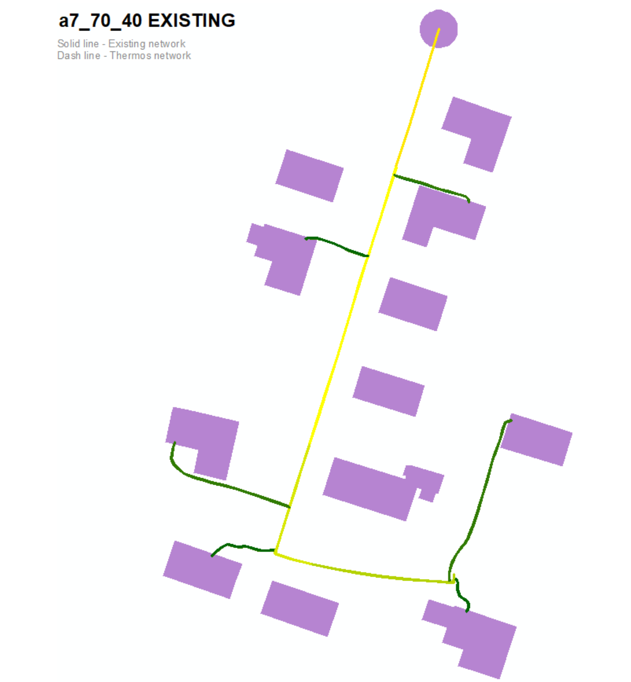
Pipe length [m] vs. Inner diameter [mm]




Total network cost [EUR] vs. Scenario




NETWORK (Solid line - Existing network, Dash line - THERMOS network)

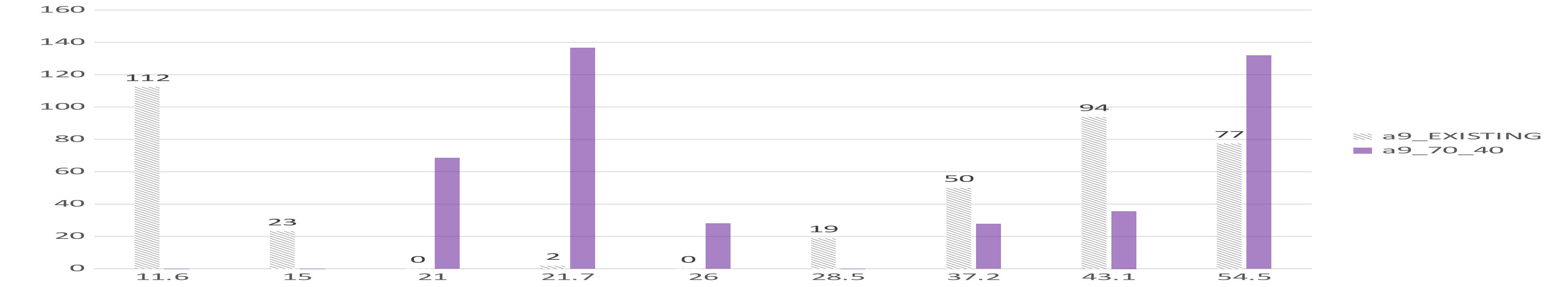
| EXISTING | THERMOS |
|---|---|
|  |  |



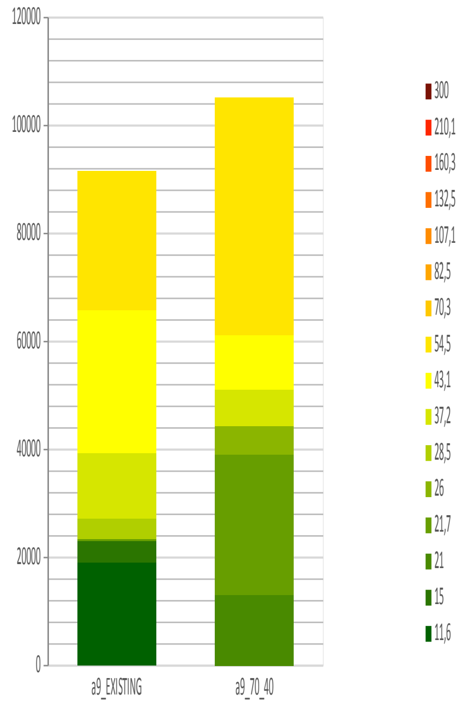


**Scenario [a9]**

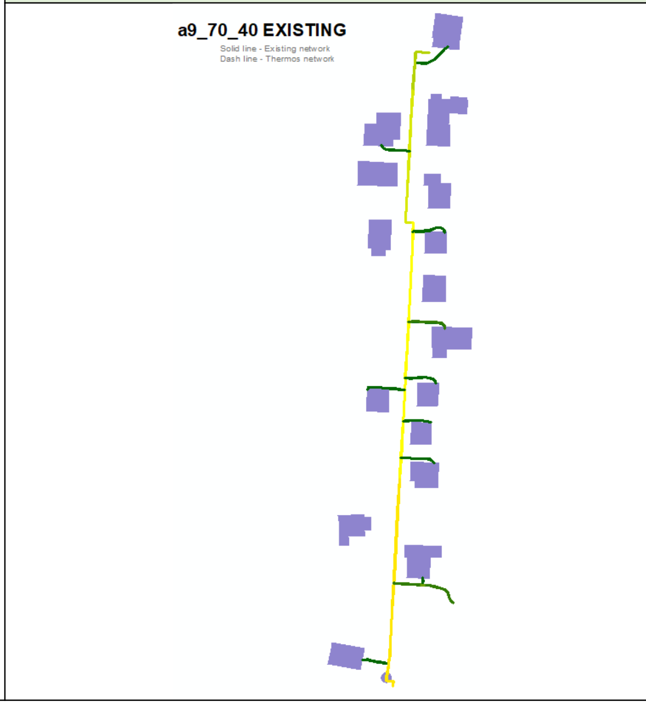
Pipe length [m] vs. Inner diameter [mm]




Total network cost [EUR] vs. Scenario




NETWORK (Solid line - Existing network, Dash line - THERMOS network)

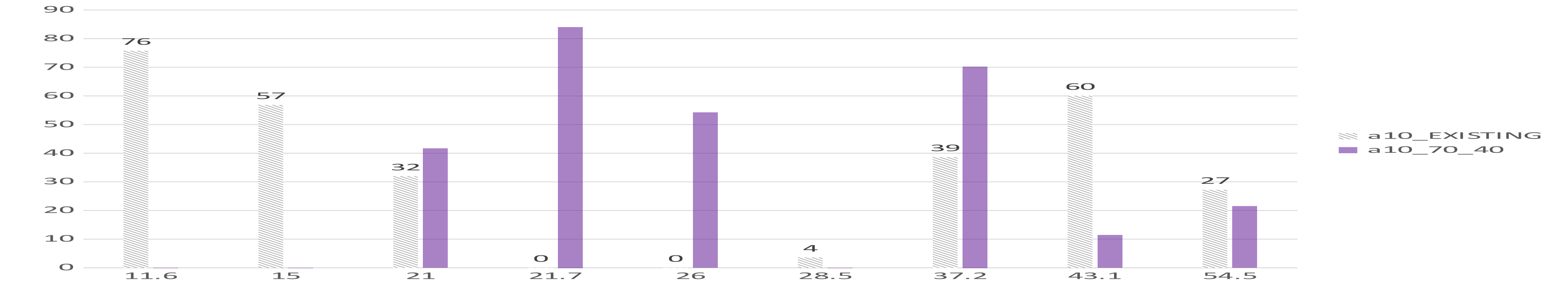
| EXISTING | THERMOS |
|---|---|
|  |  |



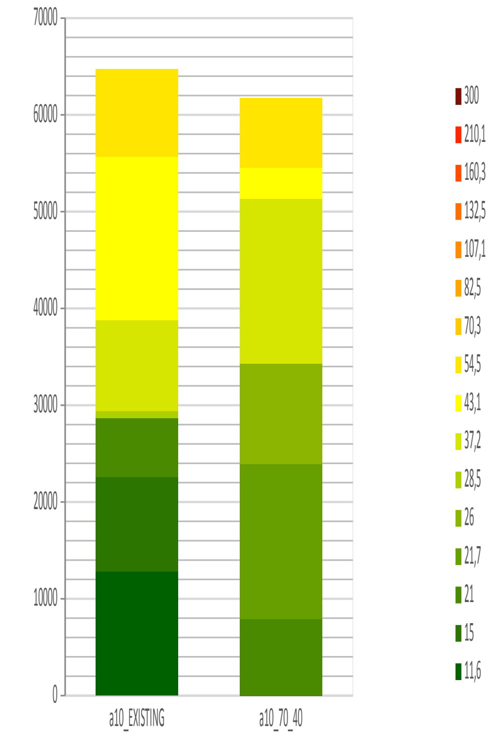


**Scenario [a10]**

Pipe length [m] vs. Inner diameter [mm]

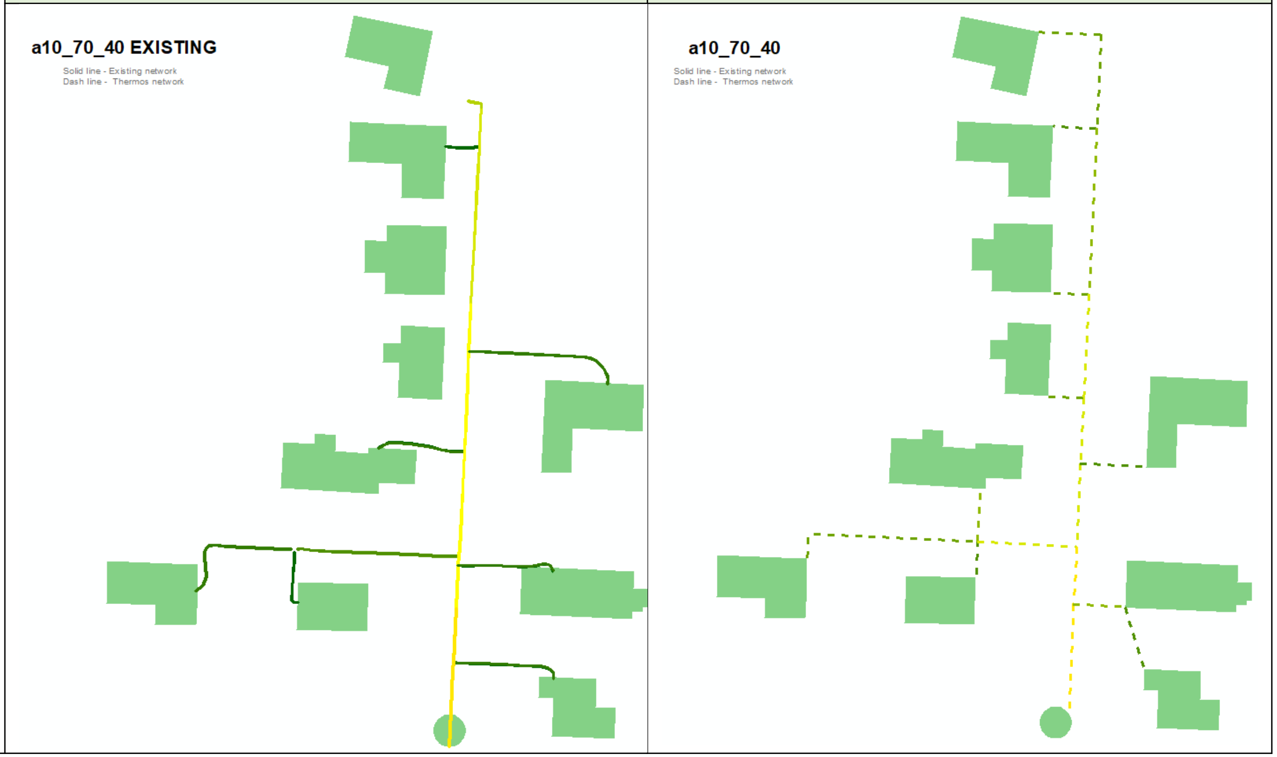



Total network cost [EUR] vs. Scenario



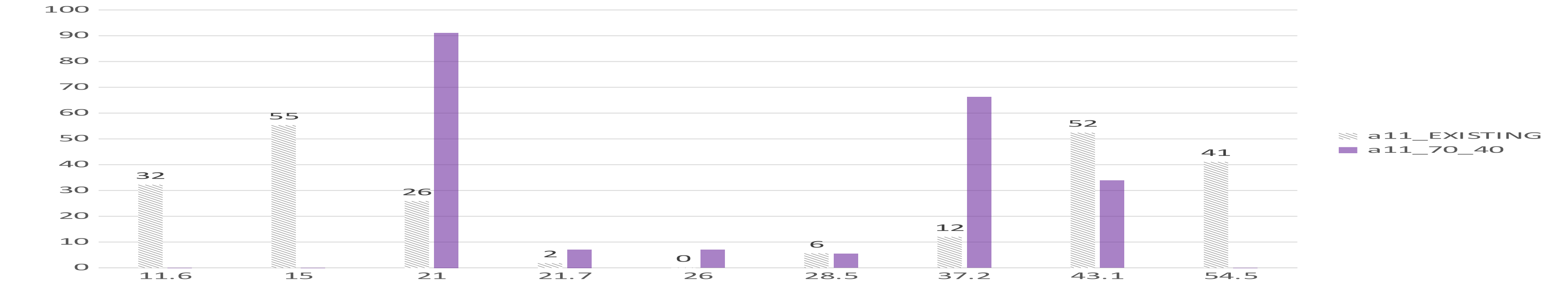

NETWORK (Solid line - Existing network, Dash line - THERMOS network)

| EXISTING | THERMOS |
|---|---|

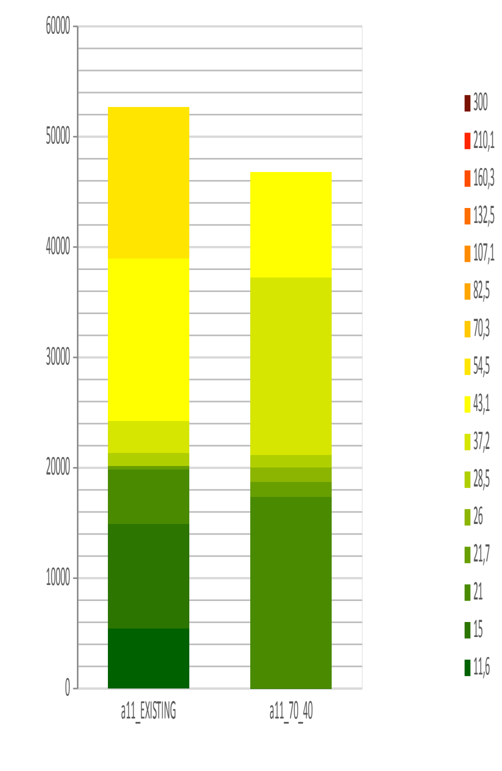



**Scenario [a11]**

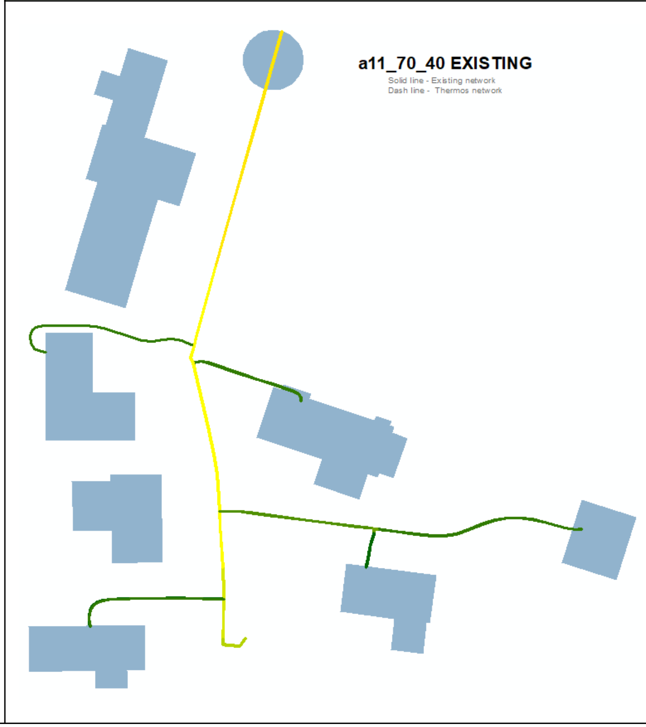
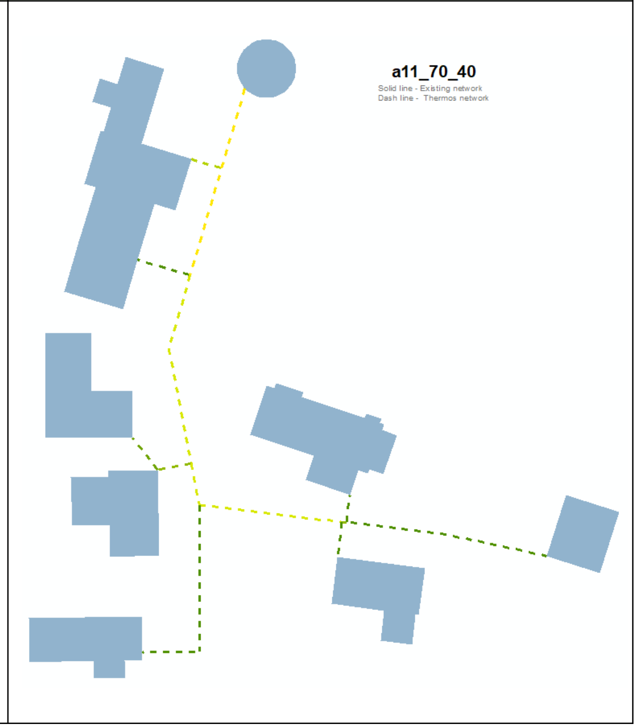
Pipe length [m] vs. Inner diameter [mm]




Total network cost [EUR] vs. Scenario




NETWORK (Solid line - Existing network, Dash line - THERMOS network)

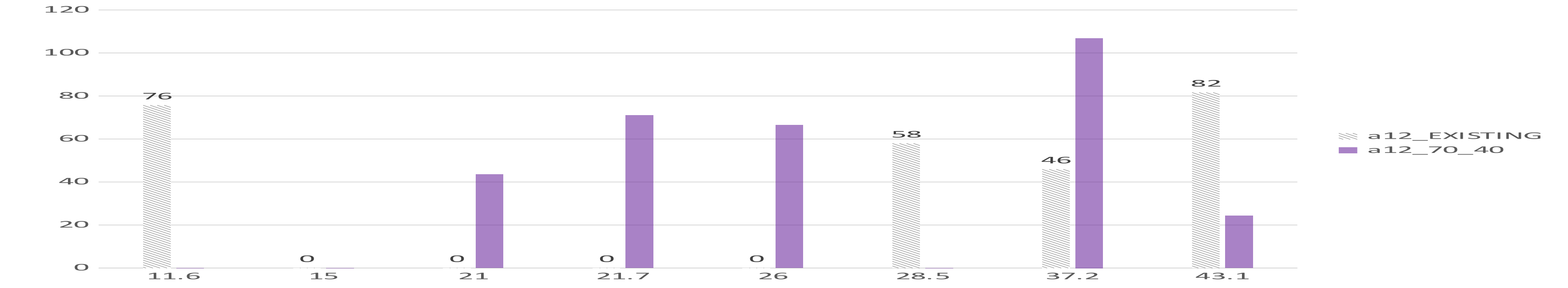
| EXISTING | THERMOS |
|---|---|
|  |  |



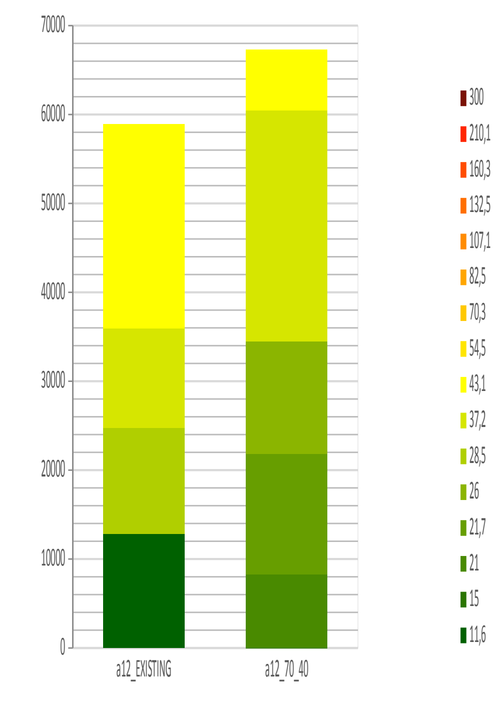


**Scenario [a12]**

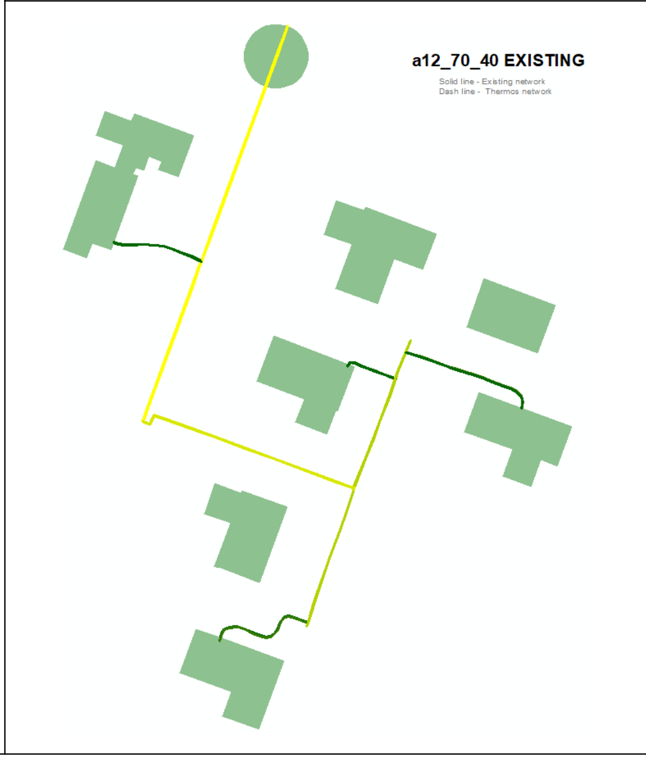
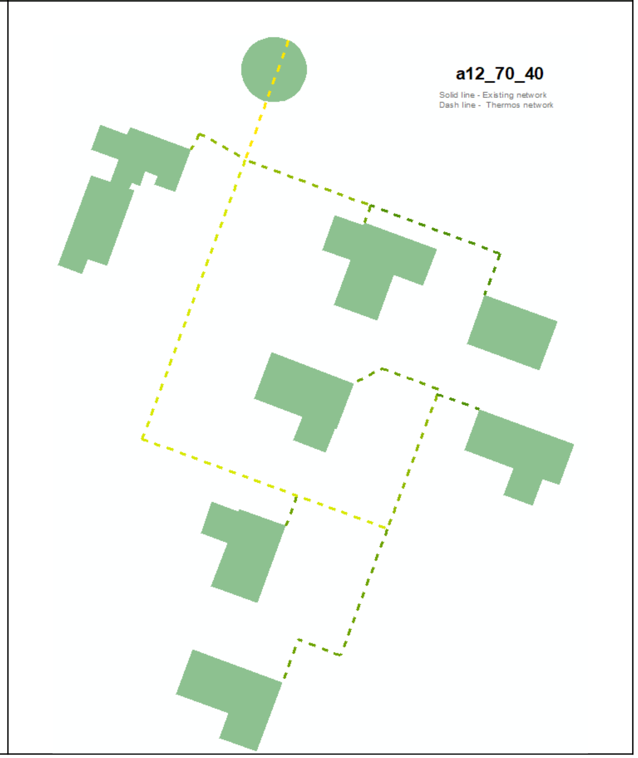
Pipe length [m] vs. Inner diameter [mm]




Total network cost [EUR] vs. Scenario



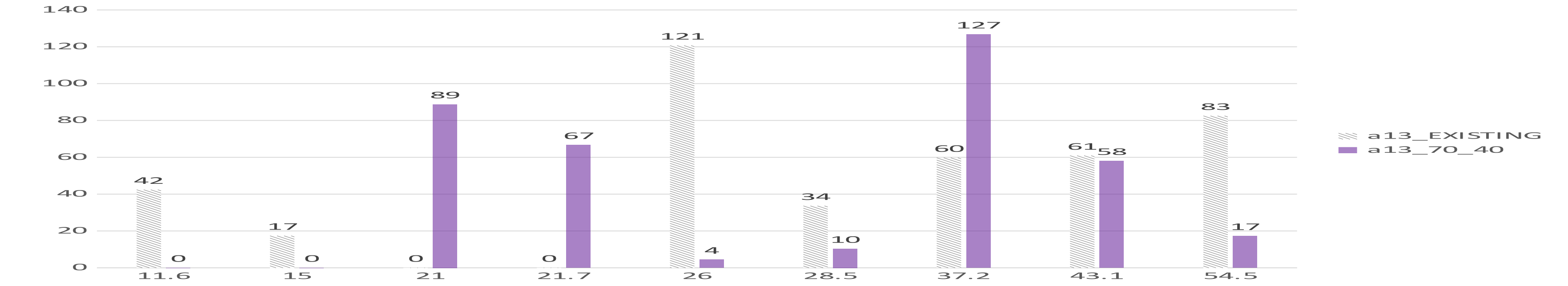

NETWORK (Solid line - Existing network, Dash line - THERMOS network)

| EXISTING | THERMOS |
| --- | --- |
|  |  |

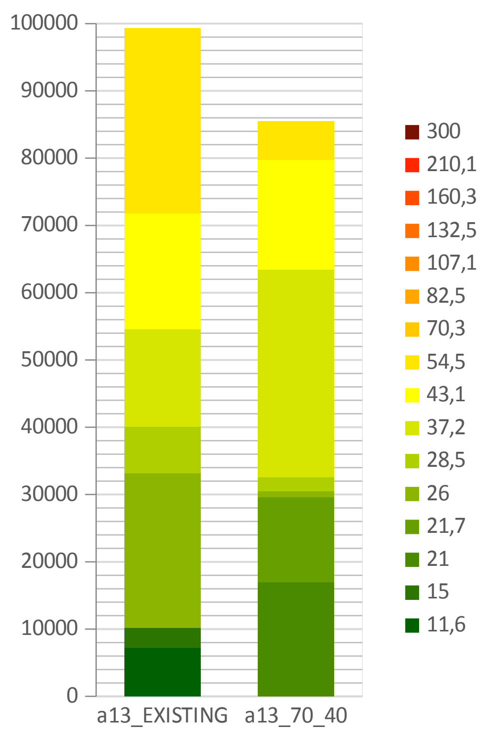



**Scenario [a13]**

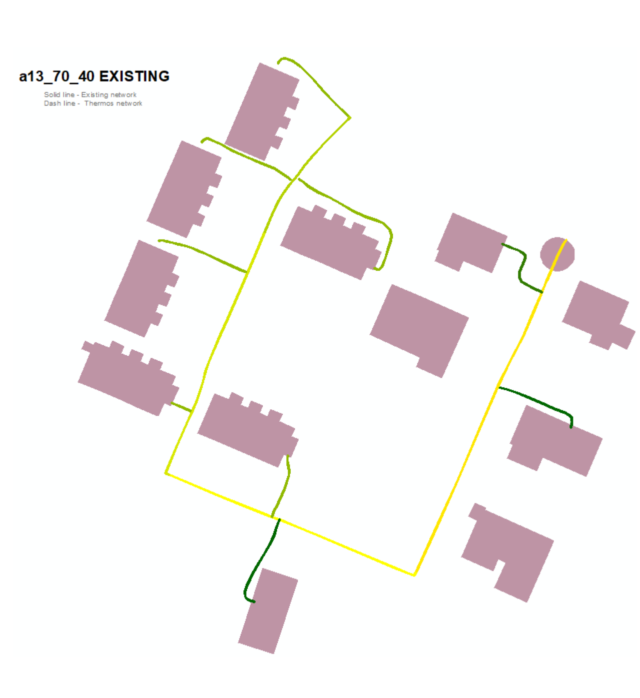
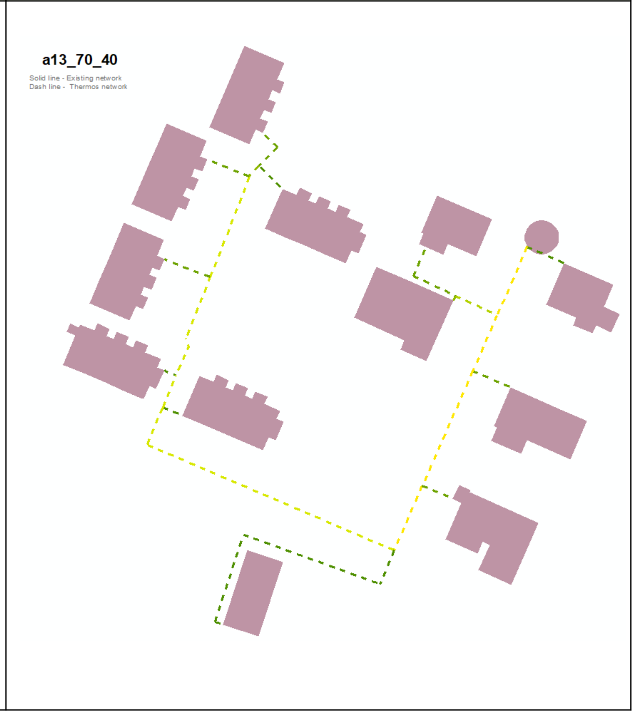
Pipe length [m] vs. Inner diameter [mm]




Total network cost [EUR] vs. Scenario




NETWORK (Solid line - Existing network, Dash line - THERMOS network)

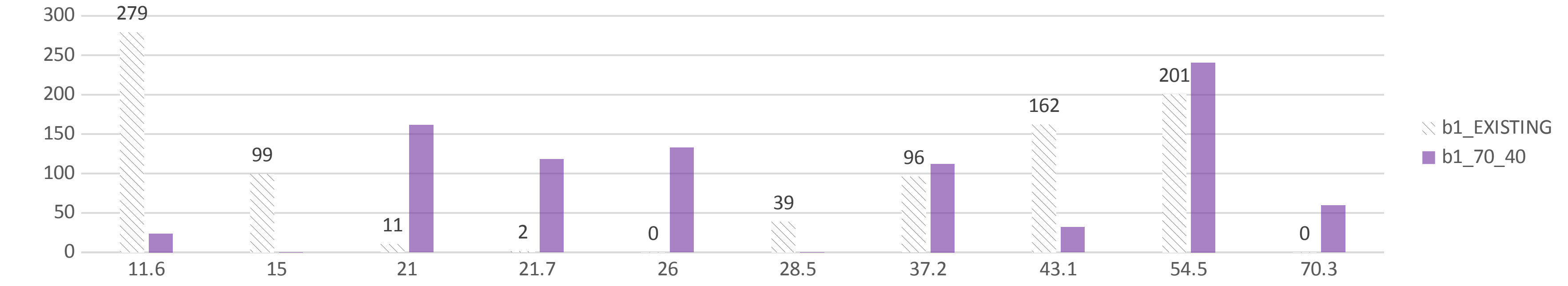
| EXISTING | THERMOS |
|---|---|
|  |  |



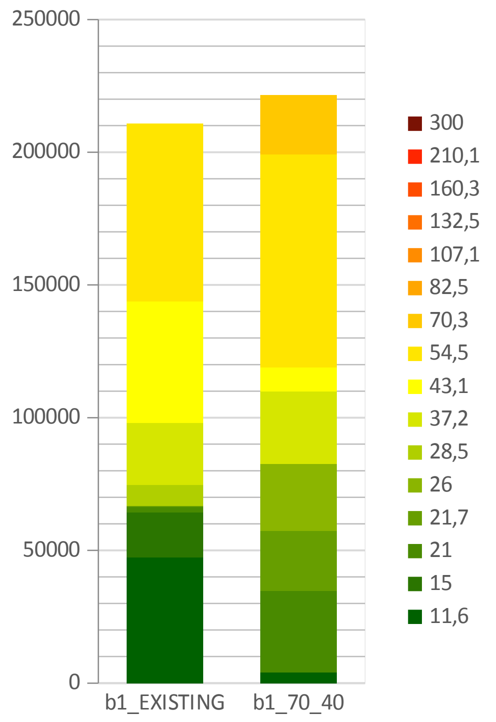


**Scenario [b1]**

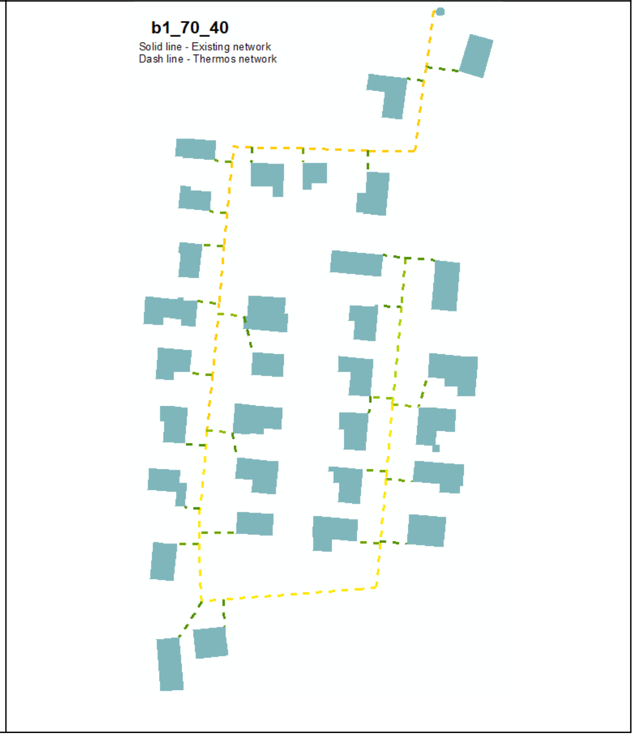
Pipe length [m] vs. Inner diameter [mm]




Total network cost [EUR] vs. Scenario




NETWORK (Solid line - Existing network, Dash line - THERMOS network)

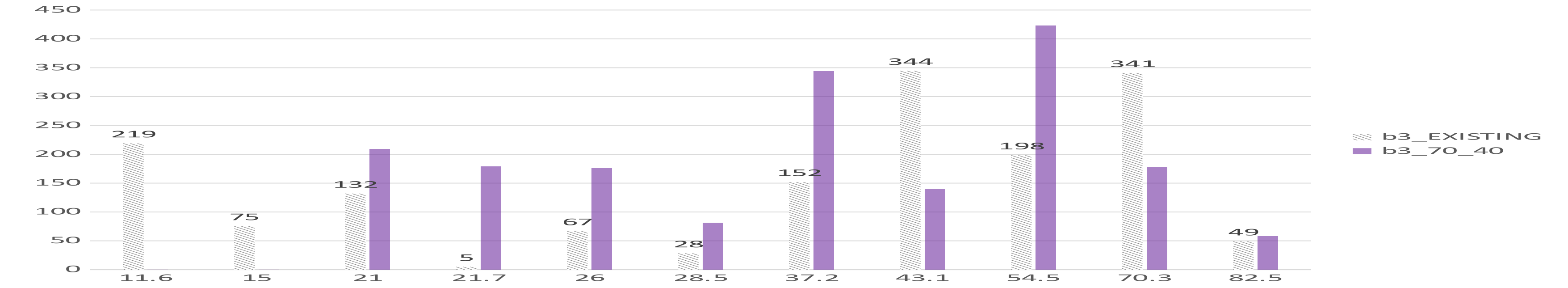
| EXISTING | THERMOS |
| --- | --- |
|  |  |



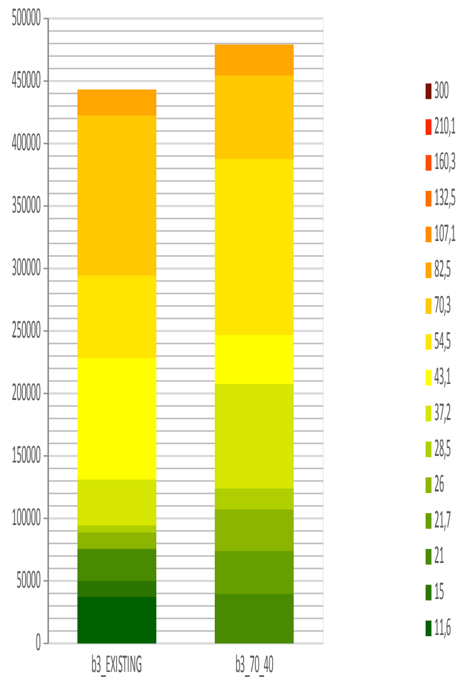


**Scenario [b3]**

Pipe length [m] vs. Inner diameter [mm]




Total network cost [EUR] vs. Scenario




NETWORK (Solid line - Existing network, Dash line - THERMOS network)

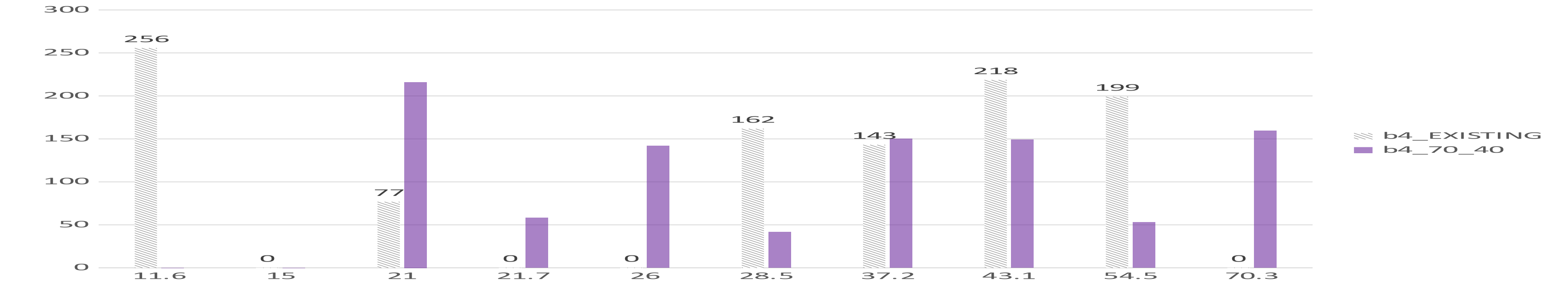
| EXISTING | THERMOS |
|---|---|
|  |  |



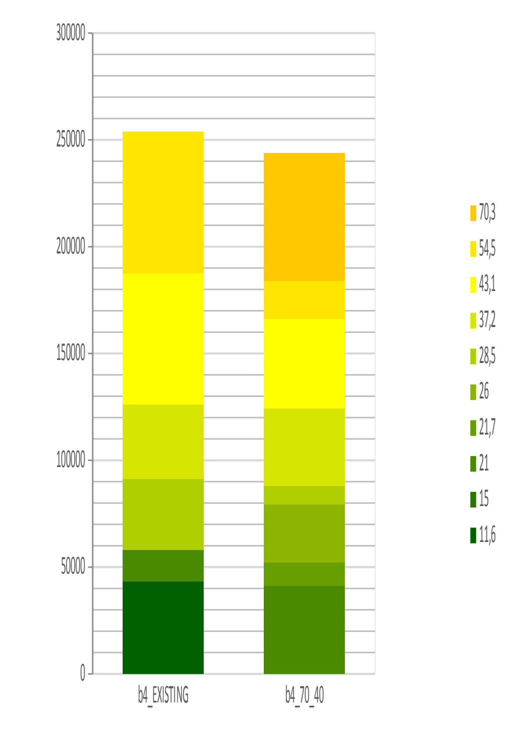


**Scenario [b4]**

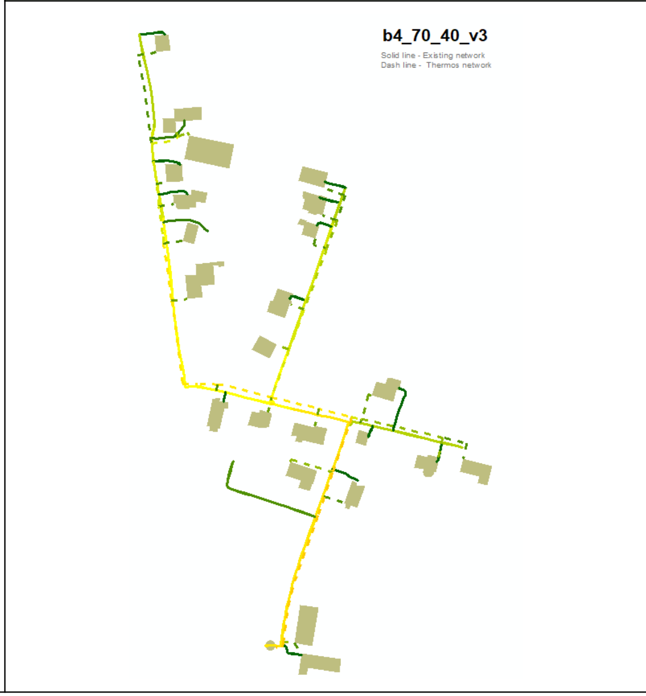
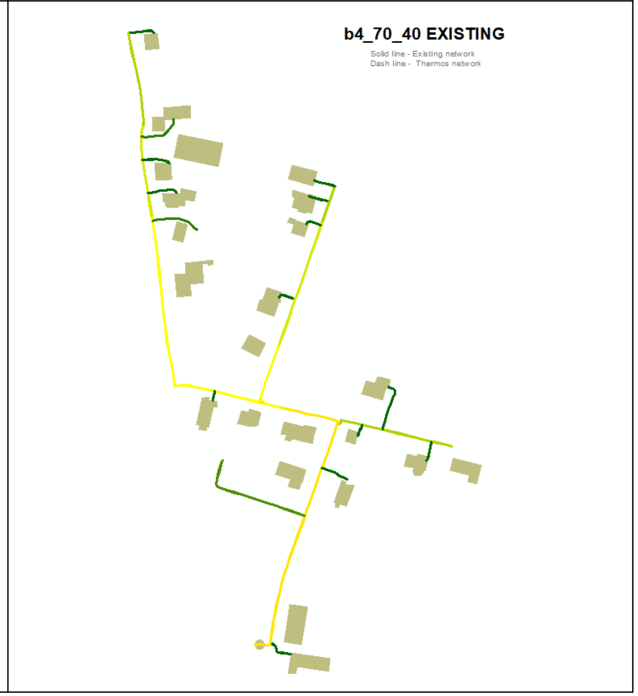
Pipe length [m] vs. Inner diameter [mm]




Total network cost [EUR] vs. Scenario




NETWORK (Solid line - Existing network, Dash line - THERMOS network)

| EXISTING | THERMOS |
|---|---|
|  |  |

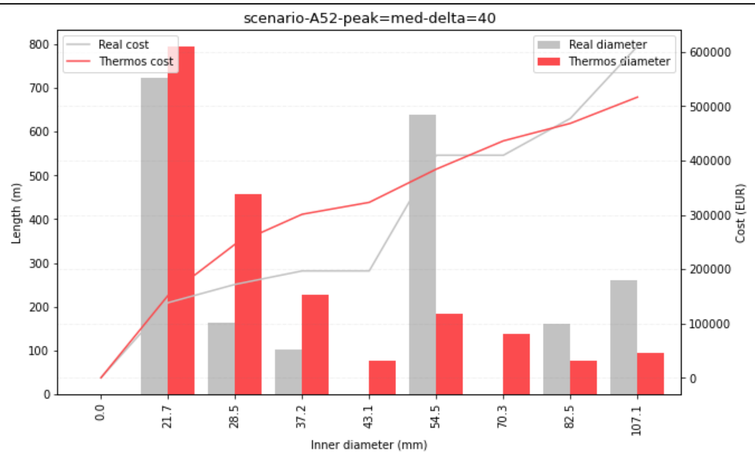




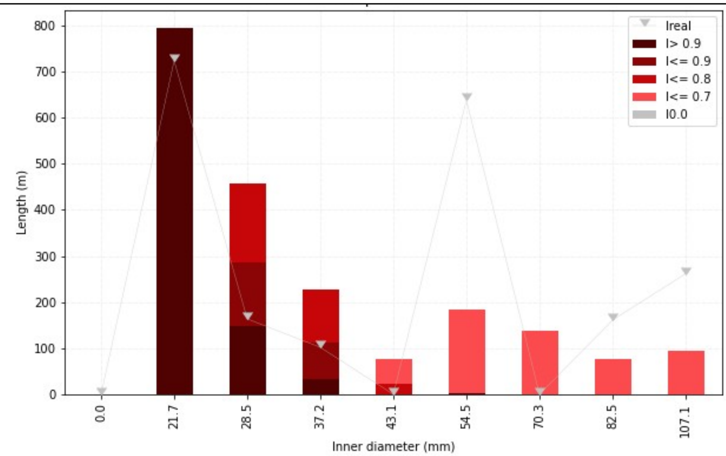
# 8 Appendix B – Aarhus scenarios

| Scenario [A52] |
|---|

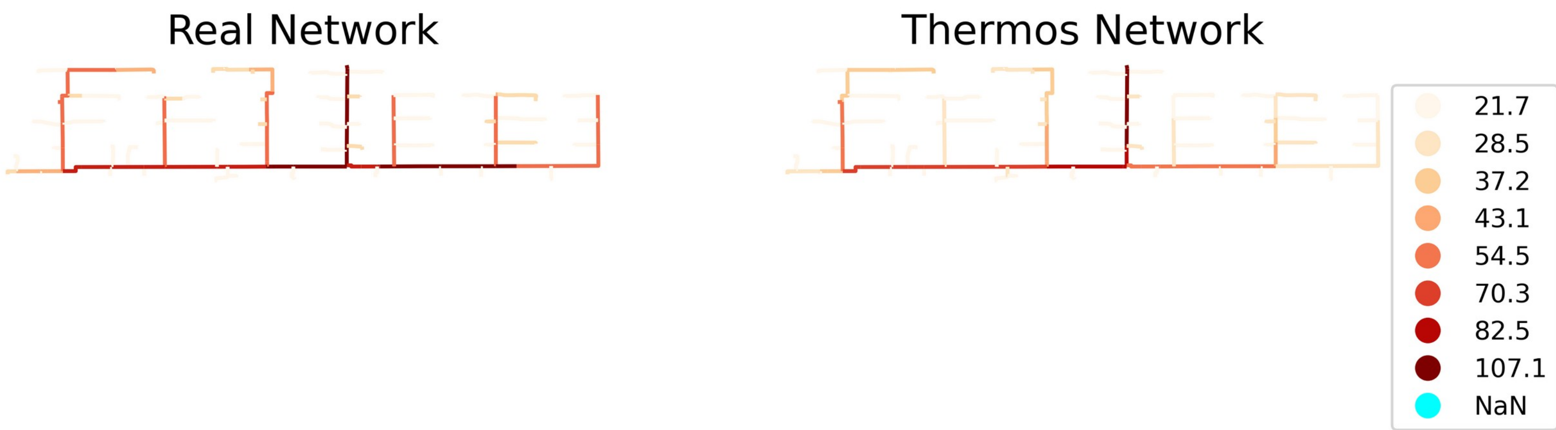
**Reference scenario**




**Diversity disaggregation***



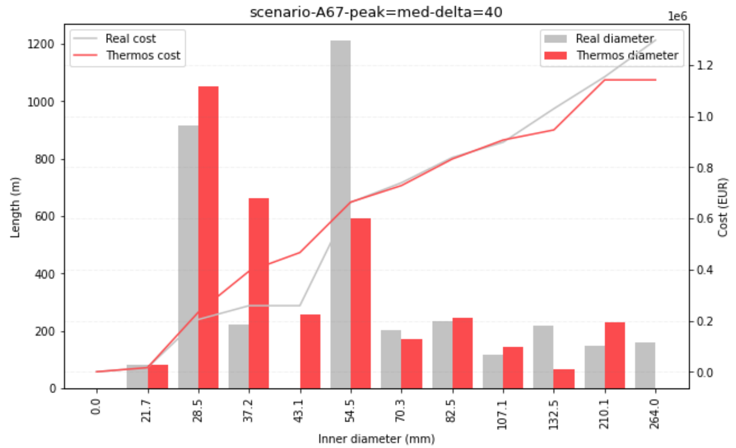

**Network comparisson***

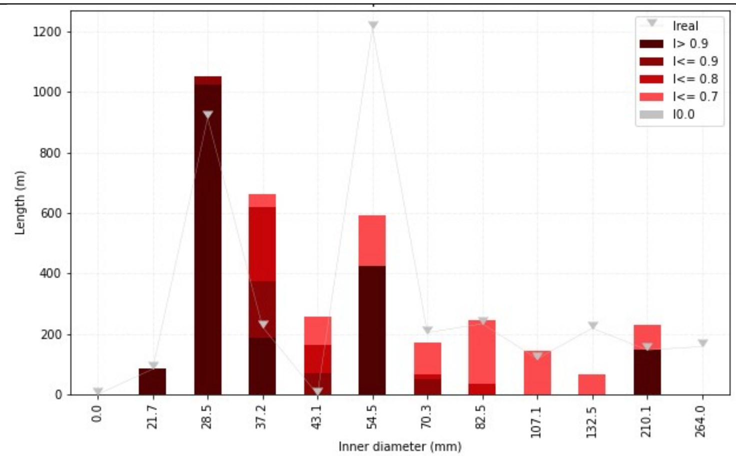



*Uses reference scenario

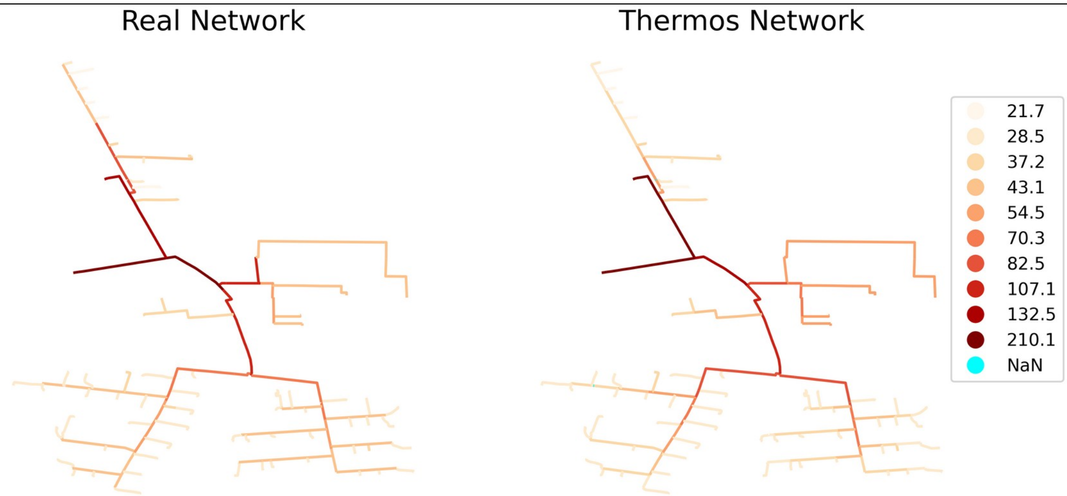
**Scenario [A67]**

| Reference scenario | Diversity disaggregation* |
| --- | --- |



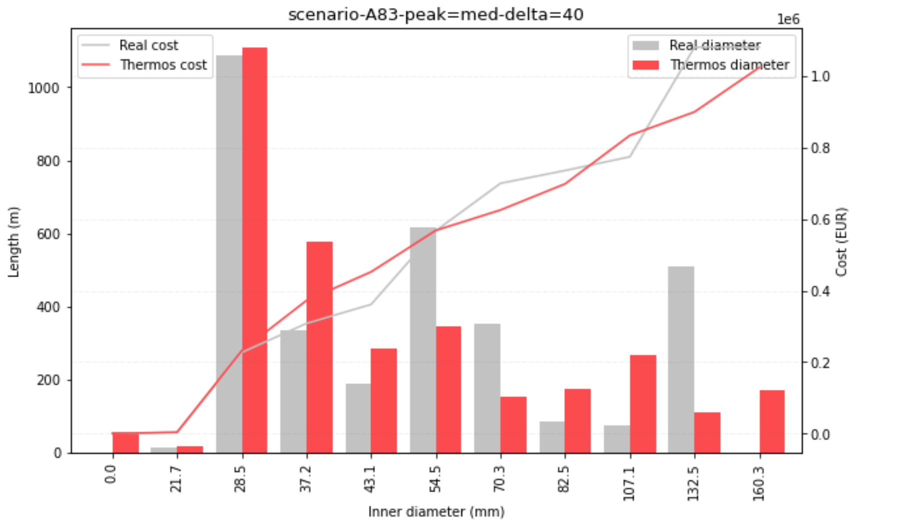



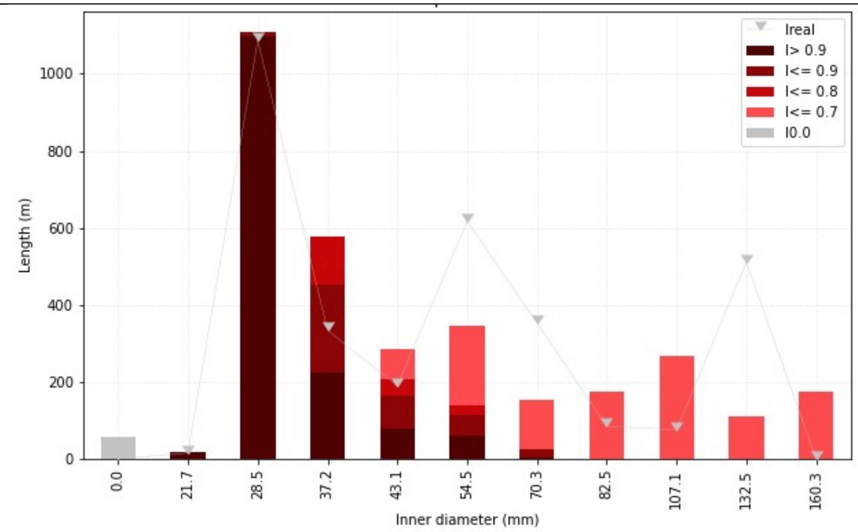

**Network comparisson***



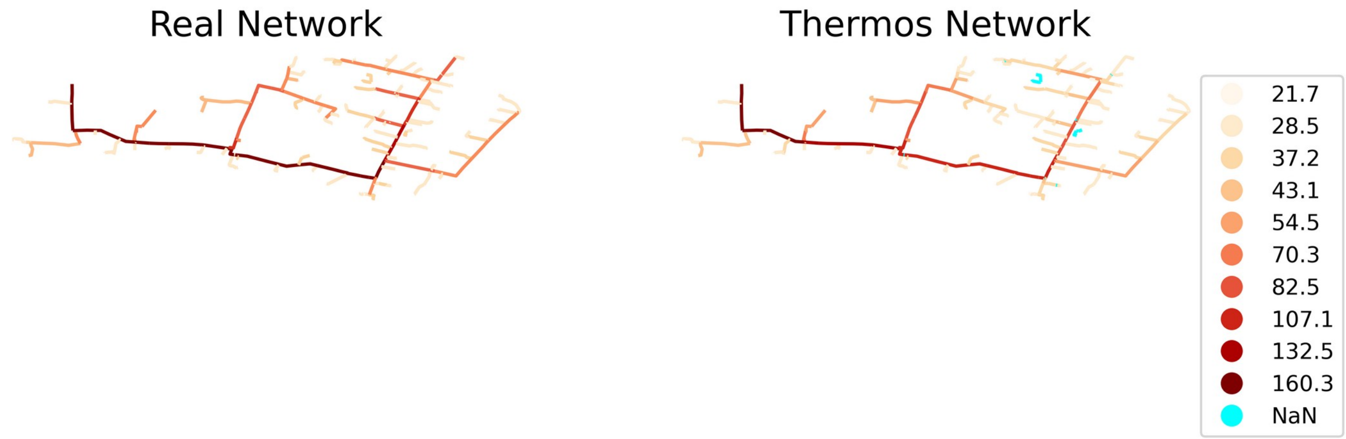

*Uses reference scenario

| Scenario [A83] | |
|---|---|
| **Reference scenario** | **Diversity disaggregation*** |



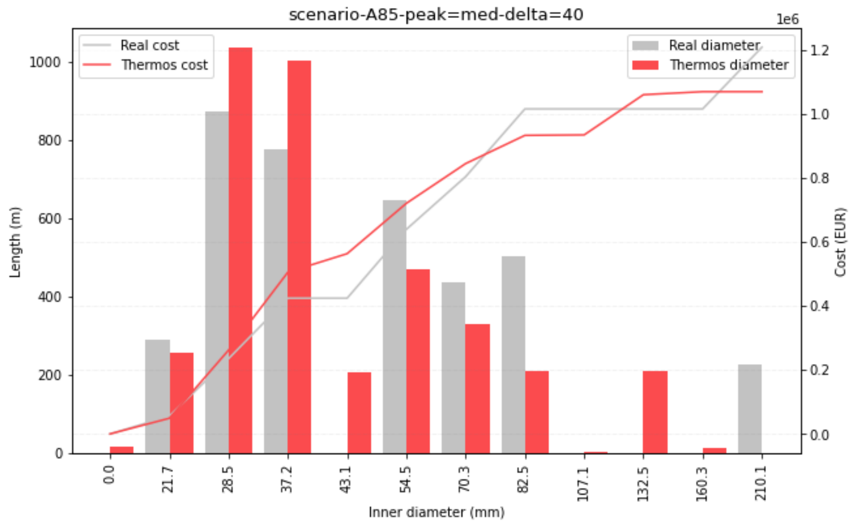



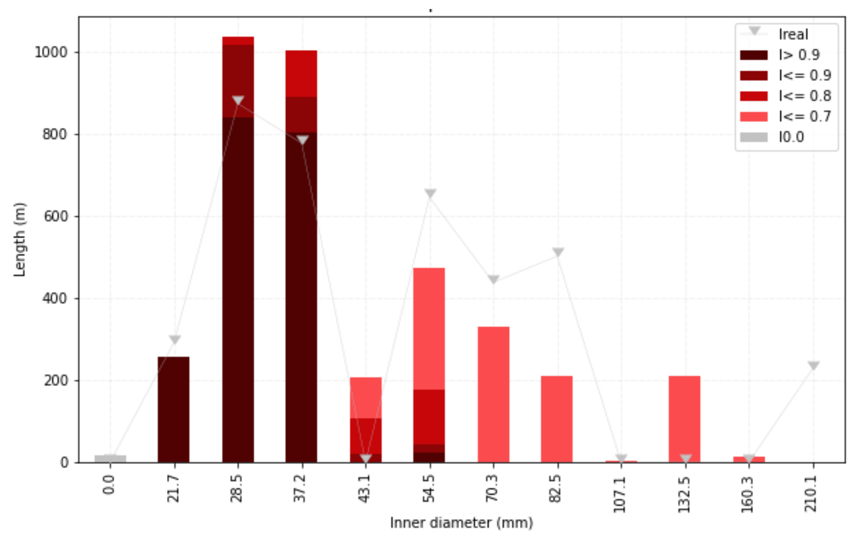

**Network comparisson***



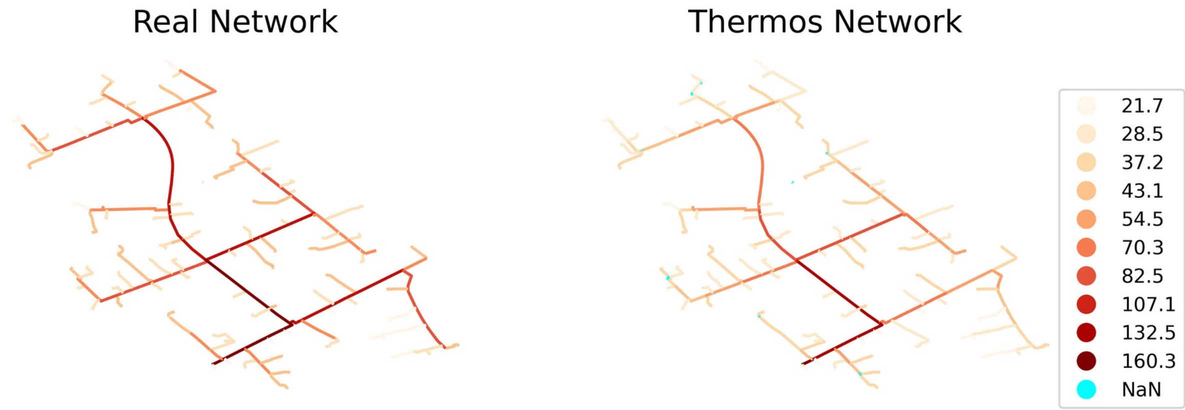

*Uses reference scenario

| Scenario [A85] | |
|---|---|
| **Reference scenario** | **Diversity disaggregation*** |



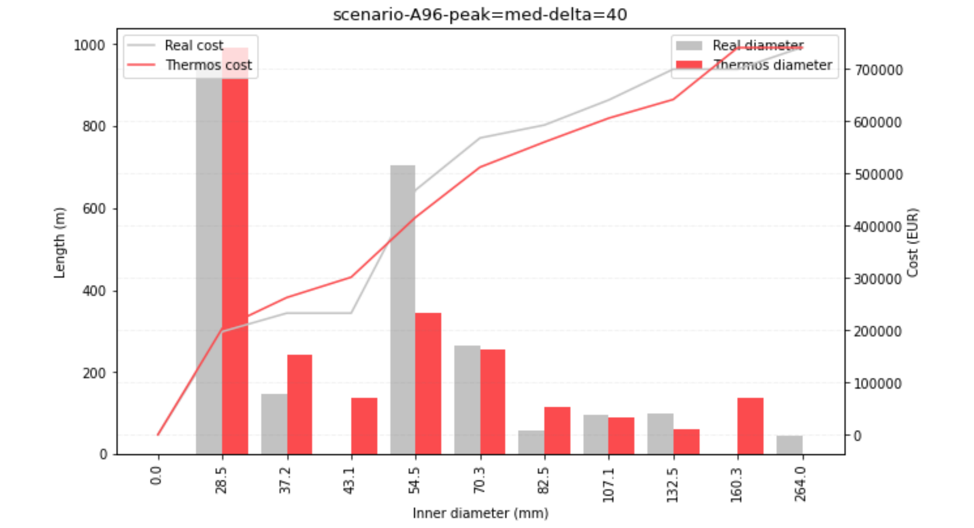



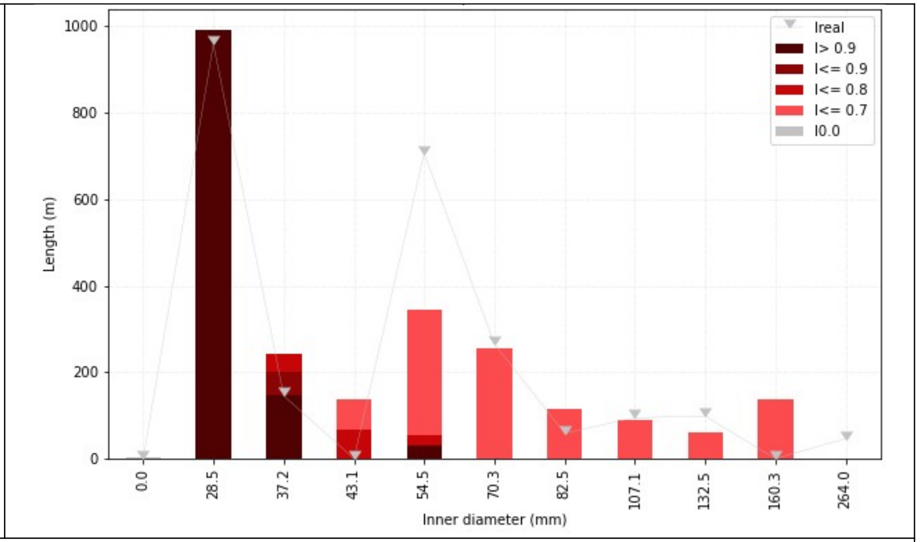

| Network comparisson* |
|---|



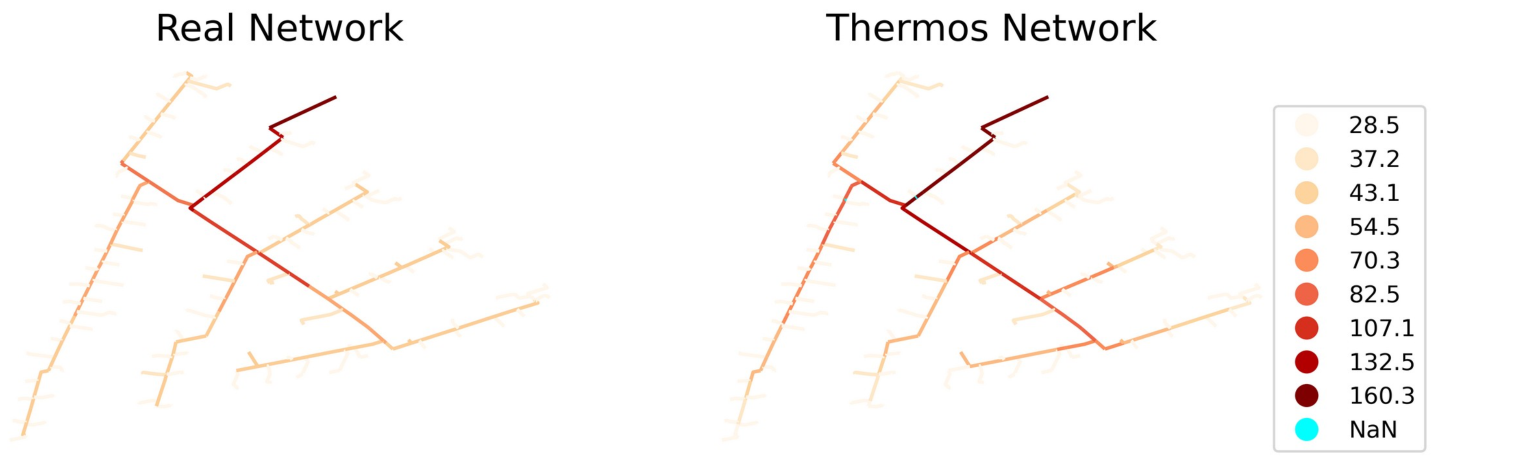

*Uses reference scenario

| Scenario [A96] | |
|---|---|
| Reference scenario | Diversity disaggregation* |



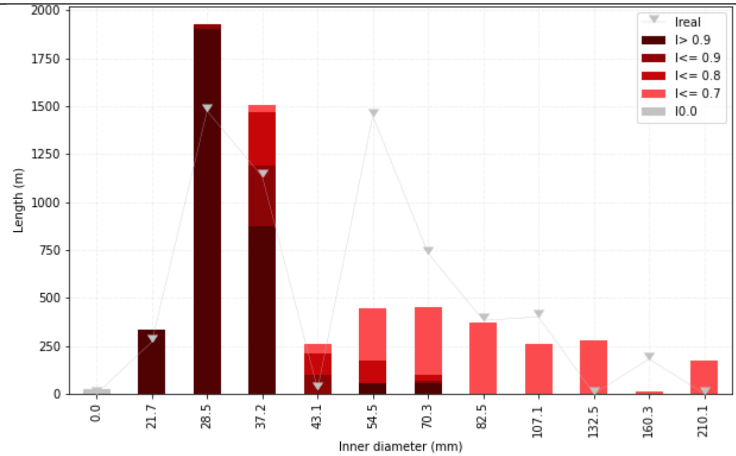




**Network comparisson***

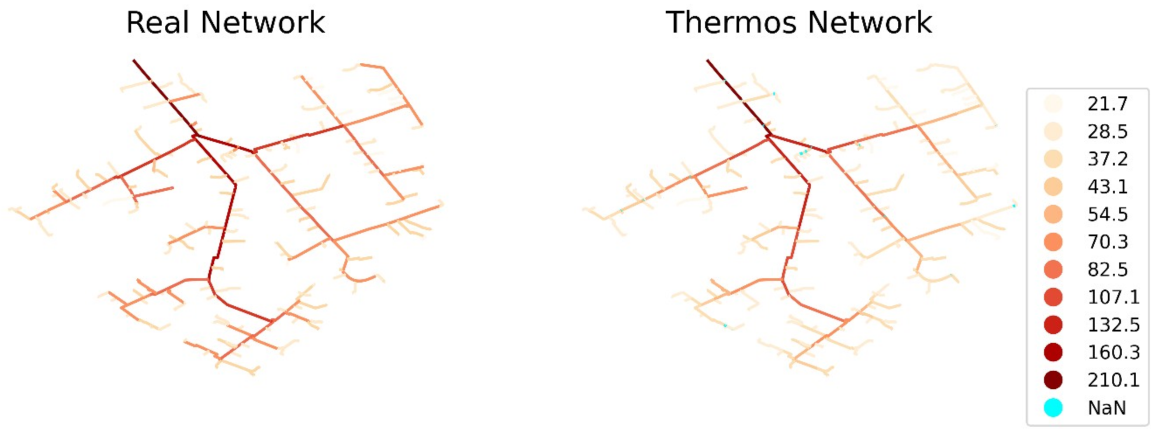



*Uses reference scenario

| Scenario [A137] | |
|---|---|
| **Reference scenario** | **Diversity disaggregation*** |

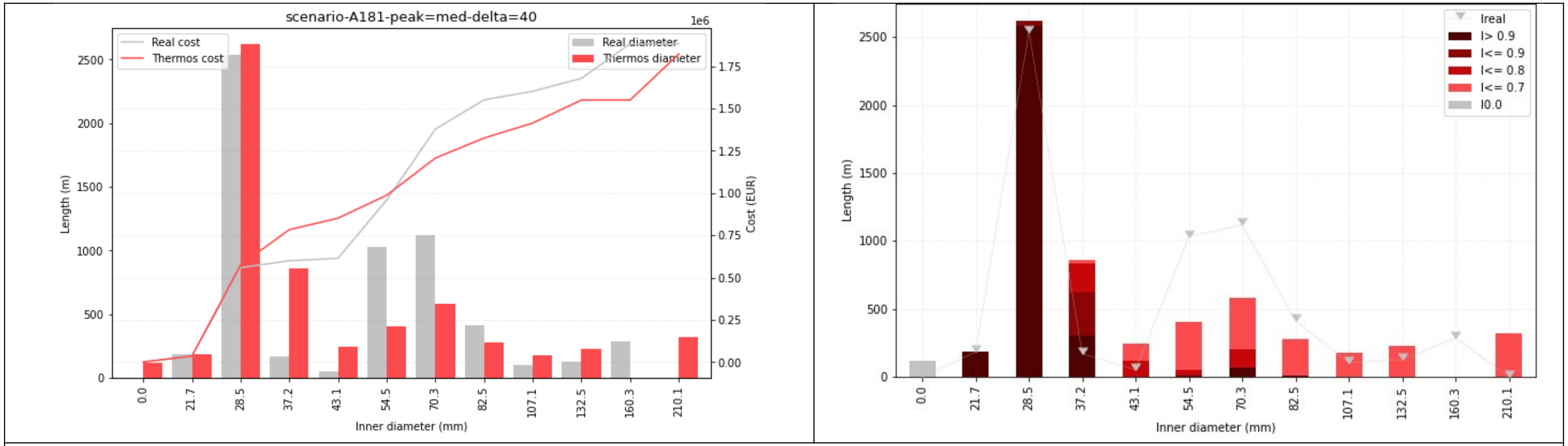




**Network comparisson***

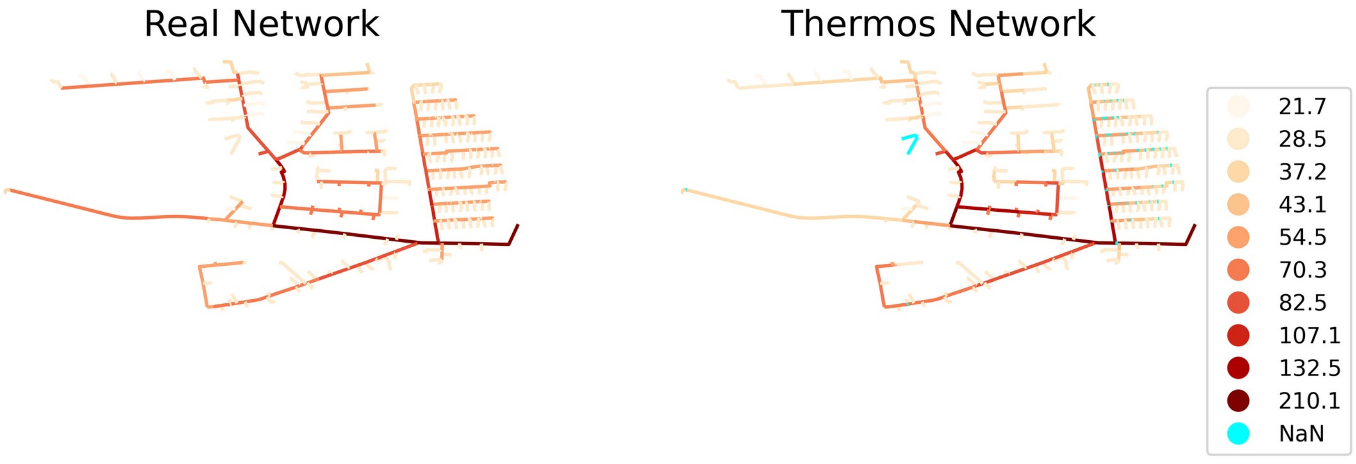



*Uses reference scenario

| Scenario [A181] | |
|---|---|
| **Reference scenario** | **Diversity disaggregation*** |

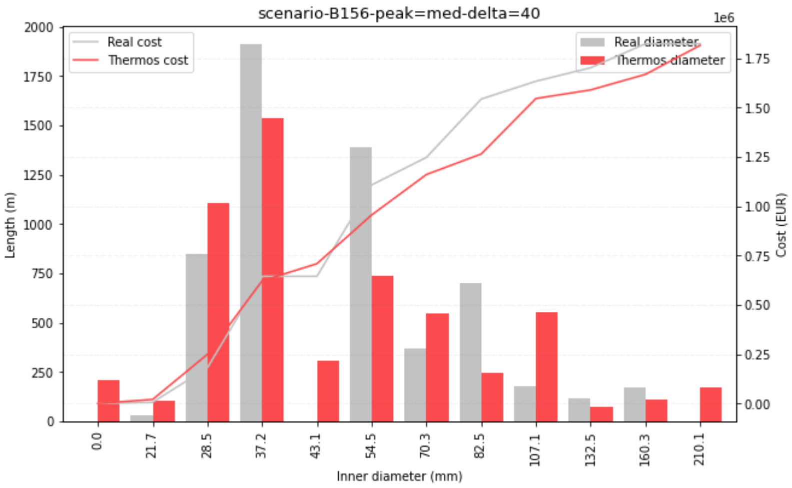
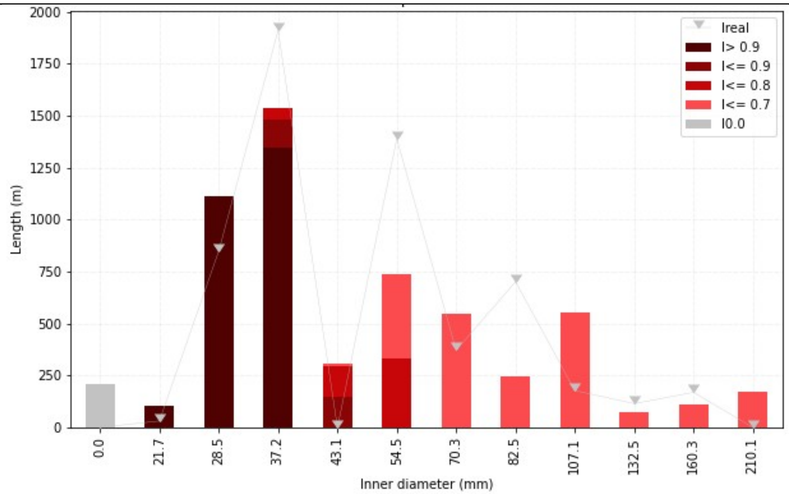



**Network comparisson***

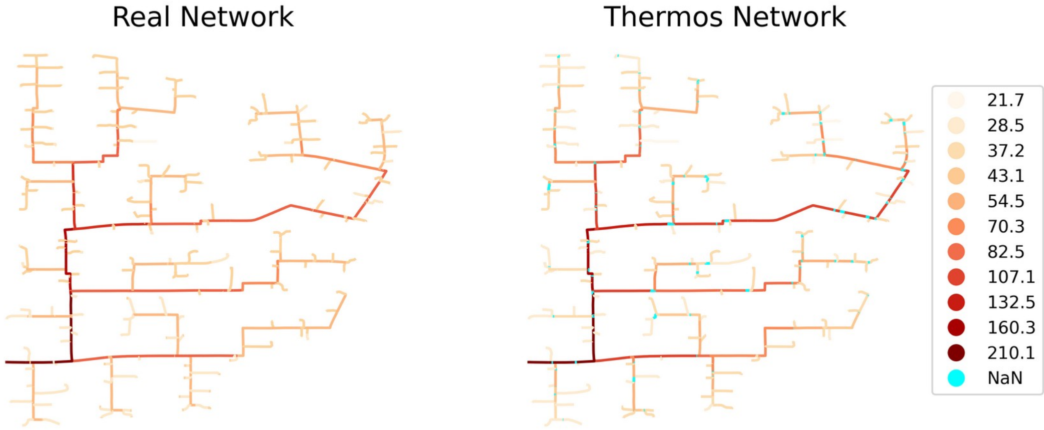



*Uses reference scenario

| Scenario [B156] | |
|---|---|
| **Reference scenario** | **Diversity disaggregation*** |

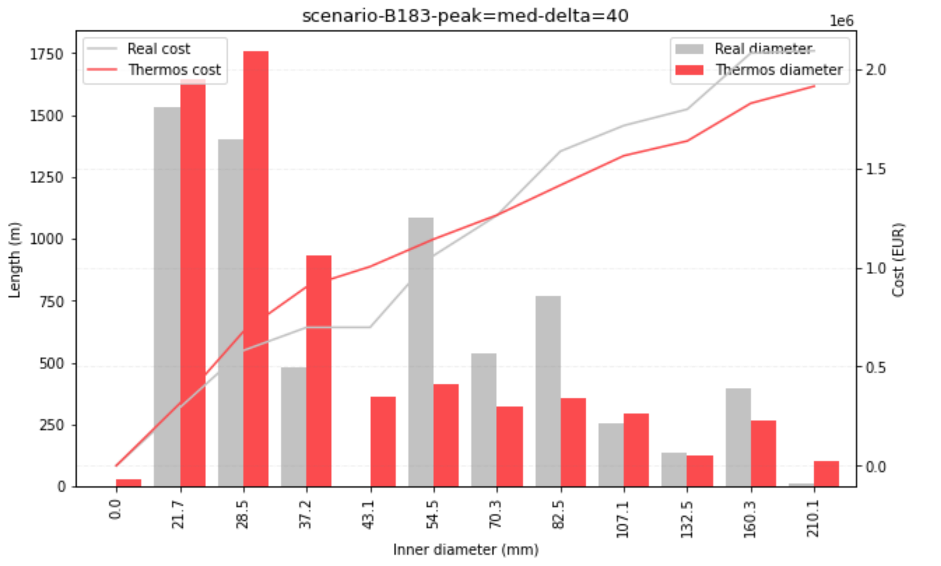
| | |
|---|---|
|  |  |

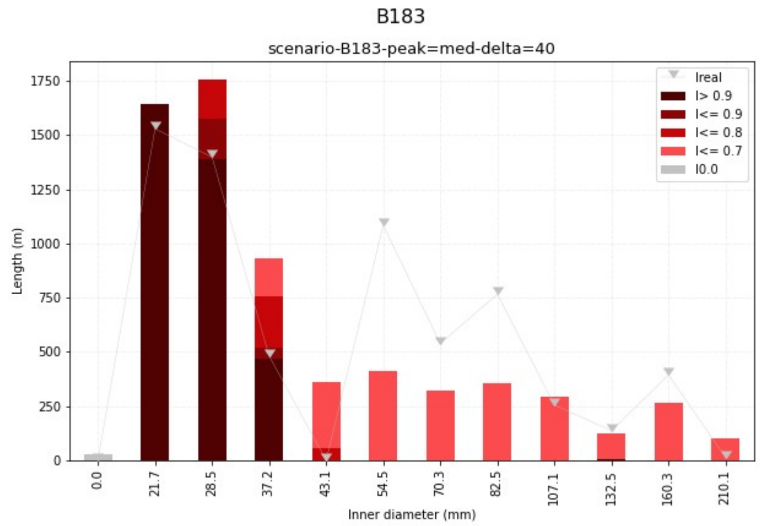
**Network comparisson***



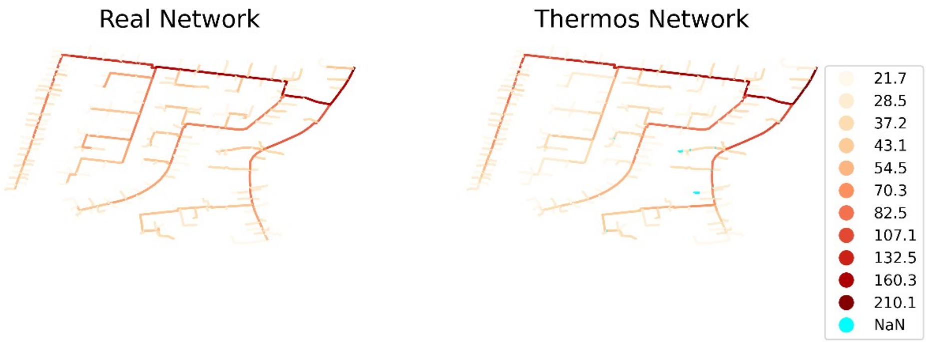

*Uses reference scenario

| Scenario [B183] | |
|---|---|
| **Reference scenario** | **Diversity disaggregation*** |



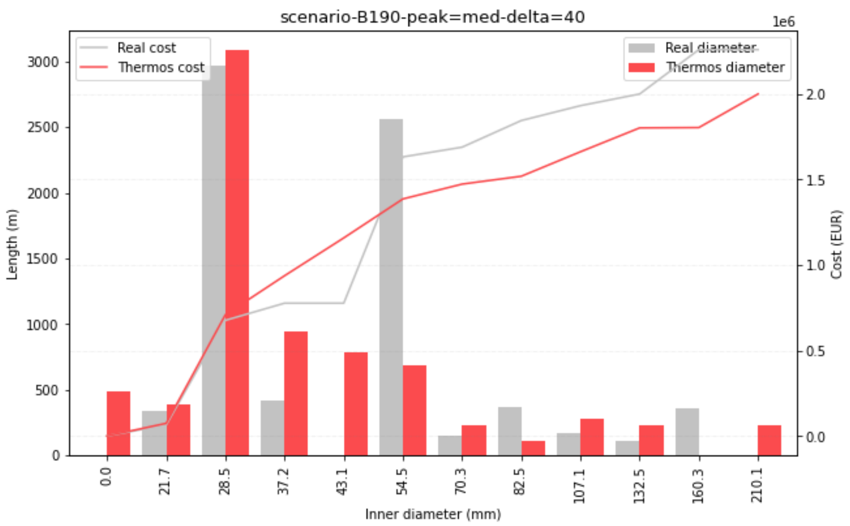



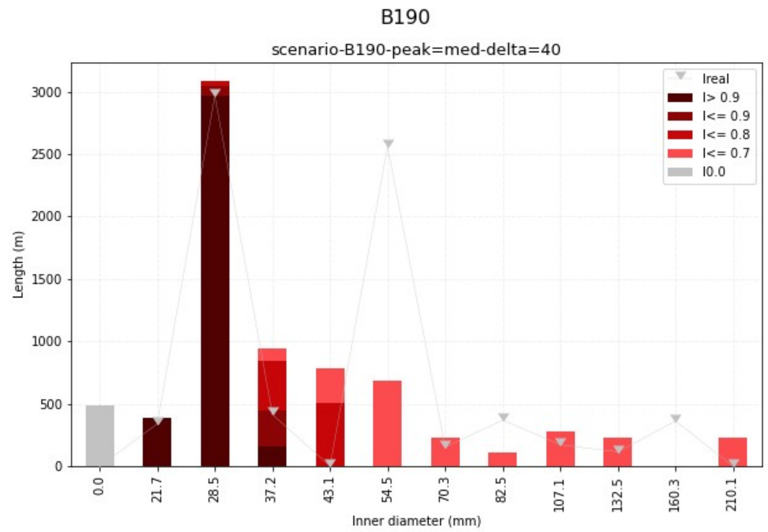

| Network comparisson* |
|---|



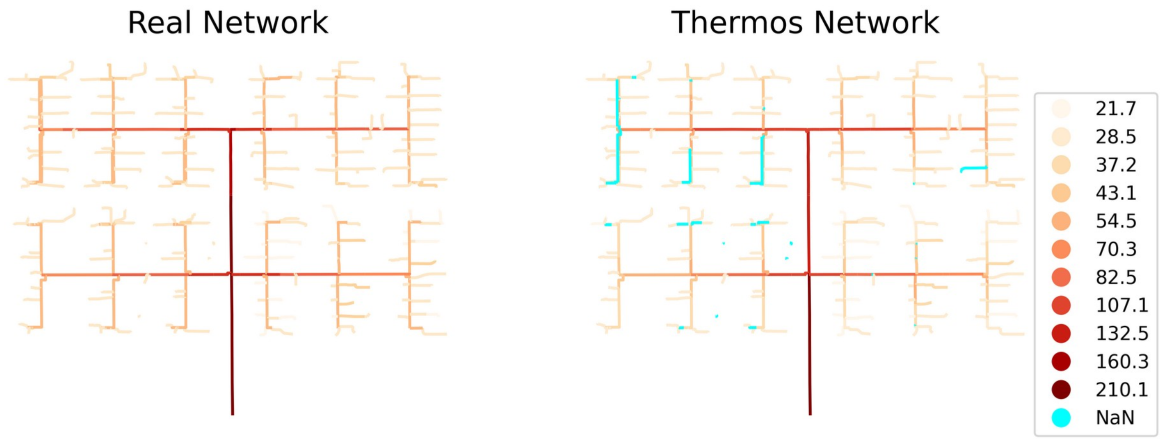

*Uses reference scenario

| Scenario [B190] | |
|---|---|
| Reference scenario | Diversity disaggregation* |



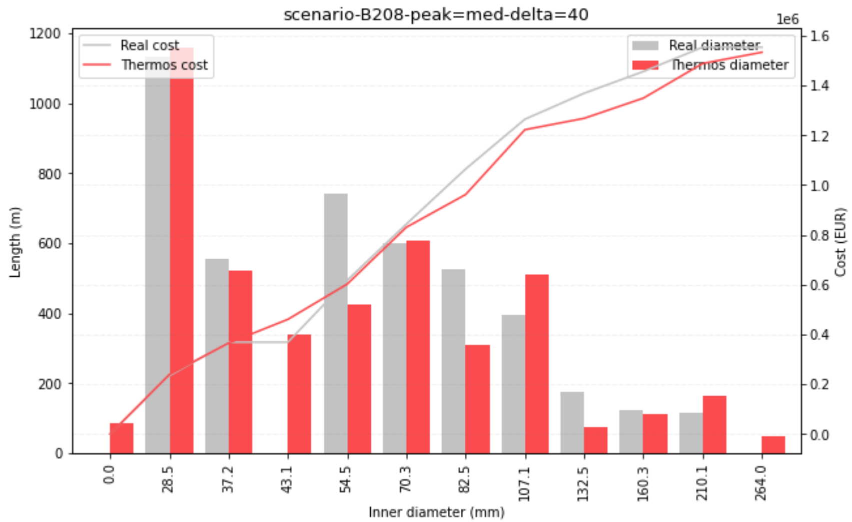



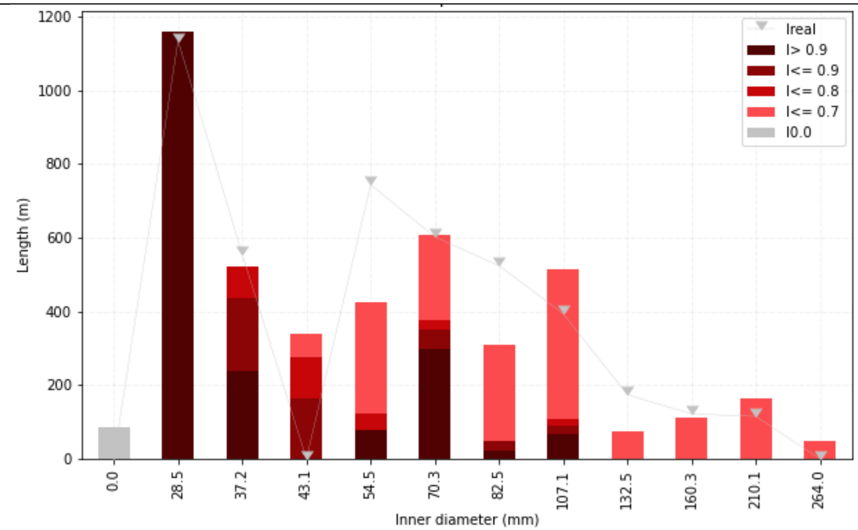

**Network comparisson***



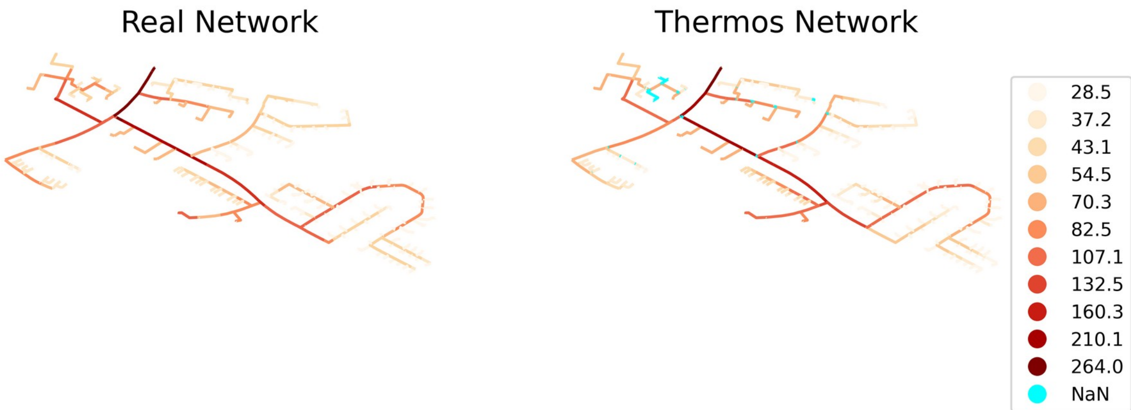

*Uses reference scenario

| Scenario [B208] | |
|---|---|
| **Reference scenario** | **Diversity disaggregation*** |



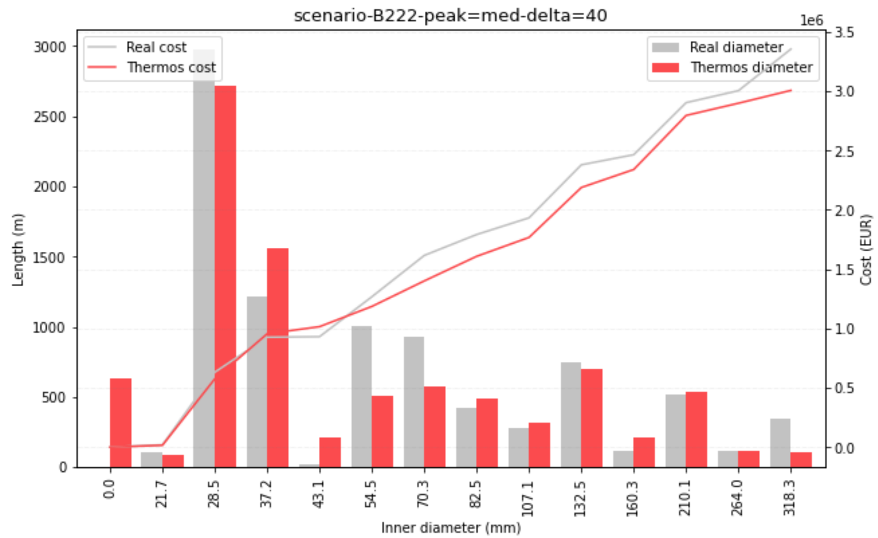



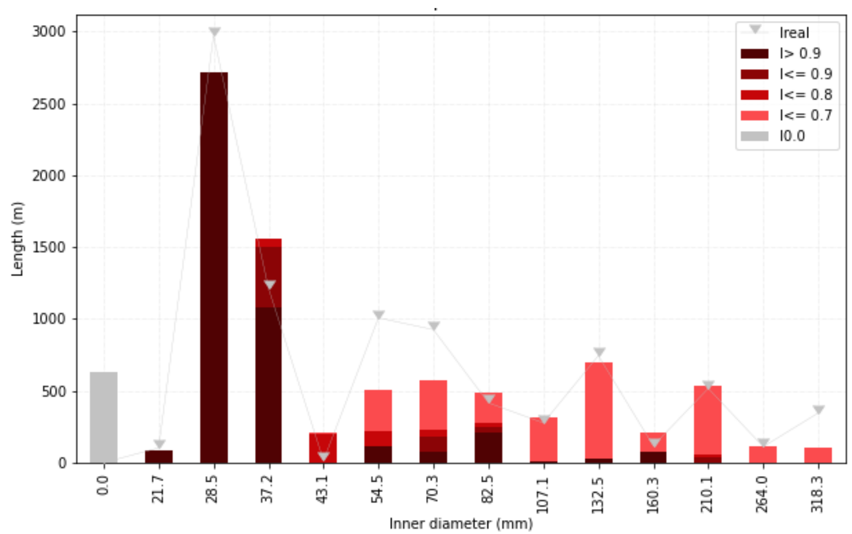

**Network comparisson***



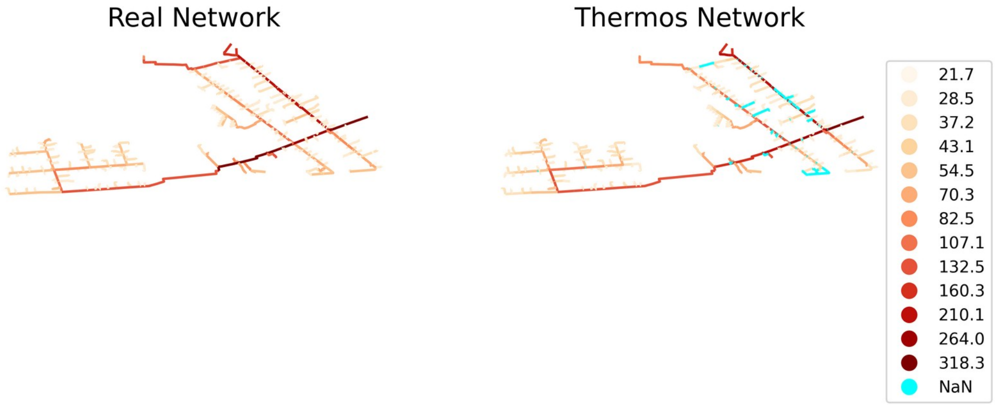

*Uses reference scenario

| Scenario [B222] | |
|---|---|
| **Reference scenario** | **Diversity disaggregation*** |



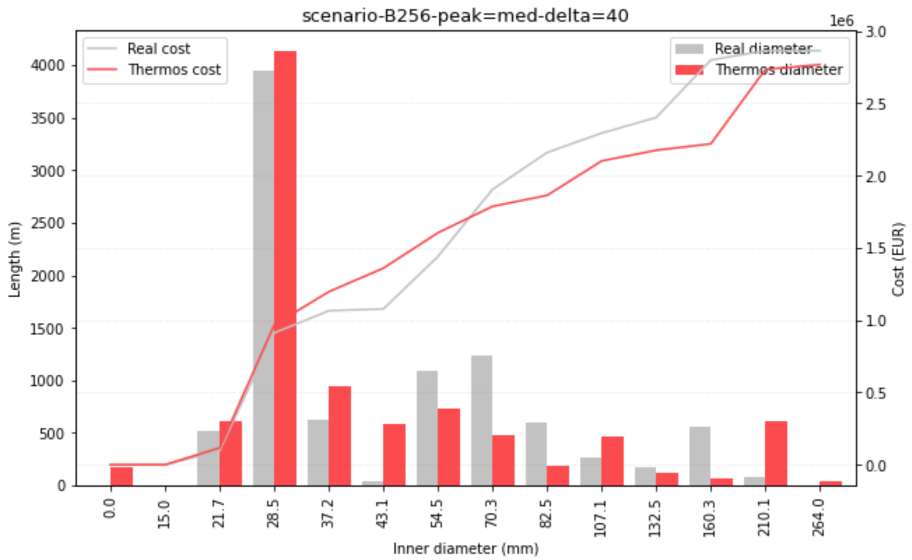
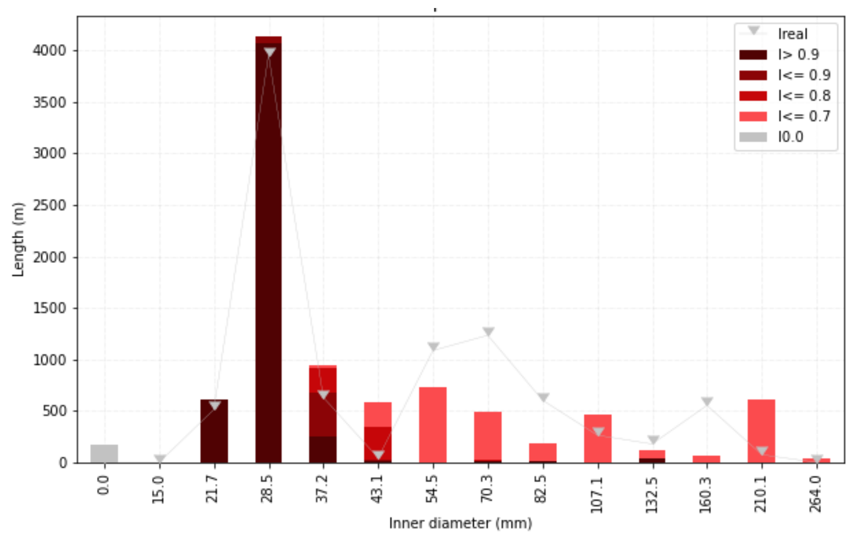




**Network comparisson***




*Uses reference scenario

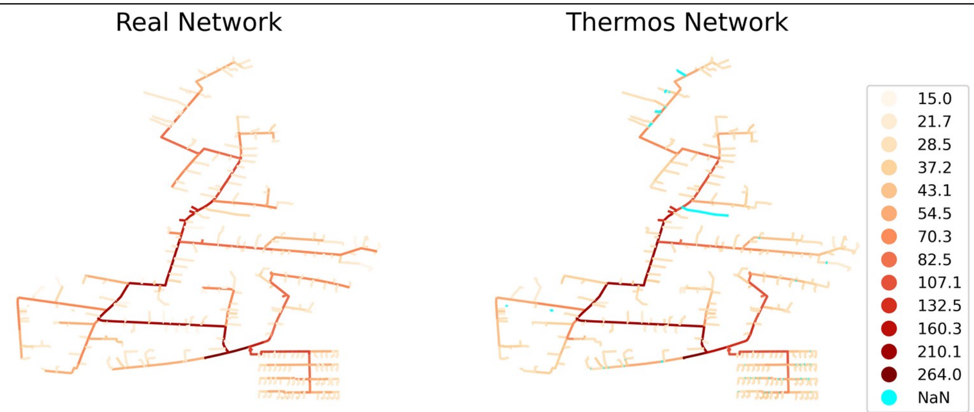
| Scenario [B256] | |
|---|---|
| **Reference scenario** | **Diversity disaggregation*** |

| | |
|---|---|
|  |  |



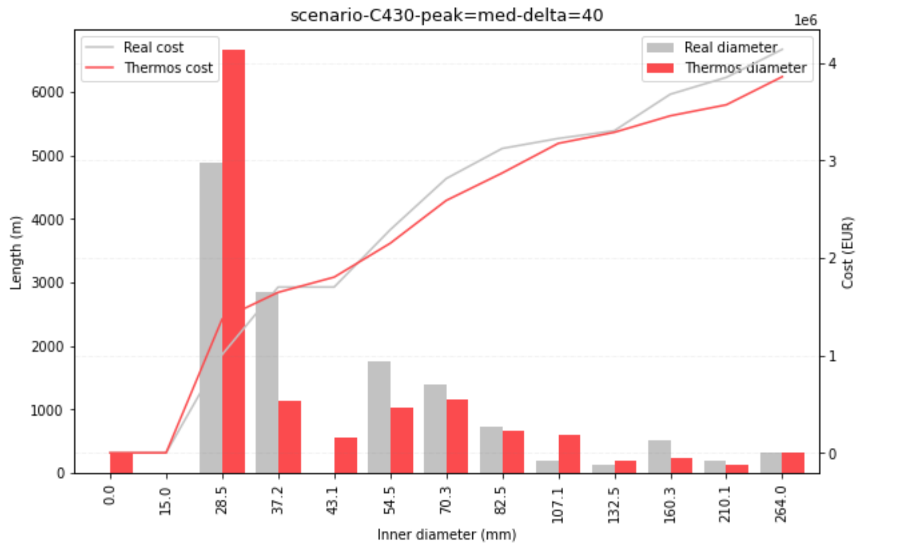


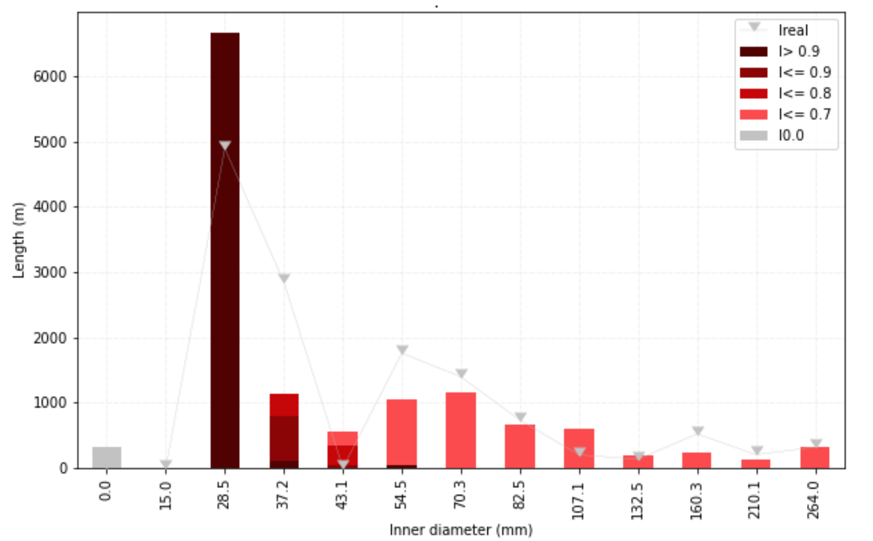
**Network comparisson***



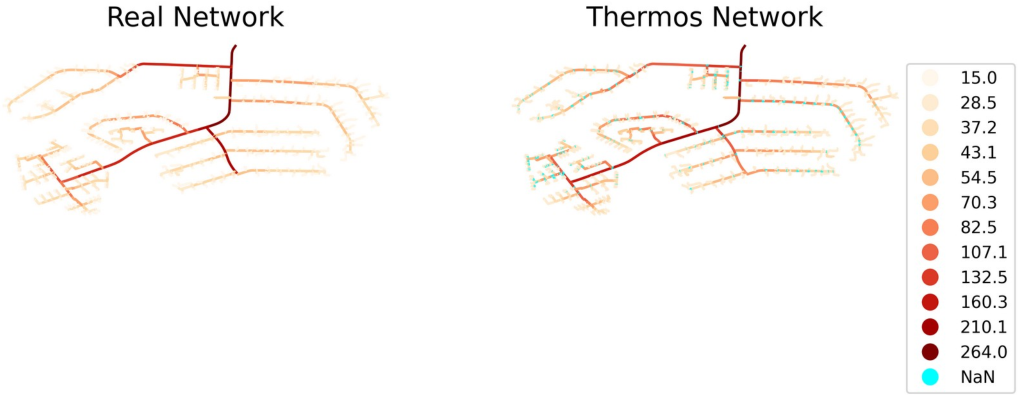

*Uses reference scenario

| **Scenario [C430]** | |
|---|---|
| **Reference scenario** | **Diversity disaggregation*** |




**Network comparisson***




*Uses reference scenario