District Energy
White paper

The importance of system boundaries when evaluating the energy efficiency of district heating systems

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When working in the district heating sector it is common to hear the question:

What defines an efficient district heating system?

While on the surface this should be an easy question to answer with simple statements like:

A system that has low heat losses, cost, emissions or a high share of renewables…

The reality, however, is a bit more nuanced. To properly address this question, we need to define the system boundary, as well as the parameters for evaluating the system's efficiency, as these can significantly impact the conclusion of whether the system is efficient. This whitepaper primarily focuses on energy efficiency, and touches on cost efficiency, where relevant.

With a narrow system boundary that only includes the distribution network, we could conclude that system A, which supplies an area with high building density and has low relative distribution heat loss, is energy efficient and system B, which supplies an area with low building density and has high distribution heat loss, is energy inefficient. If we extend the system boundary to include the heat plant, the importance of the heat plant's efficiency might be greater than the isolated efficiency of the distribution network. For example, if system A is supplied by a coal boiler and system B is supplied by a heat pump, we might shift our perception of which system is more efficient from system A to system B.

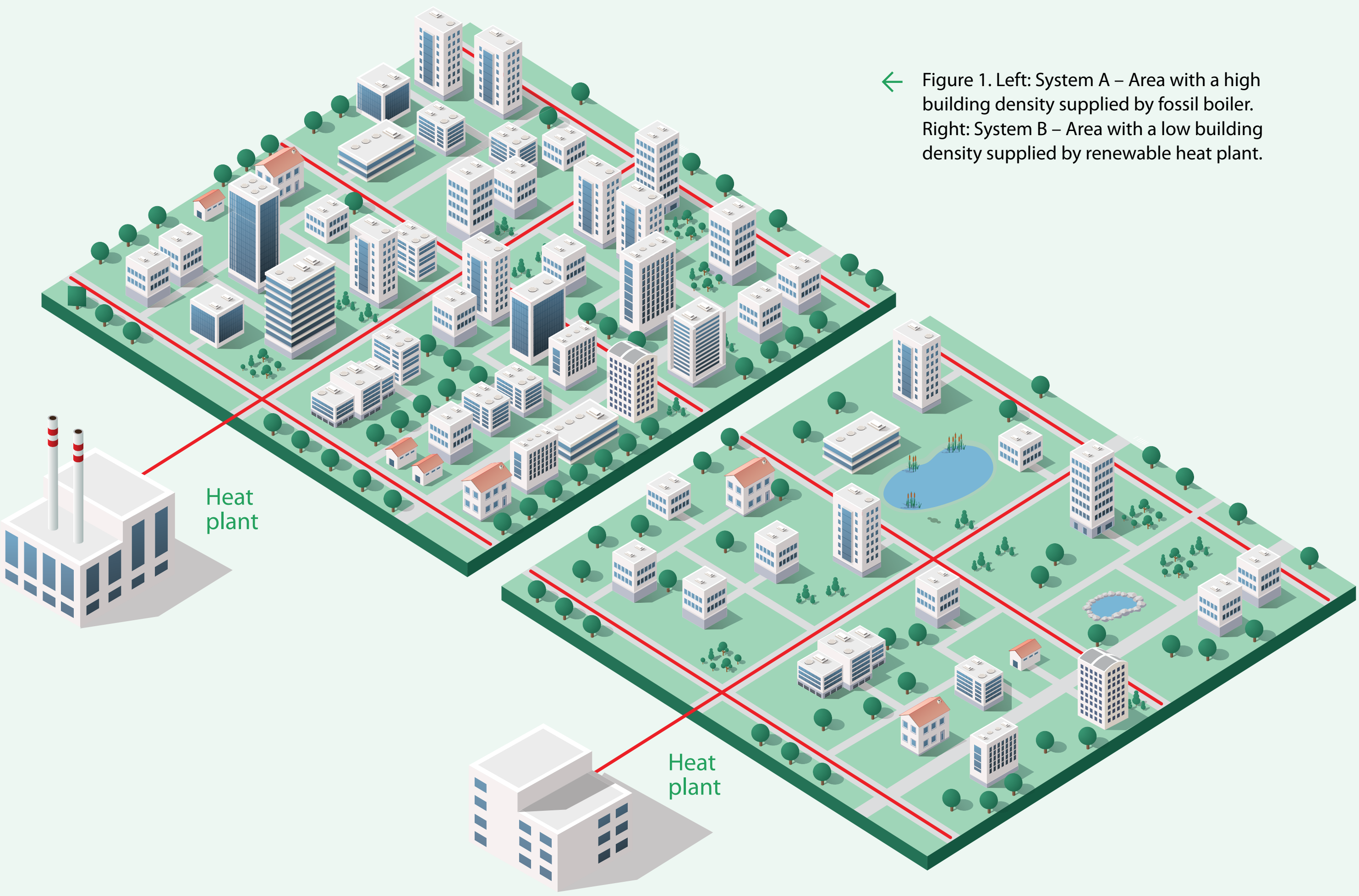
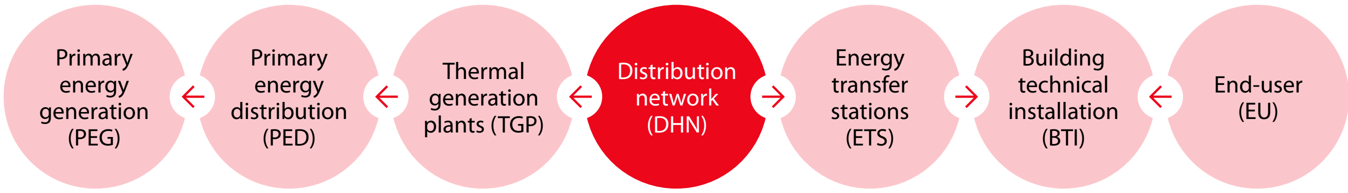


Figure 1. Left: System A – Area with a high building density supplied by fossil boiler. Right: System B – Area with a low building density supplied by renewable heat plant.

To fully understand the impact of efficiency improvements, it is important to use a broad and inclusive system boundary. This ensures that any upstream or downstream effects are accounted for and evaluated using multipliers that correspond to the respective benefits, as shown in the graphic below.



↑ Figure 2. The key system elements of the entire heat supply system, from source to sink.

The system efficiency, considering all elements within a defined system boundary, can be calculated using the following equation:

$$\eta_{SB} = \prod \eta_{SB,i}$$

Where η_{SB} represents the efficiency within the defined system boundary (SB), and η_i denotes the efficiency of the individual elements within that system boundary.

For any given district heating system, the most influential parameters to the system's efficiency are the distribution system's operating temperatures – the supply and return temperatures. Changing either one will have an impact on the system's operating cost. For example:

- Increasing the supply temperature, decreasing the return temperature, or both, will increase the system transport capacity, e.g. increase the heat delivery capacity without additional investments.
- Changing the return and/or supply temperature will impact both the variable cost of the heat generation as well as the heat plants' generation capacity.
- Lower supply and return temperatures will both increase the potential for direct heat recovery from industry waste heat sources and make heat pump-assisted heat recovery more efficient.
- Lower supply and return temperatures generally lead to higher power generation capacities in cogeneration plants.
- Increasing the temperature difference between the supply and return temperature will reduce the distribution flow requirements and consequently reduce the distribution pumping costs.
- Lower supply and/or return temperature will reduce the heat loss from the distribution system.

Changing the operating temperatures can also have negative consequences. For example, reducing the supply temperature will lead to a reduced temperature difference between the supply and return flow, which leads to higher flow requirements, which leads to increased pumping costs.

Reference system

To emphasize the importance of a broad system boundary when evaluating the impact of efficiency improvements, we will use a simplified example of a district heating system. The reference system to be improved is defined by the following parameters:

- Heat demand, measured at the heat emitters, 50,000 MWh/year
- Operating temperatures 80°C supply and 40°C return.
- 10°C soil temperature.
- The heat source is a heat pump
  - The cost of the electricity is set at 100 EUR/MWh
- Electricity for operating the heat pump is 50% renewable ($\eta_{renewable\ el.}$ = 100%) and 50% natural gas based ($\eta_{fossil\ el.}$ = 44.4%).

The efficiency of each reference system element is presented in Figure 3.

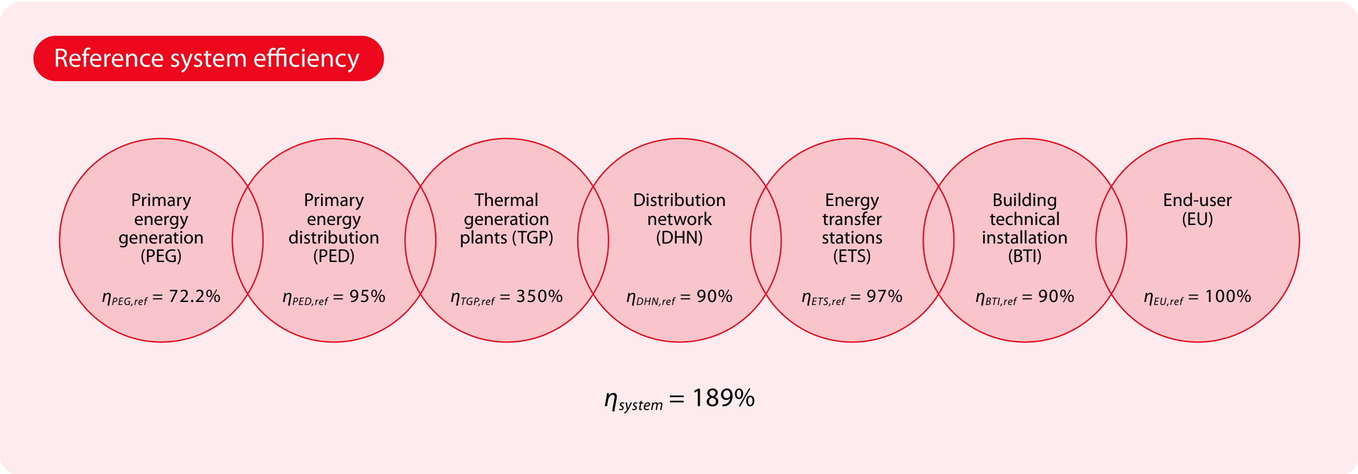


Figure 3. Full scope of the reference system and corresponding system element efficiencies.

$$\eta_{system} = \prod \eta_i = \eta_{PEG} * \eta_{PED} * \eta_{TGP} * \eta_{DHN} * \eta_{ETS} * \eta_{BTI} * \eta_{EU} = 189\%$$

We assume that the end-user utilizes all the energy drawn from the system; therefore, their efficiency is considered to be 100%.

Example of distribution temperature optimization

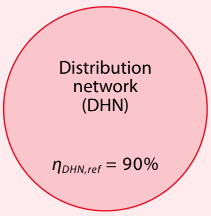
In the following example, the efficiency impact from optimizing the operating temperature is considered as the system boundary is gradually expanded from solely focusing on the distribution system towards incorporating the entire supply chain, as visualized in Figure 2.

The focus of the example is on distribution heat losses and system energy efficiency improvements as the supply temperature is decreased. The impact on the distribution pumping is disregarded, as in comparison to the benefits of the heat loss and energy generation efficiency the corresponding impact is negligible.

System boundary 1

With the narrowest system boundary, only including the distribution network, the benefits from optimizing the distribution network (DHN) operating temperatures would be reduced heat losses.

System boundary 1 – Reference efficiency



$\eta_{SB1,ref} = 90\%$

- Heat supplied from TGP:
  63,638 MWh/year
- Heat losses:
  DHN: 6,364 MWh/year
  ETS: 1,718 MWh/year
  BTI: 5,556 MWh/year
- Heat generation cost:
  Utility: 1,818,215 EUR/year
  Input energy: 18,180 MWh/year

↑ Figure 4. Reference system boundary 1.

The reference system efficiency is now calculated as: $\eta_{SB1,ref} = \eta_{DHN} = 90\%$. To quantify the heat loss of the DHN, we need to adjust the above-mentioned heating demands by factoring in the efficiencies of downstream elements. The heat delivery through the DHN is calculated based on the following formula:

$$E_{DHN} = \frac{E_{heat\ emitters}}{\eta_{BTI} * \eta_{ETS}} = 57{,}274 \text{ MWh/year}$$

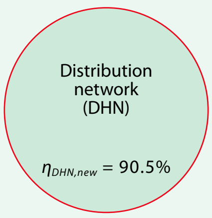
A relative heat loss of 10% for the given heat demand would correspond to 6,364 MWh/year being lost in the DHN.

Compared to manually determined operating temperatures, advanced digital solutions like Leanheat® Network have a solid track record of achieving an annual reduction of 5-8°C in the supply temperature. For the reference system, the impact of a 5°C reduction in the supply temperature can be calculated as follows:

$$\eta_{SB1,new} = \eta_{DHN,new} = 1 - \frac{(T_{s,new} + T_{r,new} - 2 * T_{soil})}{(T_{s,ref} + T_{r,ref} - 2 * T_{soil})} * (1 - \eta_{DHN,ref}) \approx 90.5\%$$

A 0.5% increased distribution system efficiency would reduce the distribution losses to 6,012 MWh/year, corresponding to 352 MWh/year heat savings, equivalent to 5.6% heat loss reduction. Given the reference system assumption, this would reduce the utility primary energy demand by ~100 MWh/year and deliver savings of 10,050 EUR/year, which is significant in light of the low investment required to implement a measure to realize lower operating temperatures.

System boundary 1 – Improved efficiency



$\eta_{SB1,new} = 90.5\%$

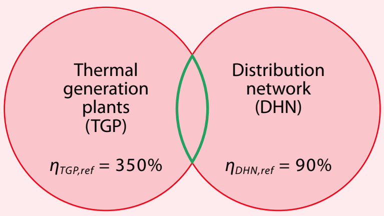
- Heat loss savings:
  352 MWh/year
- Heat demand reduction:
  0 MWh/year
- Input energy savings:
  100 MWh/year
- Cost savings:
  Utility: 10,050 EUR/year
  End-users: 0 EUR/year

Figure 5. System boundary 1 with improved efficiency.

System boundary 2

Extending the system boundary to include the heat plant requires recognizing that the distribution network's operational temperature affects the thermal generation plant's (TGP) efficiency. This is particularly relevant for renewable heat sources, such as heat pumps. The new reference system boundary is defined as follows:

System boundary 2 – Reference efficiency



$\eta_{SB2,ref} = 315\%$

- Heat supplied from TGP:
  63,638 MWh/year
- Heat losses:
  DHN: 6,364 MWh/year
  ETS: 1,718 MWh/year
  BTI: 5,556 MWh/year
- Heat generation cost:
  Utility: 1,818,215 EUR/year
  Input energy: 18,180 MWh/year

Figure 6. Reference system boundary 2.

The reference system efficiency is now calculated as:
$\eta_{SB2,ref} = \prod \eta_i = \eta_{HP} * \eta_{DHN} = 315\%$.

As the efficiency of heat generation plants is unavoidably dependent on the operational temperature of the distribution network, it is important to include the TGP when evaluating the impact of downstream efficiency improvements.

Due to the nature of heat pumps, they are particularly sensitive to the operating temperatures of the DHN. Experience shows that the heat generation efficiency increases by approximately 2% for every degree the DHN temperature is reduced. The above considered 5°C reduction in the supply temperature can therefore lead to a considerable increase in heat generation efficiency, as calculated below:

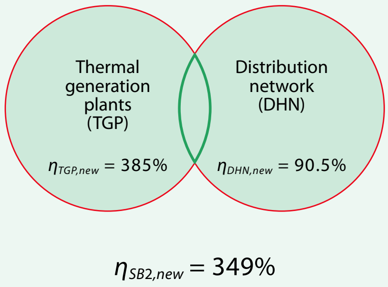
$$\eta_{HP,new} = 350\% * (1 + 5°C * 2\% / °C) = 385\%$$

It is therefore clear that improving the efficiency of the distribution network can also lead to increased efficiency of the heat source, creating a synergetic benefit. The increased heat generation efficiency improvement reduces the primary energy demand by 1,644 MWh/year, which brings the primary energy savings – including from reduced heat losses – to 1,744 MWh/year[1]. The economic impact of the improved heat generation efficiency further impacts the total amount of heat generated, both the heat consumed and the heat lost during transportation to the end-user heat emitters. For the given case, the heat generation cost is reduced from 28.6 EUR/MWh to 26.0 EUR/MWh, leading to heat generation cost savings of 164,230 EUR/year, which in this case far exceeds the savings due to increased DHN efficiency. The total utility cost savings within the improved system boundary is calculated as 174,280 EUR/year. The efficiency of the improved system is calculated as follows:

$$\eta_{SB2,new} = \prod \eta_{SB2,i} = 385\% * 90.5\% \approx 349\%$$

[1] The primary energy savings of the DHN given the increased TGP efficiency is reduced from 102 MWh/year to 93 MWh/year.

System boundary 2 – Improved efficiency



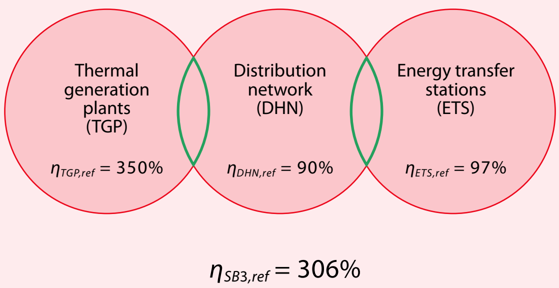
- Heat loss savings:
  352 MWh/year
- Heat demand reduction:
  0 MWh/year
- Input energy savings:
  1,744 MWh/year
- Cost savings:
  Utility: 174,280 EUR/year
  End-users: 0 EUR/year

Figure 7. System boundary 2 with improved efficiencies.

System boundary 3

The next logical step, from the perspective of district heating utilities, would be to extend the system boundary towards the end-user, as the utility may own, operate or define the requirements to the energy transfer stations (ETS) connected to the system. The new reference system boundary is as follows:

System boundary 3 – Reference efficiency



- Heat supplied from TGP:
  63,638 MWh/year
- Heat losses:
  DHN: 6,364 MWh/year
  ETS: 1,718 MWh/year
  BTI: 5,556 MWh/year
- Heat generation cost:
  Utility: 1,818,215 EUR/year
  Input energy: 18,180 MWh/year

Figure 8. System boundary 3.

The reference system efficiency is now calculated as: $\eta_{SB3,ref} = \prod\eta_i = \eta_{SB2,ref} * \eta_{DHN} = 306\%$.

As one of the purposes of the ETS is to downregulate the operating parameters of the distribution network to the requirements of the connected buildings, the particular measure of temperature optimization of the distribution network should not be expected to have a significant impact on the operational efficiency of the ETS.

Nonetheless, a change in the distribution network's operating temperatures will impact heat losses from the ETS, as well as the return temperature due to uncontrolled by-passes. The impact on the heat loss from an ETS can be calculated on the same basis as losses from the DHN. It is important to keep in mind that the impact is only on the primary side of the ETS, as the secondary side is unaffected by the change in the distribution supply temperature. In this example, we assume that there is an equal heat loss area on both sides.

$$\eta_{ETS,new} = 1 - \left(\frac{(T_{s,new} + T_{r,ref} - 2 * T_{ambient})}{(T_{s,ref} + T_{r,ref} - 2 * T_{ambient})} * 50\%_{pri} + 50\%_{sec}\right) * (1 - \eta_{ETS,ref}) \approx 97.1\%$$

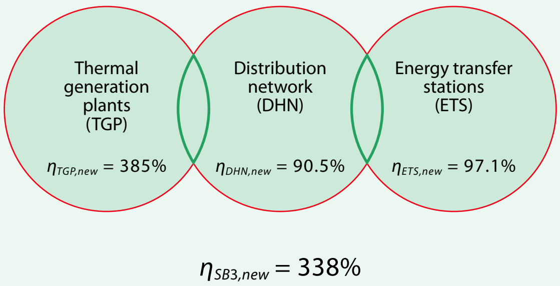
A 0.1% increase in ETS efficiency reduces the associated losses from 1,718 to 1,663 MWh/year. The 55 MWh/year heat savings correspond to ~14 MWh/year primary energy demand reduction, leading to a total of 1,760 MWh/year primary energy savings. From a traditional utility's perspective, the accounting of this heat loss reduction is different compared to the DHN heat loss, as it occurs behind the energy meter, and is therefore classified as a demand reduction. The corresponding cost savings for the end-users would be 1,580 EUR/year. The efficiency of the improved system is calculated as follows:

$$\eta_{SB3,new} = \prod\eta_{SB3,i} = \eta_{SB2,new} * \eta_{ETS,new} \approx 338\%$$

However, in the case of uncontrolled by-passes — assumed negligible in this example — a lower supply temperature, assuming the same by-pass flow rate, would lead to lower return temperatures. This, in turn, would increase both distribution network and heat generation efficiency. This is important because the potentially large negative impact of by-passes on system efficiency is not necessarily reflected in the tariff system. Since by-passes generally do not result in a meaningful heat draw-off, they are not billed to the end-user.

As the operation of the ETS can significantly impact the overall system efficiency, progressive district heating utilities have begun to include the ETS as an essential part of the business model. This approach enables utilities to ensure that the connected ETS are based on energy efficient designs that can support the operation of the upstream system, and that the ETS are correctly commissioned and continuously monitored for faults.

System boundary 3 – Improved efficiency



- Heat loss savings: 352 MWh/year
- Heat demand reduction: 55 MWh/year
- Input energy savings: 1,760 MWh/year
- Cost savings: Utility: 174,280 EUR/year End-users: 1,580 EUR/year

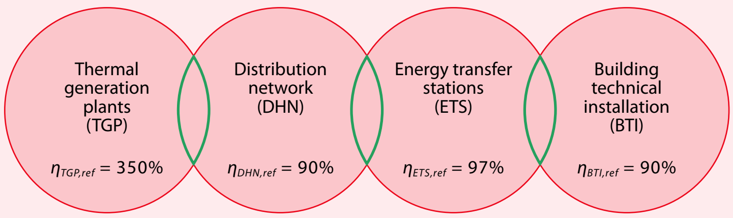
Figure 9. System boundary 3 with improved efficiencies.

System boundary 4

Continuing with the district heating utility's perspective, the next logical inclusion into the system boundary would be the building technical installation (BTI), which includes the building's internal distribution network and control equipment at the heat emitters.

However, it is worth noting that, once inside the building, it can be argued that the efficiency terminology becomes a bit ambiguous, as the focus generally shifts from system efficiency to delivered comfort level where the terms "under- and oversupply" become more relevant. However, there are typically unwanted losses in the building distribution system, due to uninsulated, or poorly insulated, distribution pipes and domestic hot water (DHW) circulation. In general, it can be expected that 10% of the heat supply to the building is lost without having any comfort value, leading to the assumption that the BTI is 90% efficient. The new reference system boundary is as follows:

System boundary 4 – Reference efficiency



$\eta_{SB4,ref} = 275\%$

- Heat supplied from TGP:
  63,638 MWh/year
- Heat losses:
  DHN: 6,364 MWh/year
  ETS: 1,718 MWh/year
  BTI: 5,556 MWh/year
- Heat generation cost:
  Utility: 1,818,215 EUR/year
  Input energy:
  18,180 MWh/year

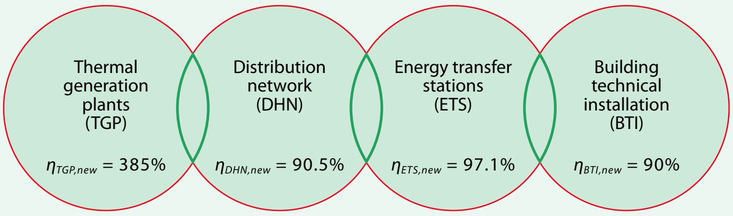
Figure 10. System boundary 4.

The reference system efficiency is now calculated as:
$\eta_{SB4,ref} = \prod \eta_i = \eta_{SB3,ref} * \eta_{BTI} = 275\%$.

With the assumption that the ETS is working as designed, the BTI would be negligibly affected — if at all — from the temperature optimization of the DHN. Hence no changes in the BTI's efficiency are expected, compared to the prior system boundary. The efficiency of the improved system is calculated as follows:

$$\eta_{SB4,new} = \prod \eta_{SB4,i} = \eta_{SB3,new} * \eta_{BTI,new} \approx 304\%$$

System boundary 4 – Improved efficiency



$\eta_{SB4,new}$ = 304%

- Heat loss savings: 352 MWh/year
- Heat demand reduction: 55 MWh/year
- Input energy savings: 1,760 MWh/year
- Cost savings: Utility: 174,280 EUR/year End-users: 1,580 EUR/year

Figure 11. System boundary 4 with improved efficiencies.

The efficiency of the entire heat supply system is inherently dependent on the BTI's operation, as the BTI determines the minimal supply temperature requirements, and the system return temperature is directly related to its performance.

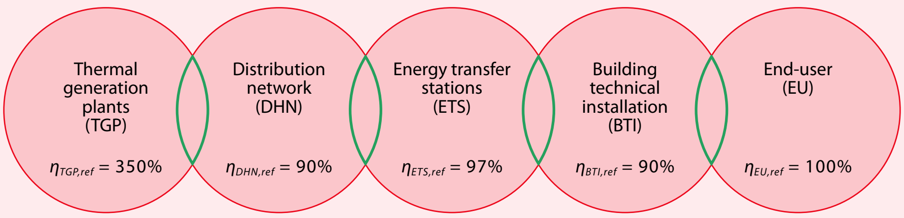
While the BTI's purpose is to ensure that end-users' comfort requirements are met, the way the BTI is designed and controlled can significantly impact the capacity required to fulfill the desired comfort level. This, in turn, has a significant impact on the system capacity and the investment cost of the entire supply system.

An optimized BTI can lead to lower supply temperature requirements, lower return temperatures, lower heating demands, lower peak capacity demands and the ability to shift demand to times with more cost-efficient heat generation.

System boundary 5

To complete the picture of the district energy system, we extend the system boundary to include the end-user. In principle, the end-user is considered 100% efficient, as their consumption level and comfort preferences are assumed to be entirely within their control. The new reference system boundary is as follows:

System boundary 5 – Reference efficiency



$\eta_{SB5,ref}$ = 275%

- **Heat supplied from TGP:**
  63,638 MWh/year
- **Heat losses:**
  DHN: 6,364 MWh/year
  ETS: 1,718 MWh/year
  BTI: 5,556 MWh/year
- **Heat generation cost:**
  Utility: 1,818,215 EUR/year
  Input energy:
  18,180 MWh/year

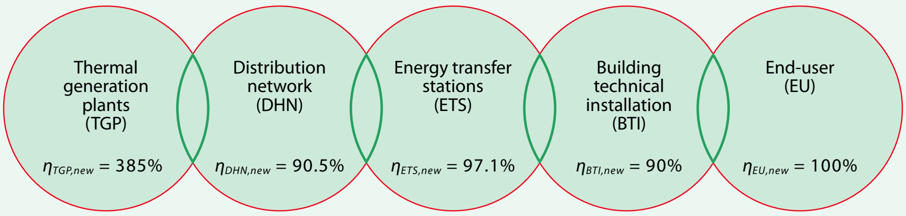
Figure 12. System boundary 4 with improved efficiencies.

As the temperature optimization of the DHN has no impact on the end-user's heat demands, their efficiency remains unchanged.

The improved system efficiency is calculated as follows:

$$\eta_{SB5,new} = \prod \eta_{SB5,i} = \eta_{SB4,new} * \eta_{end\text{-}user,new} \approx 304\%$$

System boundary 5 – Improved efficiency



$\eta_{SB5,new} = 304\%$

- Heat loss savings:
  352 MWh/year
- Heat demand reduction:
  55 MWh/year
- Input energy savings:
  1,760 MWh/year
- Cost savings:
  Utility: 174,280 EUR/year
  End-users: 1,580 EUR/year

↑ Figure 13. System boundary 5 with improved efficiencies.

While the purpose of the supply system is to meet end-users' demands, there are measures that can be applied to involve the end-user and thus increase system efficiency. Such measures include:

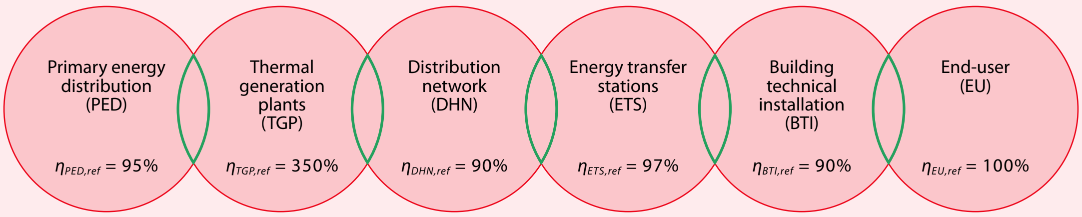
- Informing the end-user of their energy consumption and benchmarking with historical consumption levels or similar user groups,
- Making the end-user aware of incorrect/inefficient operation of their system and how to make it more efficient,
- Applying motivation tariffs, either for reducing return temperatures or for shifting end-user consumption from peak load periods.

- Considering and involving the end-user in the system operation leads to multiple benefits, such as:
- Mitigation of capacity strains
- Increased use of intermittent and fluctuating renewables, by shifting demands in time
- Potentially early detection of various system faults

System boundary 6

While system boundaries 1–5 cover the entire heat supply system, the new element in system boundary 6, the primary energy distribution (PED), elevates the focus to the entire energy supply chain, where the TGP is just one of many primary energy users supplied by the PED. This has several implications. For example, energy savings occurring within elements of system boundary 5 become lost revenue for PED and primary energy generation (PEG) operators and PED efficiency improvements become lost revenue to the last upstream element, PEG. Despite the changed focus, from a utility perspective to energy system perspective, it is important to extend the system boundary to cover the entire energy system, as the reduced primary energy demand changes the primary energy mix, e.g. shifting the primary energy generation from fossil fuels to renewable energy. The new reference system boundary is as follows:

System boundary 6 – Reference efficiency



$\eta_{SB6,ref} = 261\%$

- Heat supplied from TGP:
  63,638 MWh/year
- Heat losses:
  DHN: 6,364 MWh/year
  ETS: 1,718 MWh/year
  BTI: 5,556 MWh/year
- Heat generation cost:
  Utility: 1,818,215 EUR/year
  Input energy:
  18,180 MWh/year

Figure 14. System boundary 6.

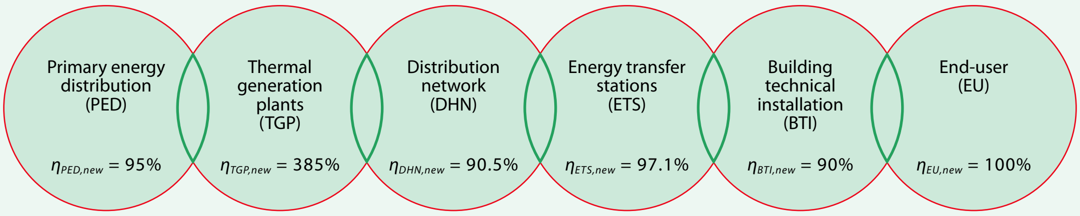
The reference system efficiency is now calculated as:
$\eta_{SB6,ref} = \prod \eta_i = \eta_{SB5,ref} * \eta_{PED} = 261\%$.

Depending on the size of the district energy system, the impact of reduced primary energy demand can range from negligible to considerable. In the considered example – a small, electrified district heating system – the reduced electricity demand is assumed to have a negligible impact on PED efficiency. The efficiency of the improved system is calculated as follows:

$$\eta_{SB6,new} = \prod \eta_{SB6,i} = \eta_{SB5,new} * \eta_{PED,new} \approx 289\%$$

Nonetheless, energy that is not supplied does not incur losses, meaning primary energy savings will occur and primary energy generation will be avoided. The corresponding primary energy savings are calculated to be 90 MWh per year, bringing the total primary energy savings to 1,850 MWh/year.

System boundary 6 – Improved efficiency



$$\eta_{SB6,new} = 289\%$$

- Heat loss savings:
  352 MWh/year
- Heat demand reduction:
  55 MWh/year
- Input energy savings:
  1,850 MWh/year
- Cost savings:
  Utility: 174,280 EUR/year
  End-users: 1,580 EUR/year

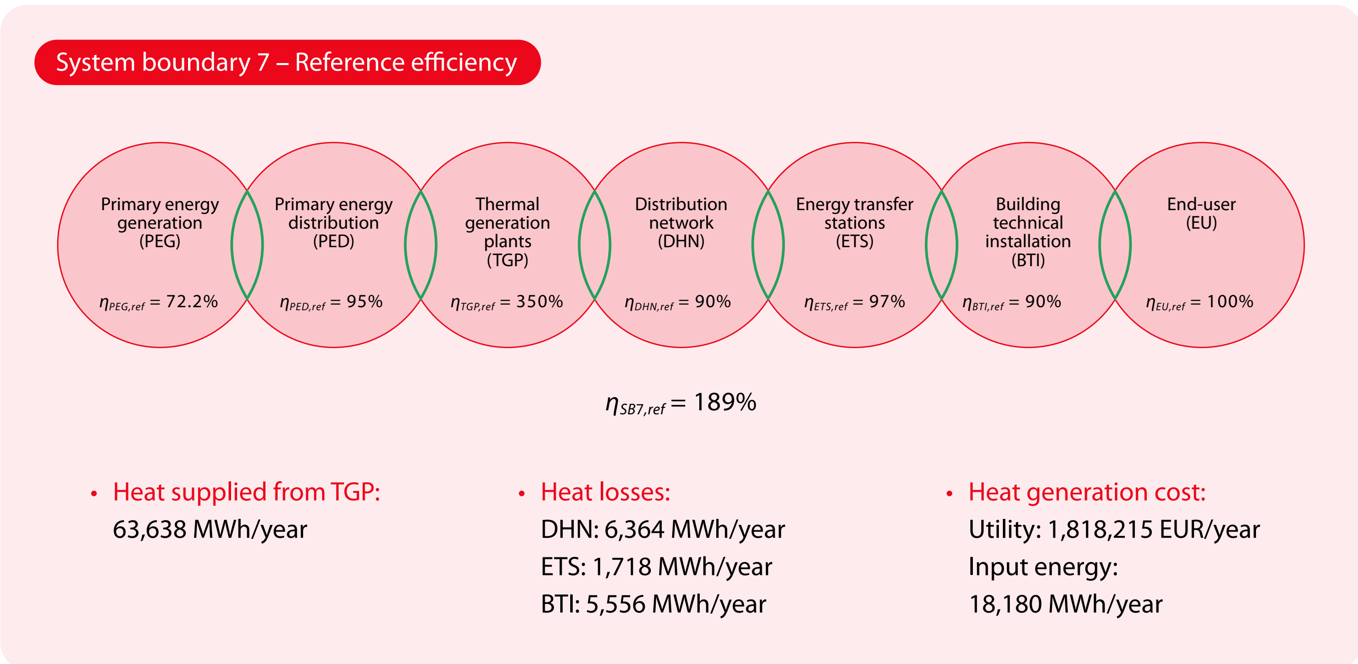
↑ Figure 15. System boundary 6 with improved efficiencies.

System boundary 7

To conclude, we include the final element of the overall system boundary – the PEG. Expanding the system boundary to include the PEG is important because of the impact reduced primary energy consumption can have on the PEG's efficiency, carbon intensity and cost.

As mentioned above, we assume that 50% of the PEG is from renewable sources, wind or solar, with 100% generation efficiencies, $\eta_{PEG,renew.}$ = 100%, and 50% is from natural gas fired power plants, where the efficiency of the natural gas-based PEG includes both the efficiency of the natural gas mining operations and the power plant efficiencies. In this example, we assumed that the gas mining, η_{mining}, and processing, $\eta_{processing}$, had efficiencies of 96% and 94% respectively. The efficiency of the gas transmission pipeline, $\eta_{transmission}$, from the gas fields to the gas power plant was assumed to be 98.5%. With a power plant efficiency, $\eta_{power\ plant}$, of 50%, the primary energy efficiency, $\eta_{PEG,gas\ based}$, gas-based power, is estimated to be 44.4%. For the reference case, the PEG efficiency can be calculated to be $\eta_{PEG,ref} = 50\% * \eta_{PEG,renew} + 50\% * \eta_{PEG,gas\ based} = 72.2\%$.

The new reference system boundary is as follows:



↑ Figure 16. System boundary 7.

The reference system efficiency is now calculated as: $\eta_{SB7,ref} = \prod \eta_i = \eta_{SB6,ref} * \eta_{PEG} = 189\%$.

At first glance, one might conclude that the downstream efficiency gains would not impact the PEG, but that assumption would be incorrect. Downstream efficiency improvements should be included when assessing the PEG, as they may lead to a change in the energy generation mix, e.g. shifting away from gas-based power generation to renewable-based power generation.

Based on the $\eta_{SB6,ref}$ and $\eta_{SB6,new}$, we calculate that the required primary energy demand is reduced by 9.7%, due to the efficiency improvements – from 261% to 289%. This reduction of the primary energy demand should naturally displace the natural gas-based power generation.

The increased share of renewable primary energy would effectively increase the overall system efficiency, as the renewable energy generation is 100% efficient.

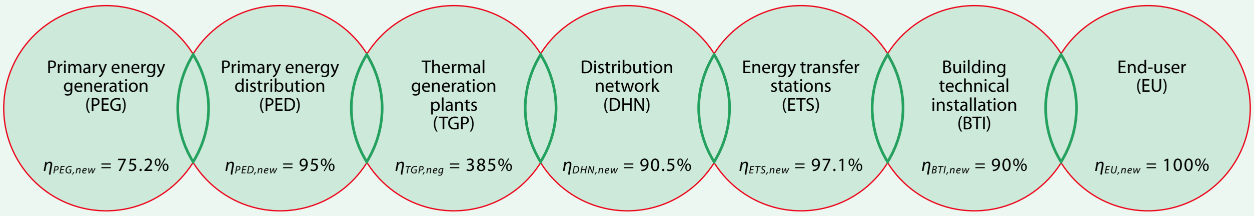
Consequently, the new split between renewable power and fossil-based power becomes 55.4% renewable and 44.6% fossil based. The new PEG efficiency is calculated as follows:

$$\eta_{PEG,new} = 55.4\% * \eta_{PEG,renew} + 44.6\% * \eta_{PEG,gas\ based} = 75.2\%$$

With this the extended system efficiency can be calculated as follows:

$$\eta_{SB7,new} = \prod \eta_{SB7,i} = \eta_{SB6,new} * \eta_{PEG,new} \approx 218\%$$

System boundary 7 – Improved efficiency



$\eta_{SB7,ref} = 218\%$

- Heat loss savings:
  352 MWh/year
- Heat demand reduction:
  55 MWh/year
- Input energy savings:
  1,850 MWh/year
- Cost savings:
  Utility: 174,280 EUR/year
  End-users: 1,580 EUR/year

↑ Figure 17. System boundary 7 with improved efficiencies.

Conclusions

- In the considered example, which is well aligned with the direction of low temperature district heating and electrified heat supply, it becomes clear that solutions that may have had a marginal impact on the operation of traditional, high temperature district heating systems in the past, have a significantly higher impact potential in the future low carbon energy system.

- In the example above, the operating temperature optimization, which is calculated to increase the distribution efficiency from 90% to 90.5% at the narrow system boundary – corresponding to a 5% reduction in heat loss – is superseded by the system benefits that only become visible when the system boundary is extended. If one would view the impact from system boundary 4, which could represent the most progressive district heating utility businesses today, the same solution would lead to an increase in the system efficiency from 275% to 304%, which implies a potentially far higher value from the solution compared to what would be considered in the narrowest system boundary. Given the assumed power price of 100 EUR/MWh, the perceived economic value for the utility when implementing DHN temperature optimization would change from 10,210 EUR/year to 174,280 EUR/year under an extended system boundary. Considering that the business case for DHN temperature optimization has been very favorable in the past, it will be extraordinary favorable in the future electrified heat supply systems.

- As the system boundary enlarges, other benefits of a solution may become apparent. For example, reducing distribution network operating temperatures goes from being a distribution heat loss reduction solution to being a solution that can bring significant efficiency improvements at the heat generation plant, and consequently reduced heat generation costs. Similarly, reducing the operating temperature can support the transition from carbon intensive energy sources to renewable energy sources, which leads to a reduced carbon footprint of the heat supply.

- As shown above, solutions addressing specific challenges may, from the perspective of the whole heat supply, appear to have a limited impact when seen from a narrow system boundary. However, the same solutions may have considerable impact when evaluated holistically with a wide system boundary, as the improvements could benefit more elements in the heat supply chain than originally considered. Those secondary impacts, both upstream and downstream, in the energy supply system, may well have significantly higher value than the impacts originally aimed for within the narrow system boundary. This underlines the importance of having a wide system boundary in mind when prioritizing new solutions to implement.

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