Report:

Utilizing excess power from PV farm in district heating – system design and dimensioning

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1	31.01.2022	Sergey Klyapovskiy	First draft
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I. Introduction

Danish government set a goal of achieving 100% renewable electricity generation by the year 2035 [1]. The majority of this electricity would be generated from offshore wind, which accounted for almost 90% of all renewable electricity production in 2018 [2]. Solar generation is the second most common renewable source, which has been rising in Denmark since 2012 and reached 1181 GWh in 2020 [3]. Solar is predicted to become even more significant due to the cost reduction in installation and operation of PV panels. Solar power could be produced both on residential (rooftop PV systems) and industrial (utility-scale PV farms) levels with a wide range of installed capacity.

Due to the nature of solar energy and seasonal variations, PV farms in Denmark would rarely deliver its peak power. One of the challenges for designing a utility-scale PV farm is to decide the size of the grid connection, which is the maximum power that the farm is allowed to deliver to the external electrical grid measured at the point of common coupling (PCC). Larger grid connection would incur larger grid connection costs as well as inverter costs and therefore the choice of the grid connection capacity represents a trade-off between the amounts of energy PV farm can sell to the grid and the investment in the grid connection and inverter.

Choosing a grid connection capacity smaller than the peak power of PV farm will result in losing the energy during hours when solar production is higher than grid connection. To minimize the loss, surplus power could be used to supply internal processes behind PCC. In this project, the excess power from PV farm is sent through a DC cable to a DC boiler installed at the local district heating (DH) facility thus allowing to receive extra benefits from utilizing PV power, while not oversizing the grid connection.

This report presents several schemes for connecting PV farm with DC boilers at DH facility and discusses their pros and cons. The most promising scheme is selected to explain how its components (number of PV panels, power electronics, DC cable, etc.) are dimensioned. An estimation of losses at the DC cable and suggestions for reducing them are discussed together with an overview of the cable and converter losses for different scenarios.

II. Schemes for connecting PV farm with DH facility

a. System description

The report considers electrical connections inside the system consisting of PV farm and DH facility. PV farm is owned by European Energy and will have an installed capacity of 20 MW. Based on information from European Energy, PV farm will have PV panels organized in DC-strings with each string having 32 PV modules of 0,6 kW each. Every 12 DC-strings would be connected to a 200 kW DC/AC inverter. An inverter loading ratio (ILR) is the ratio between the maximum DC power generated by PV panels connected to the inverter and inverter power rating. Higher ILR means that the grid connection could be made smaller, however more power from PV farm would be lost or has to be used elsewhere in the system behind PCC (this power is referred to as excess power).

DH facility is operated by BEOF. It provides DH for around 600 customers using 5 MW straw boiler. There is also a 1500 m^3 heat tank that can provide up to 80 MWh of heat. An additional electric boiler operated using the excess power from PV farm could be installed at the DH facility. Electric boiler can reduce the need for firing up the straw boiler and thus reduce emissions. Installing a DC boiler in particular would allow to use the excess power from PV farm (which is also DC) directly. BEOF is considering a supplier that can provide DC boiler units consisting of several heating elements, each element is 313 kW.

A 1,2 km cable (DC or AC) would be needed to connect two parts of the system together.

b. Connection schemes

Schemes for connecting PV farm with DC boiler are based on the design blocks shown in Figure 1. By introducing different configurations inside the blocks, three potential schemes depicted in Figure 2–Figure 4 are created.

Dimensions of components are based on the information about equipment suppliers received from both European Energy and BEOF. It should be noted that due to the lack of data about parameters of components that could realistically be used (based on existing contracts, geographical location, budget constraints, etc.) proposed schemes and selected components should be treated more like guidelines showcasing different design possibilities.

Pros and cons of each scheme are discussed using 5 categories: ease of implementation, reliability, fault protection, utilization of components and estimated cost & losses. Pros and cons are summarized in Table 1.

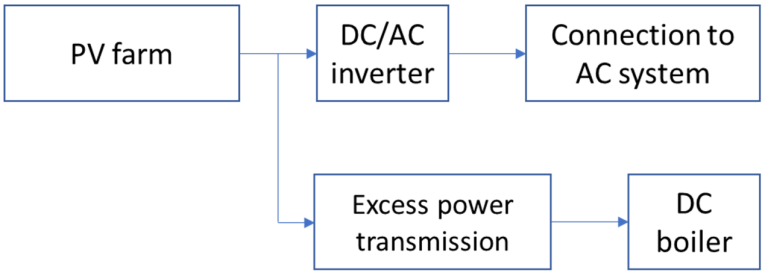


FIGURE 1 – DIAGRAM WITH NECESSARY DESIGN BLOCKS

In Scheme 1 (Figure 2) excess power is send through DC cable to an individual DC boiler unit. Each part of Scheme 1 is explained using design blocks below:

a. **"PV farm" block:** multiple PV modules are combined in a single DC-string. Since each string will be operated under slightly different weather conditions, it is proposed to install an individual DC/DC converter with maximum power point tracker (MPPT) system. MPPT system will vary its resistance in order to maximize the power output of the string at any given moment;
b. **"DC/AC inverter" block:** every 12 DC-strings are connected to a designated multi-string DC/AC inverter. Presently DC/DC converters with MPPT and DC/AC inverter are combined in one equipment unit (one box). However, to be able to send an excess power to the DH facility, it is necessary to get access to the middle point – a common DC bus – between DC/DC and DC/AC devices;
c. **"Connection to AC system" block:** utility-scale PV farm is likely to be connected to a high or medium voltage. To do that a step-up transformer has to be installed. A common AC bus is used to collect output power from multiple system modules (from 1 to 86);
d. **"Excess power transmission" block:** an excess power from each string is taken after DC/DC converter with MPPT and collected at a common DC bus. The power is further sent through a DC cable to a DH facility;
e. **"DC boiler" block:** DH facility has 86 DC boilers units each consisting of 1 heating element (86x1 = 86 boiler elements) and connected through a DC/DC chopper – a power electronics device that converts fixed DC voltage to a variable DC voltage. In this scheme it acts as a step-down transformer to lower input voltage to a voltage level of DC boiler unit.

Scheme 2 in Figure 3 addresses one of the cons of Scheme 1 by improving the utilization rate of DC boiler units by operating them through the 2nd common DC bus:

a. **"PV farm" block:** same as in Scheme 1;
b. **"DC/AC inverter" block:** same as in Scheme 1;
c. **"Connection to AC system" block:** same as in Scheme 1;
d. **"Excess power transmission" block:** an excess power from strings is collected at a common DC bus and is sent to DC/DC chopper 1 that is needed to be able to supply 2nd common DC bus with multiple power sources at the same voltage. The power is further sent through a DC cable to a DH facility;
e. **"DC boiler" block:** at DH facility there is a 2nd common DC bus that gathers the power from each system module. After that the total power could be efficiently distributed to DC boiler units with 4 heating elements through the use of their DC/DC choppers 2. Only 8 DC boiler units (8x4 = 32 boiler elements) have to be installed.

In Scheme 3 (Figure 4) the number of DC components and the need for complex DC protection are greatly decreased by using AC cable to the DH facility:

a. **"PV farm" block**: same as in Scheme 1;
b. **"DC/AC inverter" block**: same as in Scheme 1;
c. **"Connection to AC system" block**: same as in Scheme 1;

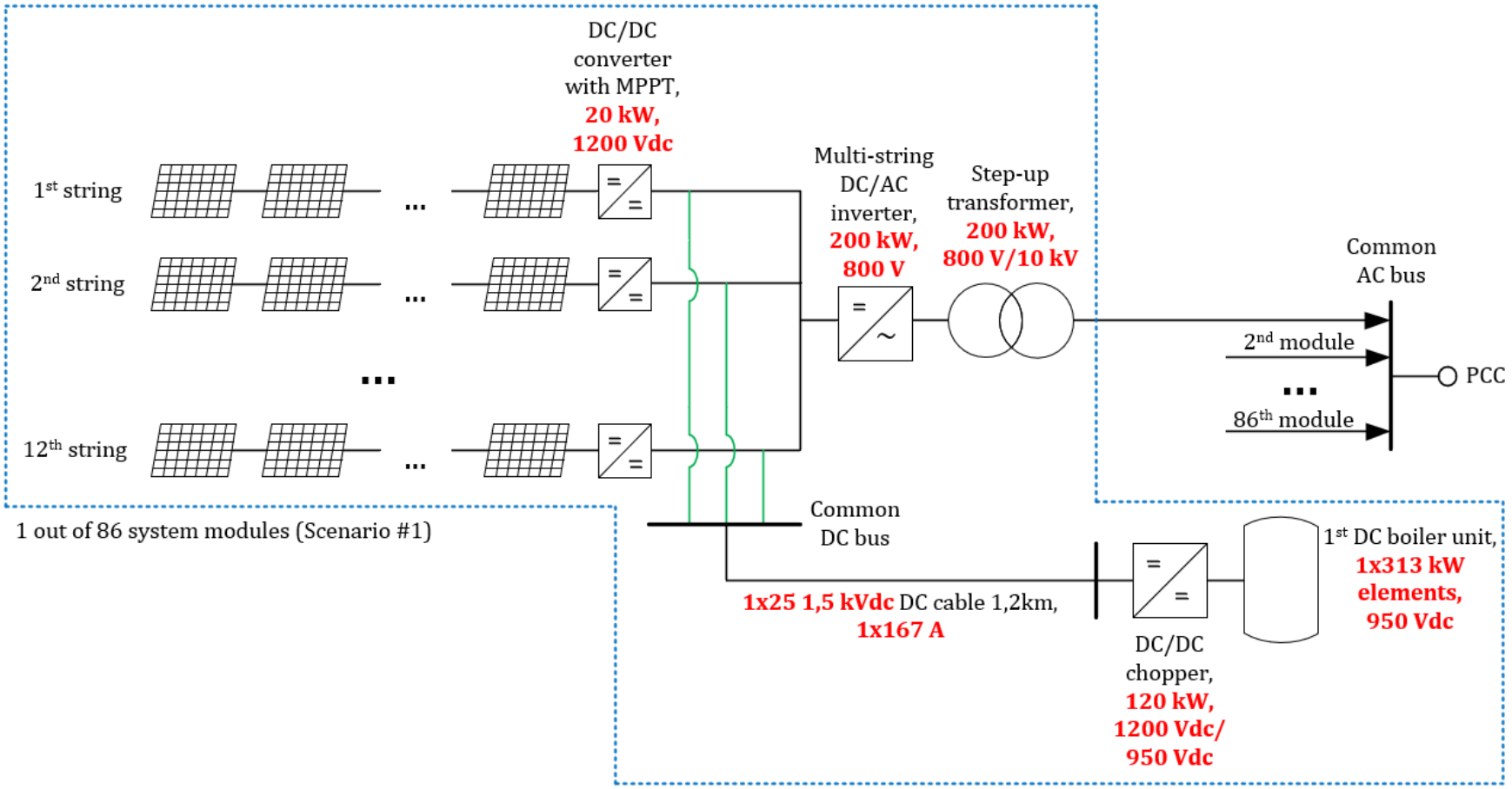


FIGURE 2 – SCHEME 1 WITH DESIGNATED DC BOILER IN EACH MODULE

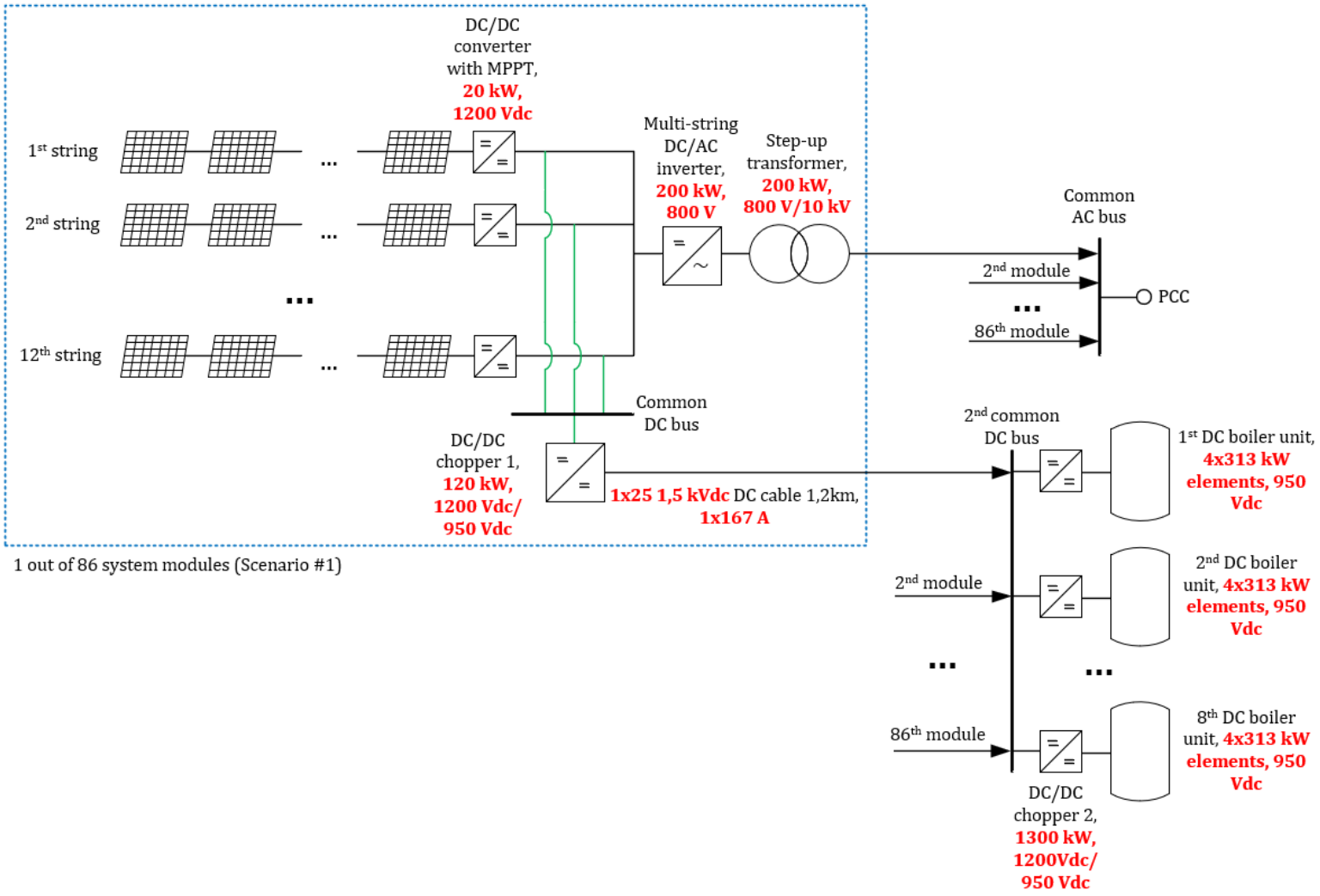
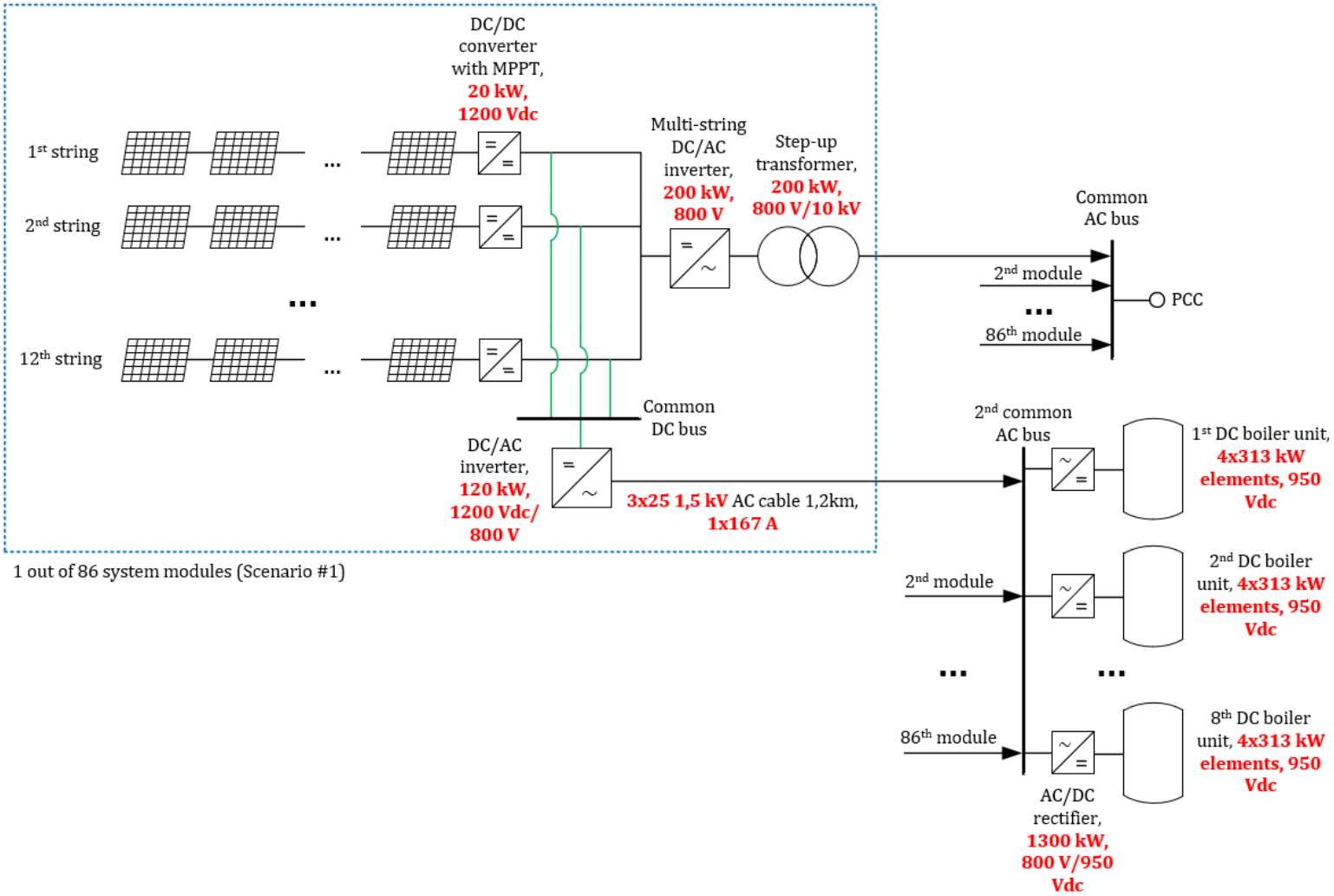


FIGURE 3 – SCHEME 2 WITH 2ND COMMON DC BUS SUPPLYING MULTIPLE DC BOILER UNITS



1 out of 86 system modules (Scenario #1)

FIGURE 4 – SCHEME 3 WITH AC CABLE AND 2ND COMMON AC BUS

TABLE 1 – PROS AND CONS OF THREE SCHEMES FOR CONNECTING PV FARM WITH DH FACILITY

Category	Scheme 1	Scheme 2	Scheme 3
Ease of implementation	**Medium:** Most of the components are combined in the system modules, straightforward integration of new modules. However, there are no standard solutions available for accessing the middle point between DC/DC converter with MPPT and DC/AC inverter.	**Hard:** Installation of the 2nd common DC bus able to withstand high power (up to 10 MW) is challenging/expensive. No standard solutions are available for accessing the middle point between DC/DC converter with MPPT and DC/AC inverter.	**Hard:** AC systems are easier to install and operate. However, due to the lack of DC cable connection this scheme is out of scope for this project and no standard solutions are available for accessing the middle point between DC/DC converter with MPPT and DC/AC inverter.
Reliability	**High:** Loss of generated PV power is reduced by having a large number of system modules.	**Medium:** Loss of the 2nd common DC bus will lead to inability to operate any DC boiler units.	**Medium:** Loss of the 2nd common AC bus will lead to inability to operate any DC boiler units.
Fault protection	**Normal:** No need for complex DC protection. DC protection is less reliable than AC, because there is no zero-crossing in the DC current. However, since each DC boiler unit is only supplied by 12 DC-strings, maximum DC power flowing in each system module is limited.	**Complex:** A fault at the 2nd common DC bus might be a challenge especially if it occurs at the time when excess power is at its maximum.	**Easy:** AC protection is much more mature technology than DC protection.
Utilization of components	**Low:** One boiler unit is powered only by 12 strings of PVs.	**High:** Instead of loading each boiler unit with low power, several boiler units could be loaded with higher power.	**High:** Instead of loading each boiler unit with low power, several boiler units could be loaded with higher power.
Estimated cost & losses	**High:** Due to each system module having individual components instead of sharing it with other modules the costs are high. Large number of components lead to higher losses.	**Low:** Due to fewer boiler elements needed estimated cost is low, however cost of protection is uncertain. Losses are lower with fewer components.	**Low:** Due to fewer boiler elements needed the estimated cost is low. Losses are lower than in Scheme 1, but higher than in Scheme 2 (AC losses are higher than DC).

d. **"Excess power transmission" block**: an excess power from each string is taken after DC/DC converter with MPPT and collected at a DC/AC inverter. The power is further sent through an AC cable to a DH facility;
e. **"DC boiler" block**: at DH facility there is a 2nd common AC bus that gathers the power from each system module. After that the total power could be efficiently distributed to DC boiler units with 4 heating elements though the use of their AC/DC rectifiers. Only 8 DC boilers (8x4 = 32 boiler units) have to be installed.

Estimation of the cost of each scheme is difficult due to the lack of components' cost data. Therefore, an indicator called "cost rating" that takes into account the number of components and their power rating is presented in Table 2 to be able to compare different schemes. Based on the cost rating schemes 2 and 3 are expected to cost less than scheme 1. It is also possible that scheme 3 would be even more cost-efficient than scheme 2 due to a wider selection of suppliers for AC components than DC alternatives.

To further improve the efficiency of the design, the amount of DC (or AC) cables could be reduced by combining power from multiple PV farm blocks (each with 12 DC-strings) before sending this power further to the DH facility. This will, however, require an installation of the 2nd common DC bus and increase the DC protection complexity.

Despite the advantages provided by Scheme 2 and 3, Scheme 1 is considered as the most optimal solution. This is due to the fact that this scheme combines high ease of implementation and good fault protection with project requirement of having a DC cable to the DH facility.

TABLE 2 – OVERVIEW OF COMPONENTS IN DIFFERENT SCHEMES AND COST ESTIMATION

	Scheme 1		Scheme 2		Scheme 3	
Component	**№ of components**	**Power rating, kW**	**№ of components**	**Power rating, kW**	**№ of components**	**Power rating, kW**
DC/DC converter with MPPT	1032	20	1032	20	1032	20
Multi-string DC/AC inverter	86	200	86	200	86	200
Step-up transformer	86	200	86	200	86	200
DC cable	86	25	86	25	0	0
AC cable	0	0	0	0	86	25
DC/DC chopper 1	86	120	86	120	0	0
DC/DC chopper 2	0	0	8	1300	0	0
DC/AC inverter	0	0	0	0	86	120
AC/DC rectifier	0	0	0	0	8	1300
DC boiler elements	86	313	32	313	32	313
Cost rating	**94428**		**87926**		**87926**	

III. Dimensioning and results

This section describes how the components shown in Scheme 1 in Figure 2 are dimensioned based on the time series data for total generated power from PV farm received from BEOF. Data from BEOF contains time series for six scenarios with their overview shown in Table 3. It is based on a one-year simulation of the combined system with one-hour time step.

TABLE 3 – OVERVIEW OF SCENARIOS

Scenario	Grid connection, MW	Heat tank capacity, MWh
SC1	10	80
SC2	12,5	80
SC3	15	80
SC4	10	120
SC5	12,5	120
SC6	15	120

Two sets of scenarios (SC1-SC3 and SC4-SC6) differ only in the heat tank capacity installed at the DH facility. SC1-SC3 considers the original heat tank capacity of 80 MWh, while in SC4-SC6 the tank capacity is increased to 120 MWh. However, since the capacity of the heat tank does not influence the total generated power from PV farm (sent to AC grid + excess power) and there is no limits how many boiler units could be installed, the dimensioning of the system with PV farm and DC boiler will be the same for both scenario sets.

Further in the text dimensioning for SC1 is described with the remarks about other scenarios at the end of the section. Input information for SC1 is shown in Figure 5, where the maximum PV power sent to the AC grid equal to 10 MW (equal to grid connection at PCC), while the highest excess power is 9,69 MW.

a. "PV farm" block

From the information from European Energy, each PV DC-string will consist of 32 PV modules of 0,6 kW each that gives 32 x 0,6 kW = 19,2 kW of power per DC-string. It would require 1032 DC-strings in order to achieve the total power shown in Figure 5 with maximum power per DC-string equal to (10 MW + 9,69 MW) x 1000 / 1032 = 19,08 kW. Each DC-string should have a dedicated 20 kW DC/DC converter with MPPT with assumed efficiency of 99%. Its output voltage is 1200 Vdc.

Every 12 DC-strings organized in system modules as was shown in Figure 2. That is why the total number of DC-strings is selected as multiples of 12.

b. "DC/AC inverter" block

Each multi-string DC/AC inverter is taking inputs from 12 DC-strings. Therefore, the total of 1032 / 12 = 86 DC/AC inverters needed for the system with assumed efficiency of 97,6%. Without excess power, every 12 DC-strings will deliver maximum of 9,7 kW x 12 = 116,4 kW to the DC/AC inverter.

European Energy expects to use the 200 kW DC/AC inverter with 1200 Vdc/800 V. Selecting a model with lower power rating (selected to be just enough to withstand maximum power of 116,4 kW, e.g. 120 kW) could be considered for potential cost reduction.

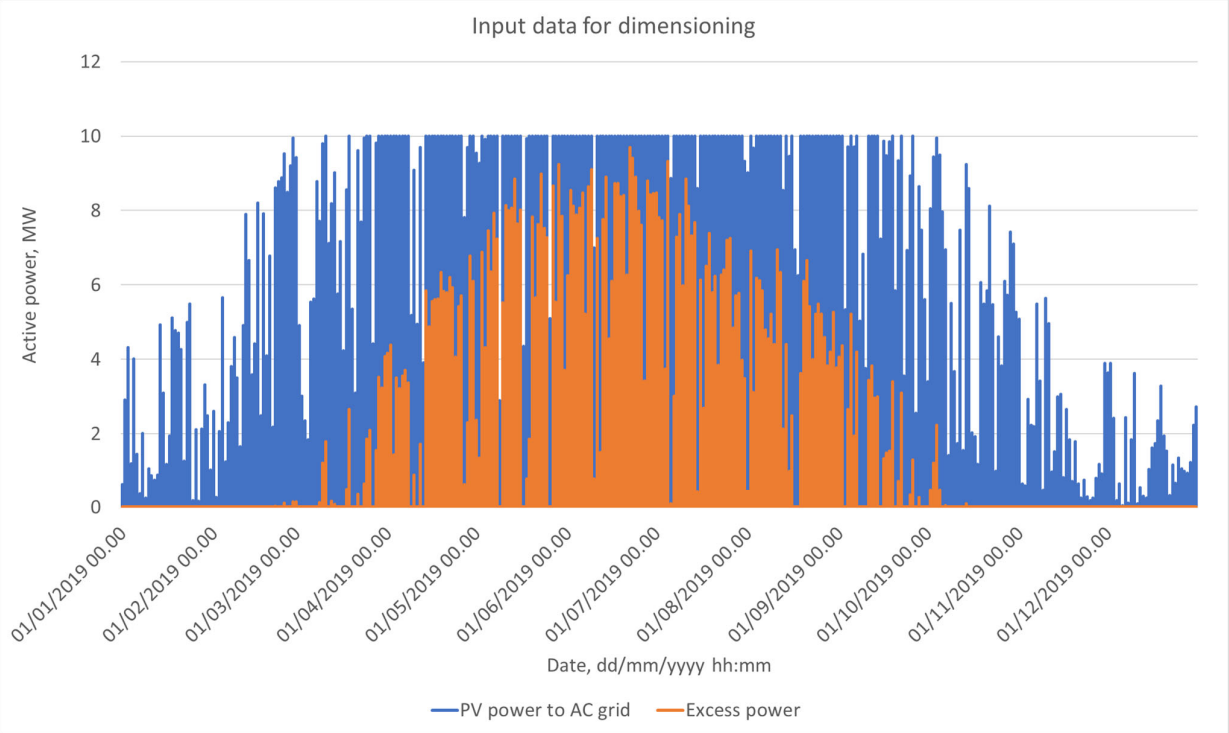


FIGURE 5 – INPUT DATA SHOWING PORTIONS OF PV POWER SENT TO AC GRID AND EXCESS POWER SENT TO DC BOILER FOR SCENARIO SC1

c. "Connection to AC system" block

It is proposed to install a 200 kW step-up transformer with voltages of 800 V/10 kV for each of the 86 DC/AC inverters. The size is selected to correspond to the inverter rating and could be made smaller to reduce cost. Each transformer sends power further to the common AC bus which is connected to the PCC.

d. "Excess power transmission" block

When total generated power from PV farm gets higher than the size of the grid connection, an excess power would be taken from each of the 12 DC-strings in a system module and sent to the common DC bus. Maximum power at the common DC bus for each system module from the input data is equal to 9,69 MW x 99% / 86 = 112 kW (where 99% is efficiency of each DC/DC converter with MPPT and 86 is the number of system modules).

DC cable could be dimensioned based on the maximum current that will flow through it. It is equal to 112 kW x 1000 / 1200 Vdc = 93,3 A. From [4] a single core DC cable with 16 mm^2 cross-section (1x16) able to withstand 125 A is selected. Cable resistance is 1,24 Ohm/km and length is 1,2 km.

A cable with smaller cross-section can lead to higher power losses that are calculated as 93,3 A x 93,3 A x 1,24 Ohm/km x 1,2 km = 12,95 kW at full power. For the whole system maximum relative power loss (compared to the maximum excess power delivered to the common DC bus) becomes (12,95 kW x 86)/(112 kW x 86) = 11,56 % at full power. Since there are only few periods when the full power will be flowing through the cable, such high losses could be accepted, if the average relative power loss during the full year is low. Based on the actual power losses profile shown in Figure 6, the average relative power loss would be 6,16%. Here and further the average values are calculated only considering hours with non-zero values.

Voltage drop at the end of DC cable is equal to 93,3 A x 1,24 Ohm/km x 1,2 km = 138,8 Vdc.

Maximum and average relative power losses and voltage drops with other cables are shown in Table 4.

TABLE 4 – RELATIVE LOSSES AND VOLTAGE DROPS WITH DIFFERENT DC CABLES

Cross-section, mm^2	Resistance, Ohm/km	Maximum relative loss at full power, %	Average relative loss, %	Voltage drop, Vdc
1x16	1,240	11,56	6,16	138,80
1x25	0,795	7,39	3,95	88,69
1x35	0,565	5,25	2,81	63,03
1x50	0,393	3,65	1,95	43,84
1x70	0,277	2,58	1,38	30,90
1x95	0,210	1,95	1,04	23,43
1x120	0,164	1,52	0,81	18,30
1x150	0,132	1,23	0,66	14,73
1x185	0,108	1,00	0,54	12,05
1x240	0,082	0,76	0,41	9,15

It follows from Table 4 that choosing a larger cross-section of the cable will bring the losses down. Generally, it is desirable to keep the average relative power loss under 5% and therefore it is proposed to use 1x25 DC cable with 3,95% of average relative loss. Larger cables could be used for transmitting excess power from multiple PV farm blocks (multiple 12 DC-strings). Selected DC cable is able to withstand DC voltage of 1,5 kVdc.

Figure 7 shows the ratio between power losses on the DC cable and available excess power from PV farm for one year (maximum relative power loss is 7,32% and average relative power loss is 3,91%).

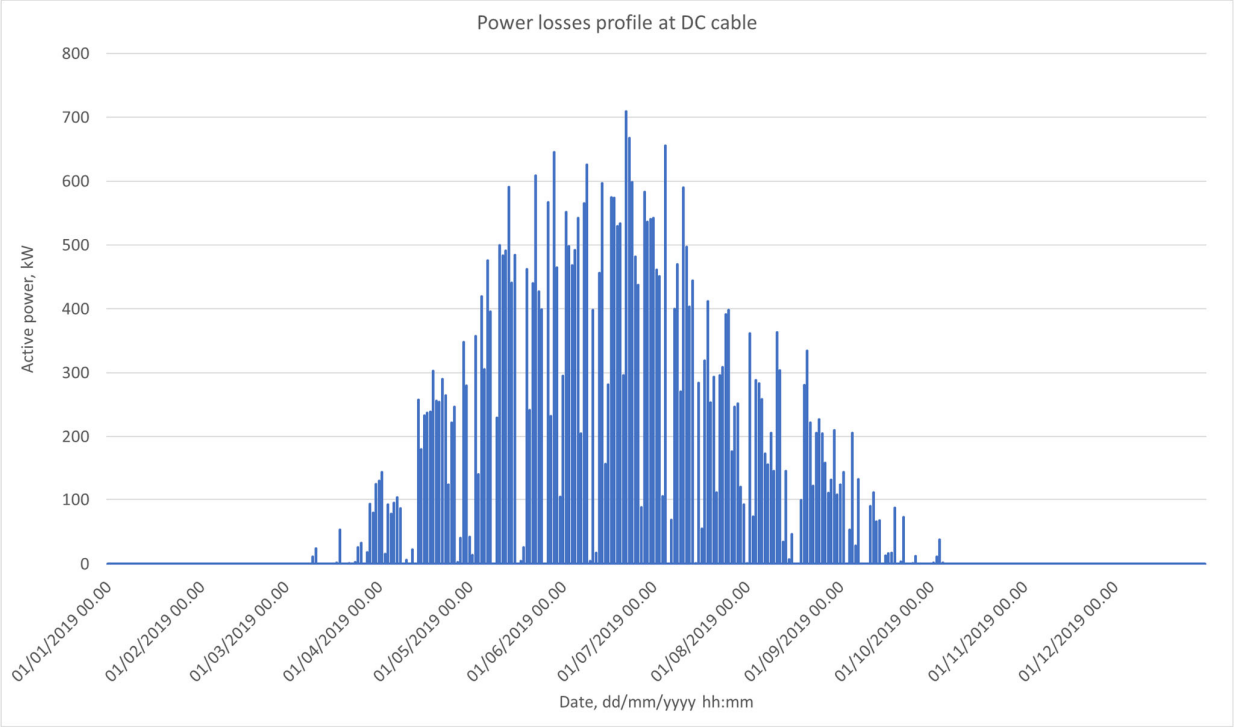


FIGURE 6 – POWER LOSSES PROFILE FOR ONE YEAR WITH 1X25 DC CABLE IN SC1

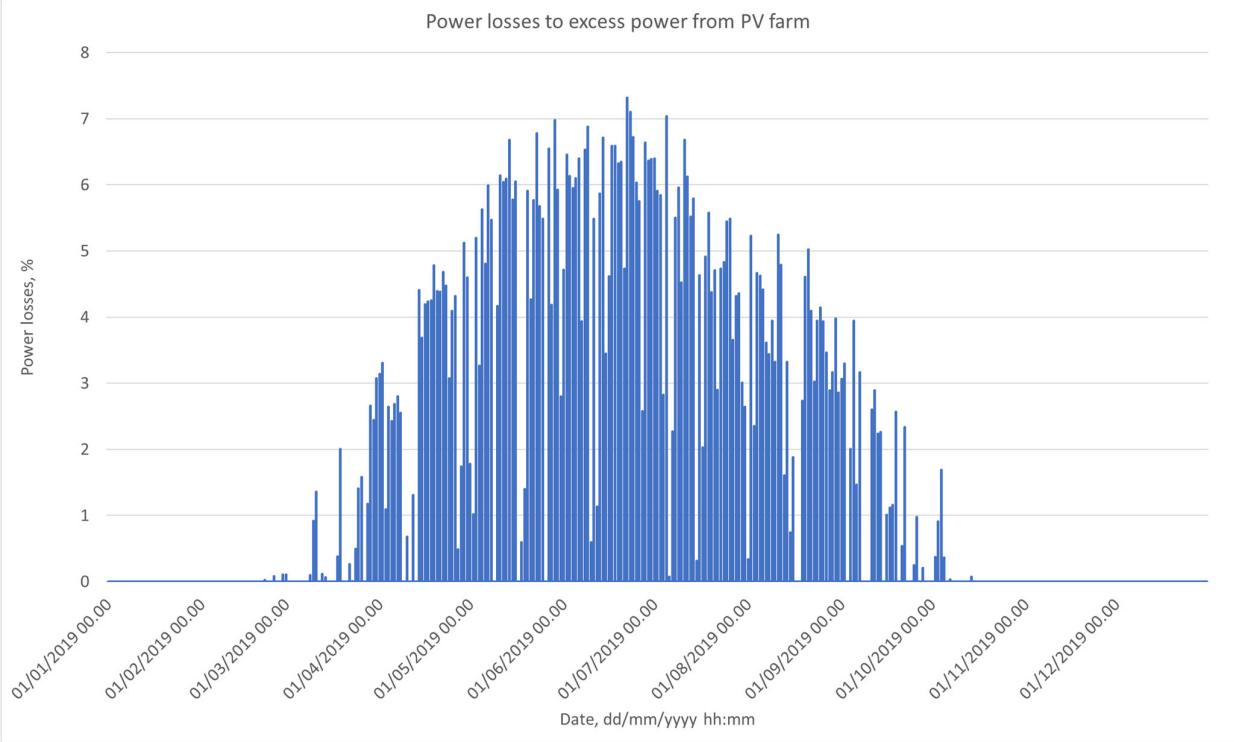


FIGURE 7 – PROFILE SHOWING POWER LOSSES IN RESPECT TO EXCESS POWER FROM PV FARM IN SC1

e. "DC boiler" block

Maximum amount of power that arrives to the DH facility after DC cable is equal to 112 kW x (100% - 7,39%) = 103,7 kW at voltage 1200 Vdc – 88,69 Vdc = 1111,3 Vdc. Based on these parameters a 120 kW DC/DC chopper capable of taken input voltage of around 1200 Vdc and delivering an output of 950 Vdc (assumed efficiency is 99%) should be used for controlling the DC boiler unit. DC/DC chopper here acts as a step-down transformer.

To dimension a DC boiler an information from BEOF had been used. As was mentioned previously selected DC boiler can include several heating elements of 313 kW each. Since power rating of even a single heating element is 3 times larger than the maximum amount of excess power from each of the 86th system modules, the highest utilization rate of a single DC boiler unit is (103,7 kW * 99%) / 313 kW = 32,8 % (where 99% is the efficiency of the DC/DC chopper). The average utilization rate is even lower.

Figure 8 shows what percentage of the excess power from PV farm would be available at the DC boiler units. At best 98% of power is available, with average available power equal to 94,14%. The lowest efficiency is 90,77% which is due to the losses is DC/DC converter with MPPT, DC cable and DC/DC chopper. The losses from the DC cable are dominating among the total losses.

Excess power from PV farm, available power at DC boiler units, cable and converter losses for scenarios SC1-SC6 are summarized in Table 5 and Table 6.

f. Dimensioning in other scenarios

In scenarios SC2 and SC3 the size of the grid connection is increased to 12,5 MW and 15 MW, respectively. This will affect several things:

- In the "DC/AC inverter" block: every 12 DC-strings will deliver the maximum power of 140 kW or 168 kW (instead of 116,4 kW in SC1) to the DC/AC inverter. However, this will not have any impact on the system's dimensioning since 200 kW DC/AC inverter would be used by European Energy;
- In the "Excess power transmission" block: maximum power at the common DC bus for each system module becomes 82,8 kW or 54,0 kW (instead of 112 kW). This will reduce the current flowing through the DC cable and smaller cross-section could now be selected;
- In the "DC boiler" block: maximum power available for each DC boiler unit will be reduced. This will have no impact on dimensioning because heating elements with smaller power ratings are not available.

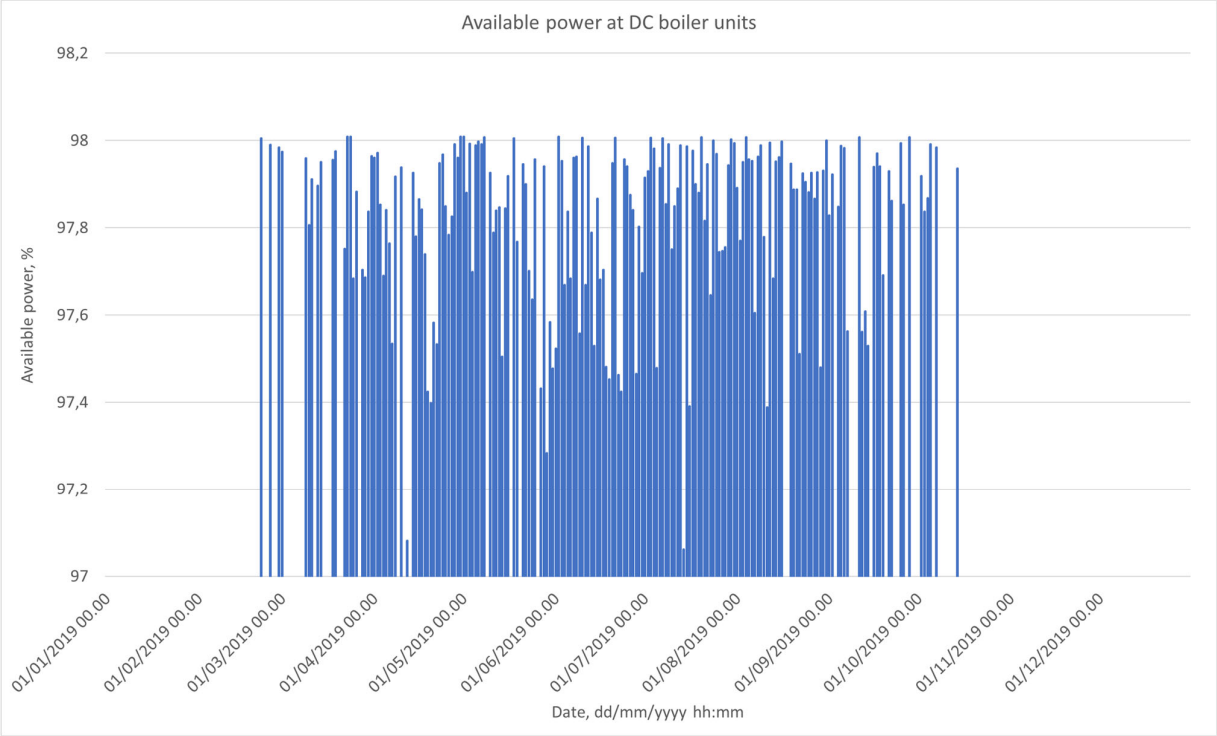


FIGURE 8 – AVAILABLE POWER AT DC BOILER UNITS IN RESPECT TO EXCESS POWER FROM PV FARM IN SC1

TABLE 5 – OVERVIEW OF EXCESS AND AVAILABLE POWER AND LOSSES

	Annual			Maximum			Average		
	SC1 & SC4	SC2 & SC5	SC3 & SC6	SC1 & SC4	SC2 & SC5	SC3 & SC6	SC1 & SC4	SC2 & SC5	SC3 & SC6
	MWh			MW			MW		
Excess power from PV farm	3981,06	1919,50	657,86	9,69	7,19	4,69	3,06	2,02	1,17
Available power at DC boiler units	3747,83	1828,50	633,54	8,80	6,66	4,43	2,89	1,93	1,13
Cable losses	155,56	53,34	11,34	0,71	0,39	0,17	0,12	0,06	0,02
Converter losses	77,67	37,66	12,98	0,19	0,14	0,09	0,06	0,04	0,02

TABLE 6 – OVERVIEW OF EXCESS AND AVAILABLE POWER AND LOSSES (RELATIVE VALUES)

	Annual			Maximum			Average		
	SC1 & SC4	SC2 & SC5	SC3 & SC6	SC1 & SC4	SC2 & SC5	SC3 & SC6	SC1 & SC4	SC2 & SC5	SC3 & SC6
	%			%			%		
Excess power from PV farm	100,00	100,00	100,00	100,00	100,00	100,00	100,00	100,00	100,00
Available power at DC boiler units	94,14	95,26	96,30	90,77	92,64	94,50	94,14	95,26	96,30
Cable losses	3,91	2,78	1,72	7,32	5,43	3,54	3,91	2,78	1,72
Converter losses	1,95	1,96	1,97	1,92	1,94	1,95	1,95	1,96	1,97

IV. Conclusions

This report presents three schemes for utilizing excess power from PV farm at the DH facility. The pros and cons of each scheme are considered based on 5 categories: ease of implementation, reliability, fault protection, utilization of components and estimated cost & losses. In the end Scheme 1 is selected as the most optimal solution and its dimensioning is further explained in the text.

Due to the oversized components that would likely be used by BEOF and/or European Energy in their respective parts of the system (DC boiler units and some of the power electronics devices), change in the grid connection observed in SC1-SC3 will lead to minimal changes in the scheme design. The only change would be the size of the DC-cable, which can be made smaller with larger size of the grid connection. Difference between heat tank capacity in scenario sets of SC1-SC3 and SC4-SC6 will not have an impact on the design.

An overview of the excess power from PV farm, available power at the DC boiler units and losses (from cables and converters) had been provided for each scenario. In scenarios SC1, SC2, SC4, SC5 the majority of the losses occur in the cables, which makes selecting a proper cross-section especially important. For scenarios SC3 and SC6, however, the losses in converters surpass the losses in DC cables. The actual and relative losses decrease if the total amount of excess power sent to DH facility is reduced. Due to this the efficiency of the scheme is higher in the scenarios with lower excess power/higher grid connection size such as SC3 and SC6.

Lack of the cost data and detailed information of what components could potentially be installed did not allow an analysis in this report be more detailed.

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