Interreg North-West Europe
D2Grids
European Regional Development Fund

PRELIMINARY GENERIC 5GDHC TECHNOLOGY MODEL

WORK PACKAGE : WPT1

DELIVERABLE NUMBER : DEL.T1.1.4

February 2021

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Data sources: European Climate Foundation, Matthiesen et al. (2019), Lund et al. (2014), Boesten et al. (2019)

Report done by: VITO

This document was produced as a cooperation of partners within the Interreg NEW project D2Grids. The D2GRIDS project aims to develop 5th generation urban heating and cooling networks (5GDHC) in Europe.

For further information on D2Grids please visit www.nweurope.eu/d2grids. For more information on 5GDHC, please visit 5gdhc.eu.

TABLE OF CONTENTS

TABLE OF FIGURES

1. Introduction

The Interreg-NWE D2Grids project [1] [2] [3] aims to increase the share of renewable energy in North-West Europe by upscaling the use of 5th generation district heating and cooling grids (5GDHC) [4].

D2Grids aims to accelerate the implementation of 5GDHC grids in three ways:

1. industrialization of the system through developing a generic technology model and product standards;
2. boosting commercialization potential of 5GDHC systems through presenting solid business plans and attracting investors;
3. demonstrate the 5GDHC technology in pilots in Bochum (DE), Brunssum (NL), Glasgow (UK), Nottingham (UK) and Paris-Saclay (FR).

The final generic 5GDHC technology model (to be produced by project's end) will be developed based on conclusions from the pilots and the standardisation process. It defines system features, basic parameters, and variations under different conditions (e.g., specific subsurface models for underground reservoirs). Following this, Deliverable D.T1.2.4 "Monitoring and evaluation methodology on the technical design, realization and operation of the pilot investment" is needed to ensure that the pilot sites properly adapt and demonstrate the 5GDHC technology model (D.T.1.1.4).

This preliminary version of the model defines the preliminary technical specifications of a 5GDHC grid[1]. In this document, the goal is to define several practical Key Performance Indicators (KPIs) that will be useful to monitor, measure and evaluate how far pilots have progressed in achieving these goals. D2Grids aims to use these KPIs to set up a methodology [D.T1.2.4] to define a label for certification of 5GDHC grids and to evaluate their status of development.

We will start from the definition and explain the key factors of a 5th generation network. To specify the content of the discussion, we have set the boundaries of the network. Next, the possible energy sources will be discussed. At the end of the document, some evaluation tools are provided to look at existing networks or to be applied in the evaluation of the pilot sites.

The definition was a work in progress and during the Steering Committee of October 2020 it was agreed upon to use the definition as is expressed below throughout the rest of the project.

[1] The terms network and grid are used simultaneous. Please check the glossary at the back to for specifications in the use of the terms.

2. Definition 5G DHC and features of the pilots

2.1 Definition

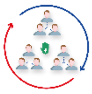
To ensure a flexible and resilient energy network to meet current and future needs, a 5th generation heating and cooling system (5GDHC) is established on the following five principles:

1/ Closing the energy loop

An optimized system allowing exchange of heat and cold between end users.

2/ Using low-grade sources for low-grade demand

In 5GDHC we match the supply with the requested quality level of the demand.



3/ Decentralized & demand-driven energy supply

Circulating energy within the system only when and where needed, as close as possible to the end-user

4/ An integrated approach of energy flows

Connecting heating and cooling to other energy flows (power grid, hydrogen conversion, solar plants, etc.) to avoid energy waste across sectors and reduce peak loads.

5/ Local sources as a priority

Avoiding big investments and energy loss during transport, while stimulating the local economy.

Elucidation

1. Heated and cooled buildings will always lose energy, which must be compensated with external sources and/or between buildings (fulfilling cooling demand delivers heat to the DHC-system and fulfilling heating demand delivers cold to the DHC-system). The idea of the 1st principle is to prevent internal waste in the system, by reusing and closing energy loops as much as possible and by using energy storage for temporal imbalance. The key factor in the 5GDHC approach is the optimal re-use of the return flows at differing spatial and time scales. We work bottom up on this principle, by first exchanging within a building/complex, second on cluster/neighborhood level, and finally at city/district level. Further optimization will not be technical, but more so in spatial planning.

2. In the future, the amount of high-grade (high exergy) sources will be limited. Apart from meeting local demand with the large available flows of low-grade energy (like shallow geothermal, industrial waste flows, conversion waste, waste from cooling processes, sewage etc.), the unavoidable amount of additionally (high-grade) supply is best taken form green sources like deep geothermal, windmills, solar, hydropower, and biomass. This allows the system to fully phase out fossil fuels and regenerate its thermal energy from the low-grade thermal energy sources.

3. Many systems are centralized and demand-controlled, for example in monitoring the return flows of energy. Those systems circulate a lot of energy which is never used. So, this principle's aim is to work bottom-up, and to start generating and circulating energy only if a demand occurs. This focuses on enabling the ability to simultaneously deliver heating and cooling services at different temperatures to different customers, exactly as demanded, when demanded, and never more than needed.

4. Many energy systems contain split incentives, which means that they do not optimize on the integral need across systems and sectors. Integration is not only important for saving energy, but also for reduced investments in capacities, like managing

peak loads. The aim of this principle is to develop a 5GDHC system to be integrated with all other energy flows in a given area (power grid, transport, industry, agriculture, etc.) to maximize optimum efficiency of energy delivery and use.

5. Often, plans are made on large scale and considering big plans with distant energy sources. The business case is not always integral, so some costs are for end-users and others seen as societal costs. The aim of this principle is what you can get locally should be prioritized above more distant sources, to save on transport losses and investments.

2.2 Features of the D2Grids pilots

The D2Grids project aims for 5GDHC pilots in Brunssum (Netherlands), Paris-Saclay (France), Bochum (Germany), Glasgow (Scotland) and Nottingham (England). This paragraph describes the features of the pilots.

The features for each pilot are that it tries to fulfil all the properties from the definition above as much as possible:

- is a low-grade thermal energy grid,
- uses low grade sources for low grade demand,
- aims for closed energy loops
- contains physically an energy source, distribution pipes, pumps, thermal storage, active energy substations (e.g., heat pumps), and heat exchangers,
- at least two different functions (heat & cold load),
- implies a fluctuating grid temperature, preferable close to ground temperature to avoid thermal losses
- aims to use 100% renewable energy,
- is integrated with the power grid that enables thermal storage of surplus electrical energy generated by RES,
- is future ready for upscaling (modular growth) technically and financially,
- allows an open access network for suppliers

The baseline document of VITO [D.T1.1.1] also describes the following additional properties:

- A smart control and safeguarding system to optimize the operation of the network
- Can be coupled to direct industrial and urban excess heat or cold
- Can be coupled to renewable heat and cold sources

3. Boundaries of a 5th generation network

To evaluate and define the status towards 5GDHC, it is essential to define what will be considered. We must set the boundaries of the network.

At this stage of the project, 5GDHC references are minimum. D2Grids will define reference scenarios in an iterative fashion during the project.

The system boundary at this stage is set as:

- Measures in/on the building are excluded from the system.
- At the boundary, there is only energy exchange.

The choice for the system boundary can be flexible. It could be at the location of the meter, depending on the local network implementation or the local legislation.

In a later phase it can be interesting to look more into detail, on a connection level or cluster level, to optimize the network's performance. In this stage we look at the broader picture and the progression of a network towards the 5GDHC principles.

The system boundary (light blue dotted line) for thermal performance is illustrated in Figure 1. The system boundary for electricity and CO_2 emission is presented in Figure 2.

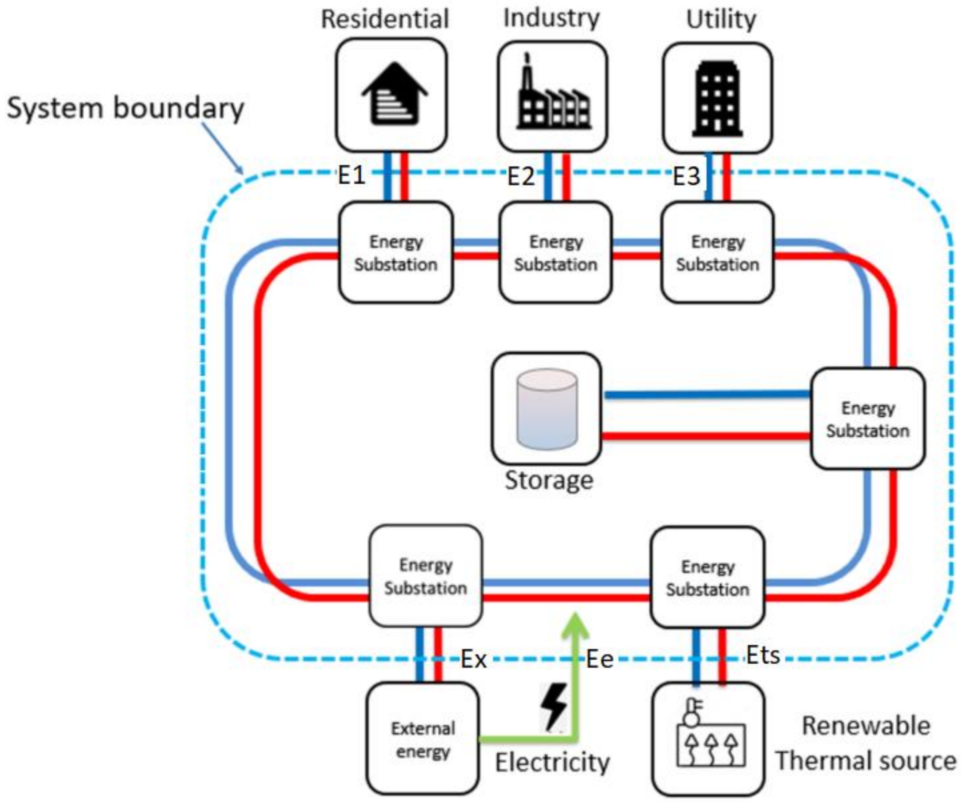


Figure 1: Illustration of system boundaries for thermal performance

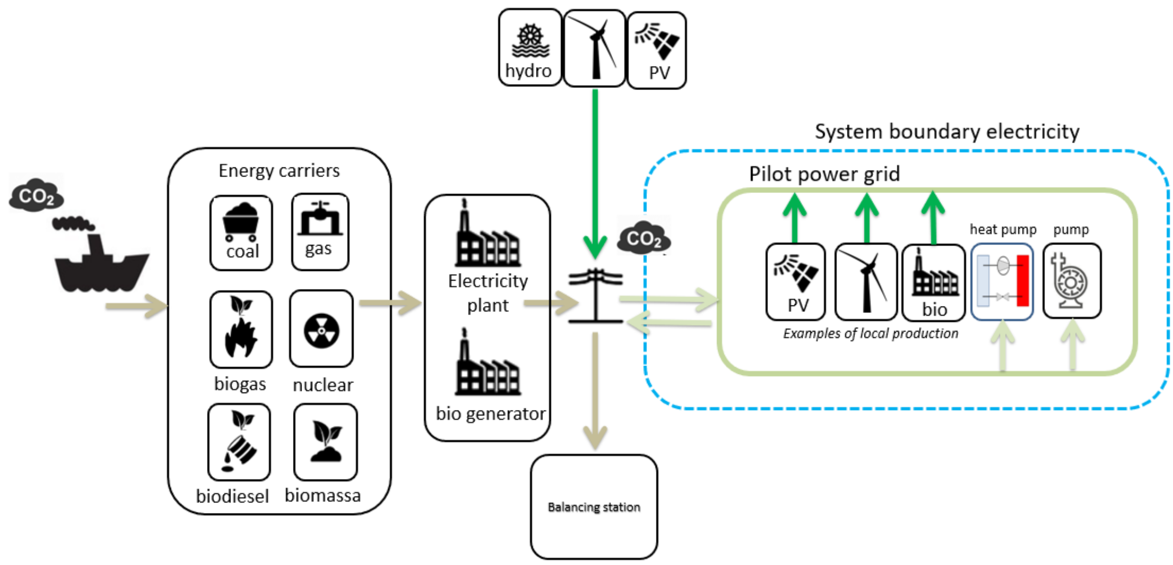


Figure 2: Illustration of system boundary for electricity and carbon emission

Electricity

Often there is no separate power grid for district heating, but a connection to an existing power grid. For 5GDHC grids:

- The system boundary should be equal to the thermal boundary.
- Electricity is input for all thermal energy suppliers. This thermal energy goes into the grid.
- We don't consider the power grid an isolated system. It will be connected to the main grid that has an average CO_2 emission. (to be determined annually).
- The power grid itself is not a separate system for our 5GDHC

Considering CO_2:

- CO_2 emissions should be allocated to thermal / electrical energy inputs. No separate system boundary required.

4. Energy

The way energy is used is very characteristic for a 5th generation network, as mentioned above in the definition (see section 2.1).

In a traditional 4th generation network, there is limited or even no energy exchange between connections to the network.

A 5th generation network is distinguished from other DHC networks by the capability of exchanging energy to other connected consumers/customers.

As referenced in *Figure 1*, one can see that there is energy exchange (over the blue dotted line) on six locations:

- Customers:
  - Residential (E1)
  - industry (E2)
  - utility (E3)
- Sources:
  - Renewable thermals source: Ets
  - Electricity grid: Ee
  - External energy source: Ex

For a 5th generation network, we must identify how well the energy is exchanged between E1, E2 and E3. Therefore, we must compare how much energy comes from the sources and how much energy is consumed by the customers.

Conversely, we need be sure that the quality of the energy conforms to the 5th generation definition. We clearly want to avoid high temperature input from CO_2 emitting sources.

In the next paragraphs, we go into the restrictions for the energy in the network and the energy input from sources outside of the system.

4.1 Net energy input

A 5GDHC ideally recovers its own thermal energy, which means the system ideally does not require additional thermal energy from outside the system. Such a system is the aim of a 5th generation network. It is however physically impossible as there will always be losses along the way.

Besides of the demand of thermal energy, the system requires electricity for the heat pumps and distribution pumps. The aim is to maximize the amount of useful (low grade) energy exchanged compared to the thermal / electrical input/work.

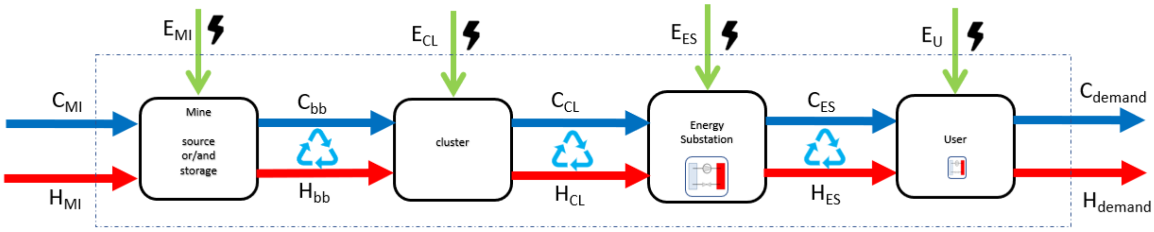


Figure 3: Different levels of energy input

The net energy input is the total energy demand of the system including both electricity and thermal.

$$Energy\ Total = Energy\ Thermal + Energy\ Electrical$$

4.2 Ranking of types of input energy

To optimize the 5GDHC goals, a ranking by preference is proposed for the types of input energy to be used in a 5GDHC heating and cooling network, defined in a way that each class can be assigned in an unambiguous way:

1. Reuse of thermal energy, by exchange between heating and cooling demands
2. Ambient thermal sources from soil, water, air, and low temperature solar heat
3. Higher temperature renewable sources like Geothermal, Solar heat
4. Higher temperature industrial waste heat, otherwise rejected in the environment
5. Renewable electricity from local sources like wind, sun
6. Electricity use at times of renewable overproduction, e.g., when spot price is low
7. Electricity mixes from the external grid
8. High temperature heat from burning biofuels, biogas, biomass
9. High temperature heat from burning fossil fuels

Input source types 1—4 are the 'low grade thermal energy sources' that a 5GDHC grid would need to gather, distribute, and exploit to the maximum possible extent. The first and highest priority is given to thermal energy that is exchanged between users, and in some sense created from nothing by the 5GDHC system. Following at position 2 are ambient thermal sources, but also renewable thermal sources with temperatures higher than the typical 'warm' temperature of the grid. It may be somewhat better if these can be used for a higher temperature demand first, with waste heat from that fed to the 5G system.

Input source type 4 is the potentially important but also contentious source of heat is waste heat coming from industry. One could again argue that this heat should first find a higher temperature application, matching the higher temperature. One could also argue that this heat is often the result of burning (fossil) fuels, associated with emissions of CO_2 (among others). The goal for this input class is to have enough strong arguments to convince any certifying organization that this is actually waste heat, and that the only alternative would have been to reject this heat into the environment via chillers or cooling towers. That is clear when the heat can be considered the result of cooling services delivered to the industry in question. The industry is then willing to pay for the service, at least as much as the alternative cooling facilities would cost. Regulation could enforce use of more sustainable cooling alternatives like 5GDHC. At least some effort should be done, by the industry itself, possibly with help from the 5GDHC grid, to reuse any high temperature waste heat internally at the same site, or its near neighbours.

Input source types 5—7 are sources of electricity from renewable sources, or from the 'grey' grid. A 5G system can optimize the moments it demands electricity to maximize renewables (often also minimize the spot market price).

Finally, source types 8 and 9 should be avoided in general, but exceptions are possible. It may be a temporary need while building a grid. Or e.g., there may be an industrial waste heat source that misses the strong requirements of type 4, but which would otherwise be wasted by rejecting it in chillers or cooling towers. Heat from a conventional heating grid usually fits here, as it is usually (re)generated by burning fuels.

4.3 Energy exchange factor

In the ideal case, a 5GDHC grid exchanges all thermal energy within the network. The exchange factor is then 100%. The total energy demand of the network is covered by exchange of energy. This is the ambition of 5GDHC, but no network could meet this at this stage. To define an exchange factor, we need to (based on *Figure 1*, see page 8) define what amount of energy is exchanged outside of the network.

A network consists of:

- Sources (preferable renewable)
- Customers (connections to the network)
- Storage[2] (buffering the heating and cooling loads)

If we want to measure the energy exchange outside of the defined boundaries, we should measure the energy exchange with the sources (Ets, Ex, Ee) **Erreur ! Source du renvoi introuvable.**. We can also measure the energy exchange between the connected customers and the network (E1, E2, E3).

The sum of all energy demands of the customers is the total energy demand for the network (E_{demand})

$$Total\ energy\ demand\ (\ E_{demand}) =\ E_1 +\ E_2 +\ E_3$$

The external energy input from the sources is the energy supplied in the network (E_{supply}):

$$Total\ supplied\ energy\ (E_{supply}) = \ \ E_{ts} +\ E_x +\ E_e$$

For the network, this would lead to:

$$Energy\ exchange\ Factor\ (EF) = \frac{E_{demand} -\ E_{supply}}{E_{demand}} x\ 100\%$$

This factor can be 0% if E_{demand} is equal to E_{supply}, this would mean that all energy injected in the network is consumed and nothing of the energy is exchanged between the connected customers.

The factor will be 100% in the ideal case that E_{supply} =0, there is no external energy needed for the network. So, a perfect exchange of energy is designed.

Required monitoring

- Net energy input/output
- Thermal demand per building

In most cases it might be useful to look at heating and cooling separately. Therefore, the above formula can be subdivided as:

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[2] *Storage is essential for 5GDHC but is not taken into account further in this calculations as it has no connection outside of the network.*

The supply streams of heat and cold take away part of the waste streams, so we can give the heat exchange (H_{ex}) and cold exchange (C_{ex}) definitions. Here we assume, conservatively, that the dissipated electricity is converted to heat, which is subtracted from the exchanged cold:

$$C_{ex} = H_{demand} - H_{supply} - E_s$$

$$H_{ex} = C_{demand} - C_{supply}$$

5. Flexibility

A 5th generation network has a good connection to the electricity grid and can help balancing the electricity grid. The first priority is to use flexibility and storage to optimally make use of the thermal grid itself. If the same job can be done by a system with smaller peak capacity, this lowers the overall investments needed in pipelines, pumps, heat pumps, etc. If peaks in thermal demand are handled efficiently, the system will automatically shave its peak demands on electricity needed for heat pumps and pumps in the system. This allows for lower investment in infrastructure, and it limits the necessary capacity of the electrical connection.

Possibly the most immediate peak-shaving devices are the DHW (district hot water) buffer tanks. The hot water buffer tanks prevent any sudden peaks in electricity, as hot water is prepared before use, in advance, by relatively modest booster heat pumps. Likewise, the thermal mass of all buildings is a built-in store of heat. Since heat losses in well-insulated buildings are modest, it is reasonable also for space heating to anticipate, and allow some time to prepare the demanded temperatures. The next step is that every building, or every energy plant serving several buildings, will have its own somewhat larger tank storage for heat and cold. Finally, the larger system will have its long-term storage that helps flatten the longer-term peaks in demand.

Once all peaks in thermal demand can be flattened and spread over a longer period of time, the system will be very robust. It will not be necessary to have high-capacity heat sources on standby, based on burning fuels. And it will not be necessary to depend on the electricity grid to satisfy peaks in thermal demand either. However, when this is achieved, the system can also provide flexibility services to an electricity generation system that increasingly depends on variable renewables like sun and wind.

Whenever necessary, the system will have a certain capability to absorb peaks in the production of electricity. This can be to maximise self-use from renewables like solar panels inside the system. It could also be to absorb production peaks on the external electric grid, from variable renewables like sun and wind.

This also works the other way round. Whenever all the systemic thermal buffers at a relatively high state of charge (SOC), it becomes possible to artificially lower the external electricity demand for a limited period, while emptying those buffers. Since variations in renewable sources like wind or sun can be predicted rather well, such a capability can help smooth a shortfall in production.

To summarize, the system as a whole can be run in several controlled modes that optimise overall peak demand of electricity, depending on the weather and any possible predictions or urgent needs from the external electricity grid:

1. A state of robust equilibrium, no special external needs. Keep all systemic thermal buffers near to optimal average state, which may depend on the weather. In this state, peaks in electricity demand are kept at a moderate level, both at all local points of demand. The system may actively decorrelate all points of electric use, e.g., avoid that not too many heat pumps turn on at exactly the same moment.
2. For a short period of time, it is possible to simultaneously switch many heat pumps on or off. It will help to absorb a short and sharp positive or negative peak on the electrical grid. This could not continue much longer than allowed by the short-term thermal buffers. After this period, the system would need to quickly decorrelate all heat pumps again and relax back to equilibrium state 1 without creating an opposite peak in demand.
3. Prepare (load/unload) all thermal buffers for a predicted state 3 or 4, for a time period that may be known. This means slowly moving to either a high or low state of charge.
4. Absorb a peak in production of electricity, moving quickly to a high state of charge. Then slowly return to state 1.

5. Lower demand of electricity below the average, to accommodate a scarcity in production of electricity. Moving to a low state of charge at a speed depending on thermal demand. Then slowly return to state 1.

In a system that can run stably in state 1, one should observe that peaks in electricity demand are (much) smaller than peaks in demand for thermal energy. The peaks of thermal flow in central infrastructure should also be smaller than peaks delivered to the end customers, thanks to thermal storage near the customers.

For a system to be able to provide the behaviour in states 3, 4, 5, it is necessary that in state 1 the system can run stably within a sufficiently wide range of the collective state of charge. Then, the complete system should be able to move its collective state of charge in a coordinated fashion. This allows the peaking action of state 2 to be maintained over a longer period. Therefore, we can compare the state of charge to the thermal demand curve.

6. Key Performance Indicators

A Key Performance Indicator (KPI) is a measurable value that demonstrates how effectively the pilot is achieving the objectives of 5GDHC. The nature of the objectives can be political, economic, social, technical, legal, and environmental. The result of a KPI is

- Conditional (yes or no),
- Quantitative (e.g. kWh, €, MW, %, x/m^2 etc.),
- Qualitative (e.g. many, maybe, etc.).

Each Key Performance Indicator should ideally have a single unique purpose: to indicate if one of the basic features is present, and where possible quantify that feature. It is important to define a set of indicators without too much overlap in this respect. If one indicator measures essentially the same as another, then it is better to choose the best of the two. The KPIs need a reference. A reference is needed to reflect upon the performance score.

6.1. Conditional indicators

Conditional indicators are made specific with the MoSCoW approach. Table 1 presents the pilot requirements using this method. MoSCoW stands for:

M - Must have this requirement to meet the pilot

S - Should have this requirement if possible, pilot does not rely on it

C - Could have this requirement if it does not affect the pilot

W - Would like to have this requirement later (or: will not have the requirement now)

Table 1 conditional indicators D2GRIDs pilots

Must have	Different heating and cooling loads A low grade renewable and/or waste energy source Bi-directional flow Active thermal energy exchange Closed thermal loops
Should have	Reduce supply temperatures to the buildings by promoting insulation measures in connected buildings Thermal storage Renewable electricity to run electrical equipment Renewable thermal energy sources Ancillary services to exploit flexibility in the system - Electricity peak load management Smart control of conversion technologies in cloud configuration Capability for modular/organic growth
Could have	Smart thermal storage technologies in cloud configuration - Thermal Storage on varying time scales and temperatures - Fluctuating network temperatures Intelligent interacting end user appliances
Would like to have	Provide thermal energy to all buildings in an urban area, regardless of state of renovation

7. Evaluation of 5GDHC status technical

The below evaluation of the 5GDHC status will help the pilots to design and to build their network more towards 5GDHC. It is not the purpose to give a hard "yes" or "no" in this evaluation, but simply indicating where optimization is possible.

7.1 System boundary

Describe where in your network is the system boundary. Is it at meter level?

7.2 Basic conditions of the network

Must have	Different heating and cooling loads A low grade renewable and/or waste energy source Bi-directional flow Active thermal energy exchange Closed thermal loops Interaction between thermal and electricity grid	Yes/no Yes/no Yes/no Yes/no Yes/no Yes/no
Should have	Reduce supply temperatures to the buildings by promoting insulation measures in connected buildings Thermal storage Renewable electricity to run electrical equipment Renewable thermal energy sources Ancillary services to exploit flexibility in the system - Electricity peak load management Smart control of conversion technologies in cloud configuration Capability for modular/organic growth	Yes/no Yes/no Yes/no Yes/no Yes/no Yes/no Yes/no Yes/no
Could have	Smart thermal storage technologies in cloud configuration - Thermal Storage on varying time scales and temperatures - Fluctuating network temperatures Intelligent interacting end user appliances	Yes/no Yes/no Yes/no Yes/no
Would like to have	Provide thermal energy to all buildings in an urban area, regardless of state of renovation	Yes/no

7.3 Evaluation of the network performance

7.3.1 Sources

We can identify how much energy is injected in the network, both electrical and thermal. Ideally both sources are 100% renewable.

System sources (external from network)	-	MWh/year
Total energy input - Electricity - Thermal (cold and heat) - high grade solid fuel - high grade liquid fuel - high grade gas - high temperature waste energy (>50°C)		 MWh_e/year MWh_{th}/year MWh_{th}/year MWh_{th}/year MWh_{th}/year MWh_{th}/year
Locally produced/used energy - electricity - low grade heat - low grade cold		 % % %

Ranking of preferable energy sources used	-	MWh/year
1. Reuse of thermal energy, by exchange between heating and cooling demands		MWh_{th}/year
2. Ambient thermal sources from soil, water, air, and low temperature solar heat		MWh_{th}/year
3. Higher temperature renewable sources like Geothermal, Solar heat		MWh_{th}/year
4. Higher temperature industrial waste heat, otherwise rejected in the environment		MWh_{th}/year
5. Renewable electricity from local sources like wind, sun		MWh_e/year

6. Electricity use at times of renewable overproduction, e.g. when spot price is low 7. Electricity mix from the external grid 8. High temperature heat from burning biofuels, biogas, biomass 9. High temperature heat from burning fossil fuels		MWh_e /year MWh_e /year MWh_{th} /year MWh_{th}/year

System sources (external from network)	-	Distance to network

7.3.2 Exchange factor

This factor must be as large as possible. 100% will not be achievable due to losses inherent to the network.

For every connection to be filled in	-	
Thermal demand (all customers) E_{demand} Thermal (heat) Thermal (cold) Total square meters cooled/heated		 MWh_{th} /year MWh_{th} /year m^2

$$Energy\ exchange\ Factor\ (EF) = \frac{E_{demand} - E_{supply}}{E_{demand}} x\ 100\%$$

The exchange factor can be improved by:

- using heat pumps with a high COP
- optimizing the routing
- smart control of the storage
- Maximum use of seasonal storage
- Matching of profiles (cold supply = heat demand)

7.3.1 Thermal storage

Thermal storage is important to define the flexibility of the network. The key question to define is: Where are the storages located?

Provided the state of charge curve of every storage vessel within the system boundaries as defined above, they can be centralised or decentralised storage facilities. The intrinsic storage capacity of building is not considered at this point.

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Glossary

Grid : the term grid and network are both used in this text. We use grid when we talk about the technical design.

Network: the term grid and network are both used in this text. We use network when we talk about the concept.

Substation: in some cases energy plant is used to indicate the substations. We prefer to use the term substation however.

Low-grade thermal energy: this is thermal energy at a temperature near to the demand, so a heat pump can at high efficiency lift or lower the temperature to the necessary value. If possible, passive heat exchange can be used.

High-grade thermal energy: this is thermal energy with a temperature that is far superior to what is demanded. This means there is a large excess exergy content in the heat (or cold), compared to what is necessary.

Decorellate: To reduce the correlation between signals