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ABSTRACT

Research into new advanced district heating concepts has increased since the first four generations of district heating were defined in 2014. This definition created a common framework for research and industry alike, and pointed to potential futures for district heating which could benefit from low-temperature heating in buildings. The fully developed fourth-generation district heating includes the cross-sectoral integration into the smart energy system. This paper defines four generations of district cooling to make a similar useful framework for district cooling. The first generation being pipeline refrigeration systems that were first introduced in the late 19th century, the second generation being mainly based on large compression chillers and cold water as distribution fluid, the third generation having a more diversified cold supply such as natural cooling, and the fourth generation combining cooling with other energy sectors sometimes into a renewable energy-based smart energy systems context, including combined heating and cooling.

1. Introduction

Studies show that district energy systems, such as district heating (DH) and district cooling (DC), allow for a low cost and energy-efficient transition towards renewable energy (RE)-based energy systems [1], enabling, for example, increased flexibility in the operation of energy conversion technologies [2], low-costs storage solutions [3], and the utilisation of otherwise non-utilised energy sources such as excess heat from industries and natural cooling from natural cold sources [4,5].

Globally, modern commercial DH has been utilised since the 1870s, and has since then expanded to around 80,000 systems delivering a total of around 11.5 EJ of heat in 2014 [6]. DH has especially seen a wide implementation in Russia, China, and the European Union (EU), accounting for around 85% of the globally delivered DH [4]. It is estimated that DH supplies 8% of the global end-user heating demand [4]. Due to the relatively high utilisation and potential for allowing a more fuel- and cost-efficient transition to RE-based energy systems, DH has been the subject of extensive focus within research [7] and is playing an important role in the EU and national energy policies.

Currently, it is estimated that nearly 20% of the total global electricity demand is used for cooling purposes, via air conditioners and electric fans in buildings. Furthermore, the electricity consumption due to cooling is expected to increase due to urbanisation, industrialisation, climate change, and as the standard of living increases globally, with some projecting a tripling of the current electricity demand for cooling [5]. Moreover, uncontrolled use of chillers creates a cooling peak and risk of brown-out. Where DH has seen a relatively wide global utilisation, DC is less utilised for covering cooling demands, only delivering around 300 PJ/year globally [4]. However, DC could provide a more efficient and low-cost option for covering cooling demands, as it allows for, e.g.,

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Nomenclature

1GDC:	1st Generation District Cooling
2GDC:	2nd Generation District Cooling
3GDC:	3rd Generation District Cooling
4GDC:	4th Generation District Cooling
CCHP	Combined Cooling, Heating and Power
CHC	Combined heating and cooling
CFC	Chlorofluorocarbons
DC	District Cooling
DH	District Heating
EU	European Union
HCFC	Hydrochlorofluorocarbons
RE	Renewable energy

natural cooling and increased flexibility in the operation of the energy conversion units. Thus, DC could also allow for better integration of RE in the energy system and potentially also for connection to DH systems [5]. Such potentials are already utilised in DH systems [7,8].

In 2014, the historical and future perspectives of DH were categorized by splitting the historical development into different generations of DH and providing a future perspective on how existing DH schemes could be modernised as well as how the future development of new DH schemes could be understood in this context. This resulted in the definitions of four generations of DH, where each generation was defined by a set of unique features that significantly advanced the technology compared to its predecessor. These generations were typically dominating DH system technology in a 30–50-year period [9].

This division into generations has created a common terminology and framework for research and industry alike that has shown to be useful for vocalising and interpreting both the historical and the future perspectives of DH. The paper defining the first four generations of DH [9] also mentions the potential to make a similar distinction for DC, but only proposes a general idea for the first three generations, and does not include a definition of a potential fourth generation, as it was outside the scope of that paper.

The core of DH and DC is that it is an infrastructure that enables cost and energy efficient thermal management of the area that they supply. Both are based on pipe networks connecting thermal sources with thermal sinks. The principal difference between DH and DC is that in DH, heat is being supplied from one or more central heat sources to its connected end-users, heat sinks; while in DC, unwanted heat is removed from the end-users, heat sources, and delivered to central heat sinks. The transport of the heat from one location to another can be achieved with different pipeline mediums, such as water or refrigerants.

Both DH and DC are clear candidates for inclusion into the smart energy system, where thermal, electricity, gas and transportation systems are planned and operated in an integrated fashion to exploit synergies and optimise the flexibility for using RE [10,11] for a carbon-neutral energy supply.

The aim of this paper is to define different generations of DC to make a useful framework and a consistent vocabulary, as that made for DH, to allow for highlighting the historical development of DC and highlighting important focus areas for the future development of DC into a smart energy systems context. The smart energy system approach is a key facilitator in the cost-efficient transition to carbon-neutral energy systems based on RE, and this paper thus provides a clear vocabulary for energy transition analyses.

First, in Section 2, we review a series of first, second, and third generation DC (1GDC, 2GDC, 3GDC) systems based on a first definition provided in Ref. [9]. Furthermore, this review identifies and extracts some of the main characteristics of 1GDC, 2GDC, and 3GDC. This is followed by Section 3 presenting a more in-depth review of systems that transcend 1GDC, 2GDC, and 3GDC, and the review identifies and extracts some of the main characteristics of this fourth generation DC (4GDC), including its relation to other parts of the energy system.

Chapter 4 deliberates if and how former generations of DC can be developed into a fully integrated 4GDC system. In Chapter 5, the definitions of the four generations are revised. Finally, some reflections concerning the four generations are presented in Chapter 6.

2. The first three generations of district cooling

As with the generations of DH presented in Ref. [9], the generations of DC are defined by the advances in the technologies used for generating and delivering the cold to the customers and the philosophies of operating the DC systems. As with DH, this is in part linked up to temperature levels, but also highly related to main technological choices and developments.

This section reviews a series of 1GDC, 2GDC, and 3GDC systems with a focus on applied technologies and common characteristics. It is based on a set of first definitions from Lund et al. [9], defining various generations as:

1. “The first generation was the pipeline refrigeration systems introduced in the late 19th century consisting of centralised condensers and decentralised evaporators with the refrigerant as the distribution fluid”.
2. “The second generation became the district cooling systems introduced in the 1960s based on large compression chillers and cold water as distribution fluid”.
3. “The third technology generation constitutes a more diversified cold supply based on absorption chillers, compression chillers with or without heat recovery, natural cooling from lakes, excess cold streams, and cold storages. The distribution fluid is still cold water”.

2.1. *The first generation of district cooling*

1GDC became the pipeline refrigeration systems that were introduced in the USA in the late 19th century [12,13]. These systems either used pressurized ammonia or brine solutions as distribution fluids.

The first ammonia system was implemented in Denver in 1889 by the Colorado Automatic Refrigerating Company [14,15]. The cold was created by an absorption chiller of about 105 kW and it used a three-pipe distribution system. The purpose was to supply cold to a storage warehouse with about 1400 m^3 capacity. Liquid ammonia ran through the distribution pipes connected to 29 cold boxes in the warehouse. Each of the boxes had an expansion process at the entrance, expanding ammonia, thus reducing it to lower temperatures appropriate for the cooling process. The cold ammonia could then be evaporated while absorbing heat from the cold box.

For the customers, piped refrigeration offered convenience at favourable costs. The alternative was mainly systems based on ice deliveries; however, such systems required space, gave off moisture to the air, were difficult to regulate, and had difficulty obtaining low temperatures. Piped refrigeration systems, in contrast, did not take up space, provided dry air, could be regulated by adjusting the expansion valve and could even provide freezing [16].

The Denver system was soon abandoned, but a similar system established in St Louis in 1890 survived until the 1960s, when it was unable to afford the relocation of its pipes to avoid a new highway [17]. In this system, comfort cooling was applied for the first time besides the commercial cooling application, but just for demonstration.

The brine distribution method was established in underground pipes by the Manhattan Refrigeration Company in 1906 in a New York city district with a power plant and nine cold storage warehouses [18]. This system paved the path for the cooling of large warehouses, small market buildings, ships, etc. in New York and was in operation until 1979.

Hence, these systems delivered mainly refrigeration services to concentrated market areas within the food supply chain. According to a later review [19], other pipeline refrigeration systems were also established in Boston, Los Angeles, Kansas City, Baltimore, Washington DC, Philadelphia, Atlantic City, Seattle, Minneapolis, and Phoenix.

A common characteristic of these 1GDC systems is the centrally generated cooling potential for customers with refrigeration demands.

Detailed information about two 1GDC systems is included in Appendix A.

2.2. The second generation of district cooling

2GDC was introduced in the 1960s and 1970s by exploiting the economy of scale effects of using few large compression chillers (and maybe some absorption chillers or river cooling as supplement in a few cases) instead of many small chillers for comfort cooling purposes. The first system was established in the central business district of Hartford, USA, in 1962, [20–22]. This system used both absorption and compression chillers and introduced cold storage in 1986. Both the absorption and compression chillers were driven by steam from the company's district steam system, thus providing a synergy between heating and cooling.

The first major European DC system was established in 1967 in the Courbevoie, Nanterre, and Puteaux areas, the western suburbs of Paris, [23]. It serves many office buildings in the La Défense area and two interconnected networks are currently operated jointly by the Enertherm and SOC companies. The system provides the cooling demand of 1.5 million m^2 of business space. The cooling medium is chilled water produced by a mixture of compression chillers and free cooling from the Seine and is transferred through pre-insulated pipes in underground tunnels.

The first German DC system was established in 1968 and still serves an office area in Northern Hamburg, originally 16 shareholders involved with 18 associated administration buildings [24,25]. This was also presented in an early global DC overview [26]. The system's capacity was later expanded in several stages by adding new chillers and expanding the pipe network. The cold supply consists of mainly electrically-driven single- and double-stage turbo-compressors.

The first major Japanese DC system was established in 1971 for the Regional City Hall area in the Shinjuku district, Tokyo, by supplying cooling to several skyscrapers with a total capacity of 210 MW. This combined district heating and cooling (CHC) system has a complex heat and cold generation system that includes some natural gas-driven CHP plants and boilers as well as a number of electrical and heat-driven chillers [27,28].

These 2GDC systems based on economy-of-scale have inspired the implementation of large DC systems both in the Middle East [29,30] and China [31,32]. The common denominator for all these systems is the high proportion of large compression chillers in the cold supply. Heat recovery and cold storage are seldom utilised.

In the Middle East, major systems are operated by companies called Tabreed, Empower, Qatar Cool, Emicool, City Cool, Arabian DC, etc. There are several of these cases and only three of them are introduced here.

The Pearl-Qatar DC system has a cooling capacity of 450 MW and started operation in 2010 [33]. It supplies cooling to 15,000 apartments, 700 villas as well as several hotels and shopping malls. The total trench length is 92 km with pre-insulated steel pipes at diameters in the range of 75–1400 mm. The network is supplied by chilled water from 52 electrically-driven centrifugal chillers. The system uses both fresh water and purified sewage water.

Dubai Metro in the United Arab Emirates has a DC system from 2010, supplying cold through 52 km pre-insulated steel pipes to all 47 metro stations. The network has five cold supply plants with compression chillers in Al-Rigga (35 MW), Al-Barsha and Al Rashidiya (26 MW each), Jumairah Island (25 MW), and Jebel Ali Industrial (15 MW), giving a total capacity of 127 MW according to Ref. [34].

The Sabah Al-Salem University case in Kuwait is a DC system with a capacity of 380 MW cooling supply from three plants that went into operation between 2019 and 2021. The system has 54 compression chillers and three thermal energy storage units to feed chilled water into a total of 46 km pre-insulated and galvanized pipes together with a 9 km water supply and drainage system [35].

In China, most DC systems operate in the climate zone of hot summers and warm winters in the south of the country. In Guangzhou, a large system with four plants has supplied cold to about ten universities since 2004 [31]. Initially, the system had a capacity of 440 MW that later has been expanded to 520 MW.

Yalong Bay National Resort in Hainan is an example from 2011 of a network with a cooling capacity of 32 MW for supplying 400,000 m^2 floor area in hotels, etc. The system also takes advantage of a large ice storage unit with 90 MWh capacity [31].

In general, in 2GDC, the philosophy changes from a food industry focus towards supplying cooling for comfort purposes. The system is further simplified as the end-user no longer has any part of the cooling generation on its shoulder – i.e., no decentralised evaporator.

Detailed information about nine 2GDC systems is included in Appendix A.

2.3. The third generation of district cooling

3GDC systems emerged in the 1990s, as the initial substitution of CFC (Chlorofluorocarbons) and later substitution of HCFC (hydrochlorofluorocarbons) refrigerants according to the Montreal protocol gave windows of opportunity for DC systems.

One early initiative was the formation of the Climespace system in the Paris city centre in 1991 [36]. At the formation, the central Les Halles cooling plant from 1978 was included as a valuable capacity asset. Later, the Seine river was added as a heat sink. The cold is generated in ten cold supply plants that can utilise a cold storage capacity of 140 MWh. This system has currently the highest annual cold delivery capacity among all DCs in Europe, almost 500 GWh per year.

Another large European system is the Stockholm system established in 1995 that is dominated by cold supply obtained from the large heat pumps providing heat to the DH system [37,38]. Today, the system supplies cooling for both comfort cooling (in malls and buildings) and process cooling (for computer sites, refrigerating/freezing equipment, etc.). The Stockholm DC systems include several smaller and larger cold supply stations based on a variety of technologies, such as compression and absorption chillers (27%), free seawater cooling (18%), and waste cooling from heat pumps (55%). The large Hornsberg rock cavern acts as a cold storage for counteracting the daily variation in the deliveries [39].

In the Gothenburg system, also established in 1995, the cold supply is instead dominated by absorption chillers based on an abundance of local waste heat from a waste incineration plant and two refineries that is made available via the Gothenburg DH system [40]. Natural cooling is also supplied from a river if the temperature is sufficiently low (≤5 °C). Otherwise, the rest is supplied by a group of absorption (connected to DH) and compression chillers. Overall, the average share of the river is 22%, while 47% and 31% are provided by absorption and compression chillers, respectively.

The Helsinki system, first established in 1998, utilises mainly the large Katri Vala heating and cooling plant for cold supply [41,42]. This system has by 2020 been extended to 562 buildings and 90 km of trench length. The cold supply consists of seven heat pumps (85 MW in total), ten heat-driven absorption chillers (35 MW in total), two compression chillers (10 MW in total), and seawater cooling (70 MW). The system includes two cold storages in rock caverns having a total volume of 37,000 m^3. This is a true example of a smart energy system in which heat and cold are supplied in a sustainable way mainly by a set of bi-functional heat pumps. The heat pumps receive the return water from the DC network at 16–18 °C as well as purified sewage water and cool it down to 4 °C for cold supply. The condensers of the heat pumps also supply heat to the DH system.

The Copenhagen system established in 2010 applies a combination of compression chillers and seawater cooling [43]. This system is known as the Hofor DC system with 52 MW cooling capacity for 62 large buildings with 1.1 million m^2 floor area. This system has seawater as the main source of cooling, providing all cooling during the winter. During the rest of the year, a combination of seawater cooling, twelve ammonia compression chillers, and one absorption chiller perform the cooling supply mission.

These Nordic examples have all implemented some proportion of natural cooling sources based on sea or river waters. Some other third-generation systems use natural cooling sources to a very high degree as early initiatives for decarbonised comfort cooling [44,45]. Natural cooling can significantly reduce the electricity used for cooling in these cases, compared to conventional air conditioning with both small and large compression chillers. Three typical early cases that use lake water for cooling are Cornell University in the USA, Toronto in Canada, and Geneva in Switzerland. One typical case that uses seawater cooling is Dalian, China.

At Cornell University in the USA, a DC system based on lake water has been in operation since 2000 [46,47]. Here, 4–5 °C water extracted from the Cayuga Lake at a depth of about 75 m is the main source of cooling to the university campus. The cold water is pumped up to the lake's surface, where the main heat exchange unit of the DC system is located, transferring cold energy to the secondary side through a 3.7 km long pipeline. The DC water supply and return temperatures are about 7 °C and 15 °C, respectively. The heat extracted from the cooling process is rejected to the lake by a return flow of a temperature between 9 and 13 °C.

Since 2004, Toronto has used Lake Ontario's water to provide 260 MW cooling to some office buildings, the Metro Convention Centre, etc., [47–50]. This system is indeed a combination of natural (main) and artificial (supplementary) cooling, where the lake's cold water performs the first step of the cooling of the return water, which enters at 20 °C and leaves at 5 °C for the second cooling step, where a chiller decreases the water temperature further down to about 3 °C. This cooling supply system is also integrated with the city's potable water supply. This required a new intake, where the lake's water, after being used for cooling the DC water, is further treated before being supplied to the city's potable water system.

The Genève Lac Nations system in Geneva has been in operation since 2009 and takes 6–9 °C cold water from a depth of 37 m [51–55]. This cold water is pumped to the surface where heat exchangers are located. Currently, the system has a pipeline length of 6 km that delivers cold to the end-users with a total of 840,000 m^2 floor area. Once fully implemented in 2035, the system is planned to be ten times larger than today [53].

Xiaoping Island in Dalian has a system that was built in 2011 to supply cooling for commercial and business buildings with 2.5 million m^2 of floor area [32,56]. In the first two phases, the cold supply came from compression heat pumps based on sewage, while heat pumps using seawater were the main instrument for the cold supply in the third phase. The supply and return temperatures of this network are 7 °C and 12 °C, respectively. Xiaoping's case is an example of a DC network that was developed in the Chinese cold climate zone.

These 3GDC systems can be characterized by a high degree of diversity in the cold supply from natural cooling, absorption chillers, cold recovery from heat pumps aimed for heating, compression chillers, and short-term cold storage units for balancing hourly cold loads and moving cooling generation from day to night hours. These systems have pronounced merit order rankings like DH and electricity systems. The synergies between DC and CHP are sometimes utilised by using absorption chillers in Combined Cooling, Heating and Power (CCHP) configurations, also known as trigeneration [57].

With natural cooling being a part of more 3GDC systems, one aspect needs to be addressed. Natural cooling will increase the temperature of the body of water where heat is dissipated, with an environmental impact depending on the resource size and the cooling demand. However, theoretical analyses for Switzerland, as presented by Gaudard et al. [58], and an actual monitoring programme from Cornell University's DC system [59] both show limited impacts. Consideration should also be given to the alternative which would often be electricity-based systems with cooling demands for power stations, though cooling would not necessarily take place into the water bodies supplying natural cooling for DC systems.

A common denominator for 3GDC is that the focus is increasingly on using what is locally available as well as phasing out refrigerants with high ozone layer depletion characteristics. In Scandinavia, the systems are even further based on energy efficiency as the waste heat is recycled into the local DH grids. Diversity and storage are common descriptors.

Detailed information about nine 3GDC systems is included in Appendix A.

3. The future fourth generation of district cooling

Early adopters of the 4GDC systems have emerged in the 2000s and 2010s, when the decarbonization of cooling became increasingly important. In these systems, less attention has been directed towards CHP and the combustion of fuels.

Lund et al. [9], though directly stating that defining 4GDC was not the scope of the work, suggested that *"A future fourth generation of district cooling systems can be defined as new smart district cooling systems more interactive with the electricity, district heating, and gas grids".* This tentative definition is applied for exploring this generation.

The main track for early 4GDC systems has been to exploit the CHC synergy by using both ends of a heat pump simultaneously or by using a combination of a separate heat pump and a separate chiller working in parallel. This is achieved by using the heat surplus obtained from cooling for covering heating demands and the surplus cold obtained from heating for covering cooling demands. Simultaneous use requires that heating and cooling demands appear simultaneously and that cooling demands are rather high compared to heating demands. But seasonal storages can also be used for storing cold from the heat pump during the winter for later use during the summer and by storing low-temperature heat from the chiller during the summer to the winter. This annual cycle of storing both heat and cold can be supported by using extensive centralised low-temperature aquifer or borehole thermal energy storages. The use of thermal storage units when exploiting the CHC synergy makes these 4GDC systems well prepared for the integration into a smart energy system where flexibility helps integrate variable RE sources.

Even if it is not possible to generate all heat and cold in CHC with or without seasonal storage, this combined utilisation of the capital-intensive heat pump is profitable. Having generated CHC as much as possible it is very profitable to generate additional heat or cold, as the heat pump is already available. It will in most cases be profitable generating additional heating while dumping the cold into an ambient energy sink. The same ambient source, e.g., sea water or wastewater can be used as cold sink in winter and heat sink in summer. See, e.g., the Taarnby case detailed later in this section, where it is very profitable to generate additional heat with the wastewater as a cold sink. Even in rare cases in which the heat market price is low and the electricity price is large, the wastewater can be used as a heat sink in summer.

The CHC synergy can either be implemented with centralised or decentralised cold supply. At centralised cold supply, the heat and cold distributions are applied with separate DC and DH networks. At decentralised cold supply, the heat and cold distributions are applied with one common network with temperatures close to the network temperatures applied in DC systems. The cold supply is then created by decentralised heat pumps used for heating. But these decentralised heat and cold supplies can also be supported by centralised heat and cold supplies for balancing hourly heat and cold demands. Hence, 4GDC systems can often have a mixture of centralised and decentralised cold supplies. But seasonal storages are mostly centralised, because of considerable economy-of-scale for larger thermal energy storages.

As earlier mentioned, centralised implementations of large heat pumps that also supply cold have been made in the 3GDC systems of Stockholm and Helsinki. These partial CHC synergies were exploited for Stockholm when the DC system was established in 1995 and for Helsinki when the first large heat pumps were commissioned in 2006. Three other examples of centralised 4GDC systems are presented below. Further information about these three systems is included in Appendix A.

The centralised CHC synergy has been the main strategy at the Stanford University campus area since 2015 [60–62]. The cooling system was developed in the 1960s for supplying the cooling demand of the campus buildings and a new DH system covering 300 buildings was coupled to that in 2015. This integration of the cooling, heating and electricity systems enabled taking advantage of opportunities across all sectors. The cold supply chain of this system includes three heat recovery chillers, four electrical chillers, and one cold storage tank with 68,000 m^3 capacity.

The first stage of the Danish Høje Taastrup case was implemented in 2016 [63,64]. This system interconnects the local cooling network of a large wholesale market for flowers and vegetables with 70 individual consumers (15,000 m^2) using two electric compression chillers. Some of these consumers need 0 °C room temperature and therefore the supply temperature for DC has to be −8 °C, while the rest can be supplied with 8 °C supply temperature.

In principle, the plant includes a serial connection of three compressors. Two compressors supply DH at a temperature of 75 °C and cold at a temperature of 8 °C to a cold water system and will in the final stage be an integrated part of the DC system in the district. One additional set of compressors boost the temperature down to −8 °C to a local network in the building. In the building, the two groups of consumers are connected in serial connection, as the second group is supplied with the return temperature from the first.

The two compression chillers work in parallel and provide cooling with glycol as the medium at -8 °C where the return temperature is −1.6 °C. The total cold supply capacity of this system is 2 MW, while the heat supply capacity is about 2.3 MW. In the final stage, the Høje Taastrup system will include a traditional DC system with several heat pump plants, ground source cooling, and a chilled water tank serving mainly comfort cooling and process cooling at a supply temperature of around 8 °C. The two chillers will then boost the supply temperature to the wholesale market from 8 °C to -8 °C.

The centralised CHC principle has also been used since 2020 in the new Taarnby system located in the Kastrup business district in Denmark [65–68]. In this case, a large-scale heat pump integrates the existing DH system with a newly established local DC network. The heat pump's capacity for cold and heat supply is about 4.5 and 6.5 MW, respectively. In addition, the system enables exploiting synergies across more sectors such as the electricity system (heat pump is electric driven), a wastewater treatment plant nearby (treated wastewater is cold sink in winter and could be heat sink in summer, and not least, the plant is located at the wastewater treatment plant), and the groundwater (as a supplement cooling source up to 2.8 MW). The system also takes advantage of 2000 m^3 cold water storage, giving flexibility for smarter interaction with the electricity grid.

When using the decentralised CHC variant, heat is supplied by local heat pumps at the customer substation by extracting a flow from the return pipe and releasing it colder to the supply pipe. Each customer substation can provide heat and cold to one building or a cluster of many buildings. One implication is that cooling in such systems may be provided at a useful temperature directly from the supply pipe. An early implementation of this decentralised CHC has been realized in the 3GDC system of Geneva since 2008. Four examples of decentralised 4GDC systems are presented below. Further information about these systems is included in Appendix A.

An early implementation of the decentralised CHC variant since 2008 has been the Heerlen system in the Netherlands [69,70]. Mijnwater characterises their system as a 5th Generation District Heating and Cooling (5GDHC) system [69], but here it will be treated as a decentralised 4GDC system. This network utilises mine water as the source for providing both heat and cold from the same network. There are in total five extraction wells; two 700 m wells for warm water supply at 28 °C, two 250 m wells drawing up cold water at 16 °C, and a fifth 350 m well making the interface between the cold and warm wells at 18–22 °C. The 7 km intermediate pipe network is a three-pipe system, including an insulated pipe for warm water delivery, and two uninsulated ones for cold water supply and return pipe. The supplied warm and cold water is regulated to the desired temperature at the end-user sites by each of the four cluster heat pumps. Here, the heat pumps increase the cold supply water temperature to 22 °C by the rejected heat and decrease the warm return flow to 8–12 °C.

The Hönggerberg campus of ETH in Zürich started in 2013 to convert its traditional heat and cold supply by using the CHC synergy [71]. The transition is planned to be finalised in 2026. The ETH buildings will then be heated by several decentralised heat pumps integrated with geothermal storage units and a waste heat recovery loop of buildings and laboratories obtained from the cooling side. The heat and cold are currently distributed by three closed loops of pipes for carrying warm, cold and free cooling/waste heat water flows with varying temperatures during the year (from 8 °C to 24 °C). For the geothermal storages, the aim is to reach 8 °C/4 °C temperature level at the end of the winter and 24 °C/20 °C at the end of the summer, enabling very efficient heat and cold supplies by the five cluster-level decentralised heat pumps.

Another Zürich case appears at Familienheim-Genossenschaft Zürich in the Friesenberg district. Since 2014, the CHC synergy has been utilised by cooperation with two external data centres [54,72]. This system takes advantage of six semi-centralised heat pumps for each cluster of buildings as well as 153 geothermal boreholes with 250 m depth each as the seasonal thermal energy storage units. In addition to this, the heat pumps provide cooling to the two data centres. The intermediate pipeline of the system that provides cold/warm water for the operation of the heat pump in different seasons operates between 8 and 25 °C (see also [73]).

Saclay University in Paris started to implement the CHC synergy in 2017 [74,75]. Their district energy networks combine RE, two low-temperature exchange networks, and heat storage units in its low-energy buildings. Some of the key factors contributing to the success of this CHC project include a mutualisation of operation and investment costs, secured future energy sales, an adequate level of subsidies based on robust criteria, a political willingness to develop the project, and management by a dedicated fully empowered local authority. The supply chain of this case includes seven semi-centralised heat pump stations at cluster level and additional natural gas boilers for heat supply as well as two 700 m geothermal wells, where the production well supplies heat at 25°-30 °C. The district energy system of the campus has cluster substations in which heat pumps provide both chilled and hot water to fulfil the thermal demands of the building blocks. Besides, the cluster substations are equipped with heat exchangers that recover the excess cooling and heating of the buildings. The maximum heat and cold supply capacities of the system are 37 MW and 10 MW, respectively, and the total annual heat and cold production/consumption are 40 GWh and 10 GWh.

4. Transitioning to fourth generation district cooling

The bulk of cooling demands in buildings worldwide is supplied by individual solutions [5]. Transitioning existing individual cooling solutions towards 4GDC is an obvious important step to allow for increased use of DC. But it is very difficult to do in a commercial way, as the fixed costs of the individual chillers in buildings are substantial, and since commercial building owners often make investment planning for a short period of time, e.g. 7 years. Moreover, the cooling demand is in general not measured directly and only accounted for in terms of monthly or daily electricity consumption.

Dyrelund and Bigum defined in Ref. [76] four implementation steps for suitable areas to transition from individual cooling solutions to 4GDC (here paraphrased and expanded from the original source):

- Step 1: Interconnecting buildings with a network saving production capacity; thus going from individual cooling solutions of a single building, to combining these buildings in a cooling network. Often some buildings have excess cooling capacity, and the newest and largest chillers can supply other buildings and thereby expensive reinvestments in smaller chillers can be avoided. Once several buildings are connected, it is possible to measure the actual cooling demand and its time-varying loads. The aggregated load information enables the estimation of the potential for implementation of large tanks with chilled water for optimising the operation.
- Step 2: Installing a chilled water tank and optimising the operation of the DC network, production plants, and providing the network with peak and backup capacity from the tank.
- Step 3: Installing more efficient and cost-effective cooling sources located within the range of the network and taking into account the storage capacity (high-temperature surplus heat from waste incinerators, absorption heat pumps, and gas turbine driven compressors, efficient ambient cooling sources, e.g., drain water, seawater).
- Step 4: Installing heat pumps for exploiting the CHC synergy, benefitting from the storage and ambient energy sources as well as ground source cooling for seasonal storage.

Already from Step 1, it is possible to locally decrease the temperature from the level of comfort cooling at around 6 °C to obtain process cooling at -8 °C or at −20 °C.

The transition from Steps 1 to 4 will also stimulate a more efficient use of end-user installations and thereby increase the supply temperature, e.g., from 6 to 10 °C, which will open for more efficient sources in the final two steps.

The transition strategy presented by Dyrelund and Bigum was inspired by a feasibility study for a large campus owner, who had information on all buildings and a 7-year budget for reinvestments and O&M costs. In the base case, the campus had 24 chiller plants and corresponding cold water networks, of which one large plant was vital for the process and one was new. By investing in new chilled water pipes connecting the local networks, instead of reinvesting in chillers, it would be possible to expand the system and implement the most important 1st step. It turned out that three to four existing large chillers might be able to supply the whole system and that a chilled water tank most likely would be more cost-effective than a new chiller.

The transition strategy could inspire energy planners and local stakeholders on how to get started in a commercial business district with 24 individual building owners, which each have their own existing chiller plant. For commercial reasons, a building owner will only be interested in joining a DC system in the case that the chiller is abraded and the DC company can deliver capacity and cold energy at a competitive price or in the case that the chiller plant has excess capacity and lifetime, and the DC company will buy capacity and cold energy at a favourable price.

In some cases, the DC company passes all four steps and goes directly to the 4GDC. An example is the Taarnby case presented in the previous section, which moreover benefits from sector integration. This cost-effective sector integration between DH, DC, sewage, sewage treatment plant, ground source cooling, and electricity turned out to be a natural solution for the publicly owned multi-utility Taarnby Forsyning [66–68]. Interestingly, there are in fact several levels of integration in this case. Treated sewage may be used as a heat source, treated sewage may be used as a heat sink for excess heat from the CHC and the plant could be located at the sewage treatment plant. In case the project had been divided between several commercial companies, the realised synergies between the sectors would have been difficult to exploit.

In case of efficient cold ambient sources nearby, it could be cost-effective to skip Step 2 and go directly for Step 3.

A previous transition case is found in the Missouri State University DC network. Here, many existing chillers were simply connected to one common network [77], thus composing a system of decentralised cold supply for several end-users and a unified network of pipes. By 2005, the university campus had multiple buildings, each of which had its own individual chillers for air conditioning, while the whole campus was supplied already by a DH network. The university then decided to connect a series of these decentralised cold supply units and make a DC network across a large part of the campus. In this way, despite the added service and maintenance costs compared to a solution based on a central production plant, a low-investment cost DC solution could be implemented by utilising existing pumps and installation at the locations. This Missouri State University system now delivers cold at 6 °C with a return temperature of 14 °C to a design-load of 14 MW. The system applies absorption chillers drawing on waste heat from power generation [78] as well as a mixture of direct expansion units, centrifugal chillers, gas-fired steam-driven absorption chillers, and air-cooled chillers.

A simple first proposal of a transition strategy can be:

- To use existing capacities in an integrated network
- To not reinvest in new chillers
- To measure the total cold supply hour by hour to the network as the basis for further optimisation and expansion investments.

5. Summary and definitions

Historically, the term district energy has been used as an overarching term for infrastructure systems that provide immediately useful thermal services via a pipe network that is connecting thermal suppliers, at one or more locations, to thermal users. Newer generations of district energy systems – including 4GDC and 4GDH – may not necessarily supply the thermal service at immediately useful temperature levels. In our understanding and definitions, we take the pragmatic stance that:

- **District energy** is a pipeline infrastructure covering urban areas that connects thermal sources to thermal sinks.
- **DH** is a collective heat supply system designed for distributing heat, from one or more heat recycling or generation units, via fluid-based pipe network operated either at temperature levels capable of immediately fulfilling heating demands of the connected end-users, or in some cases, at a temperature level requiring boosting to a higher level at the site of the end-user.
- **DC** is a collective cold supply system designed for distributing cold, from one or more cold recycling or generation units, via a fluid-based pipe network operated either at temperature levels capable of immediately fulfilling cooling demands of the connected end-users or in some cases, at a temperature level requiring amplification to a lower level at the site of the end-user.
- The **CHC** synergy can either be implemented with a centralised or decentralised cold supply. At centralised cold supply, the heat and cold distributions are applied with separate DH and DC networks. At decentralised cold supply, the heat and cold distributions are applied with one common network with temperatures close to the network temperatures applied in DC systems.

In the following four sections, the definitions of the four DC generations as described in Sections 2 and 3 are revisited, and updated definitions are suggested.

5.1. First generation district cooling

For increasing the energy efficiency and convenience of cold storages in the US in the late 19th century, collective pipeline refrigeration systems were introduced. These systems formed the basis of what we call DC systems today. Lund et al. [9] defined the first generation of DC as: *"The first generation was the pipeline refrigeration systems introduced in the late 19*th *century. They consisted of centralised condensers and decentralised evaporators with the refrigerant as the distribution fluid".*

Based on the review of what was tentatively grouped as 1GDC in Section 2.1, an updated definition is suggested by amending the principal driver or the overarching aim so that it reads:

> "The first generation was a pipeline refrigeration system connecting centralised condensers to decentralised or centralised evaporators. The pipeline distribution fluids were the refrigerant for decentralised evaporators and brine for centralised evaporators. The principal driver was to supply centrally generated cooling to the food supply chain".

5.2. Second generation district cooling

With the shift in the 1960s to comfort cooling as the principal service of the DC, the distributing fluid was changed to water and large compression chillers were established as the main tools for generating the cold. Lund et al. [9] defined the second generation of DC as: *"The second generation became the district cooling systems introduced in the 1960s based on large compression chillers and cold water as distribution fluid".*

Based on the review of what was tentatively grouped as 2GDC in Section 2.2, an updated definition is suggested by amending the principal driver or the overarching aim so that it reads:

> "The second generation is based on large compression chillers as the primary cold supply units and cold water as distribution fluid. The principal driver was to supply cooling for comfort purposes in commercial and public buildings".

5.3. Third generation district cooling

The next major change came in the 1990s, where the cold supply was diversified by introducing multiple new cooling sources, such as cold from absorption chillers and various natural cold sources. Refrigerants with high ozone layer depletion potential were phased out and some heat recovery from compression chillers was introduced as well as short-term cold storages. Lund et al. [9] defined the

3GDC as: *"The third technology generation constitutes a more diversified cold supply based on absorption chillers, compression chillers with or without heat recovery, natural cooling from lakes, excess cold streams, and cold storages. The distribution fluid is still cold water"*.

Based on the review of what was tentatively grouped as 3GDC in Section 2.3, an updated definition is suggested by amending the principal driver or the overarching aim so that it reads:

> "The third generation is based on diversified and distributed cold sources, heat recovery from cooling operation and active utilisation of short-term storages for cost and peak load optimisation. The principal driver was to maximize the utilisation of local resources and phase out refrigerants with high ozone depletion potential".

5.4. Fourth generation district cooling

The three first generations can be understood mainly on their differences in their distribution fluids and cold generating and storage facilities. Looking forward, using these previous generations of DC, alongside the needs of future energy systems transitioning towards increasing levels of RE, 4GDC can be defined.

The major driver for the 4GDC is the cross-sectoral integration into the smart energy system including the exploitation of the CHC synergy wherever appropriate. The focus is on using the heat surplus obtained from cooling during the summer for covering heating demands during the winter and using the cold surplus from heat pump-based heating during the winter for covering cooling demands during the summer. The extensive use of long-term thermal storages in this generation provides a high degree of flexibility that facilitates smart integration with other energy sectors. This smart integration facilitates the integration of variable RE sources – and thus facilitates the transition to carbon-neutral RE-based energy systems.

Lund et al. [9], though directly stating that defining the 4GDC was not the scope of the work, suggested the following definition: *"A future fourth generation of district cooling systems can be defined as new smart district cooling systems more interactive with the electricity, district heating, and gas grids"*.

Based on the review of what was tentatively grouped as 4GDC in Section 3, an updated definition is suggested by amending the principal driver or the overarching aim so that it reads:

> "4GDC consists of systems operating in synergy with other energy sectors, such as electricity and heating sectors, using centralised and/or decentralised technologies such as electric heat pumps, absorption heat pumps, ambient sources and cold storage facilities for fulfilling residential, commercial and industrial cooling demands. The principal drivers are smart energy systems integration and exploitation of the CHC synergy".

5.5. Comparison of the four DC generations

A comparison between the four DC generations is shown in Fig. 1. The diagram illustrates the typically applied technologies of each generation and the period of best available technology. However, it should be emphasized that the DC generations are not consecutive in the same way as the DH generations are, in the sense that newer generations make older generations unequivocally obsolete. DC generations are not necessarily phased out when new generations appear.

As shown in Fig. 1, a key characteristic or driver of 1GDC was the piped nature of the system, which provided convenience for customers over alternative systems of the time. Characteristics – or indeed drivers - of 2GDC are economy of scale and a safer distribution medium. For 3GDC, a driver was a decrease in electricity usage through diversification by also using waste heat as input to absorption chillers with a corresponding decrease in environmental impact. 4GDC has been driven by smart energy system integration, which improves the opportunities to utilise RE in the energy system, while also resulting more directly in a lowered primary energy supply through the reuse of waste heat from chillers for heat supply. 2GDC, 3GDC and 4GDC have naturally retained some of the convenience of the piped system introduced with 1GDC systems, though alternatives for later systems are not as impractical as the alternatives for 1GDC. In this respect, DC shares some customer benefits in terms of convenience with DH [80].

As opposed to 1GDC, 2GDC-4GDC exhibit a more decentralised nature. This is due to an organic development of the systems, limited scale benefits after a certain size and the circumstance that single-point supply systems would lead to very large pipe diameters. Heat gains in pipes are not a main driver for decentralised supply.

Regarding efficiency, a tentative increase is indicated in Fig. 1; however, this is not a main issue of this article. Also, when comparing simple conversion systems to more complex systems drawing on sector integration, the use of excess heat for heating purposes, natural cooling and more, a simple efficiency consideration does not suffice. Some specific technologies may even be less efficient than their predecessors, however, through exploiting other synergies, the transition would still be favourable from an energy system's perspective.

A main criterion for performance is thus rather the cost effectiveness of DC for the society, taking into account local conditions and the dynamics of the energy system as well as the DC system's ability to form part of a RE-based energy system. The assessment of such systems calls for holistic energy systems analyses using dedicated tools like EnergyPLAN [81], rather than efficiency comparisons between technologies.

6. Reflections on the categorization of the four DC generations

These reflections will provide comparisons of the various generations regarding main features, substitution of the previous generation, heat recycling, use of storages, centralised versus decentralised cold supply, and the ability to be part of a smart energy system.

The main reflection is that historically DC systems have been under development and still need to be in the future. The current context of fossil fuel-based energy systems will change, and DC systems have to adjust with a focus on increasing energy efficiency at the same time as providing flexibility to the overall energy system.

The main features of each generation define the four generations. Central refrigeration for the food supply chain was the main feature of 1GDC, while economy-of-scale with large chillers for comfort cooling in dense city centres was the main driver for 2GDC. Interaction in diversified systems became the main characteristics of 3GDC. The main feature of 4GDC is the smart energy systems

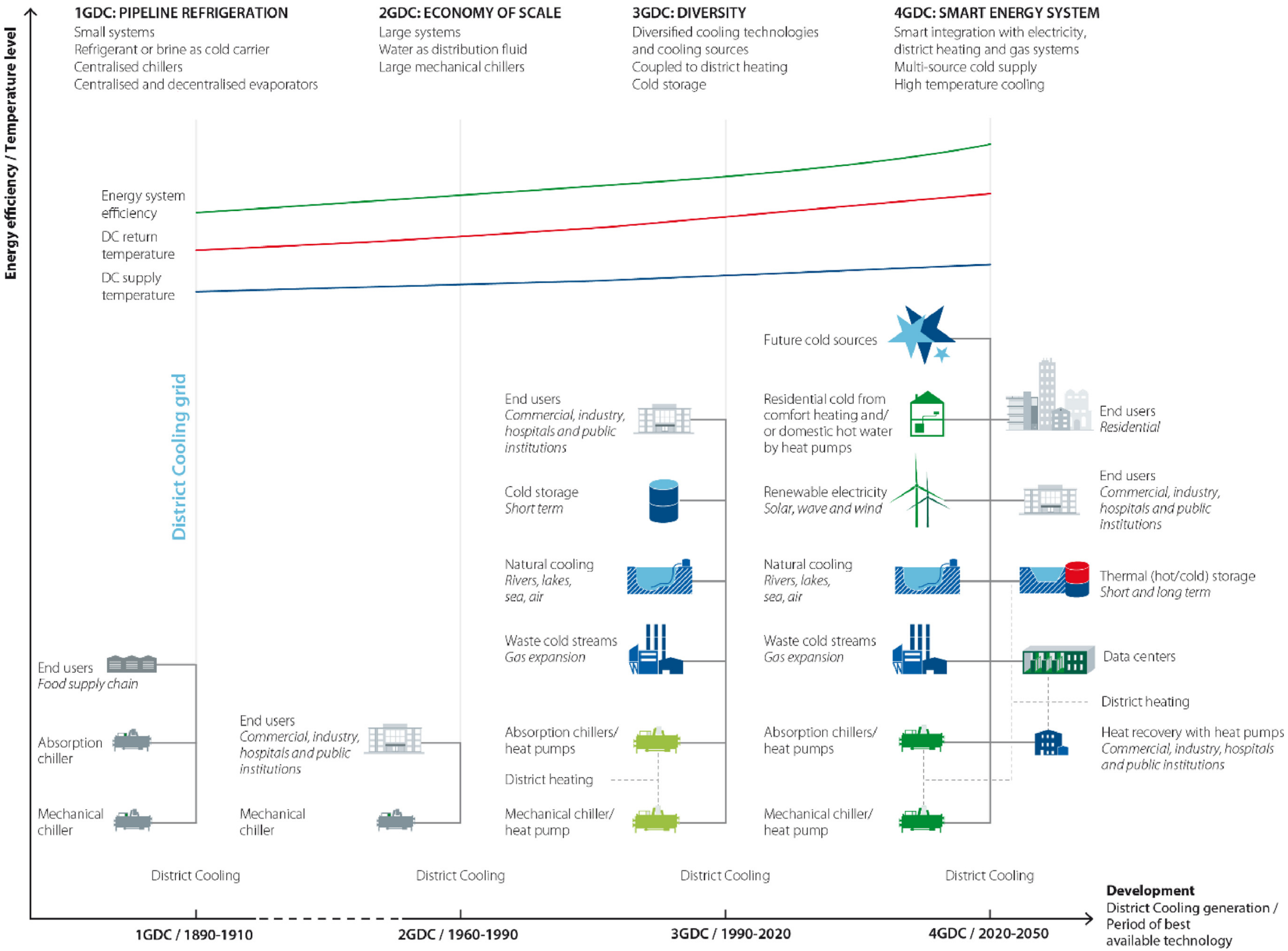

Fig. 1. *The four generations of DC. The major driver for the 4GDC is the cross-sectoral integration into the RES-based smart energy system including the exploitation of the CHC synergy wherever appropriate. Depending on the context, a 4GDC system may not include all the shown components. E.g. in climatic zones with no heat demand, current 2GDC systems may upgrade to 4GDC systems simply by integrating with other sectors and providing flexibility to the smart energy systems using solar, wind, and wave power* [79].

integration including the possible exploitation of the CHC synergy. Hence, 4GDC can be characterised as DC with flexible system integrated load and storage management in possible combination with heat recycling, giving a competitive advantage when both heat and cold are required.

Where consecutive generations of DH replaced the previous for DH, this pattern is no as clear for DC generations, as briefly touched upon in Section 5. The 1GDC is now outdated, but with regard to the three following generations, their core technologies will likely appear simultaneously at different locations for many years. Their core technologies and concepts are more related to the different climate zones of the Earth. The 2GDC concepts are mostly used in the subtropical and tropical zones where cold demands are high and heat demands are low. In the temperate zone with rather cold winters, 3GDC concepts are used, since both natural cold resources and DH systems are available in this climate zone. The early 4GDC systems have emerged on the border between the temperate and subtropical zones with both cold and heat demands.

Common for the future development of DC systems in all climatic zones is that, along with the green transition, fossil fuels will be replaced by RE-based electricity sources and thus a need arises for a smart energy system cross-sectoral integration. Thus, current 2GDC and 3GDC systems may evolve into 4GDC systems simply by adding thermal storage and using it in the active integration of renewable electricity.

Moreover, the CHC synergy should be included in relevant climatic zones. Heat recycling was initially not identified as a possibility in the first three DC generations, since the heat removed by cooling was always rejected to the atmosphere as waste heat. The early adopters of heat recycling became the 3GDC systems in Stockholm, Helsinki, and Geneva, when they started to exploit the CHC synergy. Beyond new 4GDC systems, heat recycling may also be introduced in 2GDC and 3GDC systems for future heat supply to suitable local heat demands in the vicinity of these systems.

Short-term storages for counteracting daily cold load variations were initially not implemented in early 2GDC systems. Later, the load management benefits of these storages were recognised, and several installations followed. They also became vital parts of most 3GDC systems.

The choice of centralised or decentralised cold supply in new 4GDC systems is currently not obvious. Both options have their pros and cons. The choices of cluster-level heat pumps for heating in the decentralised variant examples presented in Section 3 indicate that smaller building-level heat pumps and chillers currently may be too expensive for this application. The heat supply by heat pumps in the decentralised variant is not so flexible, since no major heat storage beyond the thermal mass in buildings is normally available for the requested temperature level after the heat pump. Hence, this heat supply variant is bound to use electricity at all times, giving a lower possibility for integration with the rest of the smart energy system, which to an increasing extent will be RE-based and decarbonised. The importance of the decarbonisation of the cooling systems is emphasized by the expected growth in this field [5].

In the centralised variant, both heat and cold storages are normally available, providing high flexibility for both services. On the other hand, it is more productive to just use one pair of distribution pipes for both cooling and heating in the decentralised version than using four parallel pipes in the centralised version. The temperature lift is also higher in the centralised version, since the heat pump must overcome the whole temperature difference between the DH and DC systems, giving lower energy efficiency for the heat pump process.

When categorising district energy, it is important to split the infrastructure into the two principal services that are delivered via the infrastructure. Historically, the principal services have been heating and cooling, which form the basis for DH and DC. Within each principal branch of district energy, the concept can be further branched into generations. These are defined based on pivotal moments where unique characteristics and features have catapulted the technology forward. Preceding and following such pivotal moments, a high level of innovation and experiments tends to sow the seed for the next level of development. While it is relatively simple to identify past pivotal moments, one has to be careful when defining the future of the technology, as the aim should not be to include every potential future scenario, but to identify the key features of today's advanced systems that separate them from the past and will, with high probability, be the key features in systems built in the decades to come. With the uncertain future in mind, there is a dilemma in what to include, and what not. A too wide definition of a category will generalise and dilute the specific characteristics, while a too narrow definition will end up in loss of the bigger picture.

To conclude, this paper has presented the first real definition of DC generations with the objective of establishing a well-founded discussion platform for DC systems and highlighting the potential development/improvement of existing DC systems, based on knowledge of the historical best in DC systems. For new system developments, both by utilities and energy transition planners, this work provides a relevant entry point on which to define and contemplate possible DC and energy system pathways.

Credit author statement

Poul Alberg Østergaard: Conceptualization, Writing – original draft preparation, Funding acquisition. Sven Werner: Conceptualization, Writing – original draft preparation. **Anders Dyrelund**: Conceptualization, Writing – original draft preparation. **Henrik Lund**: Conceptualization, Writing- Conceptualization, Writing – original draft preparation, Funding acquisition. **Ahmad Arabkoohsar**: Writing – original draft preparation. **Peter Sorknæs**: Conceptualization, Writing – original draft preparation. **Oddgeir Gudmundsson**: Writing – original draft preparation. **Jan Eric Thorsen**: Writing – original draft preparation. **Brian Vad Mathiesen**: Writing – review & editing, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A

Overview of implementations of 27 district energy systems based on different generation designs all around the world. Sorted according to technology generations and starting years.

Generation	Location	Starting Year	Cold Supply Technology	Cold Supply Capacity (MW or GWh/year)	Cold Storage	Distribution Fluid	Supply Temp. (°C)	Return Temp. (°C)	Trench Length (km)	Synergy	Purpose	Ref.
First	Colorado Automatic Refrigeration Co, Denver	1889	Absorption chiller	~0.11 MW	–	Ammonia	−4	Around supply temp.	2.4–3.2	Centralization	Cold storage units for commercial use	[14,15,17]
First	Manhattan Refrigerating Co, New York	1906	Compression chillers	?	–	Brine	−4 to +7	?	~0.75 initially	Centralization	Cold storage units for commercial use	[18]
Second	Hartford, USA	1962	Steam-driven compression and absorption chillers	22.9 MW	Cold storage in 1986 with 8000 m^3 water tank	Chilled water	5.5	15.5	6.1	Centralization and district heating coupling	First commercial district cooling system in the USA	[20–22]
Second	La Defense, outside Paris, France	1967	Compression chillers and natural cooling from river	177 GWh in 2019	–	Chilled water	4.5	14.5	28	Centralization and recently natural cooling	District cooling for a business area with several office buildings	[23]
Second	Hamburg, Germany	1968	Compression chillers	18.7 MW	3.5 MWh cold stored in the distribution network	Chilled water	6–8	15	12	Centralization and off-peak electricity scheduling	Cooling supply to Business City North for 16 shareholders with 18 buildings	[24–26]
Second	Shinjuku, Tokyo, Japan	1971	Compression and absorption chillers	210 MW	–	Chilled water	4	12	8	Centralization and district heating coupling	Cooling supply to the city centre buildings of Tokyo	[27,28]
Second	Guangzhou, China	2004	Compression and absorption chillers	520 MW	Ice storage	Chilled water	2	13	?	?	University campus buildings	[31]
Second	Pearl, Qatar	2010	Compression chillers	450 MW	–	Chilled water	4.4	?	92	Centralization	To residential and commercial buildings	[33]
Second	Metro Dubai, UAE	2010	Compression chillers	128 MW	–	Chilled water	?	?	52	Centralization	47 metro stations	[34]
Second	Yalong Bay, China	2011	Compression chillers	32 MW	Ice storage, 90 MWh	Chilled water	3.5	11	?	Centralization	Hotels and other commercial buildings	[31]
Second	Sabah Al-Salem University, Kuwait	2019–2021	Compression chillers	380 MW	Three cold storage tanks	Chilled water	6	13	55	Centralization	For all buildings within the new university campus	[35]
Third	Paris, France	1991	Compression chillers with cooling towers and river cooling	280 MW	One chilled water tank and two ice storages	Chilled water	0.5–4	?	83	Off-peak electricity scheduling, and natural cooling	Buildings, hotels, and department stores	[36]
Third	Stockholm, Sweden	1995	Compression and absorption chillers, seawater cooling, heat-pumps	335 GWh in 2020	One large rock cavern of 50,000 m^3	Chilled water	5	11	250	Natural cooling, off-peak electricity scheduling, and heat pumps	Mostly commercial buildings in the city centre	[37–39]
Third	Gothenburg, Sweden	1995	Compression and absorption chillers; river cooling	70 MW	–	Chilled water	6	16	30	District heating coupling, and natural cooling	Mostly commercial buildings in the city centre	[40]
Third	Helsinki, Finland	1998	Heat pump, absorption chillers, and sea water cooling	200 MW	Two rock caverns with 37,000 m^3 together	Chilled water	8	16	90	Heat recovery by heat pumps, and natural cooling	Mostly commercial buildings in the city centre	[41,42,47]
Third	Cornell University, USA	2000	Lake water cooling	70 MW	–	Chilled water	7	15	3.7	Natural cooling	Offices and laboratories	[46,47]

(*continued on next page*)

(*continued*)

Generation	Location	Starting Year	Cold Supply Technology	Cold Supply Capacity (MW or GWh/year)	Cold Storage	Distribution Fluid	Supply Temp. (°C)	Return Temp. (°C)	Trench Length (km)	Synergy	Purpose	Ref.
Third	Toronto, Canada	2004	Natural cooling, compression and absorption chillers	260 MW	–	Chilled water	3	13	26	Natural cooling	Office buildings in the city centre	[47–50]
Third	Xiaoping Island, Dalian, China	2006	Compression heat pumps using waste and sea water	76 MW	?	Chilled water	7	12	?	Only electricity grid	High-end offices, retail space, hotels, and apartments	[32,56]
Third	Geneva, Switzerland	2009	Lake cooling and building level heat pumps	16 + 2.9 MW	–	Chilled water	5	17	6	Natural cooling with distributed heat pumps for heating	Mostly administrative buildings for international organizations	[51,52,54,55]
Third	Copenhagen, Denmark	2010	Seawater cooling, ammonia compression chillers, and absorption chillers	52 MW	–	Chilled water	6	16	18	District heating coupling, and natural cooling	62 large buildings with 1.1 million m^2 area	[43]
Fourth, centralised	Stanford University, USA	2015	Heat recovery chillers and compression chillers	88 MW	Cold storage with 68,000 m^3	Chilled water	5.5	13.5	40	Combined heating and cooling	360 university campus buildings	[60–62]
Fourth, centralised	Høje Taastrup, Denmark	2016	Heat pumps and Compression chillers	10 MW (2 MW)	–	Chilled water to office buildings and Chilled Glycol to whole sale market	8 (and −8)	15 (and −1.6)	9	Combined heating and cooling	Office buildings, process cooling and Cooling whole sale market of vegetable and flowers at −8 °C	[63,64]
Fourth, centralised	Taarnby at Kastrup, Denmark	2020	Electric bifunctional heat pump and groundwater	10 MW	Chilled water tank wih 2000 m^3	Chilled water	8	15	1.5	Combined heating and cooling	Local district cooling system	[65–68]
Fourth, decentralised	Heerlen, The Netherlands	2008	Cluster-level heat pumps, geothermal boreholes, waste heat flows	?	Geothermal boreholes	Somewhat warmer than chilled water	16	22	7	Combined heating and cooling	Commercial, office, and service buildings	[69,70]
Fourth, decentralised	ETH, Zürich, Switzerland	2013	Cluster-level heat pumps with geothermal boreholes and waste heat from buildings	5.5 MW	431 geothermal boreholes	Somewhat warmer than chilled water	4–20	8–24	1.5	Combined heating and cooling	Space cooling and laboratory cooling	[71]
Fourth, decentralised	FGZ, Zürich, Switzerland	2014	Cluster-level heat pumps, geothermal boreholes, and waste heat from data centres	3.9 MW	332 geothermal boreholes with 250 m depth each	Somewhat warmer than chilled water	4–24	8–28	1.5	Combined heating and external cooling	Cooling of two external data centres	[54,72]
Fourth, decentralised	Saclay University, Paris, France	2017	Cluster-level heat pumps, geothermal boreholes, and natural-gas boilers	10 MW	Geothermal boreholes	Chilled water	6	12	10	Combined heating and cooling	University campus area with low-energy buildings	[74,75]

References

[1] Lund H. Renewable energy systems - a smart energy systems approach to the choice and modeling of 100% renewable solutions. second ed. Academic Press; 2014.

[2] Mathiesen BV, Lund H, Connolly D. Limiting biomass consumption for heating in 100% renewable energy systems. Energy 2012;48:160–8. https://doi.org/10.1016/j.energy.2012.07.063.

[3] Lund H, Østergaard PA, Connolly D, Ridjan I, Mathiesen BV, Hvelplund F, et al. Energy storage and smart energy systems. Int J Sustain Energy Plan Manag 2016;11:3–14. https://doi.org/10.5278/ijsepm.2016.11.2.

[4] Werner S. International review of district heating and cooling. Energy 2017;137:617–31. https://doi.org/10.1016/j.energy.2017.04.045.

[5] International Energy Agency. The Future of Cooling - opportunities for energy efficient air conditioning. Paris: France; 2018. https://doi.org/10.1787/9789264301993-en.

[6] Frederiksen S, Werner S. District heating and cooling. first ed. Lund: Studentlitteratur; 2013.

[7] Lund H, Østergaard PA, Chang M, Werner S, Svendsen S, Sorknæs P, et al. The status of 4th generation district heating: research and results. Energy 2018;164:147–59. https://doi.org/10.1016/j.energy.2018.08.206.

[8] Johannsen RM, Arberg E, Sorknæs P. Incentivising flexible power-to-heat operation in district heating by redesigning electricity grid tariffs. Smart Energy 2021;2:100013. https://doi.org/10.1016/j.segy.2021.100013.

[9] Lund H, Werner S, Wiltshire R, Svendsen S, Thorsen JE, Hvelplund F, et al. 4th Generation District Heating (4GDH). Integrating smart thermal grids into future sustainable energy systems. Energy 2014;68:1–11. https://doi.org/10.1016/j.energy.2014.02.089.

[10] Lund H, Andersen AN, Østergaard PA, Mathiesen BV, Connolly D. From electricity smart grids to smart energy systems - a market operation based approach and understanding. Energy 2012;42:96–102. https://doi.org/10.1016/j.energy.2012.04.003.

[11] Mathiesen BV, Lund H, Connolly D, Wenzel H, Østergaard PA, Möller B, et al. Smart Energy Systems for coherent 100% renewable energy and transport solutions. Appl Energy 2015;145:139–54. https://doi.org/10.1016/j.apenergy.2015.01.075.

[12] Billington N, Roberts B. Building services engineering - a review of its development. Oxford Pergamon Press; 1982.

[13] Thevenot R. A history of refrigeration throughout the world. Paris Int Inst Refrig 1979.

[14] Beach WY. Refrigeration for towns and cities by street mains. Sci Am Sci Am 1891;65:151.

[15] First NN. Frost. Am Herit 1985;36.

[16] Hawks AM. The Colorado automatic refrigerator system at denver, colo. Trans Am Soc Civ Eng 1891;24:389–92. https://doi.org/10.1061/TACEAT.0000790.

[17] Pierce M. The road to lockport: historical background of district heating and cooling. CH-95-10-1 ASHRAE Trans 1995;101:885–92.

[18] Shockley J. Gansevoort market historic district - designation report. New York City Preserv Comm; 2003.

[19] Tait R. Development of pipe line refrigeration. Ice Refrig 1916;51:174–6.

[20] Jebb William T. Central station heating and cooling in Hartford. Dist Heat 1961;47:68–72.

[21] Mirabella A. Hartford - a modern DHC system. Dist Heat Cool 1986;72:11–3.

[22] Mirabella AC. Celebrating four decades of service. https://hartfordsteam.com/news/2ndQtr2003.pdf; Loop" 2003.

[23] Lamorell Petra. Case story of district cooling of La defense. Bernoulli Syst AB 2015:1.

[24] Allkofer E. Die fernkälteanlage in der Geschäftsstadt hamburg-nord. Heizung-Lüftung-Haustechnik 1969;20:6–9.

[25] Dommann D, Weidling H. Fernkälteversorgung der Geschaftsstadt nord in Hamburg. Fernwärme Int 1991;20:587–95.

[26] Mijnlieff A. Froid À distance - fernkälte - district cooling. UNICHAL; 1970.

[27] Tokyo Gas Engineering Solutions. Shinjuku district cooling system (accessed June 14, 2021), https://www.tokyogas-es.co.jp/en/case/dhc/index.html; 2021.

[28] APEC Energy Working Group. District energy systems development roadmap study in APEC economies (final report for APEC project EWG 24 2013A). https://www.apec.org; 2015.

[29] Ali M. District cooling in the Middle East. HotCool 2016;2:14–6.

[30] Eveloy V, Ayou DS. Sustainable district cooling systems: status, challenges, and future opportunities, with emphasis on cooling-dominated regions. Energies 2019;12. https://doi.org/10.3390/en12020235.

[31] Asian Development Bank. District cooling in the people's Republic of China - status and development potential. 2017. https://doi.org/10.22617/RPT168582-2.

[32] Gang W, Wang S, Xiao F, Gao D. District cooling systems: technology integration, system optimization, challenges and opportunities for applications. Renew Sustain Energy Rev 2016;53:253–64. https://doi.org/10.1016/j.rser.2015.08.051.

[33] Cool Qatar. Pearl Qatar district cooling system, third global district energy climate award. Third Glob. Dist. Energy Clim. Award; 2013.

[34] DESMI. Dubai's metro district cooling system. https://www.desmi.com/customer-stories/dubai-metro-district-cooling-uae/; 2019.

[35] Kuwait-University. Sabah Al-Salem University City district cooling system (accessed June 14, 2021), http://ssuc.ku.edu.kw/project/bid-pack-3a-central-utility-plant-i-2-including-ancillary-buildings/; 2021.

[36] Térouanne D, Gaschignard V. A district cooling system to control impact of air-conditioning in Paris. Application for the second global district energy climate awards. Retrieved from, https://www.districtenergyaward.org/winners/2011-2/2011.

[37] Exergi Stockholm. Annual and sustainability report for 2020. Retrieved from, https://www.stockholmexergi.se/om-stockholm-exergi/arsredovisning-2020/2021.

[38] Fortum AB. High demand for district cooling and heating in Stockholm 4 Unitop ® 33/28CPY for the Nimrod power station, vols. 4–7; 2006.

[39] Naturvårdsverket. Seawater stored in rock in Stockholm provides efficient district cooling. Information facts: Swedish Environmental Protection Agency; 2011.

[40] Jangsten M. Gothenburg district cooling system - an evaluation of the system performance based on operational data Gothenburg district cooling system. Chalmers University of Technology; 2020.

[41] Energia. District cooling in Finland. 2020 statistics. 2021.

[42] Energia Helsingin. District cooling in Helsinki – the most advanced cooling solutions. 2011. https://www.districtenergyaward.org/wp-content/uploads/2012/10/District_Cooling_Finland_Helsinki_2011.pdf.

[43] Willum M. Climate-friendly cooling in copenhagen. Dist Energy 2017;103:25–8.

[44] Looney C M, Oney S. Seawater district cooling and lake source district cooling. Energy Eng 2007;104:34–45. https://doi.org/10.1080/01998590709509510.

[45] Zogg R, Roth K, Brodrick J. Lake-source district cooling systems. ASHRAE J 2008;40:55–6.

[46] Peer T, Joyce WSL. Lake-source cooling. ASHRAE J 2002;44:37–9.

[47] Final Report of USEPA Award. Assessing the feasibility of a central New York naturally chilled water project. 2011.

[48] Bélanger L. Into the Deep: enwave taps lake water to cool Toronto. Dist Energy 2005;91:16–20.

[49] Newman L, Herbert Y. The use of deep water cooling systems: two Canadian examples. Renew Energy 2009;34:727–30. https://doi.org/10.1016/j.renene.2008.04.022.

[50] Canadian Urban Institute. Canadian district energy association, Toronto atmospheric Fund. ENWAVE factsheet: deep lake water cooling, keeping Toronto cool. Int Dist Energy Assoc Website 2008;1–5.

[51] Crochet D, Ducrest JMM. Réseau thermique Genève-Lac-Nations (GLN) - etude de cas. 2017.

[52] European Commission. Rafraîchir et chauffer, le quartier des Nations avec l'eau du lac. 2011.

[53] Durandeux S. De GLN à GeniLac. 10 ans d'apprentissage dans la valorisation thermique des eaux du Léman. In: Pap. Present. ARPEA - Réseaux Chauff. refroidissement comment valoriser les ressources inexploitées Suisse Rom; 2019. Lausanne.

[54] Buffa S, Cozzini M, D'Antoni M, Baratieri M, Fedrizzi R. 5th generation district heating and cooling systems: a review of existing cases in Europe. Renew Sustain Energy Rev 2019;104:504–22. https://doi.org/10.1016/j.rser.2018.12.059.

[55] Viquerat P-A. Utilisation des réseaux d'eau lacustre profonde pour la climatisation et le chauffage des bâtiments; bilan énergétique et impacts environnementaux: etude de cas: le projet GLN (Genève-Lac-Nations) à Genève. University of Genev; 2012. https://doi.org/10.13097/archive-ouverte/unige:23016.

[56] Zhen L, Lin DM, Shu HW, Jiang S, Zhu YX. District cooling and heating with seawater as heat source and sink in Dalian, China. Renew Energy 2007;32:2603–16. https://doi.org/10.1016/j.renene.2006.12.015.

[57] Calderoni M, Babu-Sreekumar B, Dourlens-Quaranta S, Lennard Z, Rämä M, Klobut KHL. Sustainable district cooling guidelines. IEA DHC/CHP Rep; 2019.

[58] Gaudard A, Wüest A, Schmid M. Using lakes and rivers for extraction and disposal of heat: estimate of regional potentials. Renew Energy 2019;134:330–42. https://doi.org/10.1016/j.renene.2018.10.095.

[59] Upstate Freshwater Institute. Lake source cooling annual reports (1998 to 2012) n.d (accessed April 20, 2022), https://fcs.cornell.edu/departments/energy-sustainability/utilities/cooling-home/cooling-production-home/lake-source-cooling-home/lake-source-cooling-monitoring-data/lake-source-cooling-annual-reports-1998-2012.

[60] Stanford University. Stanford Energy System Innovations 2014. https://doi.org/10.1023/B:JOTA.0000005666.45436.37.

[61] Stagner JC. Stanford University's "fourth-generation" district energy system. Int Dist Energy Assoc 2016;102:19–24.

[62] De Chalendar JA, Glynn PW, Benson SM. City-scale decarbonization experiments with integrated energy systems. Energy Environ Sci 2019;12:1695–707. https://doi.org/10.1039/c8ee03706j.

[63] Schleiss U. Annex 47, Fjernvarme og fjernkøling i Høje Taastrup. 2017.

[64] Matson C. District cooling & district heating - Danish experience. Ramboll; 2017.

[65] State of Green. Smart combination of district cooling, district heating and waste water in Taarnby. 2019. https://stateofgreen.com/en/partners/ramboll/solutions/smart-combination-of-district-cooling-district-heating-and-waste-water-in-taarnby/.

[66] European Commission. Denmark. Smart sector integration through DHC in Taarnby (greater copenhagen), section 4.1. Integr. In: Renew. waste heat cold sources into Dist. Heat. Cool. Syst. Luxembourg: Publications Office of the European Union; 2021. p. 14–25.

[67] Margaryan H, Bigum F, Breen N. Taarnby's smart solution: electric-driven combined heating and cooling plus wastewater. Dist Energy 2021:107.
[68] Margaryan H, Dyrelund A, Caröe A, Trumulis A. Smart cost-effective district cooling in Taarnby. HotCool; 2021.
[69] Mijnwater. The mijnwater 5GDHC grid in heerlen. Application for the sixth global district energy climate awards. Retrieved from, https://www.districtenergyaward.org/mijnwater- 2020.
[70] Verhoeven R, Willems E, Harcouët-Menou V, De Boever E, Hiddes L, Veld PO, et al. Minewater 2.0 project in heerlen The Netherlands: transformation of a geothermal mine water pilot project into a full scale hybrid sustainable energy infrastructure for heating and cooling. Energy Proc 2014;46:58−67. https://doi.org/10.1016/J.EGYPRO.2014.01.158.
[71] Gabrielli P, Acquilino A, Siri S, Bracco S, Sansavini G, Mazzotti M. Optimization of low-carbon multi-energy systems with seasonal geothermal energy storage: the Anergy Grid of ETH Zurich. Energy Convers Manag X 2020;8:100052. https://doi.org/10.1016/j.ecmx.2020.100052.
[72] IEA HPT TCP. Anergy network Friesenberg of the family corporation Zürich - Switzerland. 2017.
[73] Edtmayer H, Nageler P, Heimrath R, Mach T, Hochenauer C. Investigation on sector coupling potentials of a 5th generation district heating and cooling network. Energy 2021;230:120836. https://doi.org/10.1016/j.energy.2021.120836.
[74] France European Commission. A semi-centralised geothermal DHC system fed by a mid-temperature loop in Paris-Saclay. Section 4.3. Intergrating Renew Waste Heat Cold Sources into Dist Heat Cool Syst 2021:44−63.
[75] Galindo Fernández M, Roger-Lacan C, Gährs U, Aumaitre V. Efficient district heating and cooling markets in the EU: case studies analysis, replicable key success factors and potential policy implications. Luxembourg: Publications Office of the European Union; 2016. https://doi.org/10.2760/371045.
[76] Dyrelund A, Bigum FP. The four generations of district cooling. HOT | Cool Int Mag Dist Heat Cool 2020:15.
[77] Duda SW. Chilled water system for University campus. ASHRAE J 2006;48:12−20.
[78] Coffin G. University of Missouri district energy system - award application for international district energy association system of the year award. https://higherlogicdownload.s3.amazonaws.com/DISTRICTENERGY/UploadedImages/06ccd955-5616-4383-af4d-ee333155fa32/University_of_Missouri_Award_Submission_System_of_the_Year.pdf. [Accessed 5 October 2021].
[79] Thorsen JE, Gudmundsson O, Østergaard PA, Werner S, Dyrelund A, Lund H, et al. The four generations of district cooling Chart 2022. https://vbn.aau.dk/da/publications/the-four-generations-of-district-cooling-chart.
[80] Chittum A, Østergaard PA. How Danish communal heat planning empowers municipalities and benefits individual consumers. Energy Pol 2014;74:465−74. https://doi.org/10.1016/j.enpol.2014.08.001.
[81] Lund H, Thellufsen JZ, Østergaard PA, Sorknæs P, Skov IR, Mathiesen BV. EnergyPLAN − advanced analysis of smart energy systems. Smart Energy 2021:100007. https://doi.org/10.1016/j.segy.2021.100007.