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ABSTRACT

Fourth-generation district heating (4GDH) has been used as a label or expression since 2008 to describe a transition path for decarbonization of the district heating sector and was defined in more detail in 2014. During recent years, several papers have been published on a concept called fifth generation district heating and cooling (5GDHC). This article identifies differences and similarities between 4GDH and 5GDHC regarding aims and abilities. The analysis shows that these two are common not only in the overarching aim of decarbonization but that they also to some extent share the five essential abilities first defined for 4GDH. The main driver for 5GDHC has been a strong focus on combined heating and cooling, using a collective network close to ambient temperature levels as common heat source or sink for building-level heat pumps. It is found that 5GDHC can be regarded as a promising technology with its own merits, yet a complementary technology that may coexist in parallel with other 4GDH technologies. However, the term "generation" implies a chronological succession, and the label 5GDHC does not seem compatible with the established labels 1GDH to 4GDH.

1. Introduction

Several studies mention fifth-generation district heating and cooling (5GDHC) as a new innovative generation of district heating (DH) systems. 5GDHC ensures less heat loss within the DH network by transmitting ultra-low temperature heat that requires local boosting to achieve the required temperature level at the end-user using heat pumps. The low transmission temperature further enables direct heat injection to the system from various low-temperature waste heat sources, thus facilitating this practice if required from a systems perspective.

The first DH generations utilized a central supply of heat at immediately useful temperature levels that was distributed to buildings using a network of pipes. DH was commercially introduced in the USA in the 1880s, where the first generation of DH (1GDH) used steam as a heat carrier [1].

As DH was developed — largely in Europe - the heat carrier was altered from steam to superheated water, and this fundamental change marks the change to the second-generation district heating (2GDH), which was to become the preferred type for new DH systems. The transition from steam to superheated water increased the efficiency, reliability, and resilience of the system [1].

The next major development denoted third-generation district heating (3GDH) occurred in Scandinavian countries adopting the DH technology. This was based on reduction of the supply temperature to below 100 °C, enabling the exploitation of a wider variety of heat sources, industrialized manufacturing of substations, and pre-insulated pipe systems buried directly into the ground. The relatively lower temperature of the DH network in 3GDH increased the distribution efficiency and enabled an economically viable utilization of high-temperature waste heat from industrial processes as well as heat supply from renewable energy sources [1].

With increased focus on energy efficiency, smart integrated energy systems [2–4], and the utilization of locally available renewable energy sources, the DH development leaped forward, leading to fourth-generation district heating (4GDH). One of the features of 4GDH is a temperature level as close to the actual temperature demand of the connected end-users as possible, at a

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Abbreviations

DH	District heating
DC	District cooling
1GDH	First-generation district heating
2GDH	Second-generation district heating
3GDH	Third-generation district heating
4GDH	Fourth-generation district heating
5GDHC	Fifth-generation district heating and cooling
6GDES	Sixth-generation district energy systems
LTDH	Low-temperature district heating
ULTDH	Ultralow-temperature district heating
CHC	Combined heating and cooling

maximum of 60–70 °C. The lower supply temperature lowers DH grid losses and enables the economically feasible integration of even more waste heat sources than in 3GDH, such as excess heat from data centres and supermarkets [1,5].

4GDH also emphasizes the increased use of heat pumps in DH systems to exploit further low-temperature waste heat sources or sources based on ambient heat. Both heat pumps and CHP units have higher efficiencies at 4GDH than at 3GDH temperature levels, which is a driver for more heat pump capacity [5]. Further, the synergy of low-temperature DH and high-temperature district cooling (DC) systems for increasing the efficiency of supply has been part of the focus of 4GDH. A central heat pump, combined with storage of heat and cold like for an aquifer thermal energy storage (ATES) enables smart operation of the heat pump with the option of storing heat from the summer and cold from the winter.

With the emergence of 4GDH, seasonal thermal storage has become a viable solution for long-term storage of seasonally available heat sources and an enabler of a smart and integrated energy system [6]. Lastly, this new generation of DH is highly compatible with low-energy buildings. The low-temperature demand of low-energy buildings has shown to increase the efficiency of the overall system [5].

As mentioned, the use of the term 5GDHC has started to appear in scientific literature lately. This perspective paper investigates the usage of this term and correlates the explicit or inferred definitions to the well-established 4GDH definition.

The paper is structured in three further sections following the introduction. In Section 2, 4GDH is characterized. This is followed by a review of the literature applying the 5GDHC label. Section 4 presents a discussion of the properties of 5GDHC compared to 4GDH. Finally, the conclusions are drawn in Section 5.

2. Definition of fourth-generation district heating

The concept of 4GDH has been defined and elaborated in Refs. [1,5,7]. District cooling is seen as an integrated part of 4GDH; however, this is not reflected in the term. In the definition paper [1], the aim of 4GDH was to meet the challenges and identify the means of reaching a future renewable energy-based heat supply as part of the implementation of overall sustainable energy systems. The basic assumption was and is that DHC has an important role to play in future sustainable energy systems – but that 3GDH had to be developed further in order to fulfill its potential role.

The first three generations were all developed within a supply context dominated by fossil fuels, although e.g. Sweden has managed to nearly implement a sustainable 3GDH system with non-fossil resources. 4GDH technologies should be designed with an explicit decarbonization purpose in mind.

In Ref. [1], 4GDH is defined as a *"coherent technological and institutional concept, which by means of smart thermal grids assists the appropriate development of sustainable energy systems"*, which is indeed a wide definition.

Unlike the first three generations, the development of 4GDH involves balancing the energy supply with energy conservation and thus meeting the challenge of supplying increasingly more energy-efficient buildings with heat to fulfil space heating and domestic hot water demands [8].

An essential economic driver is that lower temperature levels enable reductions in DH grid losses and increases in efficiencies of the heat generation technologies as disparate as CHP, heat pumps, and solar collectors. The lower temperatures of 4GDH enable low-temperature heat sources to deliver more heat with lower investments ([5,9–11]) than with the application of other generations. Lower temperatures can also reduce the need for heat pumps in favour of direct utilization of waste heat sources through heat exchangers. The possible synergy with a DC system at the production site is another feature of 4GDH. Current control principles also allow bidirectional deliveries from local heat sources in 4GDH networks by considering suitable supply temperatures and overcoming local differential pressures. This is consistent with bidirectional deliveries of 5GDHC systems.

The temperature levels of 4GDH are normally sufficiently high to cover space heating demands directly without resorting to any temperature boosting through, e.g., heat pumps at the end-users. Here, low-temperature heat sources are integrated into the operation and effective realization of smart energy systems. Some authors put their work on low-temperature DH (LTDH) or ultralow-temperature DH (ULTDH) into a 4GDH framework, though not necessarily explicitly labelling the analyzed systems as 4GDH [12–18]. Some of these analyses go down to supply temperatures below 45 °C.

Furthermore, 4GDH involves strategic and innovative planning and the integration of DH into the operation of smart energy systems, such as defined in Refs. [2,7], and it involves the development of institutional and organizational frameworks with appropriate cost and incentive structures.

In order to be able to fulfill its role in future sustainable energy systems, 4GDH will need to have the following five abilities [1]:

1. The ability to supply existing, renovated, and new buildings with low-temperature DH for space heating and domestic hot water.
2. The ability to distribute heat in DH networks with low grid losses.
3. The ability to recycle heat from low-temperature waste sources and integrate renewable heat sources, such as solar and geothermal heat.
4. The ability to be an integrated part of smart energy systems and thereby helping to solve the task of integrating fluctuating renewable energy sources and proving energy conservation into the smart energy system.
5. The ability to ensure suitable planning, cost and incentive structures in relation to the operation as well as to strategic investments related to the transformation into future sustainable energy systems.

Fig. 1 shows the development of DH networks throughout the years, as first presented in 2014 in Ref. [1], but later updated in 2018 in Ref. [5].

As described in papers [1,5] and shown in Fig. 1, the definitions of the first four generations are characterized by:

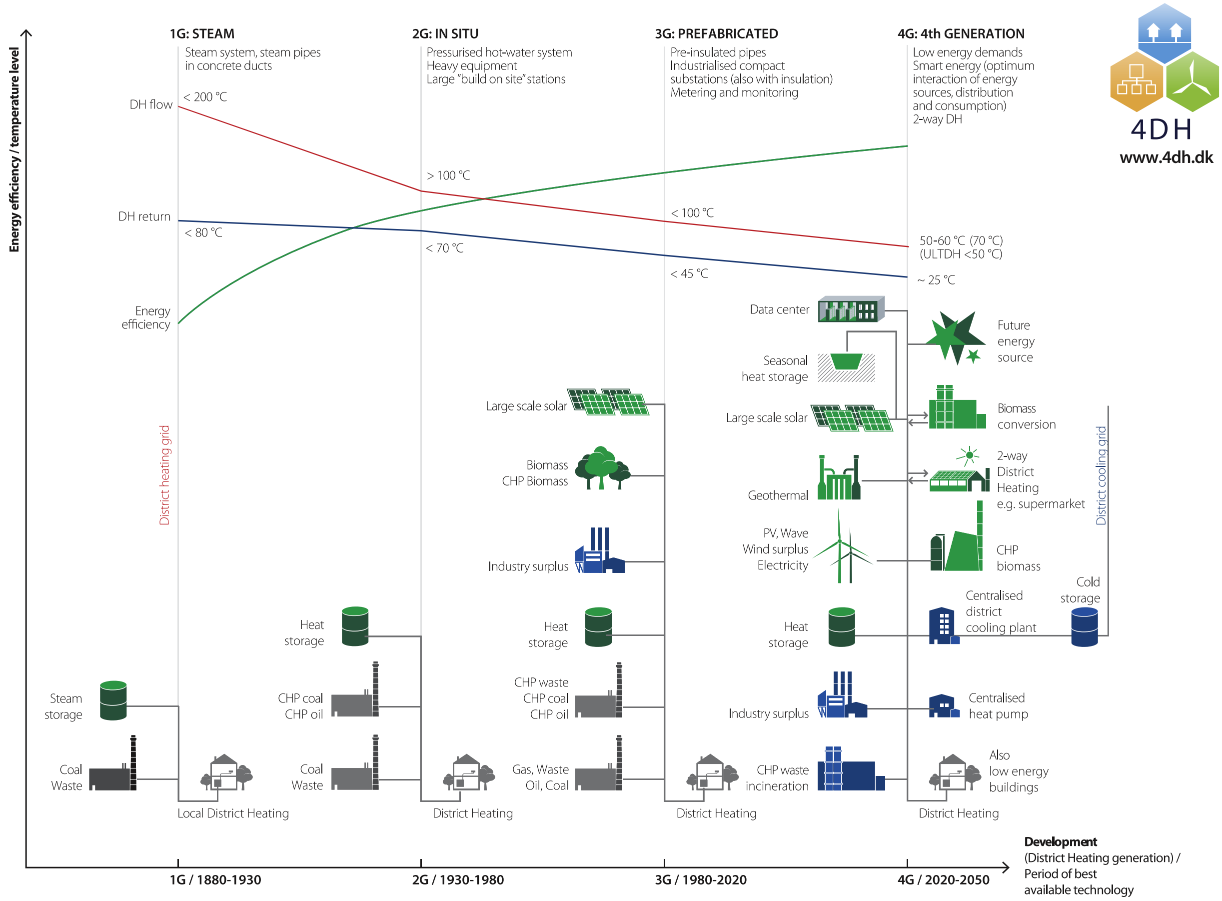

Fig. 1. *From the first to the fourth generation of district heating as published in* Ref. [5]. *Compared to the first version published in* Ref. [1], *this version includes Ultra-low temperature DH (ULTDH) and certain other features.*

- One DH generation generally represents a dominating technology in a period of some decades
- Continuously increased energy efficiency between generations.
- Continuously reduced operational temperatures between generations.
- Breakthrough component developments, as well as manufacturing and construction methods.
- The ability of a new generation to efficiently utilize new energy sources compared to the previous generation.

3. Use of the term fifth-generation district heating and cooling

Combined DHC networks at close-to-ground temperatures and with distributed heat pumps have existed since the 1990s. After the 4GDH concept emerged, the 5GDHC label started to appear in 2015 due to the Flexynets project [19,20] to denote such combined systems. Today, literature shows a wide range of design specifications for 5GDHC systems, which are discussed below.

A number of studies present innovative system proposals for the 5GDHC networks. In Ref. [21], 5GDHC is defined as DH networks operating at near-ground temperatures using a bidirectional exchange of heat and cold between connected buildings, facilitated by seasonal storage. This network requires heat pumps at the connected buildings in order to reach the proper temperature for domestic hot water.

Ref. [22] investigated a two-pipe low-temperature DH system, referred to as a *double loop network*, that consists of a hot pipe operated at a relatively low temperature and a cold pipe operated at a relatively high temperature. Ref. [23] investigated the same two-pipe system and presented the possibility for 5GDHC to become a central part of an integrated smart energy system supplying energy for heating and cooling. Here, borehole thermal storages are suggested for seasonal balancing. The system's ability to reuse low-energy sources is central in this article.

Brennenstuhl et al. [24] further demonstrate the ability of 5GDHC to integrate different heat sources by presenting a rural Plus-energy settlement being supplied by distributed heat pumps, PV, and agrothermal collectors using shallow thermal energy from the soil. In Refs. [25,26] the authors propose a new network design using a one-pipe system for supplying the decentralized heat pumps with the required energy for supplying heating as well as cooling to the households.

Vivian tested various supply temperatures in a DH network for distributed heat pumps [27]. While not referring extensively to 5GDHC, the system presented the use of heat pumps placed at the end-user, which is a common characteristic for all 5GDHC systems. Raluca-Ancuta does not specify the pipe design which is used for 5GDHC but mentions its ability to integrate low-quality heat sources via heat pumps [28].

While the articles presented above focus on system proposals, the following articles investigate the overall modelling, topology optimization, and demand balancing required to increase the efficiency of the 5GDHC systems. Barone et al. [29] solely presented 5GDHC networks as low-temperature networks (30 °C), and argue that complex regulation is required in the *"Bidirectional Low-temperature Networks"*.

While using different operational temperatures, Refs. [30–33] present 5GDHC as one- or two-pipe systems capable of supplying both heating and cooling using heat pumps at the end-users, an achievement hitherto only feasible by using a four-pipe system. Refs. [34,35] exclude the one-pipe system by solely using bidirectional two-pipe flow networks operating at near ambient temperature as the definition for 5GDHC.

The following articles are reviews of recent papers on 5GDHC networks currently in operation. Both Refs. [36,37] review existing 5GDHC networks. Ref. [36] reviews the key features of 40 DH systems defined as 5GDHC in Europe, while Ref. [37] classifies innovative district thermal systems in northern Italy and Switzerland. Both articles agree on 5GDHC being thermal networks operating at temperatures close to the ground, which is not suitable for direct heating.

Abugabbara et al. [38] present the status in literature of simulating 5GDHC systems and defines 5GDHC in its most generic form as a system that *"harnesses the shared energy concept which is realized in a network that connects 'prosumers'"*.

Ref. [39] takes a different approach by investigating both the political and the technical roadblocks to low-temperature DH. Here they define 5GDHC as both an ambient loop system and a four-pipe system having supply and return sides of both heat and cold temperatures operating at 10–40 °C, with heat pumps in the substations.

Some articles only mention 5GDHC without directly expanding the knowledge on 5GDHC. Among these, Ref. [40] uses the two-pipe bidirectional definition and emphasizes seasonal storage as being an essential component in the network. Ref. [41] defines 5GDHC as networks using lower supply temperatures than previous generations of DH (10–25 °C), which can vary seasonally to optimize efficiency. Lastly, Lagoeiro et al. [42] mention 5GDHC as being district thermal systems operating at very low temperatures and being able to supply both heating and cooling.

The common founding in the various studies is that the idea of 5GDHC is based on a thermal network able to supply and extract heat at relatively low temperatures for the operation of heat pumps for heating or cooling purposes at the end-users. The low system temperature facilitates the use of small-scale and low-temperature waste heat sources. While high-temperature DH systems are also able to use such heat sources, they require temperature boosting and investment consideration that are redundant at lower DH temperatures.

The definitions and use of the 5GDHC concept in the mentioned articles do, however, differ significantly from each other on some points, as summarized in Table 1.

Here, the definitions of 5GDHC are categorized on the basis of the temperature level in which they operate, and the different elements of the 5GDHC definition are presented. Some elements may be missing due to the lack of information in the mentioned studies. The thermal source placement refers to whether the utility company supplies heat (central), the end-users have a role in regenerating the heat network (distributed), or whether the system is able to balance itself solely using heating or cooling from the prosumers. The system temperature refers to the system's ability to work at fixed or variable temperatures.

As seen in Table 1, the most common characteristic is the two-pipe network. This network uses both cold and warm water pipes, which, together with a heat pump located at the end-user, ensures the appropriate temperature. The one-pipe network functions in the same way; however, it relies on only one ambient temperature loop to supply the needed thermal energy for both cooling and heating in the households. Most networks were defined to be operating below 30 °C, with a few operating at ground temperature or temperatures between 30 and 50 °C.

Compared to the definition of 4GDH presented earlier, the definitions of 5GDHC are mainly distinguished by using temperature adjustment at the end-users to achieve the required operational temperatures at the building level and optionally insulated pipes. 4GDH may also include heat pumps as production units in the DH system [1]. Some 4GDH studies even mention the use of heat pumps placed at the end-user for boosting temperature levels to reach appropriate domestic hot water temperatures [14,18,43–45].

The main ideas of 5GDHC, according to our assessment, are to:

a) take advantage of the synergy of combined heating and cooling in areas of mixed purpose buildings,
b) minimize the barrier of utilizing local waste heat sources and minimize upfront investment cost for the utility company, though the required initial investment at the end-users will be higher, and
c) enable less restrictive organic growth of the system, as central heat supply is not as critical, since new additional end-users will both add and use heat from the network.

From a wide point of view, the five abilities defined for 4GDH systems can also be identified as typical abilities for 5GDHC systems, however with additional considerations. The second ability concerning lower grid losses can be easily achieved. On the other hand, it can be difficult to fully implement the fourth ability of integrating with a smart energy system with the strong focus on local harmonisation of combined heating and cooling in 5GDHC systems.

4. Perception of generations

A common definition of generation is 'all of the people born and living at about the same time, regarded collectively'. A definition of a technology generation could then be 'all of the technologies introduced and operated at about the same time, regarded collectively'. A common denominator for a technology generation can also be common aims and abilities. In this case, decarbonization of the DH sector and the five abilities defined for 4GDH.

An area like telephone communication has experienced a technological development that has gone through five generations, starting with the analog first generation (1G), the digital 2G, smartphones with internet access (3G), the more data-intensive 4G [46] and so far ending with the high-speed 5G that even further enables the detachment of processing from the processing power of user devices, enabling connectivity between all sorts of electronic equipment. Here, generations are rather to be perceived as technological leaps for obtaining wider scopes, and generations are clearly linked to the technical characteristics of these scopes.

Where the generational shifts in mobile telephony have had long transition periods, the same is the case for DH generations. For mobile telephony, generations have coexisted for decades, and even now, when 5G is being implemented, 4G is still being developed; however, there is a sequential logic in the shift between generations, since each new generation has a wider scope with considerable new services.

Within DH, there are 1GDH-3GDH systems in operation that could benefit from being supplanted by or gradually phased into a 4GDH system, but as with mobile telephony, 3GDH and 4GDH systems can coexist and even form different parts of the same DH system – but as with mobile telephony generations, there is a certain sequential evolution.

Thus, 4GDH can be regarded as a general evolutional development of the three previous generations but simply better aligned

Table 1
Overview of 5GDHC characteristics in the literature.

	Thermal source design			Distribution system			Pipe insulation		System temperatures		Thermal storages		Country placement
	Central	Distributed	Self-balanced	Single pipe	Two pipe	≥ Three pipes	Insulated	Uninsulated	Fixed	Variable	Short term	Long term	
Temp. level (T)													
$T<50^{\circ}C$													
[27] (Vivian et al.)							*			*	*		Northern Italy
[22] (Tunzi et al.)		*			*		*		*		*		Denmark
$T<40^{\circ}C$													
[36] (Buffa et al.)	*	*	*		*	*		*					Unspecified
[[32] (Wirtz et al.)		*	*		*		No case study		*		*		Germany
[39] (Millar et al.)		*	*	*		*	*			*			United Kingdom
$T<30^{\circ}C$													
[35] (Wirtz et al.)	*	*			*			*	No data		*		Germany
[29] (Barone et al.)					*		No case study						
[38] (Abugabbara et al.)	*	*					No case study						
[30] (Rhein et al.)	*	*		*	*		No case study			*			
[23] (Revesz et al.)		*		*	*			*	*		*	*	United Kingdom
[31] (Allen et al.)	*	*			*		No case study		*				Colorado, USA
[26] (Rogers)	*	*		*	*	*	*		*		*	*	Ontario, Canada
[40] (Xu)	*	*			*		*					*	
[41] (Doubleday et al.)	*	*		*	*		No case study						
[33] (Buffa et al.)	*	*		*	*		No case study		*		*		
Ground temp.													
[37] (Caputo et al.)		*			*			*					Switzerland and Northern Italy
[25] (Sommer et al.)		*	*	*				*		*	*		United Kingdom
[34] (Allen et al.)	*	*			*		No case study		*				
[21] (Boesten et al.)		*			*			*	*		*	*	
[42] (Lagoeiro et al.)				No case study			No case study						
[24] (Brennenstuhl et al.)		*						*		*	*		Germany
[28] (Raluca-Ancuta)		*					*				*	*	Europe

with the unique features of renewable and recycled heat. Additionally, improved synergies with the overall energy system are available. 5GDH, on the other hand, can be regarded as a different technology compared to 1GDH-4GDH by introducing heat pumps at each consumer to adjust the supply temperature to the specific requirements, whether it is for heating or cooling purposes.

Current innovation and development of DH can be characterised by high diversity with respect to new technology solutions. Calling a group within this diversity a generation should require more extended aims and features than just other technical solutions.

This inconsistency in denominating the much discussed specific technology a generation (i.e., 5GDHC), has resulted in calling a new concept of heat distribution a generation, introducing it as the sixth-generation district energy systems (6GDES) [47], also called sixth-generation multi-energy systems. Following this trend, a proposal for a seventh-generation district heating can soon be expected. This trend will create an inflation in district heating generations and will generate confusion rather than transparency and clarity.

5. Perspectives

A first perspective is obtained by identifying the similarities between 4GDH and 5GDHC. The overarching aim of decarbonization is identical for both. To some extent they also share the five abilities defined for 4GDH, and both will be implemented during the coming decades.

Another perspective can also be identified by focusing on the differences between 4GDH and 5GDHC. The latter aims at combined heating and cooling with a joint supply network, while the former has a focus on dedicated heat and cold supply networks. A claimed synergy of combined heating and cooling dominates in the 5GDHC literature, while multiple synergies in general are exploited in the 4GDH definition.

A market and expansion perspective is that the 5GDHC concept will become more suitable and competitive in places with heating and cooling demands of similar magnitudes, where end-users can trade heat without there being obvious and cheap sources of thermal energy for heating or cooling. By acknowledging the expression of 5GDHC, the academic interest and development of new DHC concepts can be supported in countries with few DHC systems today. Similarly, acknowledging a completely new innovative technology for combined DHC can also attract more researchers and research grants in these countries.

However, the 5GDHC label is misleading as it renders the intuitive perception that a transition towards 5GDHC systems is a progression. However, improved system energy efficiency is not given for a transition from 4GDH to 5GDHC, which is generally the case for a transition towards 4GDH from a previous generation. In such perspective, the 5GDHC does not seem compatible with the established labels 1GDH-4GDH.

Therefore, 5GDHC should not be seen as a sequential or serial development of 4GDH; it is rather a parallel development. 5GDHC can even be regarded as a sibling in the larger 4GDH family of many different technology options. Hence, 4GDH and 5GDHC will never fully substitute each other but will be complementary options.

Credit author statement

Henrik Lund: Conceptualization, Methodology, Discussions, Investigation, Writing – review & editing; Poul Alberg Østergaard: Conceptualization, Methodology, Discussions, Investigation, Writing – review & editing; Tore Bach Nielsen: Conceptualization, Methodology, Discussions, Investigation, Writing – review & editing; Sven Werner: Conceptualization, Methodology, Discussions, Investigation, Writing – review & editing; Jan Eric Thorsen: Conceptualization, Methodology, Discussions, Investigation, Writing – review & editing; Oddgeir Gudmundsson: Conceptualization, Methodology, Discussions, Investigation, Writing – review & editing; Ahmad Arabkoohsar: Conceptualization, Methodology, Discussions, Investigation, Writing – review & editing; Brian Vad Mathiesen: Conceptualization, Methodology, Discussions, Investigation, Writing – review & editing.

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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