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SMRs IN DISTRICT HEATING: CASE OULU

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ABSTRACT

SMRs in district heating

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This bachelor's thesis is a literature review of Small Modular Nuclear Reactors (SMRs) and their potential use in district heating networks. The aim of the study is to integrate the available general information about the currently available technology and, through this, consider potential use of small modular nuclear power plants in district heating, using the Oulu region as a case study.

Small modular nuclear reactors are a highly possible future energy source. With climate change, it is increasingly important to find low-emission energy production methods. District heating production requires large amounts of energy in Finland, making it crucial where this energy is produced and how much emissions it generates. Nuclear power production does not produce carbon dioxide emissions during the production phase, which would reduce the carbon footprint of energy production. The size of SMR plants allows them to be located closer to settlements and urban areas, which would reduce heat losses during transportation and thus improve the efficiency of heat production.

Small nuclear power plants produce heat consistently in the same amount, and regulating the amount of energy they produce is very difficult. This creates a challenge because the energy requirements for district heating vary depending on the time of day and the season. Oulu's cool climate creates a significant difference in summer and winter district heating needs.

Keywords: small modular reactor, small modular nuclear reactor, district heating

TIIVISTELMÄ

Pienet modulaariset ydinreaktorit kaukolämpöverkossa: tapausesimerkkinä Oulu

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Tämä kandidaatintutkielma on kirjallisuuskatsaus Pienistä Modulaarisista Ydinreaktoreista (SMR) ja niiden mahdollisesta käytöstä kaukolämpöverkossa. Tutkimuksen tavoitteena on integroida saatavilla oleva yleistieto nykyisin saatavilla olevasta teknologiasta ja tämän kautta harkita Pienten Modulaaristen Ydinvoimaloiden mahdollista käyttöä kaukolämmön tuotannossa, käyttäen Oulun aluetta tapaustutkimuksena.

Pienet modulaariset ydinreaktorit ovat hyvin mahdollinen tulevaisuuden energiamuoto. Ilmastonmuutoksen myötä on koko ajan tärkeämpää löytää vähäpäästöisempiä energiatuotantomuotoja. Kaukolämmöntuotanto vaatii Suomessa suuria määriä energiaa, jolloin sillä on suuri merkitys mistä tämä energia tuotetaan ja paljonko päästöjä siitä syntyy. Ydinvoiman tuotantovaiheessa ei synny hiilidioksidipäästöjä, mikä vähentäisi energiantuotannosta syntyvää hiilijalanjälkeä. SMR-voimaloiden koko mahdollistaa niiden sijoituksen lähemmäs asutusta sekä kaupunkialuetta, mikä puolestaan vähentäisi lämmöntuotannon lämpöhäviöitä kuljetusvaiheessa ja näin myös lämmöntuotannon tehokkuus parantuisi.

Pienydinvoimalat tuottavat lämpöä tasaisesti saman määrän ja niiden tuottaman energiamäärän säädeltävyys on hyvin vaikeaa. Tämä synnyttää haasteen, sillä kaukolämmön energiavaatimukset vaihtelevat vuorokaudenajan sekä vuodenajan mukaan. Oulun viileä ilmasto tuottaa suuren eron kesän ja talven kaukolämpötarpeisiin.

Avainsanat: pieni modulaarinen reaktori, pieni modulaarinen ydinreaktori, kaukolämpö

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ABBREVIATIONS

BWR	Boiling water reactor
CHP	Combined heat and power reactor
DH	District Heating
HOB	Heat Only Boiler
IAEA	International Atomic Energy Agency
NPP	Nuclear Power Plant
PWHR	Pressurized heavy water reactor
PWR	Pressurized water reactor
SMR	Small Modular nuclear Reactor

INTRODUCTION

The future of energy production is in carbon neutral energy. The threat of global warming has made a huge need to move on from fossil fuels and the emissions they create. District heating is a very common way to heat homes and facilities. Creating greener sources for thermal energy production in district heating opens a great possibility to cut global carbon emissions. Nuclear power plants have very low carbon emissions and consequently, they could play a vital part in the future heating systems in Finland. Small Modular nuclear Reactors (SMRs) have a great potential in making this change. Teräsvirta et al. (2020) state that the northern location of Finland makes district heating systems an important part of survival. For this reason, practically all cities and larger community centers have district heating coverage. This makes it very important to find carbon-free alternatives to produce the necessary heat. Nuclear energy is expected to be able to provide an environmentally friendly option for energy production and SMRs could provide this in a safer more accessible way.

Oulu as a location in the northern part of Finland has its own set of challenges with heat production. Drastic seasonal temperature changes make district heating a vital part of the heating systems in the city. At the same time the energy demand during different seasons in Oulu varies. This creates a challenge for the heat production since the demand is not constant.

This thesis will discuss these questions: Would SMR technology be suitable for district heating? What are the advantages or disadvantages of this?

This subject has been chosen because it is an important subject for the future of energy production. It discusses an environmentally friendly option for the future of district heating. This thesis will give a general overview of the subjects of SMRs and district heating. It will also look at the possibilities of SMRs in the district heating network and the advantages as well as disadvantages of the subject. This thesis will provide a case discussion of the Oulu area on this subject.

NUCLEAR ENERGY AND NUCLEAR POWER REACTORS

The nucleaus of an atom is made of protons and neutrons. In a nuclear fission reaction the energy from bonding of the nucleus of the atom is released. In this process the nucleus splits into two or more nuclei. The process of splitting the nuclei of atoms releases free neutrons. These neutrons create a chain reaction by splitting cores of surrounding atoms. Every reaction produces heat and radiation. A nuclear power plant can convert this heat into electricity. (Galindo 2022)

1.1 Uranium

Uranium is the most common fuel used in nuclear power plants. It is a chemical element with the symbol U and atomic number 92. Naturally occurring uranium consists of three isotopes, with the isotope U-235 used as main fuel in nuclear reactors. Since the atomic number of uranium is 92, it means it has 92 protons in its core. This means that in isotope U-235, the remaining 143 components are neutrons. Uranium is a silvery-gray metal found naturally. The most common isotope is U-238. Therefore, natural uranium is not suitable for most nuclear reactors. Natural uranium must be enriched to increase the proportion of U-235. This enriched uranium is used as fuel in nuclear power plants. Nuclear fuel is very energy dense, making the fission reactions very effective in producing heat. It is often used in the form of a pellet. The pellets are roughly the size of a fingertip. One of these nuclear fuel pellets produces the same amount of energy as a metric ton of coal. In a nuclear fission reaction, the core of the uranium nucleus is split into two pieces, which are called fission products. In this process it also releases two or three neutrons. These neutrons cause the chain reaction wanted to keep a nuclear power plant going, but if not moderated the chain reaction becomes unstable. Neutrons need to be slowed down to roughly one-ten thousandth of their initial velocity. This is done with a moderator. Graphite and heavy water are the most efficient moderators, but due to high cost and technical challenges the most common moderator is standard “light” water. With the use of standard water as a coolant, the uranium fuel has to be enriched to at least 3% consistency of U-235. Since most of the uranium fuel is isotope U-238, it captures some of the spare neutrons, produced in the nuclear fission reaction, and becomes Plutonium-239. Plutonium fissions in the same way as U-235, so it is in fact a positive change in the reactor. Nuclear energy produces nuclear waste, that is highly radioactive. Nuclear waste ranges from harmless to extremely unsafe, when you consider the whole fuel cycle from mining the uranium ore to the actual use of nuclear fuel. The most hazardous waste being used fuel, it needs both cooling of the fuel as well as shielding its surroundings from radiation. After cooling down the nuclear waste, it requires long-term disposal. Effective long-term disposal has not been produced yet, but the technology and method has been created. The best method so far is deep geological disposal into thick ground rock. For nuclear waste to be disposed will the radioactivity need to be decayed to less than 1% of its original level. (Hore-Lacy 2016) In Finland Posiva has been creating a final disposal facility in the deep bedrock called Onkalo. It has different tunnels excavated at a depth of 400-430 m deep in Olkiluoto, Finland. The nuclear waste will be encapsulated safely and disposed and stored safely deep underground. (Posiva 2024)

1.2 Reactor core

Current nuclear reactors in nuclear power plants work by fission reactions. The heat from fission reactions is used to create steam. This steam spins a turbine that then creates electricity. The uranium fuel pellets are positioned inside a metal fuel rod. These rods are situated in bundles inside the reactor core. A fuel assembly consists of about 200 of these rods. The core of the reactor has often a few hundred of fuel assemblies. The number of assemblies varies depending on the power level of the reactor. The core of the reactor is in a reactor vessel, where the fuel rods are immersed in water. The water functions as a moderator as well as a coolant. The reactor core has control rods as well as fuel rods. The function of a control rod is to control the rate of the reaction. It absorbs neutrons that are released in the nuclear fission reaction. By inserting control rods into the core of the reactor, the reaction rate is reduced, but by withdrawing them the speed of the reaction increases. (Office of Nuclear Energy 2024)

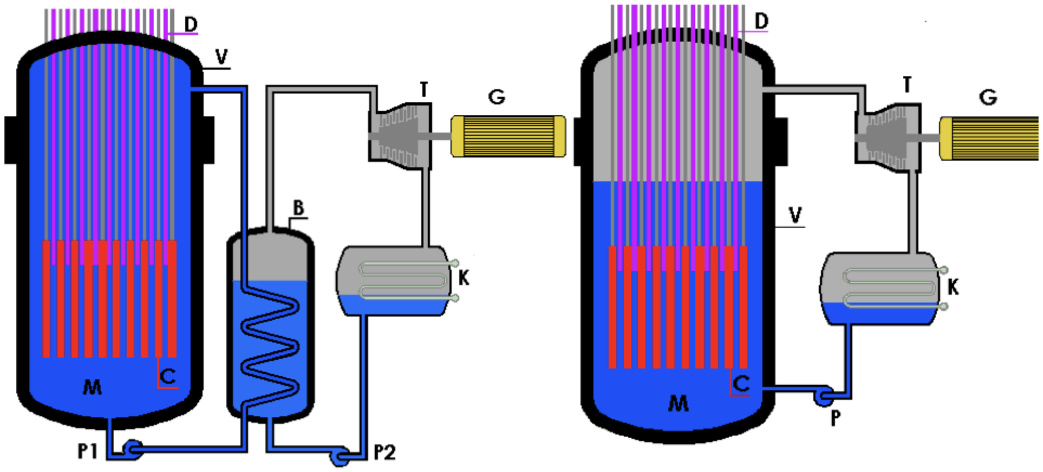
1.3 Reactor types

There are multiple different reactor types. A very common reactor type is a water-cooled reactor, which uses water simultaneously as a coolant as well as a moderator. Water-cooled reactors are divided into three major design families. Most global nuclear power plants consist of Pressurized water reactors (PWRs), Boiling water reactors (BWRs) and

Pressurized heavy water reactors (PWHRs), which are the main water-cooled reactor types. (World Nuclear Association 2024a)

1.3.1 Pressurized water reactor

In a PWR there are two loops of water circulating. The first loop is called the cooling circuit, which is held under very high pressure to prevent it from boiling. The pressure of the coolant water is around 2000 psi. The water is pumped with external pumps to the core, where the nuclear fuel rods and control rods are situated. There, the internal energy of the water increases through nuclear fission in the fuel rods. This highly pressurized water is directed to the steam generator. The steam generator gives up the thermal energy from this first circulation through the steam generator to the secondary circuit. The water in the secondary circuit is at a lower pressure, around 750 psi, which enables it to form steam. This steam is directed through a turbine, which creates electricity. The internal energy in the steam is used to spin the turbine, which cools down the steam. When the steam has cooled and turned into liquid water it is directed back to the steam generator. This loop forms the second circuit of the PWR. (Wood 2007; World Nuclear Association 2024a)



a) b)

Figure 1. a) shows the basic technology of a PWR and b) a BWR. The components shown include: B. steam generator (only in PWR), C. fuel rods, D. control rods, G. generator, K. steam condenser, M. reactor, P1/P primary pump, P2. secondary pump (only in PWR), T. turbine, and V. pressure vessel. (Castelnuovo 2005a, 2005b)

1.3.2 Boiling water reactors

As seen in figure 1. Boiling water reactors (BWR) function similarly to PWRs, but the main difference is that the circulating water is allowed to boil in the core of the reactor. As the water moves through the reactor core, it is heated through the fuel assemblies. The steam then rises to the upper part of the reactor. Water is separated through steam separators and the separated water is directed back to the lower part of the reactor. The high-energy steam generated in the core is then directed to the turbine, where it generates electricity. As the steam has gone through the turbine and cooled down, it turns back into liquid form. This liquid water is then directed back into the core of the reactor. The whole water cycle is kept at a pressure around 1000 psi, which allows the water to boil. (Wood 2007; World Nuclear Association 2024a)

1.3.3 Pressurized heavy water reactors

Pressurized heavy water reactors (PWHR) use heavy water instead of standard light water to cool and control the fission reaction. The advantage of heavy water in the reactor is that a large share of naturally occurring uranium can be used as fuel. PWRs and BWRs use enriched fuel. A PWHR has horizontal tubes, in which the fuel elements are positioned. The tank in which the horizontal tubes are is called a “calendria”. The calendria is filled with heavy water at a pressure of 14,7 psi which is atmospheric pressure. The heavy water is kept below its boiling point by cooling circuits. Inside these horizontal tubes in the calendria are situated the fuel rods in short clusters of the length of 50 cm. After the heavy water coolant has gained energy from the fuel elements it goes through a heat exchanger that transfers the heat from the heavy water to a light water circuit. In this circuit the light water turns into steam in a steam generator, which turns the turbine to create electricity. (Wood 2007; World Nuclear Association 2024a)

1.4 SMRs

The definition of an SMR is often an advanced reactor producing power up to 300 MWe, with factory-made components that can be shipped to production sites. As comparison, conventional reactor units can be over 1600 MWe in production capacity. The basic concept of producing nuclear power is the same in an SMR as in a conventional reactor, even though there are other significant differences. SMRs are designed to have a simpler design, that could be implemented into mass production to cut emissions as well as costs of production. This would enable having spare parts on hand more readily. (Hidayatullah et al. 2015; El-Emam and Subki 2021) With the nature of an SMR being small and modular, they would be able to be manufactured and then installed on site instead of custom designed for each location, like large power reactors, cutting construction time and costs. To suit the rising demand for energy, SMRs could be positioned incrementally to increase the amount of power generated. (Liou 2023) SMRs could be used with other renewable energy sources to create a very low-carbon energy system. SMRs would work as a very reliable and flexible base-load supply of energy. (El-Emam and Subki 2021)

There are over 70 different SMR designs being researched. Light water reactors include Pressurized water reactors and Boiling water reactors. Different reactor types have similarities with the technology in the reactors of conventional nuclear power plants, although they might be optimized for different applications. (World Nuclear Association 2024b)

Figure 2. shows that basically any reactor type could be used for district heating, because the temperature needed is low enough. Since compared to other applications, the temperature required for district heating is low, light water reactors would provide enough heat for the temperature of the district heating water to rise to 120°C fast enough. (IAEA 2020)

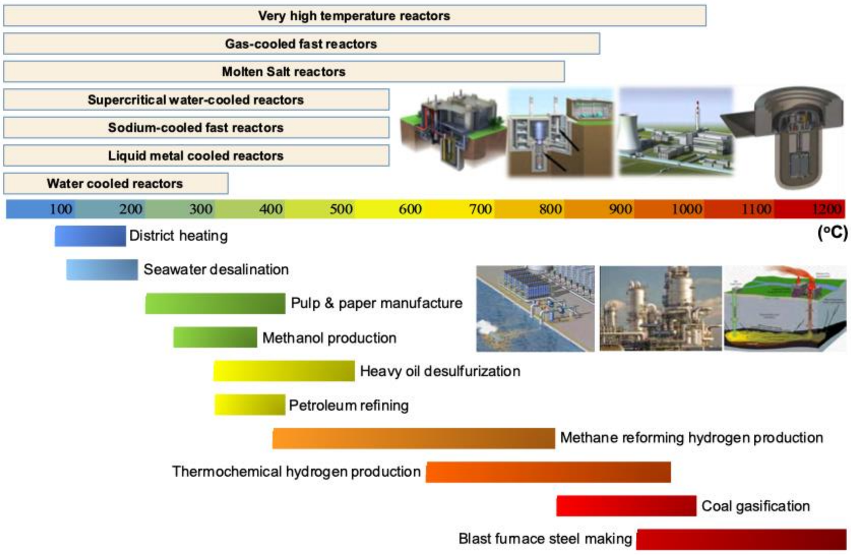


Figure 2. Different non-electric application possibilities for different types of SMRs. (IAEA 2020)

1.4.1 Light water SM-reactors

Light water reactors are the most common reactor types used in conventional reactors and therefore potentially present the lowest technological risk from SMR design point of view. They have a very similar design to most operating power and naval reactors today. The designs are mainly variations of traditional light water reactors, that have been scaled down to smaller sizes. Pressurized water reactors have been used in the United States in small military power plants. Often light water reactors produce large enough amounts of heat, whereas the efficiency of the electricity production through the turbine from the heat is much lower. (World Nuclear Association 2024b)

As seen in Figure 1. PWRs have a heat exchanger dividing two different water circulation loops. A BWR does not have this component, which simplifies the design even more. BWRs rely on natural circulation for cooling, which defeats the purpose of different circulating pumps and the power system for such. Unlike in PWRs the turbine part of the BWR system is to be treated as radioactive as well because there is no heat exchanger separating the radioactive water circulation from the core. Therefore, maintenance on the turbine of a PWR could be considered safer. (Hussein 2020)

1.4.2 Heavy water SM-reactors

Heavy water reactors use D_2O heavy water as a moderator in the core of the reactor. This enables the use of a larger share of natural uranium as nuclear fuel. The fuel of a heavy water reactor requires lower enrichment levels to obtain a high enough U-235 concentration. Heavy water has low neutron absorption, which makes it suitable to use with naturally occurring uranium fuel. (Hussein 2020)

1.4.3 SMR safety

A smaller reactor also potentially offers safety and security. The increased safety of small reactors is due to smaller amounts of fuel used as well as different passive safety systems, like natural circulation. Unlike conventional nuclear power plants (NPPs) SMRs rely on inherent and passive safety features. Inherent safety is for example a negative reactivity coefficient. This means that if the temperature of the reactor core increases or the coolant of the reactor is lost, the power of the reactor goes down. Passive safety relies usually on natural phenomena or material properties, which enables them to function without external power sources. Examples of passive safety are convective removal of generated heat. These methods of safety are seen both in convectional NPPs as well as SMRs, but they are relied upon in new SMR designs. (Hussein 2020)

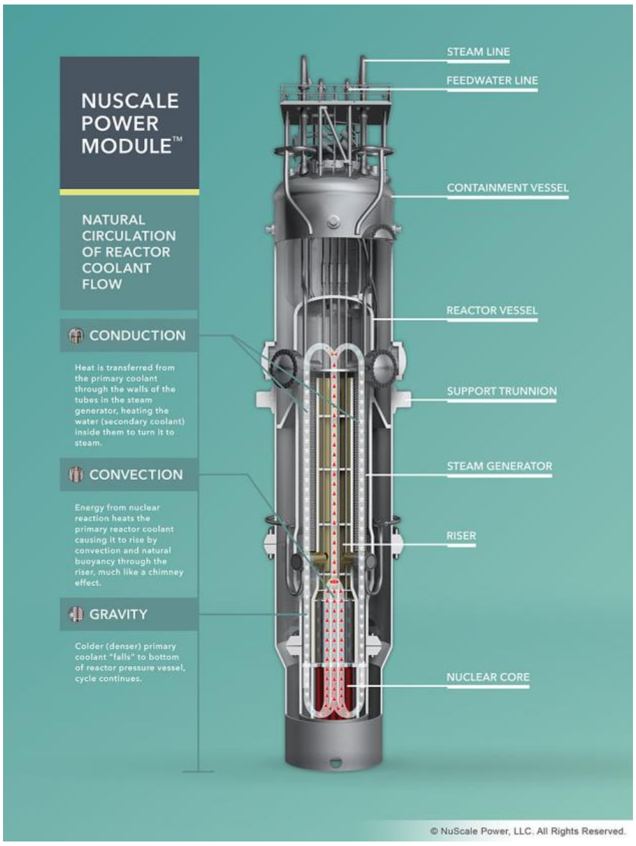
The passive safety systems do not come without some concerns. Active systems have been the main safety systems in conventional NPPs, so there is not quite as much experience with mainly passive systems. This chips on the predictability and reliability of the systems. The development of SMRs on the other hand is aiming to increase the safety of the plants to decrease the risk of large nuclear accidents and enable industrial use of SMRs. This is done through developing passive safety features. Since SMRs are smaller in size, the effectiveness of both inherent and passive safety systems is increased. (Hussein 2020)

1.5 Different design options for SMRs

There are multiple different SMR technologies being designed. For district heating the SMR design should produce heat. NuScale, NUWARD and BWRX-300 are light water reactors of different sizes. Their technology is either PWRs or BWRs, which are both researched nuclear technologies. (Nuward 2023; World Nuclear Association 2024b)

1.5.1 NuScale

The NuScale Power Module is a light water PWR reactor, which heats up high pressure water in the core of the reactor by nuclear fission reactions. This heated water travels to the steam generator where it transfers the heat to the steam generation cycle. There the heat from the steam generator heats the water to steam which then spins a turbine to create electricity. The NuScale Power Module could be used for heat production since it is part of the design to heat water. This heat could be used to heat water in the district heating system. The reactor produces 250 MW of thermal energy. When the heat in the steam has been converted to electricity, the electricity output is 77 Mwe. (World Nuclear Association 2024b) The reactor produces a much higher thermal output than what is converted into electricity. Considering this, the efficiency of the reactor in the district heating network is much higher than in electrical applications.



Heat is transferred from the primary coolant through the walls of the tubes in the steam generator, heating the water (secondary coolant) inside them to turn it to steam.

Energy from nuclear reaction heats the primary reactor coolant causing it to rise by convection and natural buoyancy through the riser, much like a chimney effect.

Colder (denser) primary coolant "falls" to bottom of reactor pressure vessel, cycle continues.

Picture 1. NuScale reactor. (NuScale 2017)

1.5.2 NUWARD

NUWARD is a SMR plant which has two independent small modular reactors in it. The reactors are light water PWRs. The thermal output of the reactors is 540 MWt per reactor. NUWARD SMR is designed to support for example heat and electricity cogeneration as well as district heating. The steel reactor vessel is immersed in water. It has passive safety systems and is designed to function for 60 years. Maintenance of the reactor is done with one reactor functioning, while the other one is in maintenance. (Nuward 2023)

1.5.3 BWRX-300

BWRX-300 is a boiling water reactor (BWR) working with natural circulation of water in the vessel. The BWRX-300 is a light water reactor that produces 300 MWe. The steam produced by the core is inside the pressure vessel, which reduces the complexity and size of the SMR. The cooling of the vessel happens passively and through natural circulation of water through the temperature difference of the heated water in the core compared to the cooled water that has given off its energy. The nuclear fuel needs to be enriched to an average of 3,81% uranium. The refueling cycle of the core of the reactor is 12-24 months. The reactor has fully passive safety systems in case of malfunctioning. The life expectancy of the design is 60 years, which enables a long period of consistent use. This design has been chosen to be the first SMR to be built in North America. (Office of Nuclear Energy 2020; GE Hitachi Nuclear Energy 2024; World Nuclear Association 2024b)

DISTRICT HEATING

In district heating heat is distributed via water in a pipeline from the heat source to the customers. The four generations of district heating have been distinguished and can help contextualize the development of district heating. The 1st generation of DH used steam as the heat supply instead of liquid water. These DH networks consist of pipes and radiators, that distribute the heat through steam. The temperature of the steam is around 100°C in 1st generation DH networks. As liquid water started to be used, the 2nd generation of DH was born. The water in 2nd generation DH systems is superheated to temperatures over 100°C. High pressure in the district heating network is used to maintain the liquid state of water in the pipeline. CHP systems were introduced into the DH networks, when the 2nd generation was created. The 3rd generation of DH does not require superheated water, but functions on water temperatures in between 70-100°C. Lower temperatures are preferred as smart and sustainable energy systems are increasingly important as the fight against climate change continues. The pipelines of 3rd generation DH networks are well insulated and strive for high efficiency. The 4th generation is often defined as having a maximum forward flow temperature of 70°C. The distinction between the 3rd and 4th generation is not always very clear. A subclass of 4th generation DH is heating and cooling through heat pumps, that sometimes is labelled 5th generation DH. (Ma et al. 2020; IEA DHC 2024)

1.6 System

District heating power plants produce heat and electricity or only heat into the heating network. The heating network heats up buildings and household water. Customers can be private citizens or industry. From the customers point of view district heating is an easy and secure option compared to other heat production methods. The heat is distributed to customers through the heating network. The heating network consists of insulated pipes which are divided into a supply water pipe and return water pipe. The heat is transported through water circulating in the district heating pipeline by the power of large water pumps. (U.S. Department of Energy n.d.) The system is closed so the same water is recirculated in the system. District heating water is cleaned and dyed. The dyeing is done to detect any possible leaks in the network. It is a non-toxic but fairly pigmented substance to clearly distinguish it from drinkable tap-water. The cleaning process of the water minimizes the amount of corrosion forming in the pipeline. (Mäkelä and Tuunanen 2015) The supply water is heated by a power plant and then travels through the pipe system to the systems target locations. In the location the thermal energy is then released to customers through heat exchangers in heat distribution centers. Return pipes transport the cooled water back for reheating. The district heating network includes multiple power plants. This gives the opportunity to change the

production seasonally depending on the demand. It also enables uninterrupted heat production during disruptions or maintenance outages. Most common fuels for district heating power plants are biomass such as wood, coal, natural gas, peat, waste, or oil. (Hillamo 2024; Kerttula 2024) Heat pumps are not a new heat source in district heating systems, but their role in energy production is increasing. They collect waste heat created by industry, wastewater treatment plants or other sources and transfer it to the district heating network. (IEA 2023)

The energy into the district heating network is often produced in Combined Heat and Power (CHP) -plants. This enables enough heat production in different seasons. The district heating CHP plant produces heat as the main product, even though the steam is first directed to the turbine to produce electricity. The heat left in the steam after the turbine as well as the waste heat from the process heats up the water in the district heating network. The power plant produces the basic level of heat into the district heating network. Separated heating plants function in peak heat demands as well as backup production plants. The separate heating plants often use oil as the main energy source. The power plants are often situated all around the district heating network to minimize heat loss and add production reliability. (Mäkelä and Tuunanen 2015)

1.6.1 Temperature requirements

The temperature requirement for heated water is often 75-115°C and the temperature of the water in the return pipes is often 40-60°C. For a low-temperature-network the temperature requirements are 55-75°C for the heated water pipes and 25-40°C in the return pipes. The water in the district heating network flows naturally through the pressure difference but also aided by a pump. (Mäkelä and Tuunanen 2015)

1.6.2 Low temperature district heating

There is a pressure to lower the temperature in the DH network for many reasons. A smaller temperature difference between the DH water and the outside temperature around the pipe reduces heat losses during distribution. It also would improve efficiency of the heat sources in the system as well as promote the use of renewable heat sources and even waste heat. The use of low-carbon heat sources and waste heat as well as flexible energy production drives the transition to lower temperature 4th generation district heating. (Garlo-Melkas 2020)

Low temperature DH is especially useful in space heating, when only lower temperatures are needed. A challenge with low temperature DH is getting enough heat for heating up household water. Often a temperature of 50°C in household water use is sufficient for no bacteria to form in the system. Whereas for most types of buildings the temperature level for heating is generally around 23°C, which is fairly low. (Schmidt et al. 2017)

1.6.3 Flexibility of district heating

The load of heat usage in a DH network consists of the heat need from customers and heat loss from distribution. There are different ways to minimize heat loss from distribution, but it is harder to affect the customers heat needs. Consumers heat usage varies radically depending on the season. Less heating of buildings is needed during summertime compared to the winter season. Load variations are also caused by daily customer heat usage behavior. (Dang et al. 2022)

Estimation is important for developing flexibility into the DH system. Nuclear power is not as flexible, therefore flexibility is needed in the distribution system or customers. Knowing the patterns of use of DH throughout the day makes estimation possible. In load shifting the highest peaks of DH load are moved to the times of smaller demand. This could be done for example by preheating buildings before peak hours or charging electric cars at nighttime. The role of consumers is very large in load shifting. It is very important to find good methods to minimize peaks in DH-loads. In addition, the demand for heat varies drastically depending on the season. During cold winter seasons the demand for DH is much higher than in warmer summer seasons. Also, variations in the climate depending on the year affect the demand in the DH network. During colder winters there might be a greater need for additional heat sources to cover the need in the DH network. Different heat storage options would be a potential cure for this problem. (Ma et al. 2020)

1.7 District heating in Oulu

This thesis is taking a case study of the Oulu region. Oulu is a city of 200 000 residents in Northern Finland. The climate in Oulu is considered subarctic, which consists of cold and snowy winters as well as short and mild summers. The average annual temperature is 3,3°C. (InfoFinland 2024) The district heating demand for Oulu area is up to 364,77 MW in the wintertime and only around 50 MW during the summer months. This is seen in Table 1.

Table 1. Average temperature, DH input power, DH input temperature average and DH output temperature average in Oulu in 2022. (Oulun Energia 2024a)

Time [month]	Average temperature [°C]	DH input power 2022 [MW]	DH input average 2022 [°C]	DH output average 2022 [°C]
1	-7,70	364,77	92,53	35,17
2	-7,00	340,04	92,94	35,63
3	-2,60	292,68	85,64	34,52
4	0,70	235,44	81,67	35,10
5	8,10	151,30	76,76	38,23
6	15,10	73,97	69,56	44,60
7	16,90	50,22	69,98	45,69
8	15,40	54,25	71,10	44,44
9	8,20	129,91	74,20	38,46
10	4,70	189,36	82,35	36,33
11	-1,60	280,06	89,32	35,16
12	-6,20	345,18	92,92	35,75

The Oulu area produces district heating from three main power plants. The power plants include two power plants in the Laanila area as well as one in Toppila. Laanila has a biomass power plant burning wood as well as SRF fuel, which is solid recovered fuel mostly from industry. The plant burns small amounts of peat as well. The biomass power plant produces electricity as well as district heat and process steam. The waste-to-energy power plant in Laanila processes non-recyclable waste into steam and heat for different industrial sites in the area. Domestic electricity and heating are produced in the Toppila power plant through burning wood and peat. The plant has also a solar plant on the outer south wall of the combustion plant. The thermal energy from the flue gases of combustion in the plant is converted into district heat. The Laanila biomass power plant provides 175 megawatts and the Toppila power plant provides 170 megawatts of district heating capacity. (Oulun Energia 2024b)

As seen in Figure 3. the input power into the district heating network varies drastically depending on the season of the year. During the summer months of June, July and August the DH input power is much lower than in the winter months. November to March the DH input power is very high, using most of the DH capacity produced in Laanila and Toppila. Since both Toppila and Laanila can produce up to 345 MWt (Oulun Energia 2024b), in January most likely separate production plants needed to be used to cover the needed input power of 364,77 MWt shown in Table 1.

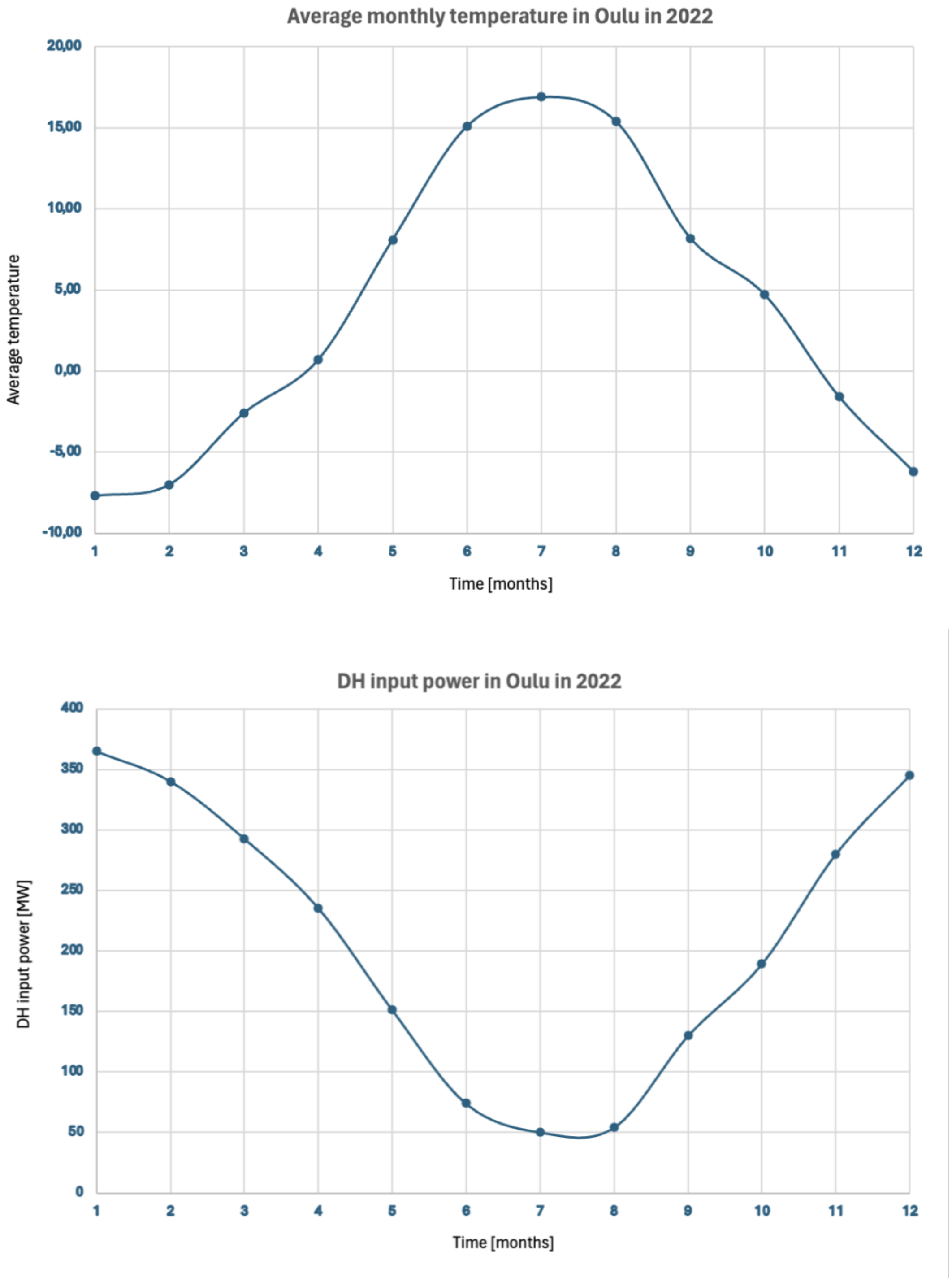


Figure 3. The top graph shows the average monthly temperature in 2022 in Oulu. The lower graph shows corresponding DH input power in Oulu during the same year. (Oulun Energia 2024b)

SMRS OPERATION IN THE DISTRICT HEATING NETWORK

Considering Finland’s northern location, district heating is a very important part of the energy system. The total demand for district heat is 46% of total energy demand. Larger communities have often one or multiple CHP plants producing heat into the system. Heat only boilers (HOBs) are used to cover peak demand. Heat pumps and different waste heat sources have also been an important addition to the district heating system. (Teräsvirta et al. 2020)

1.8 SMRs as baseload production

SMRs are modular reactors that have the possibility to have multiple reactor modules installed on the same facility. This could cater to a larger demand over time. In The Possible Role of Modular Nuclear Reactors in District Heating: Case Helsinki Region Värri K. and Syri S. researched the possibility to connect an SMR to the district heating network in Helsinki, Finland. The results show that an SMR would minimize the use of gas only to times of peak demand. Heat production in SMRs is not as easily shifted depending on demand. Therefore, the role of SMRs in DH is most likely as baseload production. Currently the CHP power plants functioning in the district heating network function as baseload production, where it is not very easy to fluctuate the amount of heat that is produced. When the demand is smaller, excess heat is directed to a turbine which converts it to electricity. The research also indicates that the investment of the SMR would decrease the average cost of production by 23% 2030 and 24% in 2050. (Värri and Syri 2019) p.13 Värri and Syri also mention the use of SMRs being more sustainable than CHP plants burning waste or biomass. Even though these might seem like attractive options for DH heat production, there are sustainability concerns, like CO2 emissions as well as other flue gases produced that require additional processing. The availability of fuel for these plants can also be limited considering rising energy needs. (Värri and Syri 2019)

Värri and Syri concluded that SMR technology seems very suitable for district heating. A single SMR module can be a good size for a fairly small DH network. The modularity of SMRs enables different production configurations which adds flexibility to the applicability of the technology. (Värri and Syri 2019)

1.9 SMR based hybrid energy system for electricity and DH

Poudel and Gokaraju created in the paper Small Modular Reactor Based Hybrid Energy System for Electricity & District Heating a simulation model for a SMR based hybrid energy system for electricity and DH. The heat generation process as well as extended safety precautions in SMRs are different than CHP plants, but the combined heat and electricity are similar. When an SMR is used with renewable energy sources like wind and solar energy, flexibility is a key need. There are various methods such as thermal energy storage, heat pumps and electric boilers being investigated to improve the flexibility of CHP SMR power production. Through a hybrid energy system of SMRs and renewable energy sources in DH, sustainable clean energy could be provided even to isolated communities. In Poudel and Gokarju’s research a NuScale SMR was connected to the system. Figure 4. shows a figure of the simulated system. The NuScale SMR produces heat, which is directed to the turbine. The turbine has also a bypass valve, which enables independent adjusting of the turbine load for short-term variations. The turbine bypass valve could bypass even 100% of the rated steam flow, if needed. The turbine bypass valve generates the energy to the condenser, pump and feedwater heaters.

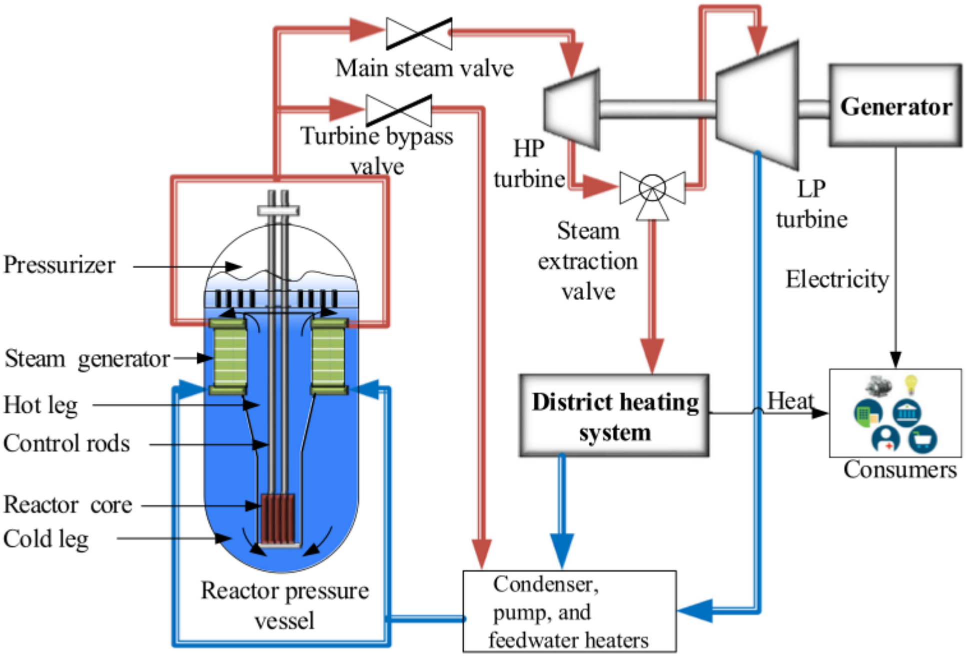


Figure 4. NuScale iPWR module generating both heat and electricity. (Poudel and Gokaraju 2021)

The main steam valve directs the steam to the high-pressure turbine. The turbine has a steam extraction valve, which enables steam extraction into the district heating system. In this system the flexibility of the operation of the SMR is in an important role. Therefore, extraction turbines, where the extraction flow can be regulated through valves is used. The steam that is not used into the district heating system is directed through a low-pressure turbine, that spins a generator. The generator produces electricity to the customers. (Poudel and Gokaraju 2021)

This model is tested with renewable energy sources also connected to the system. This is done to see the suitability of the system to provide heat and electricity while at the same time maintaining flexibility requirements. Flexibility requirements are mainly to ensure enough heat into the DH network, while the demand fluctuates depending on the day and season of the year. (Poudel and Gokaraju 2021)

This case study reveals that flexible operation of an SMR with highly variable renewable energy sources is capable of functioning and providing enough heat into the system. The temperatures in the DH network were able to be maintained at acceptable levels. This shows that it is theoretically possible to have a DH and electricity production network working with SMRs as well as renewable energy sources that are not as predictable and therefore require more flexibility from the SMR system. This study did not imply what type of climate the study was conducted in. (Poudel and Gokaraju 2021)

CONCLUSION AND SUMMARY

The interest in carbon neutral heat production is increasing rapidly. Climate change and national carbon neutrality goals fuel the search for new sustainable energy production methods and ways to cut emissions. District heating requires a large part of the energy consumption in Finland. Therefore, through decarbonizing district heating, the carbon footprint of Finland could be reduced. Nuclear energy does not produce carbon emissions while operating. SMRs could take potentially a part in creating a low-carbon energy system. The size of SMRs enables their use closer to communities, where heat is consumed. This creates a more efficient heating network minimizing the amount of heat loss and improving efficiency. Passive safety systems as well as the size of the reactors increases safety of operation. SMRs have a much higher thermal output than the electrical output created from the steam from the reactor. Therefore, thermal applications for SMRs would be very viable options.

The district heating system in Oulu could possibly benefit from SMRs. They can provide an efficient source of energy, with the operation being carbon neutral. SMR technology is a potential option in the future and therefore it is difficult to predict what type of other energy sources are used in addition to SMRs in the district heating network. If other energy sources are used as baseload production, SMRs are required to be the flexible part of the heating system. With SMRs being modular, they could be positioned around the city. This would decrease heat loss in the system since the heat source is closer to the customer.

An advantage with SMRs is their suitability for thermal applications. Most SMR technologies produce heat through nuclear fission reactions. In electrical applications of nuclear energy this heat energy is in steam which is directed through a turbine. Through the spinning of the turbine, only roughly 1/3 of the MW of thermal energy are converted to MW of electricity. Therefore, the turbine has a large energy loss, which decreases the efficiency of the system. Using SMRs in thermal applications this scale of loss of energy could be avoided. The efficiency of the energy-production system could be increased by applying SMRs in thermal subjects.

For a district heating network, it is best to look at an only-heat or heat and electricity (CHP) SMR. There are many designs that could offer heat and electricity as the byproduct. Different SMR designs using light water reactor technologies produce heat effectively and could be considered for district heating purposes. There are multiple promising design options creating heat, that could be applied to district heating networks. Most likely light water PWRs or BWRs would be the best option for an SMR in district heating. Light water reactors are the most commonly used technology in larger size nuclear power plants, therefore the technology is well tested and could be implemented on a smaller scale functionally. PWRs have a fairly simple design that is easy to apply to smaller scale. They are also the most researched reactor type, which might make public acceptance of the reactor better. PWRs as well as BWRs produce high-energy steam that can heat the water in the district heating network possibly through a heat exchanger. The NuScale Power module reactor has potential to be applied to the district heating network, since it is a Light Water PWR. With a LW PWR the uranium fuel must be refined to a higher concentration of U-235. If a Heavy Water reactor is chosen, the concentration of U-235 in the fuel can be lower and therefore closer to the concentration in naturally occurring uranium.

The NuScale Power module produces 250 MW of thermal energy in one reactor. The heating demand of district heating depends on the size of the area that is part of the network as well as weather and climate conditions. Oulu is a subarctic city with cold winters and mild summers. Therefore, the heating demand for wintertime is quite high and decreases towards summer. As seen in Table 1. the demand for input power in the DH network is around 350 MW for the winter months. The NUWARD SMR plant produces a larger thermal output with 540 MWt per reactor. The plant consists of two independent reactors. For increased flexibility for the seasonally changing district heating demand, one of the reactors could potentially be turned off during warmer seasons. This might enable the use of the SMR as added production instead of baseload production.

Flexibility of SMRs will be an important part of designing their applicability into the district heating network. The future district heating network might have other energy sources, for example renewable, that are not flexible or depend on weather conditions. In this case, the SMR must have flexible production to account for the varying heating demand in different seasons of the year as well as different times of day. Figure 3. shows the correlation between the average monthly temperature in Oulu and the needed DH input power. When the temperature is higher, the needed DH input power is much lower than when the temperature is lower. The biggest contrast in the DH input power amounts is between the three summer months and the three winter months, which can be seen in Table 1. Options like combining the SMR district heating heat production with electricity production would seem like a very efficient option. This is seen in Poudel and Gokarju’s paper Small Modular Reactor Based Hybrid Energy System for Electricity & District Heating. The method would enable seasonal and daily flexibility into the heat production while having the SMR smoothly running at a constant production rate. This could be a considerable future system to implement in the Oulu area as well. The NuScale reactor was used in Poudel and Gokarju’s paper, which would have a suitable size of reactor for the Oulu area. Figure 3. shows that for the winter months the NuScale 250 MW reactor would not provide enough heat, since the demand during those months is around 350 MW. There would need to be either two reactors in the system or a separate baseload production method to cover for the remaining 100 MW during winter season. Consequently, during the summer the NuScale reactor would produce excess heat into the DH network, since the demand is much smaller as seen in Figure 3.

SMRs have advances and limitations due to their small size and modularity. An advance with their modularity is the possible positioning closer to customers. With increased safety through passive safety systems, national regulation might change to allow closer positioning of SMRs to populated areas. This increases the heat efficiency of the DH system, when there is less heat loss during heat transportation to the customer. This shows one of the biggest challenges with SMRs being the lack of flexibility. Since SMRs are nuclear reactors, they function with a constant output. Therefore, SMRs are either on or off, there is currently no good way to have them functioning on only part of the output. SMRs work very well as baseload production. If they are used as additional production, they will still produce the same amount of energy. The excess energy will have to be turned into electricity or utilized somewhere else than in the DH network. Värri and Syri discussed SMRs as baseload production in their publication The Possible Role of Modular Nuclear Reactors in District Heating: Case Helsinki Region. There it was concluded that SMRs function very well in baseload production, but due to their small size, they enable different production configurations which increases flexibility.

SMRs could increase the flexibility compared to conventional bigger nuclear power plants by connecting multiple SMRs alongside each other. This could enable turning one or multiple SMRs off during lower demands such as summertime. Therefore, a possible concrete application in Oulu could be a scenario where there are five 50 MW heating

SMRs positioned alongside each other. As the outside temperatures rise and heat demand lowers, the reactors could accoringly be turned off. During the summer seasons when the production demand is much smaller, could most of the reactors be turned off. This would enable flexibility into the district heating networks demand. 50 MW reactors would be able to be positioned alongside each other and through that produce enough electricity into the network. This might be a possibility instead of a system that transfers the excess energy to electricity during lower heat demands like shown in Poudel and Gokarju's paper. With five 50 MW reactors the total maximum heat production is 250 MW, which would require added production from a different energy source for the peak demand winter months. Of course, it would be possible to have more than five SMRs to cover the peak demands and turn them off as the heat demand gets smaller towards the summer months.

The use of SMRs in district heating is a potential option for future energy production. It has been concluded to be suitable for district heating applications, even though the flexibility for different heating demands is a main challenge. This challenge could possibly be overcome by combining heat production with electricity production or using smaller reactors and turning them incrementally off during lower demand. As with any energy source, SMRs have advantages as well as disadvantages, but now it seems like they could be overcome with efficient planning and future legislation. The need for lower carbon emissions is a global requirement to combat climate change and SMRs could be part of the solution.

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