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DECARBONIZING CITIES:

HELSINKI METROPOLITAN AREA

Providing district heating, power and transportation fuels with advanced nuclear reactors

ECOMODERNIST SOCIETY OF FINLAND

ENERGY FOR HUMANITY

2017

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Special thanks to Technical Research Centre of Finland Ltd (VTT) for their help and expertise.

This report has been reviewed and approved by the advisory board of the Ecomodernist Society of Finland.

Published by Energy for Humanity and the Ecomodernist Society of Finland, 2017

ISBN 978-952-7139-13-4

COVER DESIGN:
Samuli Pöllänen, 2017

LAYOUT:
Viestintätoimisto CRE8 Oy, Maia
Helsinki 2017

Executive Summary

Electricity only accounts for roughly a third of our energy related emissions. Industrial processes, space heating and hot water use, along with liquid fuels for transportation make up most of the rest of our energy demand. This energy use needs also to be decarbonized by mid-century, either by electrifying it (and producing that electricity cleanly) or by replacing burning of fuels with other means.

This study presents a scenario in which small, advanced nuclear reactors are used to achieve a relatively cost-effective deep decarbonization of district heating, electricity, and transportation fuels in a city of roughly 1.5 million inhabitants. The used energy is divided as follows: 8 TWh for heat, 12 TWh for electricity, and 4 TWh for hydrogen production every year.

KEY POINTS:

- Upcoming small, advanced nuclear reactors can offer a cost-effective and reliable source of low-carbon heat and electricity for various uses, such as cities with district heating networks.

- Combined heat and power (CHP) improves the economics of nuclear reactors immensely. Instead of producing power at 35 % efficiency, they can produce heat and power at over 80 % efficiency.

- Small, high-temperature reactors can be used to produce affordable hydrogen with High Temperature Steam Electrolysis (HTSE). This can be done as part of seasonal load following of energy demand.

- Affordable hydrogen can be used to decarbonize transportation fuels by making synfuels from it, and other chemicals that use hydrogen (such as ammonia for nitrogen fertilizer).

- The annual energy use of 8 TWh of heat, 12 TWh of electricity and 4 TWh of hydrogen can be produced with roughly 4 GWth of high-temperature thermal nuclear capacity, or roughly ten small, advanced nuclear reactors with a thermal capacity of 400 MW each.

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Introduction

Energy discussion revolves around electricity, and for good reason. It is responsible for roughly a third of our emissions. We know a lot of ways to make electricity, even without greenhouse gas emissions. Electricity, electric vehicles, batteries and high-tech gadgets capture people's imaginations. What used to be a mundane business of supplying people with the electricity they need has recently grown to be a timely and even controversial topic around coffee tables and seminars alike.

While it is good that people talk more about electricity and how it is made, this focus on electricity has sidelined other important energy topics. Roughly 80 percent of our energy use is something else than electricity. Industrial heat, district and space heating and hot water and transportation fuels are still mostly based on burning fossil fuels, with the resulting emissions. While sustainable biofuels can offer a part of the solution, that part will remain relatively small, especially at the European and global scale. Even as the global trends of biofuels use can hardly be said to be environmentally sustainable or benign, they still correspond to only a few percent of our total primary energy use. We simply cannot burn our way out of this.

It is high time we started discussing how we can make high temperature heat for industrial processes affordably and without burning fuels. Or how we can synthesize carbon neutral liquid fuels for transportation, which is still more than 90 percent supplied with crude oil based fuels. Or how we can produce heating for homes affordably, without burning fuels.

This report aims, for its part, to start that discussion, and specifically bring to light some of the advantages and possibilities that small, advanced nuclear reactors can bring to the table. Read on to find out how we can produce district heating, electricity and hydrogen for synfuels for a city of roughly 1.5 million inhabitants with advanced nuclear reactors.

Background, methods and objectives

The purpose of this study and the scenario it presents is not necessarily to draw a roadmap or forecast the decarbonization of our society. Rather, it shows how nuclear power can take a significant role in decarbonizing not just electricity, but the entire energy mix. The aim is to open discussion on the topic, not to dictate how that discussion should be had.

This study explores how a city of approximately 1.5 million people can be totally decarbonized by 2050, using mainly advanced nuclear reactors. District heating, electricity, and transportation fuels all need to be decarbonized by 2050, and large-scale use of bioenergy is not a sustainable option. The Helsinki metropolitan area is used as the background case for most of the modelling, although there is little to stop anyone from scaling and modifying the energy demand profile for other locations as needed. With the large seasonal variations in heat and electricity demand, Helsinki area presents a challenging environment for any decarbonization effort. The advantage of using dispatchable nuclear energy is that it works reliably in any location and throughout the year. With a more stable seasonal demand profile, the situation becomes easier.

The future annual use of energy in the case study is as follows:

- 8 terawatt hours of district heat
- 12 terawatt hours of electricity
- 4 terawatt hours of hydrogen for transportation fuels

To simplify the model, annual demand is broken up by month. This way we can easily observe seasonal changes in demand, and it is assumed that storage systems for heat and electricity can balance the daily fluctuations in demand. VTT's[1] Low Carbon scenario for 2050 usage profile in the Helsinki metropolitan area is used for district heating, and the Finnish average usage profile is used for electricity[2]. It is assumed that transportation fuels are used on

1 Technical Research Centre of Finland Ltd

2 Using Finnish average for electricity demand profile evens out the usage for the year,

a constant basis. Also, the scope of the study stops at producing hydrogen. It can be used to synthesize other fuels and chemicals, used to increase the yield of biofuels production, or even as a direct fuel for transportation in the case that hydrogen fuel cell vehicles proliferate.

Energy intensive industry is located outside the metropolitan area of Helsinki, so average per capita energy use in Finland is three times higher than direct energy use of residents in the Helsinki area. Each country and area has a distinct energy demand mix, and this needs to be kept in mind before any wider generalizations one way or the other.

SUSTAINABLE ENERGY?

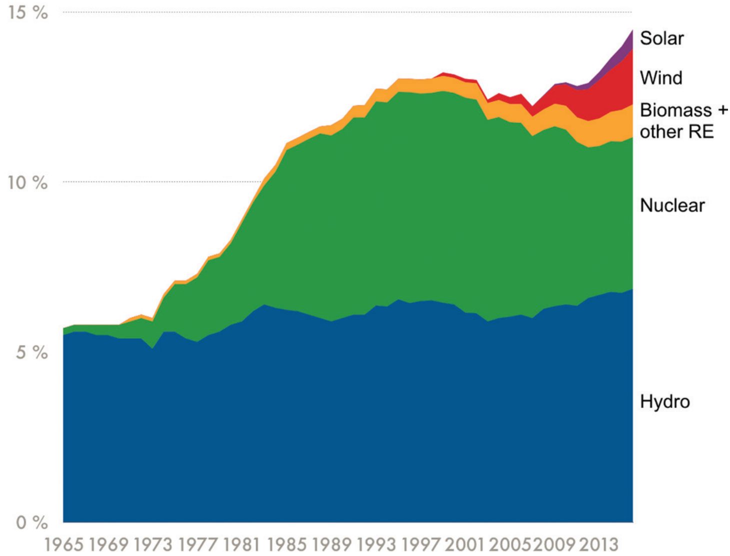
Many of us would like to decarbonize our energy system and stop climate change using primarily, if not entirely, renewable energy sources. However, this is not likely to happen, not quickly enough anyway (see graph). Credible, mainstream deep decarbonization scenarios imply a large amount of nuclear power and carbon capture and storage (CCS)[3]. So far, only the former has actually proven itself a viable tool for decarbonization.

While renewable energy sources enjoy widespread political support, even they have their weaknesses; bioenergy has a very limited scale if we want to produce it in a sustainable manner, and many think humanity is already farming and using more than its share of arable land. Wind and solar require large amounts of mined and manufactured materials and area to harvest their energy, and as intermittent energy sources, they need large scale backup capacity or storage to answer our society's 24/7 energy demand.

Right now, that backup capacity is almost always based on burning fossil fuels, which is antithetical to our goal of decarbonizing. Hydro power is very useful, but has limited scalability, as it is very dependent on good locations. It also has significant environmental consequences.

as Helsinki area has less industrial electricity use compared with the whole country. Industrial use stays high even on summer times, while residential use goes down.

3 Such as IPCC 2014 AR5 WGIII, www.ipcc.ch/report/ar5/wg3.



During the last half a century, the share of clean energy from total energy use has risen from 6 to about 14 percent, largely due to nuclear build-up in the 1970s and 1980s. Since the start of climate negotiations in the 1990s, the share has risen perhaps two percent. Data: BP 2017.

When we keep our goal in mind – curbing climate change by decarbonizing our energy system as quickly as possible – we need to remember a simple rule when it comes to clean energy. *Not all renewables are low-carbon and low-impact energy sources, and not all low-carbon and low-impact energy sources are considered "renewable".* Nuclear power is our second largest source of clean energy and, historically, our quickest way to decarbonize energy systems, and unlike hydro (which is the largest source of clean energy), nuclear power has substantial room to grow[4].

Yet nuclear has been notoriously absent from the climate discussion, or if it has been mentioned, it has been mentioned as something of a necessary evil or a bridge technology towards something else. In truth, there is nothing inherently bad about nuclear, nor is there reason to think of it as a bridge to something else. It is low

4 Any substantial demand increase will raise the price of nuclear fuel, which will unlock technologies such as recycling, breeder-reactors and uranium production from seawater, ensuring we will not run out of nuclear fuel for thousands of years.

impact, low carbon, affordable, and reliable in addition to offering high net-energy and being the safest energy source we have. One could readily argue that it is the prominent clean energy source that can power a high-energy future of a planet where ten billion people live relatively prosperous lives. In short, we should be excited about the possibilities nuclear energy offers for decarbonization.

Yet many analysts, politicians and scenarios go to great lengths to ignore or downplay both the achievements and the possibilities of nuclear.

Instead, they focus on the opportunities of renewable energy, energy storage, energy efficiency and demand flexibility. While these opportunities are huge, they are nowhere near enough in the time window we have. The intermittency of solar and wind makes it more and more expensive to add ever larger shares of them to the energy system. They require an ever-growing amount of supporting schemes to keep the lights on and houses warm. These schemes – energy storages, demand flexibility and so on – will keep improving, but they have grown too slowly, setting a bottleneck for adding more variable renewable energy into the energy mix.

If technology makes cheap large-scale energy storage available, it will make any roadmap easier to implement. It will make baseload energy providers more competitive (also those based on burning fuels), as demand fluctuations can be evened out with cheap storage and demand flexibility. Cheap storage and flexibility can cause the demand curve to flatten. The amount of baseload demand will increase and the number and steepness of demand spikes will lessen. All of this will make providing the energy needs with baseload capacity easier and more cost-effective.

Adding storage and flexibility almost always add costs and losses to energy services provided. The less we need those, the cheaper the overall system. In this regard, baseload nuclear power can offer huge advantages, as it can be used to produce a sizable part of a society's heat and power needs even without extensive storage and flexibility systems.

Before making the case for nuclear energy, the other popular clean energy sources are presented shortly. The focus is on their scale and feasibility. Scale as in "can they be scaled up to meet most of, or a significant part of our energy needs”, and feasibility as in “can they be deployed in such a way as to provide a 24/7/365 energy service in both district heating and electricity, as well as supply clean fuels to replace current, fossil oil based transportation fuels?” Even though it is an important topic, material footprints of different energy sources are not considered in this paper, except for biomass as fuel.

BIOENERGY

Bioenergy is viable on a small scale, for example as a fuel for a local, small to mid-sized district heating or CHP system with demand roughly in the 10 to 200 MW scale. When looking at larger cities of hundreds of thousands of inhabitants and annual heat and power demand in the terawatt hour scale, the amount of bioenergy needed becomes daunting, and the scale of environmental damage harvesting it can cause grows significantly. With scale, the distance and risks involved in acquiring sufficient fuel grows as well.

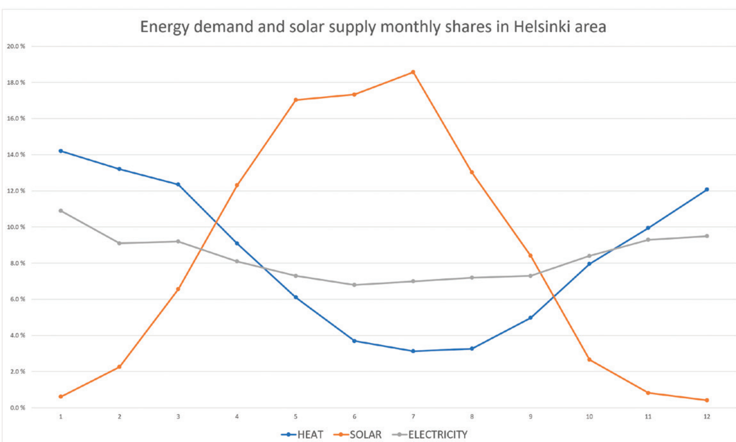
In the Finnish context, producing the district heating demand of the Helsinki metropolitan area, at 8 terawatt hours annually, with wood-based biomass, would require almost a million hectares worth of forest growth. That is, if we assume 100 % efficiency in heat production and distribution, ignore transportation of the fuelwood, and if we clean the whole annual growth from an average Finnish forest for energy. That’s roughly 50 times the land-area of Helsinki. If 12 terawatt hours electricity is included, and assuming 100 % efficient combined heat and power (CHP) production, over a million hectares needs to be added.

If we assume real-world efficiencies and use only half of forest growth for energy (which is roughly the norm today, the other half ending up as pulp, paper, timber and such), around five million hectares would be needed. Making advanced biofuels (at a ~40 % net conversion rate) to replace the roughly four terawatt hours of petroleum products used annually for mainly transportation would require another two million hectares. All of that adds up to roughly a third of Finland’s forested area of roughly 23 million hectares.

There are some estimates on the sustainable biomass availability near Helsinki area, and they are in the ballpark of one to two terawatt hours per year. In this study, the Helsinki metropolitan area is assumed to use 24 terawatt hours of final energy annually, so locally and sustainably available biofuels can only meet a few percent of the total demand.

SOLAR ENERGY IN NORTHERN EUROPE

Solar energy has been getting cheaper as manufacturing capacity has been added and technologies have been improving. The problem is, in many places, the value of solar energy has also been dropping with growth in installations and solar PV penetration. This can be seen in sunny California, where electricity has already become a waste from time to time, and producers need to pay users to get rid of it. This means it has a negative value in the marketplace, and therefore there is little value as such for society in installing more of it. Same is true for Germany with wind and solar and for Denmark with wind.



Solar insolation and demand for heat and electricity have inverse seasonal correlation in northern latitudes[5]. This poses both a storage and a value problem for adding solar production capacity.

5 Monthly shares of solar radiation are from Helsinki. Monthly profile of district heating is from VTT Low Carbon 2050 scenario and electricity demand profile is Finnish average from 2015, data from Finnish Energy.

The biggest problem here in the north is that solar has the exact opposite production profile as our annual demand profile.

A relatively small amount of solar capacity is needed to provide all of district heating for June and July (assuming that day/night and weekly cycles can be handled with storage and demand flexibility). District heat during these summer months is of least value, as it can easily be provided by the cheapest baseload sources, such as heat pumps. Yet roughly 100 times more solar capacity would be needed to meet the district heating demand in December to February. This means several things:

- After demand for summer months has been saturated, the value of solar production starts to fall fast, as most of the value that solar produces should come during these months of most production (over 50 % of annual solar insolation comes during May-July in southern Finland, and almost 80 % between April-August). This effect is called cannibalization.

- As these summer months are saturated, the value of the product falls close to (and eventually below) zero on the marketplace. This means that the value that justifies the installation investment costs needs to be gathered during the other months – when less than half, or perhaps just a quarter of production happens. This would mean that the value of such production would need to be extremely high – many times higher than the annual average cost of district heat production, and much higher than is the cost of producing the energy by other means.

- In addition, adding such production will decrease the value of other production as well – although more slowly. This production capacity makes most of its value during winter months, when both demand and prices are highest.

As such, solar can lessen emissions and even save on fuel costs if it replaces burning, but it can do so in a very limited scale with both electricity and heat. At the same time, it might make other production capacity economically less feasible, since it would lessen the value of especially summer-time energy production without removing the needs to invest in something that can also produce energy during winters. *Regardless of how much one would like the idea of solar energy, there is little economic case for its wider use from the perspective of total system costs for society and from the utility company's point of view.*

The economic case for residential solar in sunnier climes may be a completely different story depending on taxes, subsidies, or other incentives. The situation is also different in places where solar production profile better meets the demand profile, but even in the case of California, there are already problems with solar PV value[6].

WIND

Wind is more evenly distributed annually than solar, and even correlates slightly with seasonal demand variation as winter has more wind than summer, but is less predictable, day--to-day and week-to-week. Electricity from wind can be used to make heat with heat pumps or electric resistors, but it is not very cost-effective nor is it reliable enough to act as baseload for either electricity or heat.

It is not uncommon to have cold spells of high demand for heat, yet low wind speeds for a week or two. The Germans have even come up with a name for such an event that occurred in early 2017: *Dunkelflaute*. These periods of high energy demand need to be covered with other energy sources or support schemes, which then needs to justify their costs (investment, operation & maintenance, fuel) with higher prices.

The problems with wind are smaller than with solar, but wind suffers from the same cannibalization effect as solar: it eats its own value faster than the value of other production capacity[7]. From the larger point of view, wind makes other production capacity operate at a smaller capacity factor, increasing their costs, but not making them unneeded. This leads to a situation where decarbonization might grind to a halt way before a deep decarbonization of the energy system is achieved and where all investments in capacity additions look increasingly bad. Wind (and solar) solves a part of the decarbonization puzzle by decreasing fuel use in power plants, but at the same time they might make solving the rest progressively harder by making it harder to find the value needed for investments to decarbonize the rest.

6 In spring 2017, electricity prices in California were negative during sunny days.

7 Cannibalization effect is well-known in energy-markets. One good overview by energy researcher Jesse Jenkins can be found at theenergycollective.com -website here: tinyurl.com/j2j9a7j.

However, adding wind power to a flexible system like the one presented in this study is less problematic. On a monthly basis, wind power fluctuations often get evened out, and if there is surplus production now and then, it can often be put to use, as we will learn later.

GEOTHERMAL AND HEAT PUMPS

An interesting pilot project called Deep Heat is underway in Espoo, Finland. The aim is to find out if heat can be cost-effectively drawn from deep underground for the purpose of district heating (around 100 C). This technology, if successful, could provide a significant amount of the heating needs of Helsinki Metropolitan area. The key questions are the price per MWh that can be provided in the long run, and the possible limitations in having multiple sites around the area (one “hole” can only produce so much and there are only so many plausible sites available). It will be a few more years before we know the final costs from the pilot. With high share of investment cost and little in the cost of fuels, this technology is most suited for providing baseload needs.

Heat pumps are another solution that has seen significant growth recently, partly due to cheap electricity prices. While they can be used to produce part of the baseload needs, they often struggle to produce quite high enough temperatures for district heating purposes and have some limitations for scaling. This means that the amount of heat-pump energy in the network is limited, and that it needs to be “primed” with some source of hotter water. Also, future district heating networks could (and probably should) be planned for lower temperatures, which would make heat pumps and other sources of secondary waste heat even more useful than they are today.

NUCLEAR ENERGY

Nuclear energy is ideal for producing clean baseload energy for both the electricity grid and district heating network. Nuclear power is well suited to run at full capacity 24/7. This is due to the large share of capital investment in the total costs of energy produced.

This is true with wind and solar as well – if their production needs to be curtailed or wasted as discussed above, they get no savings in fuel or maintenance costs. They are even more capital-intensive than nuclear power.

Beyond supplying baseload, the situation starts to get more and more complicated also with nuclear energy.

In our case, the monthly demand difference in district heating demand can be almost five-fold. That is, the demand from December to February (~1,500 MW) can be over five times larger than demand from June to August (~350MW, mostly hot water use). Momentarily, the demand for heat can be well over 3,000 MW. With electricity, the demand difference is less than two-fold (between roughly 1,100 MW and 1,700 MW averaged over a month).

Some of this seasonal fluctuation can be mitigated by timing scheduled maintenance and refueling to periods with low demand, as is done today. The nuclear power plants in Finland and Sweden for example coordinate their annual shutdowns for the summer period of lower demand. This enables the plants, which often have load factors of 80 – 90 percent, to operate when they are needed the most and their production is of the highest value.

To grow the share of nuclear further, load following[8] can be done with nuclear power, as is routinely done in, for example, France and Germany. It has a cost, as revenue from production is lost with little in the way of fuel savings to compensate, but this does provide society with added value: a clean and stable energy system that is able to follow demand fluctuations. All methods of load following have their respective costs. Wind power, for example, can also be used to load follow.

This paper takes a bit more holistic view on the load following problem, one that renewable energy researchers have been suggesting and researching for years to mitigate the problems of intermittent production: Why not use the surplus energy of low demand periods to make synthetic fuels and then store these fuels for “a rainy day”.

While the studies often inspect the possibility of making hydrogen, methane, methanol, ammonia or other chemicals (later called

8 Load following means that power plants increase or decrease their production according to the needs of the supply and demand in the electricity grid to keep the grid stable.

synfuels) to be used in power cells, gas turbines or other power generators to provide power at night, during low winds or in the winter, this step can be skipped almost entirely with stable baseload like nuclear available. *With baseload capacity available, we only need to manage demand fluctuations, instead of managing both demand and production fluctuations.*

Baseload capacity makes the whole situation much simpler to handle. Sure, synfuels can be used to provide zero-carbon peaking power/heat as well, but they can also prove to be invaluable in deep decarbonization of the whole energy system. They can provide us with liquid or gaseous fuels for non-electrified transportation needs and feedstock for the (petro)chemical industry, such as manufacturing nitrogen fertilizers. Hydrogen can also be used to significantly increase the yields of biofuels production, by capturing the released carbon dioxide from the biofuels plant and combining it with hydrogen[9].

The scenario presented in this paper has enough baseload nuclear capacity to supply most of the heat and power needs even during the high-demand winter. During low demand in the summer, this extra capacity is used to make hydrogen with *High Temperature Steam Electrolysis* (HTSE). This allows a relatively efficient system, where there is little need to throttle back nuclear capacity, and one that also decarbonizes not just electricity and heat, but also transportation fuels and parts of chemical industry feedstocks[10]. Today, chemical industry is the third largest greenhouse gas industrial emitter in Europe[11]

Of course, there are problems. High Temperature Electrolysis is not yet proven on a commercial scale. We still need to find a way to store the hydrogen (or other synfuels made from it) between seasons. And perhaps we need to bear the cost of using our electro-

9 These yields can be doubled, according to a 2016 paper *Hydrogen enhancement potential of synthetic biofuels manufacture in the European context: A techno-economic assessment* by Ilkka Hannula.

10 This scenario does not have major industries in its demand profile, so depending on the location, the needs for different energy carriers (heat, power, fuels, hydrogen) can vary significantly.

11 More about the chemical industry and its possibilities in decarbonizing can be read from the recent study *Low carbon energy and feedstock for the European chemical industry*, http://tinyurl.com/ybyzo3ca.

lyser-facilities at less than full capacity. This might make it hard for the economics to work in a business-as-usual situation. But it needs to be remembered, that business-as-usual will likely lead us to a climate catastrophe. If the cost of emissions and particulate pollution are included in the price of burning fossil fuels – as anyone supporting a free market would strive to do to make the market operate more optimally – this situation will change drastically.

It is worth noting that these problems of storage (electricity or liquid fuels) and matching demand with supply exist – and are often far worse – in any similarly decarbonized energy system that is mainly or even significantly based on intermittent renewable energy.

CASE LOVIISA – A LOCAL PERSPECTIVE

The conversation on nuclear district heating has been almost non-existent, and when it has emerged in Finland, it has concentrated on whether it would be a good idea to bring heat from the Loviisa nuclear power station some 100 km away from Helsinki. While financially it would likely be a viable option – an investment of around 1 – 1.5 billion euros would cut six percent of Finland's emissions and a large portion of Helsinki's emissions12 – there are other obstacles as well. Many of these obstacles would likely need to be overcome in any scenario involving decarbonization of the Helsinki area district heating. The bright side is that these are not physically impossible obstacles. It is much easier to change politics, even affect economics, than it is to break the laws of physics.

These obstacles include at least the following

· **Politics.** The local utility companies in the Helsinki metropolitan area are mostly owned by the municipalities (apart from Fortum in Espoo). This adds political and public opinion dimensions to company strategies, affecting what options and technologies they choose to pursue, and can do so regardless on the merits of these technologies.

· **Rivalry**. Energy companies compete in the marketplace with each other, while district heat is a local, and somewhat monopolis-

12 As per a recent Master of Science thesis by Tuomas Paloviita: *Production solution for utilizing Loviisa nuclear units for CHP production*, 2016, Tampere University of Technology.

tic product. This makes cooperation and joint-projects somewhat harder (although not impossible), especially regarding district heat.

- **Cooperation**. Helsinki metropolitan area has several energy companies. It would likely be a good idea to combine the currently local district heating networks with stronger inter-network connections, making them more of a single large district heating network. This would require cooperation from all the local utilities, and new thinking from their current monopolistic position as both network operator and energy supplier. A co-owned district-heating network operator for the whole metropolitan area could be one solution.

- **Security of supply** (and of future price). A large portion of heat would need to be brought from Loviisa to make the pipeline and investment feasible. This would mean that substantial back-up-generation would need to be built and maintained in case of a pipeline failure or other disruptions in production. This could also give Fortum a somewhat monopolistic position in the long term to price the heat it sells from Loviisa.

Some of these obstacles also apply for any advanced nuclear scheme, at least partly. Political hurdles still need to be overcome, as well as regulatory ones. Obviously, the public attitude towards nuclear also needs to improve. Cooperation between companies would also offer significant benefits. A greater number of companies and stakeholders would lessen the financial and political risks substantially, bringing financing costs down.

Connecting the local district heating networks together more strongly and rethinking the role of the companies that now operate in the area would likely help any scheme in decarbonizing the heat supply, as it would mean a larger network and more generating capacity spread around. Siting any nuclear reactors would be easier as well if the connection to the network could be outside the more populated areas.

WIDENING THE SCOPE

While this study used the Helsinki metropolitan area for the energy mix and profile, the scale can easily be modified depending on population and local energy use profile. While local conditions are different, the basic idea is transferrable to other locations as well: using nuclear and advanced nuclear to provide baseload electricity, district heat and hydrogen for various uses can offer enormous possibilities for cost-efficient decarbonizing. Indeed, it can be said that due to the seasonal demand fluctuations in energy demand, the Helsinki area is one of the more challenging sites one could choose.

What if there is no district heating network? This is the situation in most places, although according to Europe Heat Roadmap this should change drastically in the coming decades – the aim is to increase share of district heat from 10 percent to 50 percent of households. Often these locations use natural gas, electricity, oil, and solid fuels for heating needs. In Europe (EU-28), the annual demand for space heating is over 3,000 TWh, industrial process heating over 2,000 TWh and hot water use and other heating make up almost 1,000 TWh. Well over two thirds of this energy is produced with fossil fuels. Further, 42 percent of industrial heat uses temperatures of over 500 degrees C, supplied almost exclusively by burning fossil fuels[13]. The total annual "heat market" of EU-28 countries is around 6,000 TWh, representing almost half of final energy demand.

If the local climate is such that no great amounts of heating is needed during winter, there is less incentive to build and maintain district heating networks. If district heating network is not feasible, the most prominent solution is to move to heat pumps and direct electrical heating and then using clean energy sources to provide the electricity. Hot water boilers that can offer local, smart and flexible energy storage for heating and hot water use would also help, along with solar heat collectors[14].

The infrastructure is often built for natural gas, which can be synthesized with hydrogen. This won't likely be cheap, but it is a solution that can work with the current infrastructure.

The hard, climate truth of the matter is that most burning should stop by mid-century, and this will be extremely difficult. In Germany, if natural gas was replaced with electricity, the gap between highest and lowest electricity demand between summer and winter would

13 See www.heatroadmap.eu/resources/29882_Brochure_Heating-and-Cooling_ web%20(1).pdf.

14 An interesting start-up in this regard is Solixi, which combines smart and relatively large hot-water boilers with efficient solar collectors in a hybrid energy storage solution. See <solixi.com> for more info.

grow by 87 gigawatts from the current 11 gigawatts. Responding to such a shift in demand is a tall order, made only taller with the German decisions to close nuclear power plants that currently provide both baseload and load-following services in Germany.

Ways to make affordable synthetic methane or other fuels that can be utilized with current infrastructure (gas heating and gas stoves) would be of great help, while simultaneously the Germans should clean their electricity production. The more we can use existing infrastructure, the easier, cheaper and faster the transition will be, and the less opposition new policies and technologies will likely meet. Direct electrification is, on its own, often more efficient, but it needs to be remembered that indirect electrification (making synfuels with electrolysis/hydrogen for example) can be more acceptable and require less overhaul in our existing infrastructure.

ADVANCED AND SMALL, MODULAR REACTORS

Advanced reactor usually means a "fourth generation" reactor, often not based on the currently prolific pressurized (PWR) or boiling (BWR) water technologies. Here, the definition "advanced reactor" is used broadly to also include small reactors that are based on PWR or BWR technology. These include for example the *NuScale Power Module*, which is a small modular reactor of 50 MWe.

Advanced reactors might also be rather large in size, but have other technological innovations and new ways of utilizing nuclear energy, such as the sodium-cooled Russian *BN800* breeder reactor. There are also molten salt reactors that can use either uranium or thorium as fuel, and helium-cooled high temperature pebble-bed reactors. The list is long, but the rough guideline for defining advanced reactor (at least in this study) is either new possible uses (small size, higher temperatures) and/or new mix of coolant solution and neutron moderator.

WHAT REACTORS WERE CHOSEN FOR THE STUDY AND WHY?

There are a wide variety of different designs being advanced around the world, and the scope of this paper can't take all of them into account. Some key-criteria in selecting the prospective reactors were:

· Likely commercial availability in the 2020s or early 2030s.

· Availability of key-specifications and other information.

· High enough operating temperature to make high temperature steam electrolysis feasible (around 600 °C or higher).

· Nimble operation with the possibility to offer load-following services in stabilizing the grid.

Based on these, two reactor types are looked in more detail. HTR-PM pebble-bed reactor that China is currently building, with a commercial scale first-of-a-kind finished by end of 2017 and Terrestrial Energy's IMSR (Integral Molten-Salt Reactor) that is currently being designed in North America. A western version of the pebble-bed high temperature reactor, Xe-100 by X-energy, is also presented briefly, and there are numerous other molten salt reactors under development.

One of the most important criteria for selecting reactors is that they should be commercially available in the 2020s or in the early 2030s. Anything beyond that is simply too far in the future for today's discussion, as we also need time for deployment. On the other hand, given that the legislation and regulation likely need changes to enable new reactor types and sizes, and making those changes will take years, there is no pressing need to have the reactor available today or even within the next 5 years.

The chosen reactor types represent some options, but as long as the key specifications (size, cost, availability time-frame) stay similar, other reactor types can be (and should be) evaluated as well. There are multiple ways to harness the power of the atom for the good of mankind.

The current mainstream reactors based on light-water technology (PWR and BWR), are also a valid option. The main reason for leaving them out from this analysis is their lower operating temperature. It should be noted that from purely regulatory/legislative point of view, they are easier to build in the near future, and offer interesting options for both district heating and electricity, as well as desalinating and many industrial heat applications in the sub 350 °C range.

ONE DESIGN VS MULTIPLE DESIGNS

Should only one type of reactor be built, or should there be more designs involved? There are both benefits and drawbacks to using a single design and replicating that.

Drawbacks of committing to a single design:

- If initial choice of reactor is sub-optimal, the impact will be felt by the whole fleet.
- Inherent technical / design problems apply for the whole fleet.
- Dependency on a single supplier of reactors.

Benefits of committing to a single design:

- Experience in both building the power plants and operating the reactors increase efficiency and reduce costs.
- Inherent technical / design excellence applies for the whole fleet.
- Potentially better negotiating position when choosing the reactor supplier due to larger order.

Drawbacks can be mitigated in various ways. The first two can be mitigated by choosing a reactor that has some operational history and has proven to be a good design. The third can be mitigated, at least up to a point, by doing due diligence and making careful contracts with possibilities for mutually beneficial cooperation.

The IMSR (as well as ThorCon's molten salt design) has a reactor core that is changed every few years (7 years with IMSR and 4 years with ThorCon). This means that possible problems can be fixed and improvements made with future core generations, if regulation permits it. The HTR-PM is a design that is already being built, with the first commercial scale prototype starting up in 2017 or 2018. It will, therefore, have plenty of operating experiences on it by 2020s.

If multiple designs are chosen, it could make sense to start with more traditional designs that are based on light water technology but are smaller scale than the current large reactors being built. These can become available a bit sooner and need fewer regulatory changes in Finland (and most other places). They can efficiently meet district heating, electricity production and CHP needs, and can (especially if their costs can be brought down) potentially provide heat and/or electricity for electrolysis and heat for many industrial processes. Desalination is also one service that is relevant in some locations that lack fresh water. Such reactors include for example NuScale Power Module (US) and ACP100 (China).

MOLTEN SALT REACTORS - IMSR

Integral Molten Salt Reactor (IMSR) is one of the promising molten salt -based reactor designs currently in development. It is being developed by Canadian company Terrestrial Energy (TE), and they aim to have it commercially available by 2020s.

The IMSR is a liquid-fuel reactor system that dissipates heat using a molten salt, a common heat transfer method in industry. It uses a low-enriched-uranium fluoride salt as fuel. One of the key innovations is the integration of the primary reactor components (including the graphite moderator) into a sealed, replaceable reactor core with a 7-year lifetime.

TE plans to provide IMSR-reactors from sizes of few dozen megawatts to hundreds of megawatts – with 400 MWth (190 MWe) being the first design – for applications outside the electricity grid as well, such as providing high-quality heat (600 °C) for industrial purposes and for the making of hydrogen with High Temperature Steam Electrolysis (HTSE) at competitive prices.

The reactor is also capable of ramping its power up and down flexibly.

KEY SPECIFICATIONS

Construction cost:	~800 million € / 400 MWth reactor
Cost of heat (at 600 °C):	<20 €/MWh
Cost of electricity:	~50 €/MWh
Operating lifetime of core:	7 years
Construction time:	<4 years

There are a host of other molten salt reactors being developed as well. These developers include for example ThorCon, TerraPower and Moltex, with many others as well[15].

15 More information can be found at World Nuclear association website: tinyurl.com/hmmcm5f.

HIGH TEMPERATURE GAS-COOLED PEBBLE BED REACTORS HTR-PM AND XE-100

The construction of the Chinese pebble-bed high temperature reactor will be completed by 2018. It is a gas-cooled (helium) design that can't experience a core meltdown and operates at a relatively high temperature of 750 °C. It can produce steam of around 550 – 600 °C. Due to its relatively small size per reactor – two 250 MWth reactors are operated to drive one 210 MWe generator in the pilot plant. Due to the limited size of the reactors, they can be passively cooled. The HTR-PM project later aims to have six 250 MWth reactors driving a single 600 MWe turbine (1500 MW thermal and 600 MW electrical output).

Cost estimates for HTR-PM put it at the same ballpark as similar sized PWR reactors, perhaps with 20 percent higher capital costs. The fact that the reactor can output steam at 750 °C makes its product generally more valuable, as more can be done and at higher efficiency with higher temperatures. Building the reactors is faster than traditional LWR reactors, and they are designed to be manufactured in series, which helps cut costs in the future.

The Chinese plan on using these reactors to replace their current fleet of super-critical coal plants, where they can utilize the available infrastructure and turbine generators.

Other designs on similar principle exist in the west as well, but the Chinese have the lead on actually building an operational, commercial-scale reactor. X-Energy[16] from the US is designing a western high-temperature, gas cooled pebble-bed reactor, the Xe-100. The company recently received funding to the tune of USD 40 million from the Department of Energy (DOE) to develop its reactor. The Xe-100 is a 75 MWe and 200 MWth helium-cooled pebble-bed reactor that the company says will be available by 2030. The "normal" configuration is four reactors per power plant, producing 300 MW of power. The reactor produces steam at 565 °C. Construction time per reactor is estimated at 18-24 months. The reactor modules are small enough to be trucked to the site and installed there. The estimated cost for power produced is <80 €/MWh.

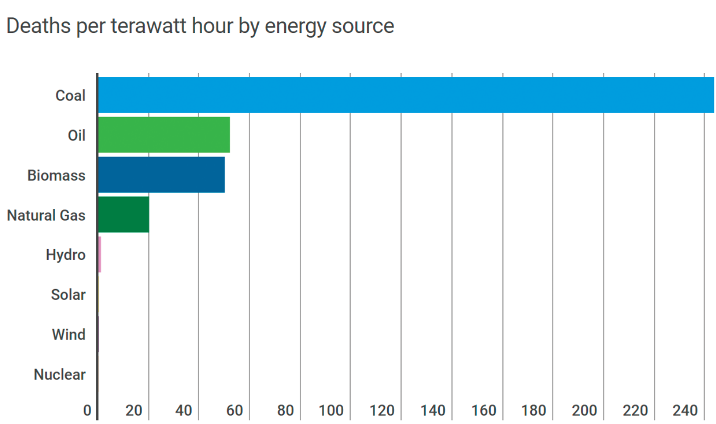
16 See X-energy.com.

One of the more interesting design feature of both types of advanced reactors presented here is their incapability to experience a core meltdown. This makes it possible (although not unproblematic, for example due to political reasons) to have these reactors near population and other industrial infrastructure, which will offer new opportunities to decarbonize our energy streams.

SITING, PERMITTING, LICENSING – WHAT NEEDS TO CHANGE?

Nuclear energy has the best safety record of all energy sources. While there are concerns for siting nuclear power plants in or near cities, and those concerns have some valid arguments backing them up, it is still a fact that even previous generation nuclear power plants, designed in the 60s and 70s and built in the 70s and 80s, have proven to be our safest energy source.

Compared with burning fuels, be they fossil or biomass-based, nuclear energy is in a class of its own. Yet burning is often allowed even in city centers. Compared with wind and solar power, the safety record of nuclear is similar, if not better.



Graph shows approximate fatalities per terawatt hour of energy produced. Source: Nextbigfuture.com, http://tinyurl.com/y8ng83ar

Current nuclear reactors that are built in Finland and in the EU are required to be built in such a way that no radiation leakage endangering the environment can happen even in the event of an accident. This should, in theory, make them feasible for siting relatively near population centers as well. In practice, this is different – both due to regulations and public opinion, that have in turn been driven by fear.

This study does not suggest any specific sites for reactors. Analyzing the many sides to that discussion is beyond the scope of this study. It does present some interesting and potentially helpful concepts and technologies that can be used to site the reactors more flexibly.

ENERGY TRANSFER CONCEPTS

With molten salt reactor such as the IMSR, the actual reactor can be several kilometers from the turbine-hall and district heating network connection, and have the energy transferred as molten salt. Of course, the longer the distance, the greater the costs of building it and the more losses there will be along the way. But this sort of flexibility of the reactor can be invaluable when siting the reactor near populated areas.

Greater temperatures also enable other interesting options for transferring the energy for even longer distances. One option is to move the energy in a closed loop chemically. This is achieved by having a steam reforming facility near the nuclear plant, which utilizes nuclear heat in the process. The resulting mixture of carbon monoxide and hydrogen is then transported via pipeline to a methanation facility at the other end, where the exothermic methanation process can supply relatively high temperature steam (over 500 °C), either for industrial use or for electricity or CHP production. After this has happened, the resulting methane is piped back to the nuclear plant for steam reforming. Other chemical reactions can also be used.

This idea was originally developed for this very purpose and researched in the 1980s: how to facilitate the cost-effective use of zero-carbon nuclear energy at places where nuclear power plants can't be built due to regulations. There are no transfer losses (unlike in long distance heat transfer), but of course there are some losses in the steam reforming and methanation ends. The amount of these losses, and therefore the economics of the whole process, depend on the catalysts and temperatures used in the processes.

The beauty of this concept is that it is a closed loop: the same carbon and hydrogen go around and around, with water coming out at one end (methanation) and added at the other end (steam reforming). While this process was researched in the 1980s, the research interest has since then dwindled. The advent of advanced, high temperature small reactors and the need to transport their energy over distances economically should rekindle interest in this concept.

PERMITTING AND LICENSING

The detailed changes needed to our current nuclear law are beyond the scope of this study, and the situation varies greatly between countries. Some broad points which need to change in the Finnish context are discussed below. A good starting point for any changes would be to *better allow us to mitigate climate change with nuclear* while realizing that it is already our safest energy source.

The Finnish process of applying for a political decision in principle is much too heavy to go through for each small reactor. There are several options to remedy this. The most radical is to acknowledge that any clean energy capacity built in Finland is in our national interest[17] in our effort to do our part in the climate fight, and remove the political decision in principle step altogether. Safety (construction permit, regulation and oversight) is done by STUK[18] anyway, and economic feasibility of any given investment is decided by those doing the investing, not by politicians.

Another, less radical option would be to set the permission process to be more flexible. Perhaps smaller reactors (to decarbonize local district heating networks for example) could be exempt from the process altogether[19], or perhaps the permission could be applied

17 Which is what the current political permission is supposed to control for, although the politics around these permissions often concentrate on anything but this.

18 Finland's independent radiation and nuclear safety authority.

19 Small research reactors don't need this permit even now, but this could be expanded for non-research reactors as well, and the maximum capacity increased from the current 50 MWth.

for a given amount of capacity that could be built in a given, longer timeframe as the utility sees fit.

Reactor licensing also needs to be made more flexible. Today, each reactor needs its own process, which is heavy and aimed at larger projects that are more unique in their nature. One option would be to grant a license once for each reactor type that is to be built (much like in the aviation industry).

The current regulation is mostly oriented towards light water reactors. This means that there can be needless redundancies in regulation that do not apply for new types of reactors. Many designs are physically incapable of having a core meltdown, for example, making "meltdown-prevention" a largely useless requirement. To address this issue, STUK should consider implementing a technology neutral design approval process.

The Roadmap – Three steps to deep decarbonization

Decarbonizing a whole metropolitan area is a big undertaking, no matter what technologies are used. In the case of relatively new types of nuclear reactors, a lot of learning needs to happen in construction, licensing/regulation and operation of the reactors. Further, there are ample examples of how hard and expensive it can be to jump-start an industry that has no existing supply-chains or experienced project management and construction crews.

To minimize these risks, this study presents a three-stepped approach:

- Start with producing heat for baseload district heating needs-
- Transition to power generation and combined heat and power.
- Finally, produce synthetic hydrogen with high temperature steam electrolysis (HTSE).

The hydrogen can then be used as a feedstock for other fuels and chemicals. The goal is a near-total decarbonization of the key emissions sources – heat, power, and transportation – in the energy sector.

This step-by-step approach allows for experience and know-how to accumulate and for new technologies to mature during the 20+ years it takes to construct and decarbonize the whole energy sector. It also spreads the investment – partly with the help of smaller reactors demanding smaller upfront investments – over those years, allowing faster returns on early investments that help fund upcoming projects.

The average construction speed should be around 200 MWth per year, give or take[20]. If a 400 MWth reactor like the IMSR is chosen, a new reactor should be started up every two years. And if HTR-PM reactor is chosen, a 250 MWth reactor should be started almost every year. The reactors are intended to be manufactured mostly in factories, not on site, so on-site work consists of constructing the surrounding facilities and installing the reactors. The IMSR power plant, for example, has a footprint of 6.8 hectares. This is in the same ballpark as the area reserved just for the famous piles of coal at the Hanasaari powerplant.

The calculations and assumptions in this roadmap are high-level. Their purpose is not to offer detailed information but to convey the general idea and possibilities, the scale of things and to act as discussion starter and catalyst. Through that discussion, the need for more detailed analysis can arise.

The total thermal capacity of the decarbonized system is in the ballpark of 4 gigawatts. Heat and power alone can be done with even less. This is less than the Olkiluoto 3 reactor has, yet it manages to provide double the amount of usable energy (compared with OL3 which produces only electricity). This is due to two factors:

- Combined heat and power, which more than doubles the total amount of useful energy (district heat and electricity) that can be derived from a nuclear reactor.
- The availability of higher temperatures which increase the efficiency of electricity production and CHP-production along with the concept of HTSE to provide hydrogen.

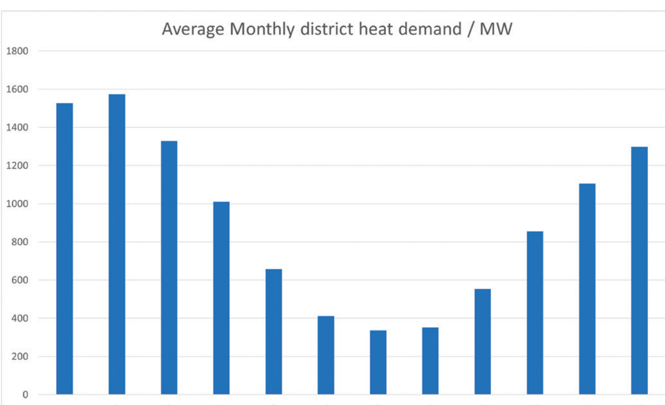
20 Compared with Olkiluoto 3 project, suffering from many delays, this is quite conservative. Even with a 15-year construction period, OL3 would be over 50% faster per year.

STEP ONE – HEAT

Our case-area uses district heat at a minimum capacity of around 350 MWth at all times – this is mostly hot water use, not space heating. During the 9 months from September to May, the base-load demand is around 600 MW. Annual average demand is around 920 MW, and the coldest 6-month average is around 1,300 MW. The estimated 2050 annual demand varies between 350 and 1,600 MW from one month to the other.

Fossil/biomass fueled power plants and boilers are better suited to meet these fluctuations in demand economically, because (unlike nuclear and non-burning renewables) a much larger percentage of their production costs comes from the fuel they use. This large variability in monthly demand during the seasons poses challenges for any decarbonization scheme, since clean energy sources are not based on burning fuels.

As we learned in the introduction, this demand profile is especially troublesome for scenarios relying on solar energy. Around 90 percent of solar radiation in Finland comes during the 7 months that have the smallest need for heating, leaving only 10 percent for those months that have over 60 percent of the annual demand (November to March). A full 50 percent of solar radiation comes during the three summer months that combined have only 8 percent of total annual heat demand.



Monthly averages for heat demand vary greatly.

Depending on the depth of the decarbonization, some of the peaking power needs can be supplied with burning fuels (coal, oil, natural gas, waste, biogas or biomass) and even electrical heaters. This study assumes that daily and week/weekend demand fluctuations can be handled with local storages and demand flexibility. Storing heat is a lot easier than storing electricity.

The baseload need of around 400 MWth is well-suited for our example SMR reactors. The standard IMSR is rated at 400 MWth (190 MWe), and the HTR-PM in its normal twin-setup is rated at 500 MWth (two 250 MWth reactors driving a 210 MWe turbine), while the Xe-100 would require two 200 MWth reactors for a total of 400 MWth. Building and operating a reactor that only produces baseload heat is both simpler, faster and cheaper than building one also capable of electricity generation as there is no need for the turbine generator, let alone a plant capable of CHP or HTSE. This allows for a smaller upfront investment and less risks in the beginning, and adds a faster stream of income at the start. The first heat-only power plant should be designed so that power generators and CHP-capabilities can be added later, as further down the road the baseload heat can be supplied with a combination of several CHP-capable reactors that can also load-follow the variable demand.

STEP TWO – CHP

Finland has long produced flexible, combined heat and power using traditional, combustion-based power plants. Fossil fuel plants like these consistently operate at over 90 percent efficiency and provide steady heat and power nationwide. Efficiency in fossil burning, however, is no substitute for not burning at all.

Some may argue that CHP plants should be among the last to stop burning, as they convert the primary energy in fuel into usable energy much more efficiently than conventional thermal plants. If the ETS (Emissions Trading System in Europe) was left to its devices, this would likely happen in such a way: burning would happen where it is most profitable and efficient and gradually stop where it was most inefficient. With all the national, political and special interests at play, the ETS has not been left to its devices. Most politicians want their city or country be the (first) one to quit coal – or at least they want to be the politician who says this, letting the public pick up the bill.

Nuclear CHP offers huge opportunities, as currently only a third of the energy released from the nuclear fuel gets used as electricity. With co-production of heat and power, the total thermal efficiency of a nuclear power plant can be more than doubled. This makes a huge difference economically, as well as from the point of view of decarbonization. The additional investments needed, compared with electricity generation only, are quite small if the district heating network is already available, yet the amount of value and cash flow produced can increase significantly, all the while emissions would decrease. Nuclear CHP is one of the few opportunities to get enormous benefits to both economics and decarbonization.

CHP-capable nuclear power is nothing new, but relatively few sites around the world have adopted the technology to produce clean industrial and district heat. Fossil fuels still provide most district heat, but secondary sources such as server-farm waste-heat and heat pumps are also growing. Replacing most of the burning in heat production represents a growing market, as nuclear is one of the only technologies that can produce high quality, low carbon heat reliably around the clock.

STEP THREE – HYDROGEN AND SYNTH FUELS

Liquid fuels, which we currently distil from crude oil, have tremendously useful properties. They are easy to transport and store, highly energy-dense and relatively safe for large-scale use in cars, airplanes, and cargo ships.

Any deep decarbonization scenario requires one of two things to happen: 1) everything is electrified or 2) we develop a clean way to mass-produce affordable synthetic, hydrogen-based fuels.

We are unlikely to manage a total electrification of our energy system within any reasonable time frame. Not in Helsinki metropolitan area, Finland, nor globally. Electricity will likely grow its share of our final energy use, but on a global level the speed will be slow. Almost half of global electricity is used by industry, almost a quarter by commercial and public services sector and about a quarter by residential sector. Over 90 percent of our transportation runs on oil, and most of the heat we use is supplied by burning various fuels; wood, oil, coal and natural gas. Air conditioning and district cooling are a rapidly growing sector of energy use as well, and with hotter climate, they will become even more popular. The infrastructure, appliances, vehicles, and machinery that use these fuels is not going anywhere in the near future.

Hence there will be plenty of use for various liquid and gaseous fuels in the future. We need to figure out ways to make them synthetically and affordably. Additionally, hydrogen is a critical feedstock in many industrial uses such as making nitrogen fertilizers. Right now, most of the hydrogen we use is separated from natural gas and coal, both of which release a lot of emissions in the process.

Electrolysis —using electricity to get hydrogen from water — is currently the only clean, market-ready way to make hydrogen, and even that is clean only if the electricity used is made cleanly. Other ways are biological (some bacteria could produce hydrogen) and thermochemical (thermolysis, which requires very high temperatures of 1,000 °C or more). Between electrolysis and thermolysis, there is High Temperature Steam Electrolysis, or HTSE, which uses Solid Oxide Electrolysis Cells (SOEC). In short, it uses high temperatures and catalysts to make electrolysis more energy-efficient and cost effective.

Literature[21] suggests that *HTSE offers (thermal) efficiencies of roughly 40-50 %* depending on temperatures used (between 500 and 1,000 °C). This compares very well with the current mainstream alkaline electrolysis which has a thermal efficiency of roughly 27 %. The electrical efficiency of HTSE can be as high as 90 %, provided sufficient heat is provided as well.

Current mainstream electrolysis technologies are alkaline and PEM, and their electricity-to-hydrogen -efficiencies are in the ballpark of 60 percent, with predictions of getting them up to 70 percent by 2030. According to a 2014 report[22], the future (2030) costs

21 For example: *Youngjoon Shin & co, Evaluation of the high temperature electrolysis of steam to produce hydrogen, International Journal of Hydrogen Energy 32* (2007) 1486 – 1491.

22 *Development of Water Electrolysis in the European Union, Final Report* (2014). See www.

of producing hydrogen with these processes are between 2.5 and 5 euros per kg (82 – 165 €/MWh), depending on process (PEM or alkaline) and future electricity prices. The low-end price is from Germany, where electricity prices for industry are lower (value used is 51 €/MWh) thanks to subsidies and additional costs to consumers (consumer total price is around 300 €/MWh). In Finland, the price is in the middle: 4 – 5 euros in 2012 and 3 – 4 euros in 2030, with total electricity cost (including taxes and transmission) set at 62 €/MWh.

With a source of low-cost but high-quality heat and electricity available, the costs of hydrogen production with HTSE can be brought down well below these estimates on PEM and alkaline costs, but there is still uncertainty on the future capital investment costs for HTSE facilities.

With HTSE, some of the energy-input for the process can be supplied as high-temperature heat, which is usually cheaper than electricity. As a rule of thumb, roughly one unit of sufficiently high temperature heat (600 – 700 °C) is used for four units of electricity. In other words, supplying heat makes the electrolysis more efficient. Higher temperatures also make electricity generation more efficient, which also increases the total thermal efficiency of hydrogen production. One area of further study is to inspect if and at what cost can (waste) heat be utilized from the HTSE-process to be used in district heating or other processes. The roadmap presented in the roadmap chapter below assumes that this is not done.

ACTING AS A SINK FOR EXCESS ELECTRICITY?

One exciting possibility is that as high temperatures are available reliably and at high capacity, nothing prevents the reactor/electrolyser-combo from buying some of the electricity from the grid in times of low prices, and to supply the heat for the HTSE with the reactors. This would maximize the use of the high-quality heat and it would also act as a sink for low-price surplus electricity, for example from intermittent renewable sources. Although the same can be done with regular electrolysers, it would be more efficient to use this surplus electricity in HTSE, as it is likely that

fch.europa.eu/sites/default/files/study%20electrolyser_0-Logos_0_0.pdf.

USES AND MARKETS FOR HYDROGEN:

- Ammonia and nitrogen fertilizer production
- Crude oil and biofuels refining / hydrocracking
- Other petrochemical industry uses
- Direct fuel for hydrogen vehicles
- Electricity production for high-demand and high price periods
- Synthetic, carbon based fuels for transportation (methane, methanol, gasoline etc)
- Other carbon-based chemicals (even synthetic food in the future)
- Steel-making by using hydrogen instead of metallurgical coal

OTHER REVENUE STREAMS FOR ELECTROLYSERS:

- Selling grid balancing services (by ramping the electrolysis process up and down as needed).
- Acting as a sink for waste-electricity (in case of lot of intermittent renewables and spare electrolyser capacity).
- Selling pure oxygen (the by-product of electrolysis).

there would be ample heat available during low electricity prices as well. The main caveat, and a case for operational optimization, is balancing the capital costs of the electrolysers if they are used at lower load factors.

Whenever the price of electricity in the marketplace would get low, and assuming there is a decent price for hydrogen to be had, it would be economical for the reactors to produce only heat (roughly two MWh for each MWh of electricity not produced), use that heat in a high temperature electrolyser and buy the electricity for the electrolysis from the marketplace.

Let's make a back-of-the-envelope style thought experiment, and assume the following (one can switch euros for USD 1:1 for this experiment):

· Cost of producing 600 °C heat with an IMSR: 20 €/MWh.

· Cost of producing electricity with an IMSR: 50 €/MWh.

· HTSE inputs are 80 % electricity and 20 % heat.

· Electricity -> hydrogen efficiency is roughly 90 % (although heat needs to be added).

· Price (value) of hydrogen in the marketplace: 75 €/MWh.

If the electricity price goes below the cost of production, for example to 40 €/MWh, it becomes unprofitable in the short term to produce it, but ramping production down does not offer much savings in the costs either. If there is spare HTSE capacity available, the operator could do the following:

· Switch from electricity production to producing heat, getting 2 MWh of heat for each MWh of electricity not produced.

· Buy 8 MWh of electricity at the marketplace for 40 €/MWh.

· Run the electrolyser, supplying it with 2 MWh of heat (from the reactor, total cost 40 €) and 8 MWh of electricity (from the grid, total cost 320 €), yielding around 7 MWh of hydrogen with a total value of 525 € (7 * 75 €/MWh).

· Instead of making 10 €/MWh loss by selling electricity at below generating cost, the operator now makes 525 € - 320 € - 40 € = 165 euros profit for each MWh of electricity he does not produce but diverts to HTSE as heat (of which, he obviously needs to pay the electrolyser capital and O&M costs).

It might also be possible to improve the final economics further and use at least some of the waste-heat from electrolysers for district heating.

As long as there is spare electrolyser capacity, this makes for an effective sink for cheap, surplus electricity (and helps to create a floor-price for electricity), taking maximum value out of it by providing high quality heat to the mix. This sink can also be created with traditional electrolysers that only use electricity, but their electricity -> hydrogen efficiency is poorer, between 60 and 70 percent. They would need 10-11 MWh of electricity (costing 400-440 €) to make the same 7 MWh of hydrogen.

Of course, any use of cheap excess electricity can be made uneconomical with poorly designed markets, such as with high taxes and high transfer fees for the buyer.

ELECTROLYSER CAPITAL COSTS

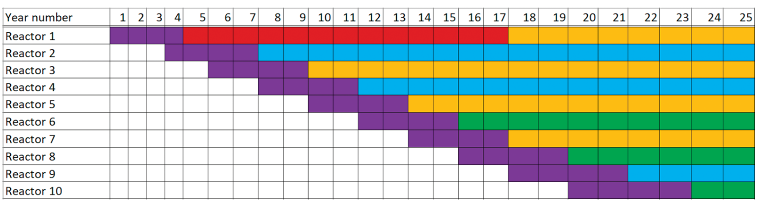
While capital investment costs play a significant role in the price of produced hydrogen, the price of the energy inputs dominate. Electrolysers produce only a couple percent of global hydrogen, so there is ample room for cost reductions with further R&D, mass-production, and supply chain development. According to a report from 2014, all electrolyser systems will come down in price significantly by 2030. The more optimistic estimates have alkaline and PEM electrolysers costing roughly 300 € / kW, with the central price-estimate at 600 € / KW.

SOE (HTSE) electrolysers are still new technology, with estimates of costing around 1,000 € / kW nearing 2030, and perhaps reaching as low as 300 € / kW in the longer term. With an electrolyser of 150 MW capacity, this translates to 50 - 150 million euros in capital costs. Some electrolyser designs can be optimized for low capital costs (if they are to be used with intermittent energy such as wind and solar) and others for high efficiency and high load-hours, depending on the use-profile.

A ROADMAP FOR CONSTRUCTION

As mentioned above, the three-stepped approach aims to build know-how and supply chains – two of the big problems plaguing new nuclear builds today – one step at a time, progressing from simple heat production to power and CHP and then on to producing hydrogen and synfuels. Below is a presentation of one such roadmap, which uses a 400 MWth IMSR reactor unit as the basic building block. In case of X-energy's Xe-100, the number of reactors would increase by a factor of ~2.5, but on the other hand, the estimated construction time per reactor is less than two years for Xe-100.

The roadmap has ten reactors built in total, starting with heat only for decarbonizing a good chunk of the district heating baseload by year 5 (if construction starts in 2030, this is year 2035). The district heating is 90 % decarbonized and nuclear by year 14 (2044), when the average capacity reaches 800 MW, half of which is flexible CHP. The electricity/CHP sector will be over 70 % decarbonized by year 18 (2048, and 85 % decarbonized by year 22 (2052), running at 1170 MWe (average). The first HTSE hydrogen facility comes online by year 16 (2036), decarbonizing around a third of the transportation fuel needs (164 MW), following by two more HTSE facilities every four years. Fuel needs would be the last sector to be totally decarbonized by year 24 (2054).



A possible roadmap for construction with a new 400MWth project starting every two years

By year 24 (2054 if construction starts at 2030) the total average capacities would be:

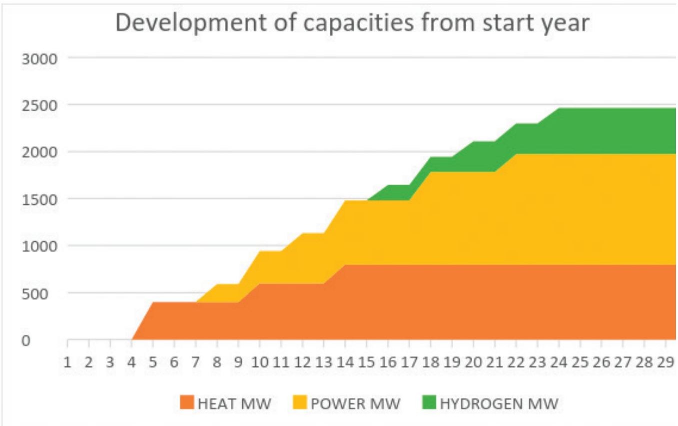
- 800 MW heat
- 1170 MW electricity
- 492 MW hydrogen

		Heat	Power	H2
Construction		0	0	0
Heat		400	0	0
Power		0	190	0
CHP		200	150	0
CHP + H2		0	0	164
Notes:	Reactor type: IMSR400			
Electricity 47,5 %, CHP 87.5 %, Hydrogen 41 %				

Key assumptions made for the roadmap

This is only one example, which has a timeline of 24 years to reach full capacity. The capacities pictured above are average operational capacities, but given the CHP capabilities of most of the plants, the maximum capacity is over 2,500 MW for heat and 1,800

MW for electricity. HTSE capacity needs to be at around 650 MW (see next chapter). The total thermal capacity of the system above is 4 GW (10 x 400 MWth).



Development of heat, electricity and hydrogen production capacities throughout the 30 years.

Of course, the future demand profile will be different from the one used here, and other energy sources, such as wind, solar, heat pumps and even geothermal heat are likely to play a significant role as well. This is a presentation of what is possible if nuclear was the main tool used and if a relatively high level of self-sufficiency in energy production capacity is valued.

The fleet is also extremely flexible and therefore future-proof, both at the reactor level and because most of the fleet is CHP capable, both for heat and power and for heat, power and hydrogen. Such a flexible system makes it possible to integrate other sources of energy to the mix as well. The reactors with accompanying electrolysers can also act as efficient sinks for surplus electricity to produce hydrogen.

Maybe transportation will be electrified more thoroughly, and we don't need as much hydrogen but more electricity. Or maybe heat demand will be smaller in the future due to better insulation, warmer climate and smart ways to capture and reuse the heat that we use. Or maybe population will grow more rapidly, increasing demand for all types of energy. The reactors will be able to answer these needs in a flexible manner, and future projects can be adjusted accordingly. It is also unknown what specific fuels we will use in the future, but it is a safe bet that most of them need hydrogen as a central building block.

While heat is a local good that is produced near to the consumer and is not easily transported for long distances, both electricity and synfuels can be imported and exported. For simplicity's sake, this roadmap assumes that little of such trading is done, but any imports and exports will help balance the system overall. If too much capacity is built, some might be sold outside, and if too little is built, electricity can be bought from other producers in the wider grid.

Next, we look at how seasonal load following and hydrogen production with HTSE can make all the difference for the economics of deep decarbonization.

Matching supply and demand

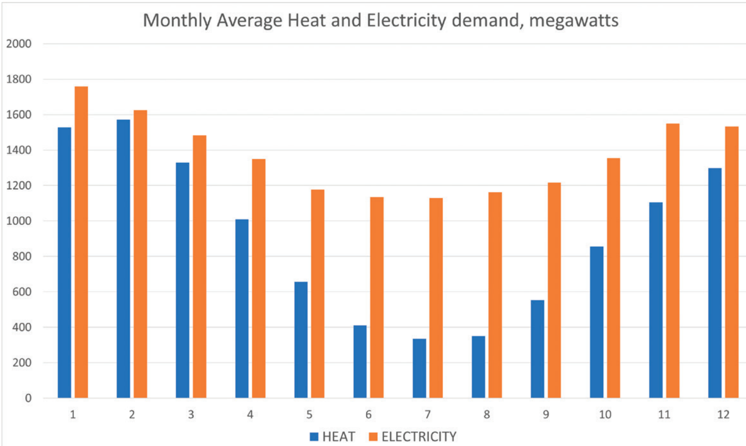
The northern demand profile is one of the most challenging there is. Both heat and electricity demand are much higher in winter-time than during the summer. While Finnish use modest amounts of air conditioning and cooling, this is a rapidly growing sector around the world.

The central problem in the northern Europe is that during winter, demand is much higher than during summer. Solar PV is only of limited use, and even for wind, there needs to be backup-capacity available somewhere for those days and sometimes weeks when the cold and calm winter weather sets in.

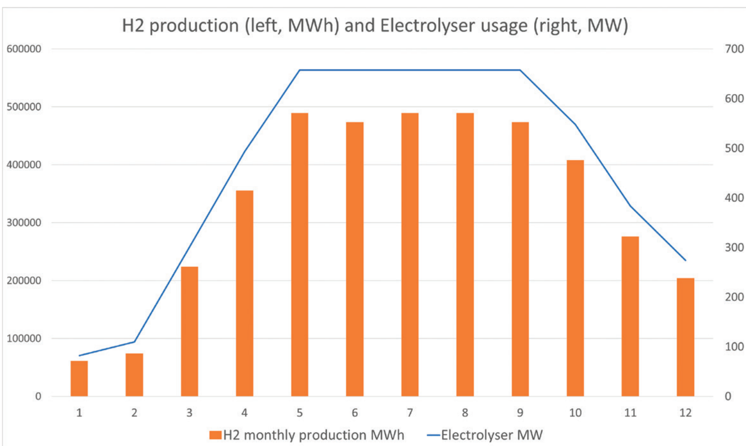
FLEXIBLE LOAD FOLLOWING

While smaller amounts of heat and electricity can be stored to account for changes in daily or weekly demand, the northern climate of Helsinki region offers a tremendous challenge for meeting seasonal variability in heat and electricity demand.

Ramping production up and down with capital intensive energy sources (nuclear, wind, solar) makes little sense from the owner's perspective, unless they are paid to do so. One option – the path



Monthly heat and electricity demand presents a challenging task for seasonal load following with any power plant.



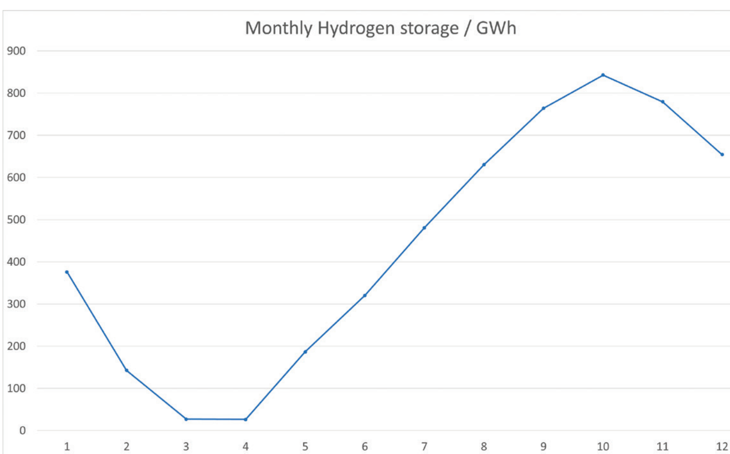
Monthly hydrogen production in MWh and electrolyser use in MW used for seasonal load following.

that is chosen in this scenario – is to make hydrogen/synfuels with the spare capacity when demand is low (May-September) and store them for periods when heat and power demand is high (November-March). *Seasonal load-following is done not with the energy source itself, but with a storage medium that can also be used for decarbonizing transportation fuels and other chemical industry feedstocks.*

Of course, the investor is then faced with investing in electrolysers which will not be used at their full capacity, or storage facilities that match this variability in production and demand, not to mention the space needed for such storage capabilities. A more detailed cost-analysis is needed to calculate the optimum mix of storage costs and number of full-load hours that the electrolyser can operate. Below is a chart with one option presented, along with a chart mapping the storage capacity needed and its use throughout the year.

In the above graphs, the average hydrogen production capacity is around 450 MW, while the maximum capacity (used for 5 months) is around 650 MW. For the three coldest winter months (December to February), the electrolysers are run at minimal capacities, between 50 and 200 MW.

In this case, the electrolyser would be used at load factor of around 70 %. While it is not optimal, it is much higher than can be achieved with solar and/or wind power surplus energy. A better load factor reduces the share of capital costs on the hydrogen produced and the need for massive storage.

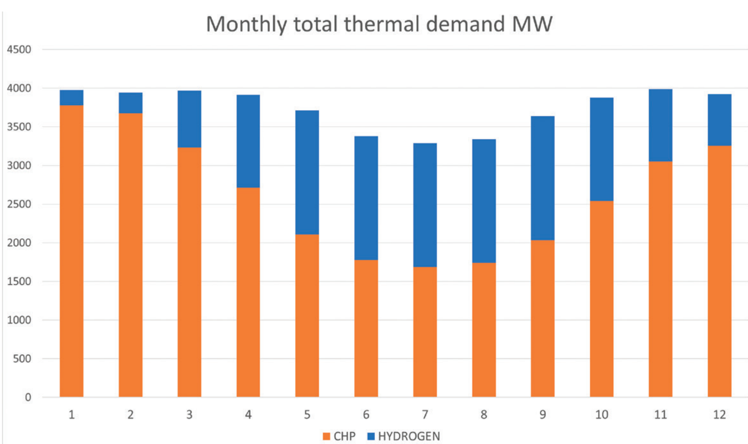


Monthly hydrogen storage varies between 20 and 800 GWh, ensuring a constant supply of hydrogen throughout the year for direct or indirect uses.

Producing more hydrogen instead of heat and electricity in the summer months would even out the maximum capacity needed and increase the load factor for the nuclear reactors. Below is chart showing the monthly demand for each of these in such a scenario. The graph uses the following assumptions: 87 % average thermal efficiency for CHP production, and 41 % thermal efficiency for hydrogen production.

The energy system would have a maximum demand of around 4,000 MWth and an average demand of roughly 3750 MWth, translating to a load factor of over 93 %. By timing maintenance and other work smartly, the reactors could run at full steam all the time.

The scenario presented in above graph is only a simplified thought experiment. More detailed modelling is needed to find out which mix of reactors, power generators, CHP-capacity and hydrogen production and storage capacity can best match the actual demand, and how much of the short-term peaks should be covered using other peaking plants. The price of hydrogen storage (or other large-scale energy storage) and the fixed costs of electrolysers affect what is the optimal mix for hydrogen production: a lot of capacity with lower overall load factor or less capacity with higher load factor but more storage.



With hydrogen production used for load following, the nuclear reactors can run at practically full steam year around.

WHAT ABOUT ENERGY STORAGE?

Any affordable, large-scale energy storage solution that might enter the market will make the scenario more efficient and easier to accomplish. If less hydrogen is needed because of electrified transportation, then less electrolysers and/or storage capacity is needed, which means that less energy production capacity is needed as well. Alternatively, there is the possibility of selling excess hydrogen or other products.

While hydrogen is hard to store, electrolysers can be used for load following, given that capital costs are not that dominant compared with energy costs and that they are often suite tolerant to ramping production up and down. Hydrogen is not likely the final product, unless fuel cell vehicles become much cheaper and more commonplace. Other, more usable and storable chemicals need to be made of hydrogen. Such chemicals include for example methane, ammonia and methanol. Many of these processes are economical to run only at full power, feeding hydrogen and other feedstocks to the process constantly. This would also mean further losses in the energy conversion. Digging deeper into these processes and their peculiarities is not in the scope of this study.

If more hydrogen is needed to meet the demand for liquid fuels and other chemicals, then more clean energy production is needed as well.

THE AFTERMATH

One of the first questions that come to mind when someone proposes a roadmap like this, or any roadmap, is "how much will it cost?". This is a simple question that does not have simple answers, as the costs depend on many things. While the scope of this report does not include detailed cost analysis, there are some things that need to be kept in mind.

First in line is the question if we indeed aim to stop climate change fast enough to stay under two, or even three degrees C of warming. From an economic point of view, this is a question of internalizing the (current and future) costs of greenhouse gas emissions to the price of burning. We need to have a price on carbon emissions, but depending on the cost-effectiveness of our solutions and the urgency of the situation, that price can vary from relatively low to very high. It is also true that while the price on carbon is ultimately a political decision, the political will to put such a price in place is directly dependent on the abundance and cost of low-carbon energy sources and technologies.

With a higher price of carbon, more and more clean technologies become competitive. In the EU, Emissions Trading System (ETS) prices carbon and the market should take care that most cost-effective solutions are used. As of now, this is not the situation. Politicians are picking the winners through subsidies, feed-in-tariffs, portfolio standards and other mechanisms.

There are too many emission allowances on the market, depressing their price so low that burning cheap coal instead of more expensive natural gas has been economically preferable. While we have paid a lot in tariffs and such in recent years to make renewable energy sources cheaper and more mainstream, there is a lack of effort from society in trying to make nuclear power cheaper as well. Indeed, nuclear is often effectively banned and/or suffers from political risk and heavy and inflexible regulation. From the climate change point of view, this is something that needs to change.

COST ESTIMATES

Estimating future costs of something often comes down to making various assumptions, and justifying those assumptions somehow. The reactors presented in this study have not yet been built and operated for sufficient periods to have hard data.

The cost estimates presented here are either industry estimates or found from the genre literature.

Terrestrial Energy, the developer/vendor of *IMSR*, has estimated the costs of producing energy with their reactor. The rough ballpark is:

- <20 euros per MWh for heat (at 600 °C, steam)
- <50 euros per MWh for electricity

The cost of a single 400 MWth IMSR reactor is estimated at roughly around 800 million euros. This would imply that the total investment cost with ten 400MWth reactors, with CHP and HTSE-capacity added as per the needs in the scenario, would be roughly in the ballpark of 10 billion euros, invested over two decades. What needs to be noted in comparison to traditional nuclear reactors – which cost roughly the same per MWth – is that these reactors offer higher temperatures and are therefore more versatile. They can be sited more flexibly in regard to size and possibility for CHP and district heating. Finally, they are built in series with the first ones bringing revenue long before the total 10 billion is reached (less money is spent on total cost of financing and interest rates).

An interesting quote from Terrestrial Energy is that they estimate hydrogen production with their reactor and High Temperature Steam Electrolysis to be commercially competitive with current methods (methane steam reform) by the time the reactor is ready to enter the market – that is, in the 2020s. Given that the price of natural gas in North America is currently quite low compared to Europe, and given that these methods of hydrogen production have externalized their costs (emissions) quite efficiently, this is very promising news.

The capital cost of the *HTR-PM* is estimated to be slightly larger (5-20%) than a conventional light water reactor of the same size. The price difference in produced electricity is small due to higher efficiencies available with higher temperatures, and there are also other opportunities to use those high temperatures. The construction times are shorter, so the capital cost should be easier to bear. The same ballpark goes for x-energy's Xe-100.

Perhaps the most promising feature of HTR-PM reactor is that *the first commercial scale prototype is practically finished* (fuel loading has started at the time of this writing), and the initial cost estimates have kept quite well. There are plans for serial production for these reactors in China to replace supercritical coal plants, so that the old infrastructure and turbines can be reused. This domestic serial production – if it goes forward – will bring costs down and make the case for exports as well.

The western version of the pebble bed, high temperature reactor, *Xe-100* by X-Energy, has an estimated cost of <80 €/MWh for electricity. This is significantly higher than with most molten salt reactors, but in the same ballpark as the new light water reactors now being built in Europe and the US[23].

As these reactors get licensed and built, we will have more accurate information on costs. Of course, a lot depends on regulation as well. What are the safety mechanisms that are required? The current safety regulation mainly concerns light water reactors, while these new reactor types often operate in a totally different way, resulting in different, often far fewer, needs for additional safety and security measures.

SECURITY OF SUPPLY AND FUEL

Nuclear fuel is very energy-dense and doesn't take much space to store. It is also much cheaper per MWh than are traditional fuels, and there is always at least a year and a half worth of fuel stored near a nuclear power plant, meaning that security of supply is high at all times. There is no need to constant trucking and shipping of biofuels and fossil fuels, nor is there need for huge piles of coal or caverns filled with oil to ensure uninterrupted supply in case of logistical problems, for example.

Nuclear fuel can be acquired from many different places and has international markets. While domestic production is not currently available, it is not an impossibility either. A larger fleet of reactors would certainly make the case for domestic supply chain more feasible economically as well. The fuel costs are also low compared to burning fuels, so even if the initial investment is larger, the fuel costs will be much lower.

Also, the reactors provide a reliable source of power for the grid, with the added benefit of being flexible to load follow if needed. As mentioned earlier, this flexibility comes in several layers. First, the electrolysers can be operated with a varying capacity, either feeding power or heat to them or drawing power from the grid to them and providing the needed heat directly from the reactors. Secondly, CHP capability makes it possible to switch between producing heat and/or power as

23 Price estimates are often hard to compare, as the assumptions such as interest rates, payback time and assumed internal rate of return can vary greatly.

needed. Thirdly, the reactors itself can be operated as load following, as most advanced reactor designs are well-designed for this. Flexible load-following is an increasingly valuable service, especially in the case that the grid has a significant amount if intermittent production from wind and solar PV. But it needs to be noted that unless the market values this service somehow, there is little incentive to provide it.

FINNISH OPPORTUNITIES AND PERSPECTIVES

It is a fact that we will need clean energy sources, including nuclear energy, and lots of it, to clean our global energy mix. Standardized, factory-made and modularized advanced reactors are aimed for markets that neither large traditional reactors nor renewable energy can fulfil. They offer high temperatures and small and medium sized units, both to make investing in them easier and to fit in the thousands of usage locations that need locally produced process heat in the tens and few hundreds of megawatts scale. Some of them are also ideal for producing hydrogen in an efficient and cost-competitive way.

One of the biggest hurdles – in addition to public perception and political risk – for these reactor vendors is to get enough orders for their reactors to justify the large upfront investment on a factory assembly line that manufactures the modules and/or reactors. A country that can offer both a solid demand for these reactors as well as high-quality material and manufacturing capacity as well as high level of know-how, is well positioned to negotiate further cooperative business opportunities as a supplier or raw material and parts, or even a manufacturing facility for reactors and modules or other services.

For example, the IMSR core is designed to be changed every 7 years, after which the used core is cleaned and inspected and possibly reused or recycled. In our scenario, a city of 1.5 million would need around 10 of these reactors for a complete decarbonization. In such a situation, and with a 7-year life per reactor, one reactor would be changed for a new one every 9 months or so, creating a solid demand for services, parts, and new reactor-cores.

Finland has high quality engineering, manufacturing and workshop capacity, steel industry (among the cleanest in the world), shipyards and car-manufacturing (as possible assembly lines for modules or reactor-cores). Finland also has highly trained workforce and one of the cleanest electricity grids in the world. Our radiation and nuclear regulator STUK is respected around the world, as well as in Finland by the general public. Finland is also a small nation that never gave up nuclear the way many of the other western countries did. While Sweden was planning on shutting down its nuclear industry, Finnish nuclear operators were applying for permits to build new reactors. Today, we are one of the few western countries that are building and planning new nuclear, and therefore have much of the knowhow and supply chains needed for further roll-out of advanced nuclear industry.

Finns are also practical people who want to keep what is promised, sometimes at almost any cost, and this applies to emissions reduction promises as well. It is getting clearer every day that nuclear energy needs to play a big part in our decarbonization efforts, given the amount of energy intensive industry and the climate we have, and that new types of reactors are needed to decarbonize beyond our electricity system. The rest of Europe, with a total heat demand of 6,000 TWh each year and electricity grid many times dirtier than the Finnish grid, is slowly awakening to the scale of the problem it faces, and the solutions it will need for deep decarbonization.

Finland, with its 300 smaller and larger district heating networks, would be an ideal location for cleaning some of its heating needs with advanced nuclear, leaving some of our bioenergy resources for more valuable uses.

Yet the larger potential for the knowhow gathered on the domestic market lies outside Finland.

Heat Roadmap Europe aims to increase the share of district heating from 10 percent to 50 percent of households by 2050. This would mean tens of millions of households moving to district heating, consuming perhaps thousands of terawatt hours of heat annually. In addition, process heat will need to move away from burning fossil fuels as well. When combined with the fact that nuclear reactors (and in this context, especially small reactors) are one of the only reliable low-carbon energy sources that can provide heat at this scale and at temperatures needed, the possibilities are staggering. Not only for reactor vendors, but also for those who have the know-how and experience in installing, utilizing and servicing these reactors. Could Finland, by being one of the first movers in this area, be a significant provider of those products and services in the larger EU and global marketplace? There is no reason why not.

Conclusions – What makes sense?

The most sensible solution for most decarbonization schemes is likely to be a mix of various clean energy sources, each according to their strengths and weaknesses. Solar in northern latitudes is unlikely to be able to play a large role in the mix due to seasonal variations that run contrary to seasonal demand variations. Wind is also intermittent, but it is more balanced throughout the year, with more production during the winter. Therefore, it would need less seasonal storage, but a significant amount of intermediate storage (days, perhaps weeks).

One of the big questions we need to answer is how to supply a reliable, low-carbon district heating service without burning much fuels? Here, nuclear reactors can offer a distinct advantage by supplying low-carbon baseload heat at relatively low prices. Heat pumps in their various applications can, and do, produce affordable heat, but they do have some disadvantages compared with nuclear reactors. For example, they can't be used to produce electricity (nor hydrogen), but instead they use electricity, which needs to be supplied reliably by other (clean) means.

Another question is how and at what scale and price do energy storage technologies develop in the coming years? Heat is easier to store in large amounts than electricity, but even heat storages have costs, and it is unlikely they are affordable for seasonal storage. It is likely that affordable baseload capacity will be a good bet in the future as well.

From economic point of view, the question for baseload demand is this: will, and at what share of total energy demand, nuclear be cheaper in providing a reliable 24/7 energy service than variable renewable energy + storage?

At least for the time being, we lack affordable large-scale storage technologies for electricity (save for pumped hydroelectricity which has limited scale). Making hydrogen with electrolysis or high temperature electrolysis could be one such technology. It remains to be seen how various technologies develop, but one thing is quite certain: if affordable and scalable storage technologies become available, any clean energy mix will benefit from them.

The energy market is changing at an uncommonly fast rate. So far, most of this change is due to political ambitions, and less due to economics or physics. Will the policies continue, or will the economies change? This uncertainty makes any long-term planning and investing difficult. Small nuclear reactors hold a distinct advantage in this context compared to mega-projects, as they can be built relatively quickly without the need to lock-in enormous construction projects for decades ahead.

From a feasibility point of view, options that dismiss nuclear as an option require enormous advances in storage technologies to work. Options that include nuclear do benefit from these advances, but can also work reasonably well without. It is easier to meet the demand fluctuations, both daily, weekly and seasonal, if the baseload capacity is provided with energy sources well suited for it.

The reality of climate change and the need to decarbonize our energy at unprecedented speed means we do not get a second chance. From that perspective, ruling out any potential technologies out of hand or on principle is highly irresponsible and goes directly against the precautionary principle. All options should be kept at the table.

Small and/or High temperature advanced reactors offer exciting possibilities for a system-wide decarbonization. For example, the possibility to run High Temperature Steam Electrolysis, HTSE, means that we can simultaneously run a much larger fleet of reactors at full power year around than would be possible when supplying only the baseload demand for heat and power, and provide clean hydrogen for decarbonizing other sectors in the society, such as transportation fuels and fertilizer industry. This can also be done with traditional electrolysers and intermittent production such as wind and solar, but it would likely mean much lower average capacity factors for the electrolysers, and therefore higher costs for the hydrogen, which in turn means slower replacement of fossil fuels.

Questions regarding hydrogen production that still need answers are:

- Will HTSE be able to be scaled up and will its capital costs be low enough to allow ramping production up and down? What about the traditional (PEM and alkaline) electrolysers?
- How well can electrolysers be used for nimble load-following, ramping their production up and down and allowing them to stabilize the electricity grid and heat network?
- How well can we store hydrogen for longer periods of time, like months?

Heat in various forms represents around half of all our final energy use in the EU. Small nuclear reactors are one of the few options we have in supplying reliable low-carbon heat for industrial processes, district heating networks and other uses in a practical manner.

Another key finding is that if nuclear reactors are used for combined heat and power, their overall efficiency and economics can improve enormously compared with producing just electricity (depending of course on the relative market prices for heat and electricity). This would lower the relative costs of our decarbonization efforts.

This report took an extreme position, supplying almost all of the energy needs with advanced nuclear. This was done for two reasons: to keep the analysis simple and to highlight the possibilities nuclear technology offers. The roadmap proceeded from simple heat-only reactors to electricity, CHP and then finally to high temperature electrolysis, inside the span of roughly two decades.

Does this scenario as such make any sense? It is safe to say it is farfetched, and that was precisely the purpose: to provoke a new angle for the decarbonization debate. And even if it is farfetched, it is not any more farfetched than other scenarios that arbitrarily limit the tools and options at our disposal. And it did achieve total decarbonization without making any outlandish claims on how energy technologies or their prices evolve.

In conclusion, it makes sense to explore further these technologies and the possibilities they hold. We need to take nuclear and advanced nuclear seriously. If we do not, we will never find out what they could have offered us, and might suffer a climate catastrophe instead.

Full disclosure and thanks

The author is a freelance writer and energy analyst. The idea to study and write about on how to decarbonize a city the size of Helsinki metropolitan area was the authors, as is the responsibility for any mistakes that might have found their way into this text.

The publishers of this report, offering both logistical support, monetary support and expertise, are Energy for Humanity and the Ecomodernist Society of Finland.

Special thanks to VTT Technical Research Centre of Finland Ltd team Tomi J. Lindroos and Ville Tulkki for their suggestions, comments and feedback. Thanks go also to reactor vendors Terrestrial Energy and X-Energy for their data and feedback. Also, FinNuclear deserves my thanks for sponsoring my writing and research.

Thanks also for all the people who read the early drafts and provided valuable feedback and suggestions.

The energy data and demand profiles used in this study were from publicly available sources such as avoindata.fi -service, Finnish Energy and VTT Technical Research Centre of Finland Ltd.

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RAULI PARTANEN

DECARBONIZING CITIES: HELSINKI METROPOLITAN AREA

This report is one of the first studies to explore how we could use small, advanced nuclear reactors to achieve an almost complete decarbonization of our society.

It explores how we can construct a fleet of nuclear reactors to provide district heating, power and hydrogen in a flexible and cost-effective way. The scope of the study covers the Helsinki Metropolitan area with a projected population of around 1.5 million people by 2050. Using combined heat and power (CHP) and high temperature electrolysis (HTSE), the significant seasonal variations in energy demand can be met while still using the nuclear reactors at high capacity.

We need to proceed on a society-wide deep decarbonization as fast as possible. This study finds that using innovative nuclear reactors as a significant part of the solution will offer huge benefits to achieve decarbonization of electricity, transport and heating.

ISBN 978-952-7139-13-4
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