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Supporters of Nuclear Energy

Newsletter

No 232 March 2018

I can strongly recommend the following well written article about carbon-free energy and its distribution: https://ekomodernismi.files.wordpress.com/2017/09/decarbonizing-cities-with-advanced-nuclear-final.pdf Although written for Helsinki it discusses important general ideas. Some of these are evident in the excerpt below, reproduced with permission.

Wade Allison, Hon. Sec.

Decarbonizing Cities: Helsinki Metropolitan Area

Providing District Heating, Power and Transportation Fuels with Advanced Nuclear Reactors

Rauli Partanen © 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.

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. The Technical Research Centre of Finland’s 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. It is assumed that transportation fuels are used on 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) [Such as IPCC 2014 AR5 WGIII, www.ipcc.ch/report/ar5/wg3]. 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.

[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. [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.]

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 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 fuel-wood, 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.

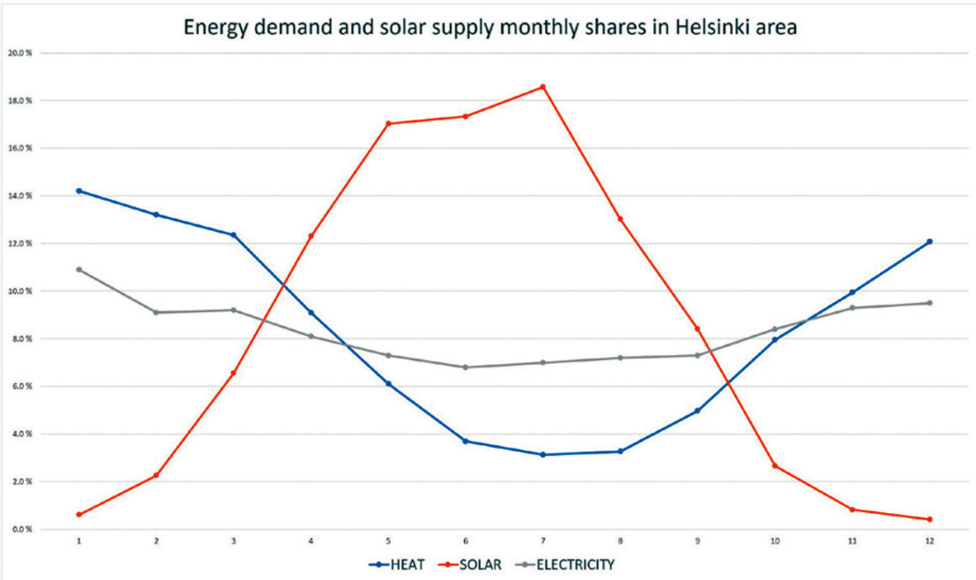
The biggest problem here in the north is that solar has the exact opposite production profile as our annual demand profile.

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.



Solar insolation and demand for heat and electricity have inverse seasonal correlation in northern latitudes [Monthly shares of solar radiation are from Helsinki. Monthly profile of district heating is from Low Carbon 2050 scenario and electricity demand profile is Finnish average from 2015, data from Finnish Energy]. This poses both a storage and a value problem for adding solar production capacity.

Published by: Supporters of Nuclear Energy, c/o Southfields, Ludgershall, Aylesbury, Buckinghamshire HP18 9PB *Tel: 01844 237602*

Web site: www.sone.org.uk E-mail: sec@sone.org.uk