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THE ROLE OF DECENTRALIZED PHOTOVOLTAIC SYSTEMS IN URBAN ENERGY TRANSITION

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The role of decentralized photovoltaic systems in the urban energy transition

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- The city is a system of mind-bending complexity, it needs to be modified to restore equilibrium with an even larger system (the ecosystem of earth), yet any modification should be done maintaining participation of everyone to avoid compromising the equilibrium of the city.
- In developed countries, economic growth and emission growth are de-coupled, on the contrary in developing countries they are correlated. **The overall reduction of emissions worldwide will require a sharp decline of emissions in developed countries and the containment of emissions rise in developing countries.**
- Several technologies exist to produce low carbon electricity, currently there are **two separate paradigms in terms of spatial organization: centralized and decentralized systems**. These two paradigms appear competitive rather than synergic, both need to be explored and developed because it is not wise to go all in on a single technology (see point 1).
- The most promising and versatile technology for decentralized energy system is **urban photovoltaic systems.**
- There is an ample research space around urban photovoltaic systems: from innovative electricity storage technologies, to demand response strategies.

Introduction: The city is large and complex, beyond our grasp, yet we must fix it

A city is a system, it is made by separate parts, their interactions and their workings constitute the working and the layout of the city. A city is a system so large, intricate, and so inexplicably incomprehensible for us, that it would be foolish to try to imagine it. Every day, a city like Helsinki consumes more than 2'500 metric tons of food (roughly the weight of 500 adult African elephant males) and 100'000 cubic meters of drinking water (roughly 40 olympic swimming pools), and it does this while also managing more than 1000 metric tons of waste, and providing thousands of GWh of electric energy in a just-in-time way (which is to say: every minute the amount is different). Nobody, can individually comprehend the workings of a large city, but the large-scale system is able to sustain itself thanks to the dedication and work of its citizens. **Cooperation and specialization are essential and only the cities that can harness the immense power of participation can prosper.**

The modern city is facing the need for a substantial change. The city is out of balance with its environment. But what can the citizens do? How can we modify something so complex that nobody understands? Can we modify the city and keep it running?

Economic growth and growth in greenhouse gas emissions are correlated, but only in developing countries.

All around the world scientists, artisans, engineers, policymakers, and other professionals are working on and around the issue of the so called 'sustainable growth'. The aim of them is to decouple the economic growth from the growth in energy consumption, or at least in greenhouse gas emissions. Evidence brought by De Bruyn et al., shows that in the early stage of development of a country, economic growth and energy consumption are correlated (i.e. if one grow, the other also grow). Conversely, at high levels of development the two become decoupled by the occurrence of changes in production and consumption.

To fuel development energy is needed, but emissions not

Analysing the relationship between energy consumption, economic growth and CO2 emissions in aggregated data from China (the country with the largest steel production in the world), Wang et al. concluded that economic growth stimulates energy demand and vice versa. Furthermore, they observed that energy demand growth encourages CO2 emissions growth. From these premises, it is expected that during the next decade the CO2 emissions will grow in the developing countries, while stable or reducing in China, and reducing in the developed countries. **This suggests that global regions should address the climate change issue in two radically separate ways.**

Developed and developing countries face different challanges, but earth belongs to all

Developing regions are faced with an inevitable increase in energy demand that risk to drive up emissions. Therefore, **they should try to reduce the carbon intensity of their energy production methods**. Mature industrial and post-industrial regions enjoy a decline in the carbon intensity of their economy, they should henceforth develop technologies and financial instruments to sharpen this decline and help developing regions to meet their target. In 1994, describing the picture of the distant earth taken from Voyager 1, Sagan wrote: "Look again at that dot. That's here. That's home. That's us. On it everyone you love, everyone you know, everyone you ever heard of, every human being who ever was, lived out their lives." For the first time in history, we can only succeed if we can work together to a shared goal, regardless of the different economic systems, religion, and levels of development.

Why do we have centralized energy systems for electricity?

Electric generators started to appear at the turn of the 19th century in the UK: in 1878 the first hydroelectric power plant, in 1881 first coal fired power plant. The ability to transform mechanical energy into electricity unlocked the possibility for electricity transmission. This new pattern, which was spearheaded by the illustrious trio of Thomas Edison, Nicola Tesla and George Westinghouse Jr., represented the birth of the traditional centralized energy systems. Prior to that time, the absence of a convenient method to transport energy, meant that energy should have been consumed where it was produced, thus mills and industrial complexes were always provided with their own generator (i.e. wind turbine, water turbine, or thermodynamic heat engine). The electric grid, the improved efficiency of large generators and the ease of predicting aggregated loads (i.e. loads composed of thousands of households or activities) favoured the dominance of the traditional centralized grid. In the centralized grid the energy was unidirectionally delivered from centralized power plants to consumers. The need to meet the demand curve favoured programmable energy sources such as coal, gas, and hydroelectricity.

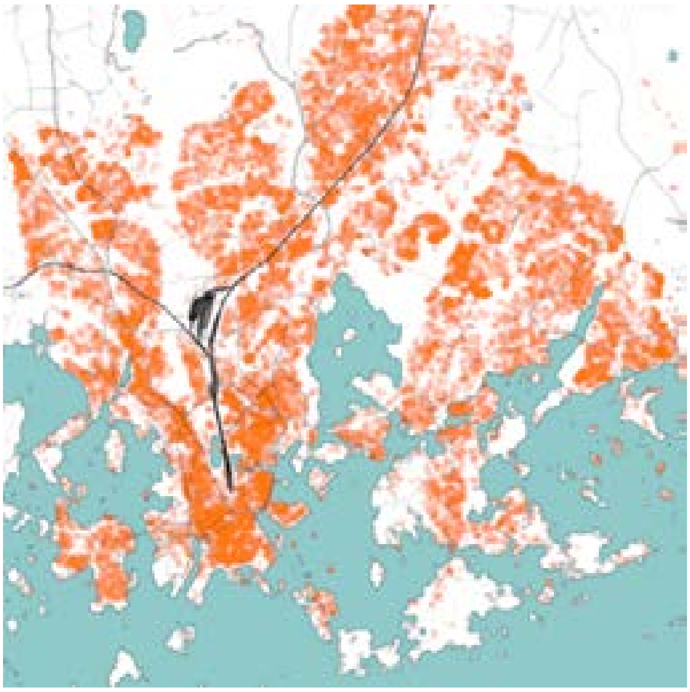
De-centralized heating is having a comeback, but it might be difficult to integrate it with the existing system.

In recent years, de-centralized energy sources have gained momentum both in the public opinion and in the energy mix. This has been due to the falling cost and surging demand for non-programmable renewable energy, and the possibility to increase resilience while reducing transmission costs. Centralized and de-centralized energy systems are different and somewhat mutually exclusive systems, recently several authors such as Liu et al. have tried to optimize the operations of energy systems featuring both centralized and de-centralized sources. Often centralized systems produce huge quantities of heat alongside the electricity. At high latitudes, such as in Helsinki, this has encouraged the development of centralized district heating. Plotting the location of some of the most widespread heating energy source in Helsinki (see Figure 1, Figure 2, and Figure 3), it is visible how the district heating is a little less prominent in areas where de-centralized heating sources are more widespread. This seems to indicate that **centralized and de-centralized heating sources are competitive rather than synergic.**

Different technologies for de-centralized electricity

To increase the adoption of decentralized energy systems, is important to understand which technologies are more promising. Wind electricity is still unlikely to spread as an urban application due to the low efficiency of small scale turbines, the trade-off between efficiency and noise reduction, and the difficulty of modelling specific urban neighbourhoods for wind resistance (Tummala et al.). Urban hydroelectric would mean to recovery residual energy from the treatment and distribution of water. According to McNabola et al. there is significant potential for energy recovery from the water industry. Nevertheless, most previous investigations have not considered key complexities such as variations in flows or turbine efficiency. Similarly, accurate costing and return on investment data are often absent or lacking sensitivity analysis. Nuclear energy and biofuels are better adapted to centralized projects, they are difficult to scale down and spread around. **The only low-carbon technology left for decentralized energy systems is solar energy: how does this perform in Helsinki?**

Figure 1. (right) *Map of geothermal heating systems in Helsinki: it is prominent in the areas of Hakuninmaa, Puistola or Jollas, it is almost completely absent in the city center. Data elaborated from Helsinki Energy and Climate Atlas.*



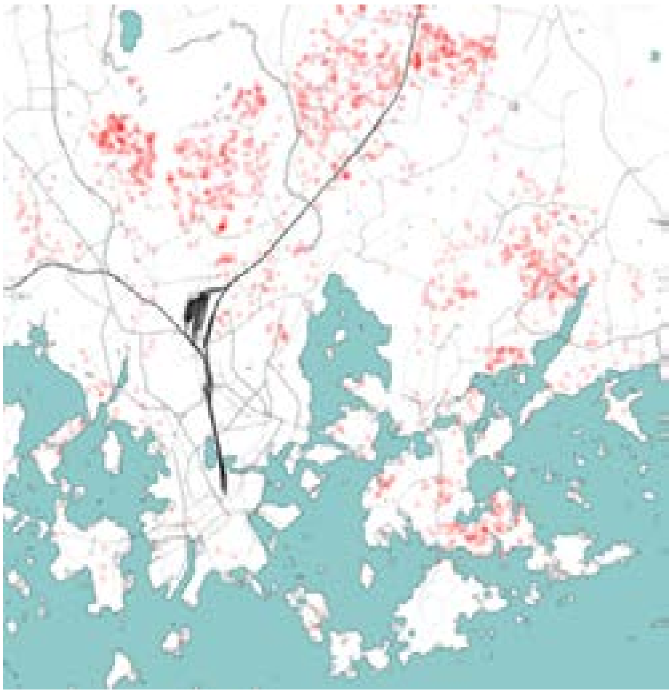


Figure 2. (above) *Map of district heating systems in Helsinki: it is the most widespread heating source, especially in the city centre. It shows visible thinning in places where other sources are more prominent, this indicates that centralized and de-centralized heating system are antagonistic to each other. Data elaborated from Helsinki Energy and Climate Atlas.*

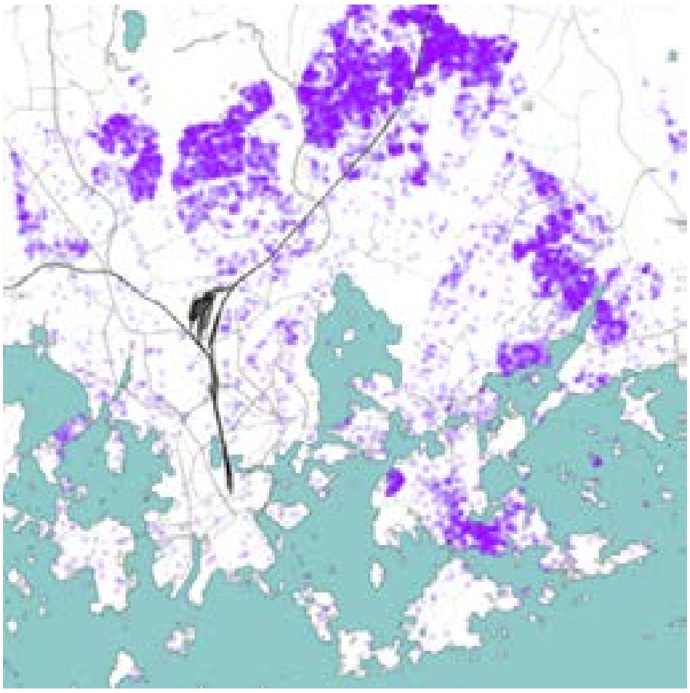


Figure 3. (right) *Map of electric heating systems in Helsinki: like the geothermal heating and other de-centralized heating sources it is almost completely absent from the city centre. Data elaborated from Helsinki Energy and Climate Atlas.*

Solar Energy in Helsinki

Truth be told, “solar energy” is an umbrella term that includes vastly different technologies, these are **solar thermal, solar thermodynamic and solar photovoltaic energy**. Solar thermal is not meant to produce electricity, but simply hot water: it consists in the circulation of water (often mixed with anti-freeze) into pipes that are heated by direct sunlight. This technology is easily de-centralized, to the point that it can also be used for solar hot showers in beaches and camping. Solar thermodynamic systems, on the other end, can produce electricity: they use concentrated sunlight to generate steam, thus spinning a turbine connected to an electric generator.

Solar thermodynamic, due to the large scale of the system and complexity of maintenance, can only be used as a centralized system. To this day there are no instances of solar thermodynamic systems in Finland. These systems are not economically feasible in wet climates as they cannot work using diffuse sunlight. The main application of solar thermal energy related to electric generation in Finland would be the improvement of fuel efficiency of heat production in existing fossil or biomass generators (see Hakkarainen et al.). Last, but not least, comes solar photovoltaic: this technology generates electricity thanks to the photo-electric effect, which is the liberation of electrons by metals when they are exposed to sunlight. **Solar photovoltaic systems have become recognizable as an emblem of decentralized energy systems**, their scalability is simply unparalleled as they range from Gigawatt scale systems to tiny generators for backpacks and even watches and pocket calculators.

Urban photovoltaic systems

Contrary to solar thermodynamic, which can produce day and night due to its high thermal inertia, photovoltaic systems exhibit a production of electricity which is determined almost completely by solar irradiation (there are minor effect due to temperature and solar angle). It is therefore impossible to regulate the power production of a photovoltaic system according to the electricity demand of the surroundings.

One solution is to install electric storage alongside the photovoltaic system: In this way the excess electricity produced at times of low demand can be stored to supply the excess demand at times of low production. Unfortunately, the unitary cost of electric storage is still high enough that even a comparatively tiny storage would increase the cost of the complete system, thus not allowing for a great flexibility. Huang et al. have elaborated upon a method I devised during my Ph.D. thesis (see Lovati et al.) to dimension and position the photovoltaic arrays and the electric storage. The objective of the method is to match, as closely as possible, the demand curve of the underlying building/district while maintaining an acceptable economic performance. The results are encouraging as it is economically feasible to cover over 20% of the annual cumulative electric demand of the district using PV, but there is room for improvement.

Emerging technologies and innovative models in urban photovoltaics

In the paper from Huang et al. it was assumed the presence of electric cars: being a purely residential district, the electric demand for vehicle charging was assumed according to the model proposed by Grahn et al. This assumption might not be advantageous in districts where electric vehicles station (thus recharge) in the central hours of the day. Piter et al. have noticed two distinctive patterns of occupation of the bicycle racks in the city of Helsinki: one exhibits a presence of bicycles during the central hours of the day, the other features occupation during night-time. **It is reasonable to assume that such patterns are shared by motorized vehicles alike, thus the electric consumption of the charging vehicles could create an additional load in hours when the photovoltaic system is producing.** This phenomenon would in turn encourage larger installation. Another interesting application, given the strong seasonal variability of solar irradiation at the latitude of Helsinki, is the use of **geothermal heat storage**. This would allow to dump underground excessive energy in summer in the form of heat, and subsequently use it during winter to warm the evaporator of a ground source heat pump. There is a whole array of new energy storage technologies that will revolutionize the seasonal storage landscape: renewable hydrogen (e.g. Proost et al.), ammonia as a fuel (e.g. Xiao et al.), redox flow batteries (see Parasuraman et al.), gravity based batteries (Moore) and liquid air batteries (e.g. Sciacovelli et al.) to name a few. In this explosion of recent technologies is essential to increase the photovoltaic system generation. The energy system of tomorrow is a whole ecosystem of complementary technologies, and it is essential to remain on the leading edge as much as possible. To be a cost-effective destination of future storage technologies, is essential to have abundant supply of energy that needs to be stored.

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