Lectio Praecursoria

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Honored Custos, honored opponent, ladies and gentlemen.

Energy systems are undergoing a major transition.

That statement may sound abstract, but I hope I can clarify it in this lectio praecursoria.

Let’s take a step back from the big picture and consider this from a more familiar perspective. To set the scene, when I talk about energy, I mostly talk about electricity. But, I will also touch upon district heating. The main focus, however, is on power systems. This refers to electricity generation, transmission, and demand, which comes from industrial and household electricity consumption.

Now, think of yourself as an electricity consumer. You have most likely seen some of the following changes in your options. Perhaps you have a contract, which is 100 % based on hydro, solar, or wind energy. You may have a fixed price - another option to have an hourly varying price. With a fixed price, you are not likely to realize if there are any fluctuations in the power system. When you do, for example, in the case of a black-out, the disturbances are already on a grand scale. However, if you have a market-based varying price, then you are probably interested in following things like: Will it be very cold tomorrow? Is there a risk for high prices? Are some of the power plants in Finland offline? How about our neighbours in Sweden? Do they have full capacity? If yes, are the transmission lines already congested? Finally, you can also follow up your consumption with remotely read electricity meters - and judge tomorrow, how costly is was, for instance, to heat your sauna today.

What I just described to you on a grass roots level and from the consumer’s viewpoint are some of the biggest trends, which affect how our life and society are powered - Now and in the future. These are: 1. moving towards sustainable yet variable renewable energy, such as wind and solar power, 2. market integration, such as EU-level energy policies and increasing importance of cross-border transmission, and 3. technological advancements, like digitalization, or flexibility in demand and supply.

Perhaps the biggest one of these trends, however, is the goal toward sustainability. It is, of course, tied to the awareness and urgency that we need to tackle climate change. Going back into the bigger picture, climate change and sustainability have been the focus points for many EU policies in recent years. The same applies to the Paris Agreement a few years ago. These policies aim at increasing renewable energy, energy efficiency, and market integration, as well as to decrease greenhouse gas emissions, like carbon dioxide emissions, which occur when fossil fuels are burned.

When we talk about sustainable electricity generation, two technologies stand out, if we look at the installment rates from recent years. These are wind and solar power. These two, however, are changing power system operations quite fundamentally. Namely, wind and solar generation depend on the prevailing weather conditions. To put it simply, seasons and weather determine how much power we have available. If the wind does not blow or the sun does not shine, there is no power to be generated. This is why they are often called intermittent or variable renewable energy.

This is completely different from a conventional power system, which is mostly based on fossil fuel generation. For example, think about a traditional power plant, which runs with coal or gas. The owner of that plant is able to assess the profitability for running it for a certain time, for a certain cost, with a relatively high certainty. Thus, the generation of a conventional plant is based on operational decisions. With more variable renewable energy in the system, there is more uncertainty about how much power can be generated - And, as a result, more uncertainty on market prices.

What’s more: electricity does not work like concrete physical commodities, such as water or gas. I’m not going into too much detail, but the electricity that we are able to access through the sockets in the walls of our homes, is not randomly sent from A to B - And it does not work like a vending machine. Instead, the power grid needs to have a specific voltage and frequency, which depend on the balance between input and output. In other words, whatever is consumed needs to be generated at the same time somewhere else. You can think of it as a scale between generation and load. If we switch on our lights at home, a minimal change can be observed in the load for the whole system. However, if a massive wind power park suddenly drops in production and demand stays the same, the scale would tip and some balancing power is needed.

This has led to new practical challenges ahead. Variable renewable energy and a system which needs to be in balance all the time, are not exactly a match made in heaven. So, how do we make sure we have enough electricity, when an increasing share of it is variable? How can we ensure that the change happens cost-effectively, and that the effects for different stakeholders, and especially for society at large, are positive?

Phenomena like these are very important to understand and assess – preferably while the change is still ongoing and it is easier to affect how it turns out. However, that is a pretty complex task to do.

First, none of these changes happen in isolation. Rather, they occur in a power system, in which there are interactions between other ongoing issues. They also involve many countries and stakeholders, which have different and typically also conflicting objectives. From the technical and operational perspective, this means accounting for the flexibility of the whole system. On another level, this means that we should not consider power systems alone but the bigger picture that they create, for example, in combination with energy efficient combined heat and power production. Flexibility is not just balancing supply or demand response - it can also be achieved by market integration, if it increases the efficient use of resources.

Storage is often discussed as a key solution to support variable renewable energy. Although electricity cannot be stored directly as electricity, it can be converted into other forms of energy. These include storage solutions like pumped hydro storage, or newer technologies such as large-scale battery storage. What this means in practise is that one can use currently available electricity, for example, to pump water to a higher altitude or to charge a battery. When that energy is needed later on, it can be discharged - with a technology specific efficiency loss, of course. In large quantities, storage can change the dynamics of power markets quite drastically because it is able to shift electricity from excess to scarcity. It breaks the need to generate everything exactly at the time of consumption. This means that in large quantities, storage will affect electricity prices as well. And, the way storage is used, also depends on who owns it, which makes it even more interesting and challenging to assess.

Like we already discussed, there is a tradeoff between sustainable variable energy and security of supply. Mitigating this tradeoff incurs costs, for example through storage or balancing power. The electricity markets in many European countries, and elsewhere in the world such as parts of the US, have been restructured and liberalized a couple of decades ago. The aim was to increase economic efficiency and competition. Therefore, at present, no single entity has full control over the ongoing transition but it can be directed through policies and regulations. These include taxation, subsidies or mechanisms like EU’s emissions trading system.

This also means that power generation decisions are not centralized to one company or state. Rather, they are settled on wholesale markets, in which supply and demand are matched. Therefore, how much power is sold and generated and what the prices will be is a consequence of multiple stakeholders’ decisions on what they want to produce or buy and at which cost. As a result, electricity price will reflect the marginal cost of the most expensive technology that is used. Economically, this means that the markets are functioning effectively and welfare for the whole system is maximized. In reality, many power systems like the Nordic one comprise price areas or countries, which will add some complexity to the setting. To put it simply, if transmission capacity is sufficient, all areas from the same system have the same price - if not, the regional prices diverge.

However, it is worth considering whether the assumption of perfect competition is always valid. Is it possible that some power producers are big or powerful enough to affect markets? This is called imperfect competition. In effect, some or many producers would have the ability to affect markets so that the price is above marginal costs. This is called market power and it could mean that producers are strategically withholding capacity to increase prices in their favor. Legislation prohibits the use of dominant market position. Still, power markets are based on large conventional companies which may have significant market shares. For example, the largest power producer in France has a market share of over 80%. Besides, electricity demand is rather inelastic, meaning that many consumers need a certain supply of electricity. Also, transmission constraints may restrict access for further competition. Market power could be hard to observe. Therefore, it is worthwhile to consider, on which assumptions companies base their production decisions.

What makes this speculation interesting is not only whether this happens in reality or not. For one, there is some evidence of it from various countries. Nevertheless, from a policy perspective, there is a more striking insight. Namely, if some or all companies are able to exert market power, then the outcomes may be completely different from what is expected based on standard approaches such as the assumption of perfectly competitive markets. What this means in practise is, for example, when and how much energy storage is used, where investments are made and how large they are. Eventually, the decisions of companies and other market participants affect whether implemented policies or regulations are successful - Or not.

In order to account for these complex systemic changes, mathematical models offer us valuable decision support. In particular, electricity market structures can be represented by combining concepts from microeconomics with tools of operations research. In this thesis, we have used optimization, complementarity modeling, and simulation, among other methods, to assess the ongoing energy system transition. This thesis aims to shed light on the economic, technical and environmental effects that things like energy storage and combined heat and power have on the rest of the energy system. The goal is to understand how flexibility and economic efficiency can be maintained in a system with more variable renewable energy and more market integration. The results highlight how important it is to consider energy system as a whole, and the different objectives of all stakeholders, when thinking about new regulations or investments. Failing to account, for example, for market power, interactions between electricity and district heating, or interconnections between neighbouring countries, could lead to a completely different outcome than expected. For example, unintended consequences on CO2 emissions or an increase in market power. This means, that to understand the energy system transition and to sustain a fair and efficient market environment, we need to take a systemic viewpoint. Therefore, we must base decisions and policies on a thorough analysis on different stakeholders' objectives and how they relate to different market structures.

I ask you professor Steven Gabriel, as the opponent appointed by Aalto University School of Science to make any observations on the thesis which you consider appropriate.