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ENGINEERING MARKETS FOR CONTROL: INTEGRATING WIND POWER INTO THE DANISH ELECTRICITY SYSTEM

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Rasmus Ploug Jenle

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PhD School in Organisation and Management Studies

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CBS COPENHAGEN BUSINESS SCHOOL
HANDELSHØJSKOLEN

Engineering Markets for Control

Integrating Wind Power into the Danish Electricity System

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Abstract

The present study involves an inquiry into the making of a Danish energy system based on renewable energy sources. Focusing specifically on one of the major barriers to the introduction of renewable energy sources known as the intermittency problem, emphasis is put on how fluctuating electricity generation from wind turbines has been integrated into the Danish electricity system. The study focuses on the ways in which the integration of wind power in Denmark has involved the introduction and reconfiguration of a series electricity markets known as Nord Pool. Significantly, these electricity markets are engineered as control arrangements for electricity system equilibrium maintenance. When attempting to integrate wind power into the Danish electricity system by introducing or reconfiguring these control system market arrangements, metrics from economics are used to describe the ideal outcome or objective to be attained through market construction. Coupling these empirical observations with a line of inquiry concentrating on the use of knowledge, skills, and know-how in market design and management associated with the 'performativity programme' in the social and human sciences and especially economic sociology the thesis is framed by the following research question: *How have control systems engineering and economics been mobilized in the endeavor to integrate wind power into the Danish electricity system through electricity market design and management?* Answering this research question involves an analysis of three different instances of electricity market construction. All three cases demonstrate how integrating wind power into the Danish electricity system has been approached as a matter of electricity market construction increasing the capacity of Nord Pool to exert control and maintain equilibrium in the electricity system. In addition to producing insights into how the intermittency problem is being handled in Denmark, the present study seeks to augment the performativity programme in two ways. One way is to show how control systems engineering, being an understudied form of expertise within the performativity programme, has played a crucial role in the design and management of a series of markets. The other is to show how economics, being a form of expertise studied extensively by the members of the performativity programme in other empirical settings, has had heretofore undescribed functions in market design and management.

Abstract (Danish)

Denne afhandling beskriver en undersøgelse af indsatsen for at skabe et dansk energisystem baseret på vedvarende energikilder. Der fokuseres på en væsentlig barriere i forbindelse med introduktionen af vedvarende energikilder, idet der spørges ind til, hvordan vindmøllers fluktuerende elproduktion er blevet integreret i det danske elsystem. Undersøgelsens omdrejningspunkt er det faktum at vindkraftintegration i en dansk sammenhæng er blevet tilgået ved at introducere og ombygge en række elmarkeder, der samlet går under navnet Nord Pool. To væsentlige aspekter af denne proces udforskes. For det første vises det, at disse markeder er blevet opstillet som ingeniørfaglige kontrolsystemer med henblik på at opretholde ligevægt mellem produktion og forbrug i elsystemet for på den måde at sikre stabil systemdrift. For det andet bliver det understreget, at økonomiske metrikker anvendes til at skabe mål for vindkraftintegration ved hjælp af markedskonstruktion, der i sidste ende skal sikre opretholdelsen af ligevægt i elsystemet. Ved at sammenholde disse observationer med en nysgerrighed omkring brugen af viden og ekspertise i forbindelse med markedsdesign og markedsskabelse - som undersøgt inden for bestemte dele af økonomisk sociologi - er det følgende forskningsspørgsmål blevet stillet: *Hvordan er økonomiske metrikker og ingeniørfaglige begreber vedrørende kontrolsystemer blevet mobiliseret i forbindelse med vindkraftintegration gennem elmarkedskonstruktion?* Besvarelsen af dette forskningsspørgsmål indebærer en analyse, hvori der inddrages tre forskellige cases, der hver især følger vindkraftintegration gennem elmarkedskonstruktion. I alle tre tilfælde vises det, hvordan vindkraftintegration er blevet tilgået gennem elmarkedskonstruktion med det formål at styrke Nord Pools evne til at udøve kontrol og opretholde ligevægt i elsystemet. Udover at skabe indblik i måden hvorpå vindkraft bliver integreret i danske elsystem, er denne afhandling kendetegnet ved en ambition om på to måder at bidrage til udviklingen af nyere dele af økonomisk sociologi. På den ene side gøres der opmærksom på vigtigheden af ingeniørfaglige begreber vedrørende ligevægt og kontrolsystemer i forbindelse med markedsdesign og markedsudvikling i specifikke situationer. På den anden side vises det, hvordan økonomiske begreber i form af metrikker får tilskrevet en ny og af økonomisk sociologi endnu ubeskrevet rolle i forbindelse med markedsdesign og markedsudvikling.

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Introduction

The research described in the following has been part of an effort to take a closer look at attempts to integrate renewable energy sources into the Danish energy system. The study has been motivated by the societal problems associated with emissions from the burning of fossil fuels, which have also helped spark the introduction of renewable energy sources in Denmark and many other countries. These problems include smog and its effects on human health (Sim & Pattle, 1957), which is relatively local in character (Haagen-Smit, 1952), as well as acid rain, which is less so (Likens, Wright, Galloway, & Butler, 1979). The most extreme example of a borderless cause of concern triggered by man-made carbon-based energy systems is found in the way emissions from the burning of fossil fuels influence the greenhouse effect. Gasses such as CO_2 help trap radiation from the sun within the earth's atmosphere, advancing global warming (Bowman, 1990; Rohde et al., 2012). But even though the health of various life forms is a large part of what has motivated countries such as Denmark to opt for an increase in the amount of energy delivered from emission-free sources (The Danish Government, 2011a), other factors have also been significant. And to appreciate how renewable energy integration has become a significant issue, it is worth briefly considering key historical aspects of Danish energy system development which have led to a growing proportion of the energy supply coming from renewable energy sources.

In Denmark, wind power has long been the most widespread renewable energy source (Danish Energy Agency, 2012a). The history of wind power in Denmark is said to have started around the time when oil became a strategic element in conflicts in the Middle East (e.g. Mitchell, 2011). The Danish energy supply had already been affected, for example, by the Six-Day War of 1967. But the really significant impact of oil's role in international conflicts came about in 1973, when the Arab members of the Organization of Petroleum Exporting Countries (OPEC) began to base promises of future oil delivery on the stance taken by their buyers regarding the Yom Kippur War. Oil deliveries would be adjusted in accordance with each country's attitude towards the conflict. When the Danish Social Democratic Prime Minister Anker Jørgensen expressed unconditional support for Israel at a private meeting in Middelfart, Denmark was categorized as a country eligible for boycott in a manner similar to the USA and the Netherlands (Rüdiger, 2007). Even though a total boycott was avoided, the increase in oil prices resulting from a general 25 percent reduction in supply from the OPEC countries thoroughly impacted the everyday lives of the Danish population. As 95 percent of all energy consumption at the time was based on imported oil (The Danish Government, 2011b), the prices of necessities like gasoline and heating increased drastically. Legislative measures made to cope with the issues included a national ban on lighting in stores during nighttime, and by November 10, 1973, speed limits were established on the roads of Denmark. On November 25, 1973, the ban on driving known as ‘car free Sunday’ was imposed (Danish State Archives, 2014).

One outcome of this situation was that Danish energy system development in the late 1970s came to be characterized by an emphasis on the security of the supply, by means of a new energy supply portfolio. The first official Danish energy plan of 1976 accompanying the Danish Law on Energy Policy Measures of 1976 (Danish Ministry of Commerce, 1976a) emphasized a transition from oil to coal, nuclear power, and domestic energy resources (Danish Ministry of Commerce, 1976b). Emphasizing domestic energy sources effectively implied using natural gas extracted from the North Sea, and renewable energy sources were given a small role in the overall plan. However, the emphasis on nuclear power on behalf of Danish officials such as politicians and the Electric Utility Association was met with a strong popular countermovement, which came to play a central role in the disappearance of nuclear energy from Danish energy planning and policy. Part of the success of the Danish anti-nuclear movement has been attributed to its involvement in the promotion of alternative energy sources through collaboration with interest groups associated with wind power. The constellation of various social movements, with differing goals but overlapping interests, turned out to be effective in creating and mobilizing pro-wind power stakeholders (Karnøe, 2012). And it was within this setting that the first Danish wind turbine was connected to the grid in 1975 (Pallesen, 2013).

The percentage of electricity delivered by wind power in the Danish electricity system has increased with varying momentum, and reached 39 percent of national electricity production in 2014 (Bredsdorff, 2015). The 1990s saw an exponential growth in wind power production, which to a large extent was a result of a series of policy initiatives in favor of putting up wind turbines. Feed-in tariffs and the remuneration of plant construction costs were of major importance (Danish Energy Agency, 2009). With the election of a new liberal-conservative government, wind power expansion came to a drastic halt in the 2000s (e.g. Karnøe, 2012). The percentage of wind power in the Danish electricity system later began to rise once again, and the current plan is to have wind power cover 50 percent of the total Danish electricity demand by 2020 (The Danish Government, 2011a). While grid integration of wind power was not so much a technical problem when wind turbines were a small and marginalized power source, the large proportion of electricity produced by wind turbines now poses an operational challenge to the Danish electricity system. And to see how wind power integration has become a significant infrastructural challenge in Denmark, it is worth briefly considering some key characteristics of electricity and electricity systems.

Equilibrium required

In the context of wind power integration, an important property of electricity is that it cannot be stored. Energy from electricity can be stored after conversion, but not without significant losses (e.g. Wittrup, 2013). Then there is the systemic requirement for equilibrium between generation and consumption. The task of achieving this equilibrium in an electricity system is basically the task of making sure that input equals output at all times. If input and output in an electricity system are not equated, stationary frequency deviations will occur. If the problem isn't solved, worst-case problems such as brown-outs and black-outs will occur (e.g. Hoogwijk, van Vuuren, de Vries, & Turkenburg, 2007). The issue can be approached by considering the fact that electrical equipment of all varieties requires a specific amount of electricity in a specific format to work. And since there is no storage capacity in the wires of the electricity grid, generation and consumption have to be equated at all times. If we momentarily disregard other features of electricity systems such as the fact that transportation is associated with a loss, the need for constant equilibrium maintenance becomes clear in noting how the connection between consumers and suppliers is immediate in this context. As the wires transporting electricity from A to B have no capacity to help ensure that generation corresponds to consumption, the necessary changes made to maintain equilibrium have to apply to a form of generation or consumption activity. The established approach to equilibrium maintenance in electricity systems has traditionally involved having supply follow demand (e.g. Karnøe, 2013). As consumption changes, generation from thermal power plants is adjusted accordingly. But as a growing proportion of electricity is supplied by wind turbines, equilibrium maintenance by means of the supply-follows-demand approach becomes increasingly difficult.

The challenge is apparent when considering the characteristics of electricity production by means of wind turbines (e.g. Danish Energy Agency & Danish Ministry of Taxation, 2009a; 2009b). One significant feature of electricity generation by means of wind turbines is that production cannot be increased at will by the plant operator. Production from modern wind turbines can, however, be decreased if need be. Another important feature is that output is exponentially related to input in most of the wind speed spectrum. Except within the highest and lowest ranges, a variation in wind speed will lead to an exponential variation in electricity output from a wind turbine. In other words, the difference between variations in wind speed and electricity output are greatest when a wind turbine works in the middle range of its production capacity under middle wind speeds. Also of significance are the facts that middle wind speeds are by far the most common condition, and that variations in the middle of the wind speed spectrum are the most difficult for meteorologists to model precisely. The task which needs to be completed in order to ensure the functioning of the electricity system in this context is thus a matter of balancing supply and demand when electricity production becomes increasingly uncontrollable. This basic challenge of systemic renewable energy integration is popularly referred to as the ‘intermittency problem’ (e.g. Massey, 2012) and variously applies to all electricity systems which include weather-bound generation technologies such as wind turbines and photovoltaic panels. In a general sense, fluctuating electricity generation is not well suited for a system which bases equilibrium maintenance on responsive electricity production.

The problem of intermittency in electricity production, or the electricity system’s incapacity for handling volatile electricity production, surfaced in Denmark through discussions of ‘critical excess electricity’ (Danish Energy Agency, 2001). This debate centered on the risk of having more electricity than could be consumed and exported, thus requiring significant down-regulation of the system. It also came to revolve around the increased potential for power shortages (Elkraft

System & Eltra, 2001). Here the problem was basically conceived of in terms of what to do when the wind is sparse. Despite the fact that many central actors over the years have been skeptical about the electricity system's potential for integrating fluctuating energy sources (Karnøe, 2010), the percentage of wind power in the Danish system roughly grew from 0 in 1980; to 6 in 1990; to 10 in 2000; to 20 in 2010; and is still rising (Danish Energy Agency, 2012a). Following the conceptualization of the problematic effects associated with wind power, a conceptual solution was made. The solution has been given a number of names such as "smartness" (Smart Grid Research Network, 2013), "intelligence" (The Danish Government, 2011b), and "flexibility" (The Danish Government, 2011a). It is the work that goes into the making of flexibility which is of interest here. In other words, the present study has looked into the efforts to construct an electricity system which is able to meet demand using fluctuating input.

Cued by these facts, the wider area of inquiry begins to materialize. More specifically, that area is the organization of the electricity system for the achievement and maintenance of equilibrium in reaction to the increasing proportion of electricity produced by means of wind power. The thesis is in this way centered on the intermittency problem, and involves a description of the work that has gone into building the capacity for maintaining equilibrium in the Danish electricity system. It documents an inquiry into how the Danish electricity system is made to maintain equilibrium with an increasing proportion of fluctuating electricity production.

Much of the work on the intermittency problem looks at the potential future of the Danish electricity system, and addresses what can and should be done (e.g. CEESA, 2011). Here the idea is to take a step back and document some of the concrete work done to mitigate CO_2 emissions by following one of the biggest infrastructural projects in Danish history, a project which implies changing more or less the entire Danish electricity system within the next 40 years (The Danish Government, 2011a). The country has the world's highest proportion of electricity generation from wind turbines relative to total electricity consumption (Energinet.dk, 2014a). Denmark also has the notable ambition of having an energy system based on 100 percent renewable energy sources by 2050, and wind power is central to the achievement of this goal (The Danish Government, 2011b). When it comes to fluctuating electricity production from renewable energy sources, Denmark constitutes an “extreme case” (Flyvbjerg, 2006). Here the need for measures to integrate volatile electricity production on a national scale is at its strongest. These circumstances imply that efforts towards wind power integration are relatively extensive and well explicated. And while the issue of wind power integration in energy system development is debated internationally, (e.g. Sinden, 2007), the matter has been dealt with on a particularly large scale in Denmark.

Electricity markets

As is apparent at this point, investigating renewable energy integration in Denmark as a problem of balancing input and output has to involve a focus on the arrangements for equilibrium maintenance. But while there are many arrangements which are relevant to equilibrium maintenance in the Danish electricity system, the electricity market is central when considering the intermittency problem at a systemic level. As stated by the former Deputy Director of Planning from the then- transmission system operator (TSO) of eastern Denmark (the TSO has the responsibility for making sure that the transmission system functions as planned, which includes ongoing equilibrium maintenance):

> …the most important solution is actually the framework. It is not – technology is very very important, but the framework, how you regulate this, is actually even more important than the technology. And the way we choose to do that from 2000 and on, is via the international electricity market

(Lindboe, 2013, 0:22:40-0:22:52)

The fact that markets proliferate in the context of Danish electricity system development is apparent from many of the documents produced by and for national authorities in relation to energy planning and policy (e.g. H. K. Jacobsen et al., 2010). This widespread embrace of markets has also led to the notion of the “market based energy system” (Energinet.dk, 2013a, p. 5), created by the Danish TSO.

It is here worth noting that references to a single Danish electricity market can be misleading. The Danish electricity market is part of a common Nordic wholesale electricity market named Nord Pool, and has several types of constituent markets.

The electricity market arrangement of relevance to wind power integration in the Danish electricity system is constituted by Nord Pool exclusively. Nord Pool is central due to how the liberalization of electricity in Denmark established that particular market arrangement as the means to maintain the crucial equilibrium of the electricity system. As will be described in detail later, the equilibrium of the electricity system was equated with the equilibrium of the electricity market. In other words, having a well-functioning electricity system became an issue of establishing a well-functioning market. In effect, making a systemic change for increasing the capacity to maintain equilibrium with an increasing proportion of fluctuating electricity supply became a matter of market construction. The present inquiry has thus followed the work that has gone into endowing Nord Pool with the ability to deal with the intermittency problem.

As will also be made clear when describing the liberalization of electricity, Nord Pool was not introduced for the purpose of solving the intermittency problem. Having Denmark enter the Nordic wholesale electricity market was but one initiative in a large wave of liberalization in Europe. But the transition from central planning to market-based coordination did however coincide with the escalation of concerns associated with increasing the proportion of electricity produced by wind turbines (e.g. Danish Energy Agency, 2001; Hvelplund & Meyer, 2007). When it became a priority to begin adding resources for maintaining equilibrium in the Danish electricity system, the electricity market constituted the framework within which these new means were added. Hence, the efforts of wind power integration described here are accounts of electricity market development.

Research question

In documenting the work that has gone into solving the intermittency problem in a Danish context, the present thesis follows three instances of wind power integration through market construction. First, it shows how Nord Pool replaced central planning as the means to maintain balance between input and output in the electricity system. The equilibrium of the electricity market came to represent the equilibrium of the electricity system. In this case it is also made apparent how the ability of Nord Pool to maintain equilibrium with an increasing amount of fluctuating electricity generation has been expanded by building electricity market infrastructure in the form of wires or transmission system interconnectors (TSIs). Specifically, the making of an electrical connection between eastern and western Denmark is analyzed. The approach is epitomized in what is known as the “export strategy” (H. Lund & Clark, 2002), and involves moving electricity over greater distances in order to be able to connect wind power producers with more supply and demand side resources for equilibrium maintenance. Second, an experimental market arrangement named EcoGrid on the Danish island of Bornholm is followed. Here, the traditional supply-follows-demand approach to ensuring equilibrium in the electricity system is reversed. The approach involves a push towards having consumption follow production, by training and equipping electricity consumers to react to prices reflecting the requirements of the electricity system. Third, the approach to calculating the most efficient ways to solve the intermittency problem through Nord Pool in the context of Danish energy planning is explored. Doing so involves following the making of a widely used piece of software for electricity market simulation, along with a central source of technical data on energy system components to be used with the model in a Danish context. By considering these three illustrative examples of the work involved in integrating renewable energy sources into the Danish energy system, an overarching research question can be stated. It embodies a focus on the way the capacity to maintain equilibrium in the electricity system by means of the electricity market was established and augmented.

Research question 1: *How has the introduction and reconfiguration of the Nordic electricity market characterized the endeavor to integrate fluctuating electricity supply into the Danish electricity system?*

Having presented an overall research question, an issue here becomes one of specifying how it was made and how it has been approached. Making the methodological position explicit should facilitate an understanding of the research question and the inquiry as a whole. But it will also enable the introduction of a more specific research question explicitly informed by the conceptual resources supporting the present inquiry. The following section thus initially elaborates on the commitments, beliefs, and attitudes forming a basis for the inquiry. It then goes on to show how adherence to these ideas has led to the application of a number of principles, concepts, and techniques, which are then introduced individually. Doing so implies shifting emphasis from the maxim of pragmaticism and the doctrine of realism to the practical approaches and ideas applied in the effort to stick to them. Before moving on to an outline of the analysis, a body of concepts from recent developments in economic sociology is then suggested as a relevant supplement to the orientation of the inquiry in understanding wind power integration as approached through Nord Pool.

Approaching Nord Pool

Elaborating on the methodological approach here starts by touching upon the position from which the inquiry has engaged with wind power integration through Nord Pool. That position is a version of what van Fraassen (2002) called "the empirical stance". The notion of the empirical stance was suggested by van Fraassen as part of his description of what empiricism has been and could be. This implies, notably, the ability to specify what it can mean to be an empiricist. An important point here is that the empiricist movement has historically tended to run into logical problems when treating specific beliefs about the world as definitive for the philosophical position of empiricism. Being consistently characterized by a critique of the idea of metaphysics along with an admiration for the empirical or positive sciences, empiricism begins to run into trouble when adopting the 'Principle Zero' entailed in so many other positions and the debates among them. Principle Zero is the idea that: "For each philosophical position X there exists a statement X+ such that to have (or take) position X is to believe (or decide to believe) that X+" (van Fraassen, 2002, p. 41). Adopting a factual thesis about the world such as, for example 'empirical experience is the one and only source of information', places empiricism in a bind. By being based on a belief or factual thesis of what the world is like or what there is, naïve empiricism becomes no different from the metaphysical statements it sets out to critique. The notion of something being metaphysical is here not taken to signify anything more elaborate than the quality of being *a priori* or out of reach of empirical experience (e.g. Fuglsang & Olsen, 2004). And in this case, X+ simply becomes the *a priori*. To van Fraassen, taking a viable empiricist position preserving the rejection of metaphysics and the insistence on the empirical grounding of inquiry necessarily involves violating Principle Zero by identifying and occupying a position which consists of more than beliefs about the world. The empiricist orientation or position here consists of a "…stance (attitude, commitment, approach, a cluster of such – possibly including propositional attitudes such as beliefs as well). Such a stance can of course be expressed, and may involve some beliefs as well, but cannot be simply equated with having beliefs or making assertions of what there is" (van Fraassen, 2002, p. 47).

The idea of the stance enables a discussion of many of the aspects of inquiry which are left out when focus is limited to the discussion of beliefs. It is a way of stressing what the inquirer is doing when conducting and reporting on a study. Moreover, taking an empirical stance implies becoming a specific kind of researcher. But giving consideration to the idea of the stance not only allows for the specification of the empirical stance taken as part of the present inquiry, it also makes a type of critique not referring exclusively to beliefs possible. It is here worth noting that this is not a way of making all debates and positions ultimately subjective. Rather, it can be a way to address crucial facets of inquiry such as "A disregard for evidence, a refusal to submit one's ideas to natural selection by relevant experiment or to engage in vigorous testing when nature does not put them to the test (these are some examples, none of them factual beliefs!)…" (van Fraassen, 2002, p. 48). Importantly, a stance is inconceivable in the total absence of beliefs. Taking an empirical stance does thus not imply a new empiricism freed from the problems of requiring beliefs. It involves preserving aspects of empiricism by relating them to ideas about the world, but without having them spring from these beliefs: "The important point is simply that a stance will involve a good deal more, will not be identifiable through the beliefs involved, and can persist through changes of belief" (van Fraassen, 2002, p. 62).

What follows in this section is an elaboration of a version of the empirical stance involved in the present inquiry. In an overall sense, this implies a commitment to the realm of empirics as the reference for inquiry and forming of beliefs. This is not least so with respect to the products of inquiry itself: "For the empiricist, science is…what teaches us to give up our beliefs. All factual beliefs are to be given over as hostages to fortune, to the fortunes of future empirical evidence, and given up when they fail, without succumbing to despair, cynicism, or debilitating relativism" (van Fraassen, 2002, p. 63). And as the maxim of pragmaticism (e.g. Peirce, 1905a) has been central to conducting the study while taking an empirical stance, we will here turn our attention in its direction.

Pragmaticism

Adhering to the maxim of pragmaticism and believing it to be true is here discussed as connecting with the doctrine of "scholastic realism" (e.g. Peirce, 1905b). The way the pragmaticist maxim hinges on the doctrine of realism is referred to as pragmaticism throughout.[1] To make the different points clear and illustrate their practical implications for this thesis, selected parts of the material will be discussed with reference to more contemporary work when relevant.

The pragmaticist maxim has been given various forms in the work of Peirce, and by comparing two of these expressions of pragmaticism, some of its main aspects can be highlighted. The original formulation was introduced in the now-classic article with the telling title *How to Make Our Ideas Clear*. It states: "Consider what effects, that might conceivably have practical bearings, we conceive the object of our conception to have. Then, our conception of these effects is the whole of our conception of the object" (Peirce, 1878a, p. 293). What pragmaticism does is to attribute absolute centrality to empirical experience in the process of inquiry. It does so by insisting on the exclusion of all other inputs for conception on the basis of the fact that knowledge about them is unattainable. In this way, pragmaticism was a reaction to the idea of metaphysics. Making our ideas clear thus implies an effort to dismiss what Peirce also called make-believe: "You only puzzle yourself by talking of this meta-physical 'truth' and metaphysical 'falsity,' that you know nothing about. All you have any dealings with are your doubts and beliefs, with the course of life that forces new beliefs upon you and gives you power to doubt old beliefs" (Peirce, 1905a, p. 168). As it is a logical implication of the general idea of metaphysics to be unassailable by human reasoning, the idea is here not to try to counter the possibility of the existence of this quality. Rather, pragmaticism suggests that the idea of metaphysics is uninteresting and its further discussion irrelevant.

[1] Using the term pragmaticism rather than pragmatism has the advantage of specifying what pragmatism is here understood to be. Witnessing early on the abuse of his original term pragmatism, Peirce introduced the word pragmaticism to signify the original concept using an expression "…ugly enough to be safe from kidnappers" (Peirce, 1905a, p. 166).

An example can be provided by applying the maxim to itself. Doing so is basically a matter of comparing the different specifications of pragmaticism. First, recall the original definition of pragmaticism provided above. This has to be used to approach the definitions of pragmaticism. Second, consider the later definition of pragmaticism provided by Peirce:

> …a *conception*, that is, the rational purport of a word or other expression, lies exclusively in its conceivable bearing upon the conduct of life; so that, since obviously nothing that might not result from experiment can have any direct bearing upon conduct, if one can define accurately all the conceivable experimental phenomena which the affirmation or denial of a concept could imply, one will have therein a complete definition of the concept, and *there is absolutely nothing more in it*
>
> [Italics in original] (Peirce, 1905a, p. 162)

If the maxim of pragmaticism is then applied to compare these two definitions, the idea itself becomes clearer. Applying pragmaticism to itself helps facilitate the process of considering only the conceivable effects we conceive the maxim to have. If this is done, the idea is that no more can be known about the maxim. That is, the aggregate effects should signify the complete conception of the object. The main point of pragmaticism can thus be said to be found in the comparison of the two notions or definitions provided above. In making the comparison while adhering to pragmaticism, one would in some way have to consider: What empirical and practical difference would it make if one or the other notion was true? In the case of the two specifications of the pragmaticist maxim, there is no discernible practical consequence of one or the other being true. And as there are no practical implications of moving from one definition to the other, they refer to essentially the same thing. Put more broadly, the position demands that inquiry proceeds by tracing what "…exists, *ex-sists*, that is, really acts upon other existents…" [Italics in original] (Peirce, 1905a, p. 176). And before moving on to describing how these ideas have been translated into a more concrete research strategy, the way pragmaticism is here coupled with the notion of realism will be briefly elaborated on.

Realism

Implied in the above maxim of pragmaticism is the doctrine of realism. Whether due to the debates going on at the time, or to something entirely different, the position outlined by Peirce often emphasizes the already at that time long-established implications of realism. It is expressed explicitly in statements about it being the idea that there are "…real objects that are general, among the number being the modes of determination of existent singulars, if, indeed, these be not the only such objects. But the belief in this can hardly escape being accompanied by the acknowledgement that there are, besides, real *vagues*, and especially real possibilities" [italics in original] (Peirce, 1905b, p. 492). Put very briefly: "That is *real* which has such and such characters, whether anybody thinks it to have those characters or not" [italics in original] (Peirce, 1905a, p. 176). But the more interesting implications of the doctrine of realism in this context can be explored by turning to the way it is understood in concert with the pragmaticist maxim. The point is that while:

> …we may define the real as that whose characters are independent of what anybody may think them to be…it would be a great mistake to suppose that it makes the idea of reality perfectly clear. Here, then, let us apply our rules. According to them, reality, like every other quality, consists in the peculiar sensible effects which things partaking of it produce
>
> (Peirce, 1878a, p. 298).

One is here once again reminded that reality is in fact a conception of reality. And the meaning of reality is thus also something which needs to be determined by having it accord with its consequences. In the context of this or any other inquiry, an effect of real objects is to produce beliefs. Beliefs are in their most general form ideas about the state of the world as accessible through empirical experience, or that which is contrary to doubt (e.g. Peirce, 1905a). True beliefs are beliefs in the real, and false beliefs are beliefs in fiction (Peirce, 1878a). With this in mind, one can then discern a significant consideration in the intersection between realism and the maxim of pragmaticism by considering what is involved in inquiry and the process of having real objects produce beliefs. An example could be found in the notion of experimentation: "…an experimental phenomenon is the fact asserted by the proposition that action of a certain description will have a certain kind of experimental result" (Peirce, 1905a, p. 174). The idea is here that certain modes of inquiry produce certain sorts of results. The same was expressed in the way scientific investigators were hypothetically expected to reach the same results as their methods were made commensurate: "The opinion which is fated to be ultimately agreed to by all who investigate, is what we mean by the truth, and the object represented in this opinion is the real" (Peirce, 1878a, p. 300). Through studies of logic and scientific reasoning, Peirce observed that the process of inquiry involved a lot of work for the making of reality. One way this was addressed can be found in his discussion of the operation of 'synthetic reasoning':

> Its rule is, that a number of facts obtained in a given way will in general more or less resemble other facts obtained in the same way; or, *experiences whose conditions are the same will have the same general characters*…in the case of synthetic inferences we only know the degree of trustworthiness of our proceeding. As all knowledge comes from synthetic inference, we must equally infer that all human certainty consists merely in our knowing that the processes by which our knowledge has been derived are such as must generally have led to true conclusions
>
> [Italics in original] (Peirce, 1878b, p. 718)

Further elaborating on the implications of adhering to the pragmaticist maxim and the doctrine of realism can be done by considering it along the lines of a series of more or less common assumptions made by researchers, as described by John Law (2004). As was touched upon previously, the position involves an orientation towards the broad idea "…that there is, indeed, a *reality that is out there* beyond ourselves" [Italics in original] (Law, 2004, p. 24). The idea of a reality beyond ourselves can then be supplemented and specified by considering how the concept of 'independence' is handled by means of the present pragmaticist position. The term independence serves as a way of pointing to the matter of whether these real external objects are "…*independent of our actions and especially of our perceptions*" [Italics in original] (Ibid.). And here, again, the maxim of pragmaticism has to be applied. One has to make clear what is actually implied in referring to actions and perceptions. In a general and least interesting sense, it is fairly straightforward to observe that there are real external objects and phenomena which do not depend on what we do or think. The idea was also part of the definition of realism. One cannot act or imagine any state of affairs into being. But of greater importance here is the idea that "…it is only the outcome of persistent and conjoint inquiry which enables us to give intelligible meaning in the concrete to the expression 'characters independent of what anybody may think them to be'" (Dewey, 1916, p. 715). On one hand, the state of the world is not dictated by action or cognition. But on the other hand, it is pointed out that "Reality…is not independent of the apparatuses that produce reports of reality" (Law, 2004, p. 34). The idea that reality has to be made to exist guides this thesis throughout, and is also explicitly reflected in the choice and character of concepts along with the conclusions presented here.

One way to operationalize pragmaticism in taking an empirical stance has here been to conduct the inquiry in accordance with an ambition of seeing things through the eyes of others. In approaching the actors involved in electricity market construction for wind power integration, the idea has been to "…grasp their concepts, to follow their distinctions, to appreciate their beliefs and, so far as possible, to see things their way" (Skinner, 2002, p. 3). Only by also seeing things their way can the inquiry be expected to encompass what the actors are really doing, and what enables them to act the way they do. This orientation will prove to be particularly relevant to the analysis of Nord Pool with regards to how different forms of knowledge and expertise have been central to wind power integration in Denmark. As this idea has served as a significant resource for the inquiry, the concepts involved in doing so will be introduced in the following section.

Seeing things their way

An idea which has been significant to seeing things their way and providing an accurate and detailed description of the enterprise of wind power integration in Denmark is the notion of symmetry. As part of the history of science and technology studies (STS), symmetry as applied here can be seen as an extension of Bloor's (1976) insistence on the idea that both false and true beliefs merit sociological explanation, and that these explanations should be treated in the same way. Taking an empirical stance and committing to the pragmaticist maxim implies that this idea has to be generalized. Having the notion of symmetry as part of the approach thus means:

> …to assert that everything deserves explanation and, more particularly, that everything you seek to explain or describe should be

> approached in the same way…you don't want to start any investigation by privileging anything or anyone. And, in particular, you don't want to start by assuming that there are certain classes of phenomena that don't deserve to be explained at all
>
> (Law, 1994, p. 10)

The reference to symmetry can here be considered in two ways. One is that it is a logical necessity following from the empirical stance and the maxim of pragmaticism. The other is that it serves as an instrument for approaching Nord Pool while respecting the empirical ambitions of the inquiry. A distinctive implication of this approach as part of the social sciences is that it forces the inquiry to initially attribute the same significance to humans and non-humans. It does so by demanding that the observer does not change registers when moving between, for example, the technical, social, economic or political aspects of the empirical situation at hand (Callon, 1986a). The need to see things their way in a certain sense thus also applies to the inclinations and influences of the material components partaking in the phenomenon under investigation. An important rule here, which is closely related to the notion of symmetry, is that of agnosticism (Ibid.). Agnosticism is founded in the wider idea of symmetry in the sense that it points out the fact that there is no reason to assume that the observer conducting the inquiry is in any way different from the actors being studied (Law, 1994). The rule prescribes that social scientific explanation be put on par with the understandings and explanations of the situation made by the actors constituting the object of study.

It should be stressed that an agnostic approach does not imply that scientific production simply becomes a matter of reporting the explanations provided by the existents or actors themselves. And the rule of agnosticism does not negate the rule of generalized symmetry by considering the actors studied as part of a different realm of reality, in effect of their own and potentially differing stance. The idea is simply to try to look into what has been done in the empirical situation in part by means of knowledge, without making judgments about the character and status of the beliefs involved. Mobilizing such judgments would make it hard, if not impossible, to identify what forms of knowledge and beliefs are at stake in the introduction and reconfiguration of Nord Pool for wind power integration. Thus, a large part of the means for action involved in approaching the intermittency problem would disappear. What agnosticism does here is to help make sure that the knowledge and beliefs of the actors involved are allowed to surface and be taken into account, rather than dismissing them to a greater or lesser extent through the transmission of the preferred explanation. Finally, there is the rule of free association (Callon, 1986a). Free association implies an attempt to shed all *a priory* social scientific distinctions by demanding that the results of analysis cannot be used as a point of departure for inquiry. Rather, the observer should trace what exists in the empirical situation by following how the actors define and arrange the elements which are used to build and explain their world.

Operationalizing the maxim of pragmaticism by applying the above rules has enabled an appreciation of how control systems engineering in various forms has played a crucial but not immediately accessible role in the process of market construction for wind power integration. In part because it provides a shared language capable of connecting different actors, Nord Pool is publicly addressed using the terminology of economics (Behrmann, 2013; Nielsen, 2013; Kofoed-Wiuff, 2013). But as the analysis will show, Nord Pool was conceived of and functions as an engineered control system in the strict sense of the term, and has been continuously developed as a control system in several ways. What the engineers involved were doing was to use established parts of the technical sciences to create a market arrangement intended to achieve results described by economics. To produce these insights, considering the intellectual traditions, ideas, and explanations of the actors involved in wind power integration by means of Nord Pool has been central. And to be sure, the terminology of economics most often can and does describe and prescribe the changes which occurred around the introduction and reconfiguration of Nord Pool as related to wind power integration. But control systems engineering has been a central form of expertise in relation to market design and maintenance. It is here worth explicating a point which by now has been made a number of times in order to clarify the empirical stance, maxim of pragmaticism, and the sociological resources or rules for inquiry introduced in the above. Approaching Nord Pool generally involves an effort to stand back. There is no reference to the idea of the researcher being able to step out of the worlds of which s/he is part. In fact, quite the opposite is the case. If the maxim of pragmaticism is applied to this situation it is found that:

> …there is but one state of mind from which you can 'set out,' namely, the very state of mind in which you actually find yourself at the time you do 'set out,' – a state in which you are laden with an immense

> mass of cognition already formed, of which you cannot divest yourself if you would; and who knows whether, if you could, you would not have made all knowledge impossible to yourself?
>
> (Peirce, 1905a, 167)

But as a researcher, there is still room to maneuver when it comes to steering the extent to which preconceived ideas are forced upon the world. And as was made clear in the discussion of the empirical stance, pragmaticism, and realism, it is central to the approach that not 'everything goes'. Even though they are made just as with anything else, true beliefs or beliefs in the real are still fundamentally different from false beliefs or beliefs in fiction. In short, "True ideas are those that we can assimilate, validate, corroborate and verify. False ideas are those that we cannot" (James, 2009, p. 82). In other words, these features are practical or empirical expressions of the quality of a statement or proposition known as truth. Clarity and precision in matters of fact and analysis can exist, but do of course still have to be made. And researchers can do better or worse in this undertaking. The commitment to doing well in this respect is understood as vital. In this way, the empirical stance described here is about "…genuinely submitting to the constraints which the endeavor to provide an accurate representation of reality imposes" (Frankfurt, 2005, p. 34).

Studying wind power integration through the introduction and reconfiguration of Nord Pool is part of an attempt to document the work that goes into mitigating the problems associated with fossil fuel-based energy systems. It has not been the ambition to falsify or generate general statements or theories. Rather, the goal has here been the production of an explanation of wind power integration through qualitative, situated, literary description. Doing so obviously implies dealing with and relating to a substantial amount of wider concepts and ideas. And while the analysis of the making and remaking of Nord Pool also involves producing abstractions which might be applicable to other empirical settings, the generalization of findings and the implications of the findings for general conceptualizations have not figured as ends in themselves. As part of an ongoing academic conversation, the ambition has here been to produce a series of contingent statements which can augment a part of economic sociology by widening the understanding of the roles and functions of knowledge in the making of markets. That is the case with control systems engineering, in the sense that this form of expertise has not previously been described as playing a generative role in market construction. However, the understanding of the quite extensively investigated role of economics in the context of market making is also expanded. But before moving on to describing how this stance has led to the inclusion of concepts chiefly originating from recent developments within economic sociology, a number of the research tactics deployed in order to respect the above rules need to be introduced.

Techniques

A relevant set of exercises and devices for accommodating the above rules has been provided by Howard Becker in his volume on the *Tricks of the Trade* (1998). And while many of them have helped push the inquiry forward, only a limited selection will be presented here. One is the adaptation of the idea of the null hypothesis. Well known to statisticians, the null hypothesis involves working with a hypothesis the researcher suspects to be false. Proving the hypothesis wrong does not point to what is true, but proves that an alternative to the hypothesis is right. This can, for example, involve hypothesizing that two variables are only related by chance. When a relationship between the variables is found and the null hypothesis stating that there is no relationship between them is rejected, it can be claimed that there is a smaller chance that these results would have been produced if the hypothesis the researcher believes to be true was not true. One way of adapting the null hypothesis thus involves making random assignments by considering the actors partaking in the introduction and reconfiguration of Nord Pool for wind power integration as if nothing had led to them be there and act in that way. In other words, it involves approaching them as if they "…were assembled in some analog of assigning everyone a number and then using a table of random numbers to assemble the required cast" (Becker, 1998, p. 21).

Apart from random assignments, another way to draw inspiration from the line of thinking involved in the null hypothesis has here implied a focus on strangeness. When one is confronted with something alien or incomprehensible, the idea is to consider it non-sensible and then make that very character of the empirical situation into a null hypothesis. Again, the idea is to have "…hypotheses you take up because you think they're not true and think that searching for what negates them will get you to what is true" (Becker, 1998, p. 24). An alternative to doing so which has also been applied here involves working with the assumption that the actions studied make perfect sense, and that it is simply the researcher who does not know the sense it makes (Becker, 1998). The exercise is similar to what Skinner (2002) has suggested by insisting on having the researcher assume that the actors studied are rational.

Another technique deployed in the effort to stand back and respect the above-mentioned stance, maxim, and the implied rules for research, is to trace what empirically exists by conceiving of the empirical setting as a machine and engaging in a process similar to reverse engineering. The exercise attunes the inquiry to the way the elements of interest in the empirical setting have been produced, while helping to ensure that crucial aspects of the situation are not left out on account of preconceived ideas. In this way it serves to continually stress that what is being studied is an outcome. The operation thus involves having the researcher draw up a social machine consisting of diversified components which produces "…the results that your analysis indicates occurs routinely in the situation you have studied…[one should include] all the parts – all the social gears, cranks, belts, buttons, and other widgets – and all the specifications of materials and their qualities necessary to the desired result" (Becker, 1998, p. 39). Constructing such a machine has many of the same practical implications as applying the notion of the socio-technical *agencement* (STA) (e.g. Çalışkan & Callon, 2010) described later. But as will also be made clear, since the machine image can tend to point to the repetitive or reproductive elements in an empirical setting, an aspect highlighted in the notion of a STA which it sometimes captures less well is variation through connectedness. One technique to get at just these aspects involves conceiving of the empirical setting as an organism. As a general idea relevant for sensitizing the inquiry to paying attention to all the elements connected to the object of interest, the reference to ecology enables an appreciation of how the "…pieces of the system in question are connected in such a way that the output of each of the sub-processes that make it up provides one of the inputs for some other processes, which in turn take results from many other places and produce results that are inputs for still other processes, and so on" (Becker, 1998, p. 41).

A concrete exercise applicable when trying to stand back and respect the rules of the inquiry which is made clear in light of the biological imagery is turning actors into activities. In order to put established typologies on hold as part of the inquiry, the idea is to direct attention to outcomes and what is being done in order to avoid basing the analysis on the transmission of select types from other situations. Doing so implies working with the idea that actors tend to do either what they have to do or what they want to do, and that there is no reason to expect an actor to act consistently as situations change.

Having stated how Nord Pool has been approached through an empirical stance, pragmaticism, rules of research, and a series of related techniques, the methods for data generation can here be introduced. Following the section on data generation, the body of concepts most consistently drawn upon throughout the study is presented and the academic conversation in which the inquiry partakes is outlined.

Methods

Generating data in a way compatible with the empirical ambitions of the study has involved a number of qualitative methods. And while the choice of methods has been influenced by several aspects of the study such as access, time, and the available resources, one single factor has been given priority. To the greatest possible extent, studying the introduction and reconfiguration of Nord Pool in relation to wind power integration has been dictated by the empirical state of affairs and the making of data formats relevant for understanding them (Callon, 1991). This does not mean, however, that inquiry could not have been conducted differently. There is much to suggest that the combination of qualitative methods outlined below is highly relevant for inquiring into topics such as the role and functions of knowledge and expertise in electricity market design and maintenance. But it is also worth considering the fact that these topics of interest and lines of inquiry are themselves products of input such as ways of thinking and established research skills. Thus, it can be argued that it would be difficult to appreciate the crucial details of, for example, the role of knowledge and expertise in wind power integration as market design and maintenance by means of quantitative methods exclusively. But it is here prudent to recall that the endeavor would be hard because it has been made to be that way. Aspects of the inquiry such as research interests and the direction of curiosity also necessarily hinge on the research training and wider history preceding the initiation of the study.

Before touching upon each of the main methods applied in the study, it should be noted that data generation has been an ongoing activity since the initiation of the inquiry in March 2012. However, most of this type of work has been conducted between November 2012 and December 2014. The choice to use a number of different methods was made in part in recognition of how some aspects of wind power integration through the introduction and reconfiguration of Nord Pool were more easily accessible in specific formats. But with reference to the rule of synthetic inference (Peirce, 1878b), this was also done to compare and encompass the various materials produced by the different methods. Doing so made it possible to corroborate and validate empirical results. And in this sense, inquiry has here built on the idea of triangulation (e.g. Kipping, Wadhwani, & Bucheli, 2014).

Interview

Data generation has to a great extent involved conducting formal interviews. Interviewees were most often selected on the basis of snowball sampling (Noy, 2008) whereby interviews were used to clarify the relevance of and secure access to new interviewees. Since wind power integration through the introduction and reconfiguration of Nord Pool implies diverse forms of work distributed across various settings, this tactic proved particularly well suited to the effort of tracing the existents making the biggest difference in the situation of interest (e.g. Callon, 1986b; 1991). In total, 32 different respondents participated in semi-structured interviews (e.g. Bryman, 2004). All sessions, except the one telephone interview conducted, were audio recorded. Central interviews have been written out using intelligent verbatim transcription. Other interviews are at present in the process of being transcribed as part of a larger and shared research project.

List of interview participants		
Name	**Role**	**Time**
Hans Henrik Lindboe	Consultant and Partner (EA Energy Analyses). Former Deputy Director of the Planning Department - Elkraft System.	2013, August
Klaus Thostrup	Head of Market Development (Energinet.dk).	2013, October
Paul-Frederik Bak	Former Planning Director (Eltra).	2013, November
Emil Mahler	PhD Fellow and market designer (Technical University of Denmark).	2013, September
Jacob Østergaard	Professor and market designer (Technical University of Denmark).	2013, September
Maja F. Bendtsen	EcoGrid Bornholm Project Manager (Østkraft).	2013, September
Randi K. Jørgensen	EcoGrid Bornholm communications manager (Østkraft).	2013, September
Chano	EcoGrid Bornholm electrician and consumer trainer (Østkraft).	2013, December
Torben	EcoGrid Bornholm electrician and consumer trainer (Østkraft).	2013, December
Jesper	EcoGrid Bornholm electrician and consumer trainer (Østkraft).	2013, December
Jesper	EcoGrid Bornholm electrician and consumer trainer (Østkraft).	2013, December
Lars	EcoGrid Bornholm electrician and consumer trainer (Østkraft).	2013, December
EcoGrid participant 1	Household retail electricity consumer and EcoGrid participant.	2013, December
EcoGrid participant 2	Household retail electricity consumer and EcoGrid participant.	2013, December
EcoGrid participant 3	Household retail electricity consumer and EcoGrid participant.	2013, December
EcoGrid participant 4	Household retail electricity consumer and EcoGrid participant.	2013, December
EcoGrid participant 5	Household retail electricity consumer and EcoGrid participant.	2013, December
EcoGrid participant 6	Household retail electricity consumer and EcoGrid participant.	2013, December

List of interview participants		
Name	**Role**	**Time**
Anders Kofoed-Wiuff	Consultant and Partner (EA Energy Analyses).	2013, April
Brian Mathiesen	Associate professor and energy planner (Aalborg University).	2012, April
David Connolly	Assistant professor and energy planner (Aalborg University).	2012, April
Hans Ravn	Head of the BALMOREL project (RAM-løse edb).	2013, January
Helge Ø. Pedersen	Consultant and Partner (EA Energy Analyses). Former Planning Director (Elkraft System).	2012, September
Lars Bregnbæk	Consultant and Partner (EA Energy Analyses).	2012, September
Jan Nielsen	Head of the Climate Secretariate (Aarhus Municipality).	2013, April
Mette Behrman	Project Manager in the Climate Secretariate (Aarhus Municipality).	2013, April
Jens Pedersen	Energy system analyst (Energinet.dk).	2012, September
Jørgen Boldt	Consultant and developer of the Technology Catalog. Former head of the secretariet for the Danish Commission on Climate Change Policy.	2013, August
Marie Münster	Researcher (Technical University of Denmark). Former assistant developer of the Technology Catalog.	2013, March
Kenneth Karlsson	Researcher (Technical University of Denmark).	2013, March
Kristoffer S. Andersen	Economic Advisor (Danish Energy Agency).	2013, September
Sigurd L. Pedersen	Senior Advisor (Danish energy Agency).	2012, September

Doing semi-structured interviewing meant that each session took the form of a conversation around a limited number of topics using open questions. Apart from the electricity consumers partaking in the EcoGrid project, respondents were interviewed with reference to their role as professionals working with system development from different vantage points within the energy sector. As the respondents took time to be interviewed during busy office hours, interviews often lasted for about an hour. Apart from fitting neatly into the busy schedules of the respondents, the time frame of one hour was usually also what was needed to establish and complete a relaxed conversation around central aspects of their work. While the majority of the sessions involved a single respondent, a number of group interviews (Denscombe, 2003) were also conducted. Group interviews were most often undertaken with the participation of two interviewees, but did in one instance include three. Interview sessions with more than one participant were most often arranged by letting an interviewee invite along others they considered able to contribute. Group interviews tended to facilitate comprehensive discussion of various topics in effect of bringing more than one expert opinion to the table. In some instances however, interviewing groups necessarily involved a variously successful effort to prevent pre-established dynamics and roles from drowning out the voices of select respondents.

One interview tactic which proved effective focused on asking ‘how’ rather than ‘why’ (Becker, 1998). Asking open questions in this manner was done in order to avoid normative connotations and help ensure that the interviewer did not come across as judgmental. Asking ‘how’ often led respondents to provide comprehensive stories which tended to include influences and factors apart from those explicitly linked to themselves and their own work. In the case of the EcoGrid experiment, interviews and the observations touched upon below were all conducted with a co-researcher. While demanding consideration of the fact that the presence of two interviewers or observers can be more overwhelming, generating data in cooperation with another researcher was productive in several ways. Sharing the work of taking notes, paying attention to detail, and picking up on various aspects of a situation or response tended to increase the richness of the interviews and observations.

It is worth noting that even though a significant amount of time has been spent conducting interviews, their presence in the analysis text is fairly limited. Although interviews have provided indispensable input for the inquiry, their role as points of reference tends to be in the background of the analysis. The fact that interviews are cited less than documents, for example, reflects a decision and effort to apply publicly accessible sources in presenting the arguments entailed in the analysis. The same applies to the manner in which the observations that were made as part of the inquiry have been included in the body of the text. And in accordance with this orientation, processing the interview material has involved bricolage analysis as opposed to, for instance, a coding format (Kvale & Brinkmann, 2009).

Observation

Following market reconfiguration for wind power integration led to a small amount of participant observation (e.g. Kristiansen & Krogstrup, 2002), which often included informal interviews. A portion of these were made during half-day and two-day workshops along with a more extended course on energy planning and energy system development, while some were conducted while sitting in on a course about mathematical modeling at the Technical University of Denmark. Another series of observations was made on the Danish island of Bornholm as related to the EcoGrid project. On Bornholm, observations were made in several different settings. A day of observations took place in Villa Smart, the EcoGrid demonstration house where the introductory sessions for EcoGrid participants were held. Two days were spent driving around with the EcoGrid electricians responsible for setting up equipment and doing demonstrations and consumer training in the domestic context. All observations were field observations (Kristiansen & Krogstrup, 1999) in the sense that they implied entering a setting not originally established for the purposes of the present inquiry. The format of trailing the EcoGrid electricians was helpful in many ways. For one, it enabled quick access to several instances of on-site training and the making of a specific form of electricity consumer. And in part due to them constituting a kind of entourage to the EcoGrid electrician, the presence of observers and their questions in the homes of the EcoGrid participants tended to be treated as unintrusive.

Documents

A series of written materials has been included by way of content analysis of exemplary documents (e.g. Justesen & Mik-Meyer, 2010). These documents are often technical reports and policy papers created as input for decision making in the context of Danish energy system development. However, another significant type of document applied in the analysis has been published scientific papers and books. Especially in the context of following the application of different forms of knowledge and expertise in the introduction and reconfiguration of Nord Pool, scientific publications have proved to be of great importance. Whereas scientific publications on their own tended to only provide a very narrow route to insight about how ideas change and have effects in action, in part due to how they black box their own making (Warwick, 2003), coupling these documents with other data formats prevailing in the inquiry made a significant difference. In scientific writing, the conceptual cornerstones of the work involved in the process of electricity market design and management were displayed with pellucid clarity. And in a setting where economics and the technical sciences are often intertwined (Cf. Mirowski, 2002) and the input from control systems engineering is collapsed into the wider discourse of economics, such publications have been central to sorting out the inputs for market construction and wind power integration. In this sense, documents played a significant role in an important process of discovery.

Having noted central aspects of the way Nord Pool has been approached, it should here be made clear how the inquiry has mobilized a specific body of concepts from economic sociology. Doing so is not meant to suggest that these concepts are in any way treated as fundamentally different from what has been described above. Rather, it is because these concepts in aggregate make up a central part of a specific programme of inquiry. The research programme in question also constitutes the foundation for the main academic conversation in which the present study takes part. Due to these reasons, this specific collection of ideas will be presented in a concerted fashion while sometimes also providing a background for their description.

The performativity programme

Since the publication of Austin's (1962) canonical *How To Do Things With Words*, terms such as 'performative', 'performativity', and 'performation' have come to be some of the most pervasive concepts within the social sciences. This has in large part been due to the work of writers such as Judith Butler (e.g. 1997) in feminist and cultural theory and Michel Callon (1998a) from science and technology studies (STS) (du Gay, 2010). And while it is clear that these terms have found varying uses in a number of instances (Muniesa, 2014), it is specifically the notion of performativity as introduced by Callon which is of interest in the context of the present study.

As Callon's thesis on the performativity of economics was given empirical backing primarily by Donald MacKenzie's work on financial markets (e.g. MacKenzie, 2003; 2006), the idea came to be an important foundation for STS when walking into economic sociology and forming what is known as the "new new economic sociology" (Mcfall, 2009; Mcfall & Ossandón, 2014). The proliferation of the performativity thesis is given its most clear expression in the derived scholarly agenda concerning the relationship between economics and market construction named the "performativity programme" (Çalışkan & Callon, 2010; see also for example Callon, Millo, & Muniesa, 2008; MacKenzie, Muniesa, & Siu, 2007a; Kjellberg & Helgesson, 2006).

In order to understand Callon's idea of performativity and thus provide a basis for the forthcoming discussion, the terminology here has to be clarified. In his now-classic introduction to *The Laws of the Markets*, 'The Embeddedness of Economic Markets in Economics' (Callon, 1998a), Callon's more general idea of what is here called performativity was applied in order to change the way the relationship between economics and markets is conceived of. It was argued that "…economics, in the broad sense of the term, performs, shapes and formats the economy, rather than observing how it functions" (Callon, 1998b, p. 2). Other names for related notions then followed, and the use of terminology within the field has not been entirely consistent. Since the introduction of the basic idea, the use of the concepts "performation" (Callon, 1998b) and "co-performation" (e.g. Callon, 2007b) have been suggested as part of a mission to introduce terms which reflect and specify what is implied in this particular notion of performativity. These various expressions will in the following be used in order to structure a brief elaboration of the notion of performativity.

Working within speech act theory and developing Wittgenstein's observation that words are deeds, Austin (1962) originally introduced the notion of performatives as a contrast to constatives as part of a critique of the idea that the workings of language are essentially representative. Whereas constatives are sayings involved in the making of a statement or provision of a description (e.g. 'the cat is on the mat'), performatives are speech acts that are actions - such as making a promise or apologizing (e.g. ‘I promise to come by on Saturday’). Callon’s change from performativity to performation and co-performation has to a great extent been made in an effort to specify “How to get rid of Austin without losing him” (Callon, 2004). The idea is here to avoid conceiving of performativity in the original way as presented by Austin, i.e. the idea that performativity is a property of statements. Rather, performation “…is an action: it is performativity as an activity or a material operation” (MacKenzie, Muniesa, & Siu, 2007b, p. 15). This difference in conception can to a great extent be made clear by considering it in light of the way Callon couples it with the notion of the *agencement* (Deleuze & Guattari, 1987), or what is called the socio-technical *agencement* (STA) (e.g. Callon, 2005; 2007a; 2008). A STA is a methodological term designed to respect and render visible the multitude of forces potentially influencing economic processes and the construction of markets (Çalışkan & Callon, 2010). The socio-technical *agencement* denotes an arrangement or assemblage of heterogeneous elements carefully adjusted to one another and which has the capacity to act in certain ways in effect of its configuration. And by pointing to the way markets are made without ascribing primacy or function to any one form of constituent element, the notion of the STA embodies the pragmaticist approach.

The idea of Nord Pool being a market STA helps stress that the Nordic wholesale electricity market is an outcome, and it demands that the inputs which exist in the context of market construction are followed. As was also pointed out when discussing the rules and techniques of the present study, this specific idea is a starting point for helping inquiry along. However, for reasons unknown, the idea that phenomena exist as part and outcome of such heterogeneous assemblages is often treated as a sort of finding or conclusion in its own right (see for example Bøhling, 2015). When considered in light of the idea of the STA, economics and economic processes become part and parcel of the same thing. Economics no longer represents an independent reality, but inevitably helps constitute its object:

> This means that there is nothing left outside of *agencements*: there is no need for further explanation, because the construction of its meaning is part of an *agencement*. A socio-technical *agencement* includes the statement(s) pointing to it, and it is because the former includes the latter that the *agencement* acts in line with the statement…
>
> [Italics in original] (Callon, 2007b, p. 320)

Seen in this way, it becomes evident that representations such as economics are inescapably performative in a general sense. Performativity in Callon's understanding signifies a general point about the inseparability of representations and their objects as part of a STA. This becomes clear from statements such as the one made about the Black-Scholes formula studied by Donald MacKenzie. In this context it is stressed that "The formula that is born performative, and remains so, seems to be constative when the world (finally) acts according to it" (Callon, 2007b, p. 321). When introduced into the discussion of the anthropology applied in the wider social sciences in general and economic sociology in particular, the notion of the STA helps make clear Callon's original critique of previous conceptions of the central idea of the economic agent. Here the economic agent is distinguished from the *a priori* rational egoist assumed by, for example, neoclassical economics. It is also stressed that the economic agent is not an actor whose actions are structurally determined by, or embedded in, the wider workings of society as suggested by much of sociology. Rather, economic man exists to the extent that s/he is made to exist:

> Yes, *homo economicus* really does exist. Of course, he exists in the form of many species and his lineage is multiple and ramified. But if he exists he is obviously not [to] be found in a natural state – this expression has little meaning. He is formatted, framed and equipped with prostheses which help him in his calculations and which are, for the most part, produced by economics
>
> [Italics in original] (Callon, 1998b, p. 51)

In light of the idea of the STA, it becomes clear what is meant with the catch phrase that performativity implies an idea of "truth as success" (Callon, 2007b, p. 316). Instead of the idea of truth as a form of correspondence between a representation and its object caused by some inherent feature of the model, a model becomes true. Or using Callon's words, "…it is preferable to say that the world it supposes has become actual" (Callon, 2007b, p. 320). It should here be stressed that it is on the topic of representation that one can find a noteworthy difference between Callon's original statement and central work from within the performativity programme. Apart from stressing that it partakes in the process, Callon never ascribed specific roles to economics in the performation of markets. But other widely influential works within the performativity programme did just that (e.g. MacKenzie, 2006). Making this distinction will prove to be of importance due to how the present thesis seeks not only to demonstrate how control systems engineering has been central to the design and maintenance of Nord Pool. The ambition is also to widen the understanding of the role of economics in the making of markets. In other words, it is the issues around the role and use of expertise in the actualization of that specific form of knowledge which is of interest. But before elaborating on this particular point, it is worth taking a step back and further considering the performativity thesis. When applying the pragmatic maxim in considering the idea that economic markets are shaped, performed, and formatted by economics, it immediately becomes a priority to explicate what is concretely entailed in the term 'economics'.

Economics at large

With reference to Granovetter's (1985) notion of the embeddedness of economic action in social structures, Callon introduced the idea that "…economy is embedded not in society but in economics…" (Callon, 1998b, p. 30). Subsequently, the performativity programme articulated as its central aim "…to study all the theoretical and practical, expert and lay knowledge, know-how and skills developed and mobilized in the process of designing and managing market STAs" (Çalışkan & Callon, 2010, p. 19). But in order to maintain the universality of the performativity thesis, economics has to somehow be made commensurate with all these elements in the process. Enter the idea of an "economics at large" (Callon, 1998b). This concept helps to keep the performativity thesis relevant at the most general of levels by equating economics with all the know-how, knowledge, and skills which go into market design management. In other words, one has to incorporate "…within economics all the knowledge and practices, so often denigrated, that make up for example accounting or marketing" (Callon, 1998b, p. 30). The concept of "law" (Callon, 1998b, p. 28) is also ostensibly included in the idea of economics at large. Taken to its extreme, economics at large includes all the resources which can be associated with economics as an academic discipline in the context of the making of markets:

> To make a formula or auction system work, one has to have tools, equipment, metrological systems, procedures, and so on. To establish relations that 'exist' between monetary masses and price levels, to act

> on the one in order to control the others, there have to be institutions, systems of observation, codification and data collection, tools for analyzing large numbers, and so on. A host of professions, competencies, and non-humans are necessary for academic economics to be successful. Each of these parties 'makes' economics. They are engaged in the construction of a world described and performed by statements and models that we readily agree belong to the world of economics, in the strict sense of the word
>
> (Callon, 2007b, p. 333)

What is important here is that this understanding implies that economics becomes an *ex post* established category potentially encompassing anything. The way this works is underscored by the way much the same applies to the idea of what an economist is: "…I use the word 'economist' to denote all agents who participate in the analysis and transformation of economic markets…" (Callon, 2007b, p. 336). This understanding of economics ensures that the performativity thesis constitutes the sought-for tautology. Economics performs the market through processes of design and management, while that which is involved in performing the market through design and management work qualifies as economics. But an issue which then arises pertains to the matter of guidance. How to learn from it? How to make empirically relevant distinctions? This issue has been expressed in the concern that the performativity thesis becomes trivially true, while under its banner researchers do not "…look closely enough at the details of what does and does not count as legitimate 'economics' among the agents" (Mirowski & Nik-Khah, 2007, p. 198).

One way to deal with the issue of guidance is to deploy the idea of "economics in the wild" (Callon, 2007b). This distinction is a particular application of the more general categories of "secluded research" and "research in the wild" (e.g. Callon, Lascoumes, & Barthe, 2009). When strictly an academic discipline, economics is "confined" (Callon, 2007b) to the laboratories of select institutions. In contrast, economics in the wild denotes the activities involved in market construction taking place on the ground. In this way the idea of economics in the wild serves as a means of subdividing and specifying economics at large. The study of the history of fishing in Norway made by Holm (e.g. 2007) has been treated as a case in point. The inquiry demonstrated the importance of distinct forms of expertise such as halieutics, marine biology, and population dynamics in the making of a market for fish. Such forms of knowledge are included in the idea of economics at large by considering them as part of a process of “co-performation” (Callon, 2007b). Acknowledging the importance of other distinct inputs is promoted by considering other forms of expertise as inevitable aspects of a practical performative economics:

> Economics in the wild is not pure economics; it is mixed with engineering, life sciences, and management science – its complexity and heterogeneity constitutes its strength and makes it irreplaceable. But it is also about calculations, optimizations, and the management of rare resources. It is imbibed and impregnated by the anthropological program of ‘confined economics’
>
> (Callon, 2007b, p. 338)

Introducing the idea of economics in the wild provides a way to focus inquiry and sensitize an investigation to other forms of knowledge and expertise than economics in the more strict sense of the term. But it is only one way. For it is a practical example of the more general idea that in the process of inquiry, something such as the concept of economics in the wild needs to be added to the performativity thesis in order for it to be put to work in an empirical setting. So it goes for all these tautologies. One can take as a different example the well-established sociological notion of “institutional isomorphism” (DiMaggio & Powell, 1983). It points out how institutional pressures make organizations within organizational fields become increasingly alike, while that which qualifies an organization as part of an organizational field is that it responds these pressures in this way. Contemplated in strict isolation, such notions do not present much of an input for inquiry. On their own, they make little concrete practical difference. And as the essential aspect of their character is the fact that they are necessarily always true, it makes limited sense to treat them as, for example, a contingent statement. These tautologies are unassailable. One way to put this is to stress that they are immune to what Popper (1959) called “falsification”.

As with the pragmaticist reaction to metaphysics, a way to relate to these tautologies can be to discard them as uninteresting. And when it comes to the performativity thesis as a universal statement about a state of the world, walking away is the solution chosen here. However, taken as a concept or contingent statement in its own right, the notion of performation has much to offer the understanding of Nord Pool. Wind power integration through the introduction and reconfiguration of Nord Pool is to a great extent about performation in the sense that it is an instance of "…the process whereby sociotechnical arrangements are enacted, to constitute so many ecological niches within and between which statements and models circulate and are true or at least enjoy a high degree of verisimilitude" (Callon, 2007b, p. 330). The upcoming brief outline of the analysis will thus demonstrate how the notion of performation does have bearing on significant practical aspects of integrating wind power into the Danish electricity system through the electricity market. It helps frame how solving the intermittency problem has been approached by drawing out issues of knowledge and expertise involved in the way Nord Pool has been introduced and reconfigured in order to maintain equilibrium in the electricity system.

Within the performativity programme, the most prolific way to empirically operationalize Callon's notion of performation has involved an emphasis on the role of knowledge and representations in the making of markets. In other words, the performativity programme has often traced the role of the circulating statements and models themselves. An important example of this focus can be found in the work of Donald MacKenzie (e.g. 2003; 2006; MacKenzie & Millo, 2003). Emphasis has been directed towards economists and economics, in the more strict sense, to the extent that one of the most frequent critiques of the performativity programme is that it overstates the role of these agents. The cause of this emphasis has been attributed to the fact that many ideas and researchers within the performativity programme have ties to the field of STS, which in turn has a history of dealing with knowledge and representation (e.g. Bryan, Martin, Montgomerie, & Williams, 2012; Riles, 2010; Mirowski & Nik-Khah, 2007). Within this stream of the performativity programme, out of all the possible ways in which economics and its object can co-evolve as a STA, the one of greatest priority denotes the manner in which the entity claiming to represent the world helps remake that world in its own image. This particular dynamic has also been specified as Barnesian performativity, and is present in situations where the "…practical use of an aspect of economics makes economic processes more like their depiction by economics" (MacKenzie, 2007, p. 55). While also interested in the role played by knowledge in the wider performation of Nord Pool, the present thesis takes a different route in specifying the impact of know-how and expertise in this context. It does so by pointing out how work with equilibrium maintenance through the introduction and reconfiguration of Nord Pool includes several instances of market construction based on three products of technical science. Concretely, expertise here takes the form of control systems engineering for the making of homeostatic control systems, open- and closed-loop control systems, and linear programming or higher order control systems.

In relation to Nord Pool, control systems engineering constituted the "engine" (MacKenzie, 2006) that economics has proven to have been in some financial markets. But the role of economics as part of the introduction and reconfiguration of Nord Pool is also taken up, and it is made clear that economics was indeed also part of the construction of this particular electricity market. However, rather than constituting the main driver in a process of market performation, economics was included in the making of Nord Pool by, in effect, providing the objectives which were set to be achieved through a process of market construction enabling or improving control system operation. The way this works is in the end specified by considering the role of economics using John Searle's (2001) ideas on conditions of satisfaction, direction of fit, and direction of causation. Drawing on the performativity programme as encompassed in the new new economic sociology, the conceptually informed research question addressed throughout the analysis can here be introduced.

Research question 2: *How have control systems engineering and economics been mobilized in the endeavor to integrate wind power into the Danish electricity system through electricity market design and management?*

In documenting the role of control systems engineering in wind power integration through the introduction and reconfiguration of Nord Pool, the study augments the performativity programme in a way similar to other inquires' documenting the role of knowledge from other fields than the discipline of economics (e.g. Muniesa, 2014; Riles, 2010). The main point which should be noted is that the knowledge and expertise going into market design and maintenance in the context of Nord Pool is rooted in both control systems engineering and economics. And as will be made apparent in the following section, the former has served as a means while the latter has signified or described the ideal ends for the process of market construction. The means are more specifically homeostatic control systems

(Schweppe, Caraminis, Tabors, & Bohn, 1980), open- and closed-loop control systems (e.g. Nise, 2004), and linear programming (e.g. Dantzig, 1963) or "higher order" control systems (Dantzig, 1957). The ends described by economics are measures in the form of liquidity (e.g. Keynes, 1930), price elasticity, and societal value or aggregate consumers and producers surplus (Marshall, 1920). Answering research question 2 thus augments the performativity programme in two ways. One is in how it demonstrates that control systems engineering is a generative form of expertise of great importance to market design and management in certain situations. Another is the manner in which economics is shown to have a function in the making of markets different from the one described by the performativity programme up until this point in time.

Outline

Each of the three analytical chapters is devoted to describing the involvement of the technical sciences and economics in market construction in one of these three forms. As with the three different empirical settings in which they are located, homeostatic control, open- and closed-loop control, and linear programming, are variously related and to some extent overlap. In this way, the three approaches to control are all present in all of the empirical accounts. But as each form is central to one of the three cases explored in relation to the introduction and reconfiguration of Nord Pool as part of wind power integration into the Danish electricity system, they are emphasized accordingly.

Homeostatic control | *Liquidity*

Chapter 1 describes the introduction and later reconfiguration of Nord Pool. Here it is explained how the economic mode of electricity system operation changed from central planning to an electricity market form. It is shown that a market was built around the central process of merit-ordering the dispatch of power plants by means of linear programming (e.g. Pinson, 2014). In fact, the algorithm at the heart of Danish electricity system operation was the same before and after the introduction of the market (Bach, 2013). The pursuit involves following the dominant way wholesale electricity markets have been conceptualized, and the particular manner in which the notion of homeostatic utility control by means of electricity markets (Schweppe et al., 1980) has materialized in Denmark. The arrangement is a price-based control system for maintaining the crucial equilibrium between input and output in the electricity system. Alongside optimal allocation and the attraction of new producers, equilibrium maintenance was one of the specified objectives associated with the introduction of the electricity market in Denmark. The objective of equilibrium maintenance was set to be reached by having buyers and sellers act in a concerted fashion and achieve mutual adjustment through use of the new system, utilizing price as the control signal. In effect, Nord Pool was established as the framework by means of which the intermittency problem was to be solved. It is then pointed out that wind power integration through expansion of the means by which homeostatic utility control is exerted via Nord Pool has been pursued in various ways.

In this case, attention is turned to a category of initiatives for renewable energy integration characterized by attempts to have electricity generated by wind turbines valued in a more hospitable way in Nord Pool. Starting from the idea that electricity market prices reflect the state and 'physics' of the electricity system, these initiatives generally seek to arrange things in a way so as to avoid having electricity produced by wind turbines sold at low, zero, and negative prices. A concrete example is found in the making of a transmission system interconnector across the Danish waters called The Great Belt. The cable linked the wind power intensive pricing zone in western Denmark (DK1) with the alternate production and consumption profile of eastern Denmark (DK2). The process is here argued to correspond to increasing the liquidity of electricity generated by wind turbines, which has had the effect of improving valuation in a way congruent with the specified objective of wind power integration. In the context of building TSIs for these purposes, the notion of liquidity as a measure of the ability to trade in a market plays a key role in market construction and renewable energy integration. But what started out as a descriptive or analytical measure in economics was in this case used to conceptualize what should be achieved through increasing the means by which Nord Pool can function as a homeostatic control system. In short, the amount of supply- and demand-side resources for maintaining equilibrium in the electricity system by absorbing fluctuations in wind power generation was expanded by connecting DK1 to DK2. Solving the intermittency problem predominantly found in DK1 was thus here a matter of changing the material market infrastructure (MacKenzie, 2008) of Nord Pool so as to increase the means by which homeostatic control could be exerted.

Open- and closed-loop control | *Price elasticity*

Chapter 2 moves from following the making of a transmission system interconnector to documenting efforts of renewable energy integration taking place in a more closed setting. Here the inquiry has focused on an economic experiment for the construction of markets (Muniesa & Callon, 2007) named EcoGrid. Taking place on the Danish island of Bornholm, EcoGrid involves 2000 retail electricity consumers and a platform arrangement for experimentation in between the laboratory and full-scale formats (Ibid.). EcoGrid has the purpose of producing knowledge about the potential for making a new form of retail electricity market, and the new market arrangement has been made to supplement the series of auctions which make up the Nord Pool control system. EcoGrid is shown to have been conceived of as a new form of subsystem within Nord Pool, one intended to expand the use of price as a control signal. While working in several different ways, the intention behind the new market is to have retail electricity buyers adjust consumption to changes in price presented in five-minute intervals. By having retail electricity consumers react to rapid shifts in price, the idea is to have price function as a control signal in a way which is similar to the way it works on the wholesale market. But in contrast to the double-sided auction in some of Nord Pool's established markets, which are based on the idea of homeostatic control, EcoGrid requires a different arrangement.

In order to operate within small time intervals, the experimental market design was set up as a bidless system modeled on the more general ideas of open- and closed-loop control systems and frequency adaptive power energy reschedulers. In this way, EcoGrid is set to expand the use of price signals for control and equilibrium maintenance by turning flat-rate electricity consumers into suppliers of upwards and downwards system regulation. The process is here argued to correspond to increasing the price elasticity of retail electricity as expressed in the short term. Here, price elasticity as a measure of the variation in demand as caused by a variation in price is shown to have been included in the design of EcoGrid. Price elasticity here describes the dimension of economic life which the engineered control system is set to reconfigure and manage. And in contrast to the case of increasing the liquidity of wholesale electricity, the notion of price elasticity supplied by economics helping to specify the desired outcome of market construction is here an integral part of control system and market design. Experimenting with the control of consumer conduct in EcoGrid involves training and equipping the retail electricity buyers involved, in order to have them react to the incentives presented by the new system. Emphasis is put on the ways in which providers try to make consumers both willing and able to act in accordance with the specific programme of economic action implemented through EcoGrid.

Linear programming | *Consumer and producer surplus*

Chapter 3 focuses on efforts of renewable energy integration to allow for economic experiments in a laboratory rather than a platform setting. There is thus a shift in the analysis implying the inclusion of another significantly different empirical setting. In being followed in the wild, through a platform, and into laboratories, the efforts of renewable energy integration under inquiry are located increasingly far away from an implemented solution to the intermittency problem. The analysis thus moves from documenting actual full-scale changes in the transmission system, to experimental changes in a limited part of the distribution system, to the making of prerequisites for computer-based electricity market representations.

The chapter focuses on efforts to depict an ideal Nord Pool, and is dedicated to documenting the construction and implications of a widely used software programme for electricity market representation named the Baltic Model of Regional Electricity Liberalization (BALMOREL). While discussing the making of BALMOREL, the making of an essentially mandatory source for technology data for electricity market modeling is also described. Following the making of an effectively obligatory reference stipulating the qualities and costs of energy system components in the context of public energy planning projects implies tracing the construction of the Danish Energy Agency's Technology Catalog. It is here pointed out how BALMOREL and the Technology Catalog are included in the efforts to solve the intermittency problem, through being used in the making of scenarios constituting the techno-economic inputs for building actualized energy policy recommendations regarding the reconfiguration of Nord Pool (e.g. Danish Commission on Climate Change Policy, 2010). When Nord Pool was introduced as the means to reach objectives such as equilibrium maintenance, lower electricity prices, and investment in generation capacity, it was made to play a similar role in the laboratories of Danish energy planners. Here BALMOREL helps make scenarios stipulating the format of energy system operation and configuration Nord Pool should produce in the years to come, as related to a set of quantified political, technical, and economic circumstances and requirements. Technical circumstances are typically the costs and qualities associated with energy system components such as power plants at a given point in time. These qualities and costs are in turn described in the Technology Catalog, which functions as a form of a best available technology list. BALMOREL simulates a perfectly functioning Nord Pool by operating and composing a virtual electricity market through linear programming using the General Algebraic Modelling System (GAMS). And within this setting, emphasis is placed on the way linear programming has been conceived of and developed as a form of "higher order control" (Dantzig, 1957) for the optimization of production systems. The basic functioning of this higher order control system is then shown to have been coupled with a concept of demand in the form of responsive requirements for system output in order to simulate market dynamics.

It is then highlighted that linear programming is an established generic approach to running the basic merit-order dispatch of power plants in electricity markets (e.g. Hogan, Read, & Ring, 1996). Electricity market representation is thus here based on central parts of Nord Pool and BALMOREL being the same. Considering that Nord Pool does not work as intended (e.g. Danish Energy Association, 2013), the approach to reaching the objectives set out for the market has to some extent become one of representing what Nord Pool in principle should do in order to then help realize that state of affairs through the use of policy. And the solution to the intermittency problem is an inevitable part of what needs to be realized. Insights into electricity market representation are thus important for seeing how Nord Pool's capacity for exerting control and solving the intermittency problem in the short and long run has been understood through and reinforced by means of a third kind of control system. Linear programming or higher order control is a central part of what informs various actors about how to most economically endow the electricity market with the capacity to integrate wind power (e.g. Aarhus Municipality, 2012). And for the third time, a measure from economics is shown to have been included when mobilizing a form of control system in the attempt to integrate wind power into the Danish electricity system. The notion of producer and consumer surplus is highlighted as being used to describe the criteria for optimization introduced in the design and operation of BALMOREL.

Throughout the three cases of market performation and wind power integration, economics is shown to have provided a point of reference for market design and management by describing the state of the world in need of realization. The way this has worked, specifically, is here understood by considering how conditions of satisfaction (Searle, 2001) implied in economics as a representation of markets have been incorporated into the making of objectives of market construction when introducing or improving control system operation for electricity system equilibrium maintenance. The direction of fit and direction of causation (Ibid.) of economics as a representation of an empirical state of affairs are shown to have been reversed in the process.

Summary

While describing the motivation for the present inquiry as being grounded in concerns related to the problematic effects stemming from fossil fuel-based energy systems, a backdrop for the study was provided. A historical context for better understanding the subsequent description of the technical aspects of the intermittency problem was then provided. After noting how the liberalization of electricity in Denmark established the electricity market as the framework for operating and composing the Danish electricity system, an initial research question focusing on the introduction and reconfiguration of Nord Pool for wind power integration was presented: *How has the introduction and reconfiguration of Nord Pool characterized the endeavor to integrate fluctuating electricity supply into the Danish electricity system?* The making of the question and the approach to answering it were then discussed as involving a number of different components. Specifically, the empirical stance and maxim of pragmaticism were described as being actualized by means of a number of interrelated rules, techniques, and methods of research. Having clarified the position taken up in the inquiry, a body

of relevant concepts from the performativity programme of the new new economic sociology was then introduced. A conceptually informed research question explicitly focusing on the role of knowledge and expertise in the performation of Nord Pool for the integration of wind power in the electricity system was then formulated: *How have control systems engineering and economics been mobilized in the endeavor to integrate wind power into the Danish electricity system through electricity market design and management?* A short outline of the analysis addressing the issues implied in answering the research questions then demonstrated how the present study augments the performativity programme in two ways, in addition to producing insights into how the intermittency problem is being handled in Denmark. One way is to show how control systems engineering, being a form of expertise previously unstudied by the performativity programme, has played a crucial role in the making of a series of markets. The other is to show how economics, being a form of expertise studied extensively by the members of the performativity programme in other empirical settings, has had heretofore undescribed functions.

Homeostatic control | Liquidity

> Homeostasis is a biological term referring to the existence of a state of equilibrium…between the interdependent elements of an organism. It is appropriate to apply this concept to an electric power system in which the supply systems and demand systems work together to provide a natural state of continuous equilibrium to the benefit of both the utilities and their customers. A set of interrelated physical and economic forces maintains the balance between electric supply and customer load
>
> (Schweppe et al., 1980, p. 1151)

> …the objective is to make the electricity market liquid, so it will be able to incorporate the increasing amounts of electricity from renewable energy
>
> [Author's translation] (Energinet.dk, 2012a, p. 12)

To describe the particular way control systems engineering and economics have been mobilized as part of a process of market construction when integrating wind power into the Danish electricity system, we must first establish several facts. It is initially shown how the liberalization of electricity and Denmark's entry into the Nordic wholesale electricity market implied introducing a new form of control device for maintaining the crucial equilibrium in the electricity system. Homeostatic utility control came to replace the overall supply follows demand approach to equating input and output, as the equilibrium of the electricity system was displaced into the equilibrium of the electricity market. Nord Pool is highlighted as being an engineered market conceived of, implemented as, and functioning as a control system. In this way, the empirical scope of the performativity programme is augmented by pointing to control systems engineering as a generative form of expertise in market design and maintenance. The chapter then unfolds how the introduction of Nord Pool in Denmark brought with it a specific way of understanding the intermittency problem and how it could be solved. Wind power integration became a matter of electricity valuation in terms of how low, zero, and negative prices paid for electricity generated by wind turbines were to be avoided. We then see how ensuring the value of electricity generated by wind turbines was pursued by expanding the means by which homeostatic control can be exerted. In the present case, doing so implied increasing the liquidity of wholesale electricity. As an example of this wider and established approach known as the “export strategy” (H. Lund & Clark, 2002), the making of a new transmission system interconnector is described. By making an addition to the electricity grid, the ability to trade electricity produced by wind turbines was increased and the tendency to produce low, zero, or negative prices diminished. Increasing the liquidity of electricity generated in an area relatively rich in wind turbines meant that more resources for absorbing fluctuations in electricity generation became available. As a metric, liquidity was used to describe an objective or outcome to be reached by expanding the material infrastructure of Nord Pool and letting the market exert homeostatic control. The empirical scope of the performativity programme is in this way extended again, this time by noting how economics is included in market design and management by helping to describe an outcome to be realized by means of constructing a control system in the form of a market.

To clarify how the present form of wind power integration works, the wider Nord Pool arrangement will be introduced. The more general aspects of the Danish electricity market are described by following the conceptual components informing the engineering of a homeostatic control system and their actualization through the liberalization of electricity. Tracing the introduction and reconfiguration of Nord Pool as related to wind power integration here constitutes the first of three examples of how control systems engineering has been a generative form of expertise in market performation. Similarly, the present chapter provides the first of three examples of approaches to wind power integration where economics is shown to have supplied a measure used in conceiving of a state of the world to be actualized by market construction for the introduction or improvement of control system operation.

Introducing Nord Pool

The making of a market for electricity in Denmark was part of a bigger wave of liberalization in the European Union (EU) starting in the 1980s. Under the banner of the single market, the electricity sector was liberalized along with other traditional monopolies such as air travel, rail, and telecommunications. At the time, having market forces organize supply and demand was seen as the solution to the economic recession (Frederiksen, 2012) following a financial crisis which was in many ways reminiscent of the one which occurred in the latter half of the 2000 decade (Østrup, 2011).

The first concrete document on the liberalization of electricity was a 1988 Green Paper by what is now the European Commission. In this document, two ways into the 'deregulation' of the electricity sector were outlined. One suggestion was to open up all publicly accessible electricity grids to third parties, thus dissolving the monopoly of the established electricity companies. The other was the process of unbundling the vertically integrated companies, separating production, transmission, and distribution. And in spite of its formal status as an input for debate, the Green Paper "…predicted what later happened in a fairly detailed fashion" [Author's translation] (Hoffmann in Petersen & Rüdiger, 2009, p. 53).

The attitude towards liberalization, on behalf of the actors in Danish the electricity sector, seems to have been marked by a complicated array of technical, legal, ethical, and financial considerations for and against trading electricity in a market. Some of the main issues were technical feasibility, fairness in international competition, and the fact that Denmark had some of the lowest electricity prices in Europe. Whilst not being explicitly against the principle of liberalization, the industry most often took a hesitant stance on the subject, in part as a result of not being able to settle the questions it raised in a manner which could be commonly agreed upon (Petersen, 2009). In contrast, the Danish government, led by the Social Democratic party, had at the time managed to reduce its focus to two main aspects of liberalization. And against that backdrop, the liberalization of electricity was not seen as much of a practical problem. As put by the then-Danish Minister of Environment and Energy:

> We had a double opinion I would say. A strong apathy towards the basic way of thinking involved in neoliberalism. Conversely, it was easier to adjust to these changes in Denmark than in other places, because we have so few regulated sectors compared to other countries. We have very little state-owned industry, actually the least within the EU. So that is why we, in the Danish Social Democrats, when we had

> to take a stance on the matter of this new and growing phenomenon, we found that we did not like the sound of it, but also that we in many ways already had a society like that
>
> [Author's translation] (Auken in Petersen, 2009, p. 209)

Another significant factor was the Danish electricity sector's close collaboration with Norway and Sweden. Significant amounts of electricity had been transmitted between the three countries long before the idea of a Nordic electricity market was launched. There were strong professional ties between the centralized actors in the Scandinavian electricity sectors, which were allied in the cooperative then called Nordel. Fueled by interests and ideas such as those of the liberal government named Syse, along with the problem of how to price the large amount of cheap electricity available from different forms of hydropower (Bach, 2013), the Norwegian electricity sector was the first in Europe to introduce an electricity market of the sort now so widespread; that is, a market using spot prices. When Sweden joined soon after, the skepticism of the Danish electricity sector was challenged (Petersen & Rüdiger, 2009).

Supplementing the wider move towards liberalization in Europe, a number of domestic factors also had a role in facilitating Denmark's entry into the Nordic wholesale electricity market. As in the neighboring countries, the electricity companies were to unbundle production, transmission and distribution. In 1998, the electricity supplier of western Denmark, Elsam, was split up and a new company named Eltra became the transmission system operator of western Denmark. In eastern Denmark, the organization named Elkraft was split to form Elkraft System and Elkraft Transmission in 2000. Here Elkraft System was made responsible for system operation while Elkraft Transmission took over grid development and maintenance. The electricity sector's unbundled TSOs were then set to be merged with the gas infrastructure responsible Gastra in order to form Energinet.dk. In 2005, Energinet.dk was formed as a single Danish state-owned transmission system operator. Some of the parties involved in the merger sensed that the placement of the new headquarters of the organization could be controversial, as it would mean that many employees would have to move or find new jobs. This anticipated conflict of interest was later realized (e.g. H. Ø. Pedersen, 2012; Lindboe, 2013).

It was within this context that Eltra chose to have western Denmark enter Nord Pool. Within Eltra, Denmark's entry into Nord Pool was seen to be more or less inevitable. And helped by a company president who had few reservations about the use of markets, Eltra initiated the process of market entry to show that it was already handling the challenges of the future. Importantly, this was done to suggest that Energinet.dk would be best based in western Denmark. The same group of people from Eltra also understood the entry into Nord Pool as a confirmation of Eltra's commitment to Nordel. In contrast to countries such as Norway, where the law around liberalized electricity was a central reference point in the process of making the market arrangement, western Denmark ended up entering Nord Pool before a Danish legal framework was in place. The ambition was to have the market arrangement approved post factum in the final Danish legislation, which it was (Bach, 2013; 2007).

Entering Nord Pool

Having touched upon some of the factors which led to the introduction of an electricity market in Denmark, we now move our focus to the design, implementation, and functioning of Nord Pool. Doing so involves outlining some of the conceptual materials and ideas implied in the making of a system for homeostatic utility control in the form of an electricity market. By drawing on an outline of control systems engineering and homeostatic utility control along with the way these notions have been implemented in Denmark, the workings of wind power integration as a process of market performation can be illustrated. The approach to wind power integration is in this way mapped by documenting how an electricity market and homeostatic control system was introduced and how its capacity for maintaining equilibrium between input and output was increased.

In this first of three cases, increasing the ability to control electricity input and output meant following the often-applied strategy of building transmission system interconnectors. Making a description of how this works entails a brief elaboration of how electricity system operation came to imply running an electricity market. Describing this move makes it possible to see how price analysis became significant for understanding the character and scope of the intermittency problem, along with the means for how it could be solved; that is, how wind power integration was conducted through electricity market construction.

The shift to operating the Danish electricity system by means of Nord Pool can be seen as imposing one established equilibrium-based system on another. When Denmark entered Nord Pool, the achievement of equilibrium between input and output in the electricity system became equivalent to attaining equilibrium between supply and demand in the Nordic wholesale electricity market. Electricity system operation was transformed into the running of an electricity market. It is here worth briefly elaborating on this frame, as the work done to strengthen homeostatic control by increasing the liquidity of wholesale electricity produced by wind turbines depends on it.

Trading electricity in Nord Pool is facilitated by means of a series of different auctions and price- setting mechanisms, which makes talk of Nord Pool as a single market overly simplistic. These auctions and pricing schemes are made to complement each other so as to ensure the achievement of equilibrium at any moment in the operation of the electricity system. In looking at how Nord Pool works, it should be stressed that running the electricity system by means of a market is not in every way different from how it was undertaken before liberalization. Operating the electricity system by means of central planning was in several ways as much an economic undertaking as running it by means of market coordination is. Entering Nord Pool implied a number of changes, but elements such as the basic algorithm for merit-order optimization amongst power plants remained the same (Bach, 2013). Cost and price analysis had long been established as procedures included in the way the Danish electricity system was operated. And building transmission system interconnectors in order to have the power plants with the lowest costs, such as wind turbines, deliver electricity as cheaply as possible to as many consumers as possible is no more a feature of the electricity market than of central planning (e.g. Thostrup, 2013) (See Boiteux (1960) for a discussion of merit-ordering power plants according to expenditure or marginal costs associated with production under a central planning regime).[2]

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[2] Boiteux here interestingly also describes "Peak-load pricing", which was an early attempt made by Electricité de France to introduce variable tariffs reflecting differences in the costs associated with electricity production at various loads. These tariffs worked to change the

The way Nord Pool works resembles central planning in several ways. A good example is found in the auction known as the spot market. By incorporating the uniform pricing principle in a blind double-sided auction, an arrangement is made which in principle should ensure that electricity suppliers will provide asking prices corresponding to "…their marginal opportunity costs of energy in each of the blocks of power that they offer" (Kahn, Cramton, Porter, & Tabors, 2001, p. 72). The important point to take away here is the fact that the way the market was constructed enabled the reuse of the merit-order optimization established prior to liberalization. The algorithm at the heart of the Danish electricity market is the same as the algorithm at the heart of central planning. By making a market arrangement facilitating a stream of asking prices reflecting the costs associated with electricity production, giving priority to the cheapest electricity producers could be done using the same algorithm. And the mechanism for merit ordering or sorting suppliers is based on running a linear program (Hogan et al., 1996; Pinson, 2014; see chapter 3). In this way, the change in electricity system organization which was realized when Denmark entered Nord Pool did not imply going from a non-economic to an economic mode of operation. It implied moving from one economic arrangement to another. Marketization is of course only one way among many by which "…objects are constituted as being 'economic'" (Çalışkan & Callon, 2010, p. 2), but in the case of Danish electricity system operation these two modes were not entirely different.

The change in the organization of electricity system operation from central planning to market coordination was, with respect to the supply side, a matter of reconfiguring the arrangement for doing marginal cost-based economic calculations and producing merit-ordered production schedules. In accordance with the arrangement described in the upcoming section about price-setting in

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timing of consumption in a way that was better suited to the material properties of the available production facilities. The argument for introducing homeostatic control systems in the form of electricity markets will soon be shown to have been based on the same concern. The founders of the idea of using electricity markets for homeostatic utility control have also pointed out how some of their equations for calculating prices in the market were inspired by and similar to the tools of central power system operators (Schweppe, Caraminis, Tabors, & Bohn, 1987, p. 175).

Nord Pool, initial market entry implied that the responsibility for doing economic calculations was redistributed from the once-centralized Elsam, to the unbundled electricity system actors in western Denmark. Rather than have Elsam do economic calculations to minimize the costs of running the electricity system by dispatching electricity from the plants with the lowest costs, buyers and sellers would now do economic calculations in order to digitally circulate asking prices and bids. These bids and asking prices would be taken into account and paired by Eltra using a database program named Panda (e.g. Wiegand, 1999) to make a merit-order optimized list associating prices with points in time at which buyers and sellers would be obliged to consume and produce specified amounts of electricity. In order to understand much of the basic functioning of Nord Pool, it can be helpful to keep the ties with central planning in mind. Some auctions help maintain equilibrium between input and output by having buyers and sellers commit to generating and consuming specific quantities of electricity at various points in time. They are the markets within Nord Pool based on 'scheduling' (Østergaard, 2013). There is thus still a common reference to some of the electricity markets within Nord Pool as mechanisms for 'planning' who will buy and sell a specified amount of electricity every hour of the year (e.g. L. H. Rasmussen, 2011). However, there are also other markets in Nord Pool which function differently, due to their having to operate within shorter time frames. Here other methods are applied, as in these markets there is no time for the ongoing scheduling of equilibrium.

Eltra had two main references in learning how to go about making these changes in electricity system operation. One was the practical experiences of their Norwegian colleagues in Nordel. Eltra 'copied' as much as they could, and a lot of what they came to know they learned from their collaborators to the north. Eltra's other main source of inspiration in making electricity market equilibrium imply electricity system equilibrium was the book *Spot Pricing of Electricity* by Fred Schweppe, Michael Caraminis, Richard Tabors and Roger Bohn, published in 1987. Often called 'the yellow bible' (Bach, 2013), *Spot Pricing of Electricity* constituted an abstract and conceptual form of input for market construction. The material for the publication was produced over a number of years by a group of engineers at the Massachusetts Institute of Technology participating in a working group on homeostatic control in power systems (Schweppe et al., 1987). The book introduced a number of ideas which in aggregate form the notion of spot pricing of electricity (SPOE), and was written as a manual for market construction, providing instructions for how to organize an electricity market framework. Significantly, the basis for conceiving of electricity markets through SPOE is homeostatic utility control (e.g. Schweppe et al., 1980; Tabors, 1981). And as will be made clear, this form of control was adopted with the introduction of Nord Pool. However, the full range of ideas implied in SPOE were not introduced in Denmark. SPOE implies having the TSO centrally calculate prices by taking into account demand, costs associated with running available power plants, and the transfer capacities of the grid, and then having buyers and sellers trade among themselves. Instead, the notion of homeostatic utility control was introduced in a format similar to locational marginal pricing (e.g. Hogan et al., 1996). Here homeostatic utility control is actualized by having the TSO run auctions and pricing arrangements mainly based on asking prices and bids made by the suppliers and buyers.

Two market aspects which Eltra copied from their Norwegian colleagues were the making of a stakeholder forum and a monthly market report (e.g. Bach, 2007). The stakeholder forum arrangement was inscribed in the draft document of founding principles of the new and recently unbundled TSO, stipulating that the forum was introduced to ensure an ongoing dialog with relevant actors. The forum contained between 12 and 14 members with different roles and interests in relation to the electricity sector, ranging from members of the Danish Parliament to representatives from the new distribution companies. The forum functioned as a central medium of communication between the different actors, and helped to build understanding and legitimacy around the introduction of the market. The idea of having a stakeholder forum was even made part of the law of Energinet.dk when the TSOs covering eastern and western Denmark were later merged (Danish Ministry of Climate, Energy and Building, 2011a). Communication and agreement related to the new routines and roles for buyers and sellers in the market were also aided by the ongoing shared ownership and established history between various actors. The new distribution companies, which were to be some of the biggest buyers on the wholesale market alongside large companies from the energy intensive industry, owned the new TSO of western Denmark and the six central power plants in that area. Thus, even though the organization was formally unbundled into various parts, the people involved and the overall ownership of the various entities remained one and the same. These close ties led some to point out the potential for a lack of conflicting interests and competition involved in the arrangement (e.g. Fastrup, 1997). The monthly market report included graphs and written accounts about the development in prices and the amounts traded. It was sent out in order to create insight into the way the market worked. These efforts resulted in an arrangement which functioned in basically the same way as Nord Pool does today.

Having pointed to some of the many aspects of the making of an electricity market in Denmark, emphasis can here be placed on the involvement of different forms of knowledge in electricity market design and management. Specifically, expertise is described as coming from control systems engineering and economics. These two inputs for electricity market performation are shown to be particularly important for understanding how wind power has been integrated into the Danish electricity system. It is by considering the role of control systems engineering and economics in wind power integration through electricity market construction that the performativity programme is supplemented in two ways. On one hand, control systems engineering is shown to be a generative form of expertise in market design and management. In the context of Nord Pool, electricity markets are conceived of and implemented as control systems for maintaining equilibrium in the electricity system. On the other hand, economics is shown to be included in the process of market construction by providing a measure used to describe an outcome or objective to be reached by means of market construction improving control system operation. In this first case, attention is directed towards the idea of homeostatic utility control. Touching upon the ideas implied in homeostatic utility control will help clarify the concrete configuration of the Nord Pool market arrangement as a form of control system. And pursuing wind power integration as a matter of increasing the liquidity of wholesale electricity or the means by which homeostatic utility control can be exerted will begin to make sense against this backdrop.

Control

To see how homeostatic utility control by means of a series of interconnected auctions and pricing arrangements under Nord Pool has been implemented to maintain equilibrium in the Danish electricity system, we will begin with an introduction of the way the concept has been developed. This short primer should also serve as a wider background upon which to understand the issues related to the notion of control throughout.[3]

Originally, the word ‘control’ referred to a comparison of actual and intended behavior. However, the contemporary use of the term by engineers was described in noting that “…when applied to technology it is used in the more active sense of bringing them together” (Nightingale, Brady, Davies & Hall, 2003, p. 484).[4] Involving a form of applied mathematics, engineered control systems are used to regulate things as diverse as liquid levels in chemical plants, the movements of elevators, or the angles of telescopes. Due to its wide applicability, the making of control systems is a subject which spans a number of different disciplines including electrical, mechanical, aerospace, and chemical engineering.

Control systems consist of subsystems and processes, with processes also known as plants. These subsystems and processes are arranged for the purpose of controlling the outputs of the plants. A control system basically facilitates an output or response in reaction to a given input or stimulus. To introduce some of the terminology of control systems engineering, the example of a room temperature control system can be considered. Apart from providing a simple point of reference, the idea of a room temperature control system is also relevant due to how similar arrangements have been included as subsystems in Nord Pool recent attempts at introducing new means for equilibrium maintenance through homeostatic utility control.[5]

In the type of control system which is typically involved in regulating the temperature of a room, the plant could be a furnace and the subsystems could

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[3] The following elaboration may seem excessive, but it is necessary because this explication of the ideas involved in the making of control systems will have been put to full use by the end of the thesis.

[4] As a specific part of the technical sciences, control systems engineering to a great extent developed out of what has become known as ‘cybernetics’. For nuanced accounts of this intellectual and practical movement see Hacking (1998) and Pickering (2002; 2010). For a history of the intertwined relationship of cybernetics and the discipline of economics see Mirowski (2002). For an original statement about cybernetics see Wiener (1961).

[5] The actual use of room temperature control systems will be described in chapter 2.

include a potentiometer and fuel valves. The potentiometer features a dial indicating temperature, and has the capacity to convert the position of the dial into a control signal in the form of a specific voltage in an electronic circuit. Due to this function, the potentiometer is known as an input transducer in the room temperature control system arrangement. The signal from the potentiometer regulates the setting of the fuel valves, which here constitute the controller subsystem. The fuel valves control the workings of the plant or furnace, which in turn adjusts the temperature of the water circulating in the radiators. The radiators in turn produce an output in the form of a specific room temperature. A control system is in this way set in place to realize a desired response in the form of a specific room temperature, by producing an actual response in the form of the desired room temperature following from the regulation of the furnace via the fuel valves as based on the setting of the potentiometer. Control systems are generally engineered to bring about one or more practical advantages in certain situations. The reasons for making control systems can be summed up as the possibility for power amplification, remote control, convenience of input form, and compensation for disturbances (Nise, 2004). For example, remote control and convenience of input form are practical advantages of the above-mentioned room temperature control system. Rather than going to the boiler room and manually putting fuel in the burner, room temperature can be conveniently adjusted by regulating the behavior of the furnace through the turn of a dial at a distance.

The distinction between open-loop and closed-loop control systems (e.g. Dounis & Caraiscos, 2009) also needs to be introduced. What distinguishes an open-loop from a closed-loop control system is that a closed-loop control system is characterized by the capacity to automatically compensate for disturbances which distort the output of the system. A disturbance in an open-loop control system, such as the one described above, can be found in the form of a change of seasons. The difference between requested and actual behavior known as steady-state error in situations where the system has had the time to make the requested changes will vary with the seasons in an open-loop room temperature control system. Thus, in the example provided above, changes in the weather are not compensated for. In this way the setting of the fuel valves which leads the furnace to viably produce a specific room temperature varies between summer and winter. This difference is in turn due to how the temperature outside influences the temperature inside. Even though the dial on the potentiometer would be set to 21 degrees at all times, it would not lead to the same result during both summer and winter. If the control system was calibrated on a relatively warm day, the actual room temperature realized when having the dial set at 21 degrees on a cold day would be relatively lower. The disturbance in the form of a higher degree of cooling of the building and system implies that the input involved in turning the knob to 21 degrees now only leads to an output room temperature of, say, 17 degrees.

The points in the system where disturbances are incurred or corrected are known as summing junctions (Nise, 2004). Closed-loop control systems are also called feedback control systems due to how they can measure and correct the final system output, also known as steady-state response, and negate steady-state error. In other words, closed-loop control systems can make up for a distortion in output caused by the various disturbances which may occur. This can be achieved by adding a sensor or output transducer which measures the actual output, also here known as the controlled variable. The output transducer is placed in a feedback loop connected with a summing junction between the input transducer and the controller. The signal from the output transducer and the input transducer is then compared in the summing junction. If there is a difference in the message contained in these two signals representing desired and actual behavior, the difference will be added to the signal leaving the summing junction. The modified signal thus serves as a corrected form of input for the controller. The controller then drives the plant in a way that negates the difference between actual and desired behavior and in the end making up for the disturbance. Converting the open-loop room temperature control system into a closed-loop control system could be done by adding a thermostat. The thermostat would use a form of thermometer to measure the output. It would then convert this measurement into a signal running back along the feedback path through the summing junction and into the controller, and this would make the controller adjust the amount of heat produced by the furnace if needed. The process managed via the feedback loop would in turn bring input and output closer together, negating the effects of disturbances, for example, in the form of a change in outside temperature.

Having very briefly and selectively introduced key elements of control systems terminology, the focus can now be turned to how control systems have been applied in the maintenance of the equilibrium between consumption and generation in electricity systems. In briefly elaborating on the historically established means of control regulating electricity systems, the intermittency problem is revisited as an equilibrium control issue.

A supply follows demand philosophy

In spite of their many historically apparent and differing characteristics (e.g. Hughes, 1983), electricity systems in industrialized countries have traditionally been constructed and operated to accommodate the requirement of equilibrium in a specific way. The initially established approach to configuring and operating electricity systems implied what has been called a "supply follows demand philosophy" (Schweppe et al., 1980, p. 1151). Under this arrangement originally run by means of central planning, the buyer pays a pre-specified, constant, and seldom updated price per KWh for the right to consume any amount of electricity. Supplementing the use of production planning, a series of control system arrangements is deployed as part of this approach to electricity system operation in order to maintain the crucial equilibrium between generation and consumption. Whereas the exemplary closed-loop control system described above used temperature measurements for feedback and control of the heat level in a room, these systems use the frequency found in the electricity system as the controlled variable. Doing so is possible due to the fact that system frequency accurately reflects the balance between generation and consumption. When generation is less than consumption, system frequency decreases. When generation is greater than consumption, system frequency increases. After defining a desired steady state in the form of a standard frequency at for example 50 Hz, deviations or steady-state errors in either direction point out the precise need for up- or downwards regulation of the system. Frequency control systems can involve an active human element by having an operator monitor system frequency and manually adjust electricity production from a specific regulating unit. However, a more contemporary and widespread approach to realizing the overall idea of having thermal power plants turn production up and down in accordance with demand is found in the form of various Automatic Generation Control (AGC) systems:

> AGC function is essentially a supervisory control function which attempts to match the generation trend within an area, to the trend of the randomly changing load of the area, so as to keep the system frequency…An AGC system monitors the system frequency and the

> tie line flows, computes the net change in the area generation required (generally referred to as area control error, ACE) and changes the set points of the generators within the area so as to keep the time average of the ACE at a low value
>
> (Imthias Ahamed, Nagendra Rao, & Sastry, 2002, p. 9)

Providing buyers with the right to consume a limitless amount of electricity and pay a pre-specified, constant, and infrequently updated price per KWh while running AGC systems in a way which implies that supply follows demand, has been understood to have a series of unfortunate implications. These undesirable effects were highlighted in the effort to create and present new ways of controlling electricity systems, and they were generally related to two issues. One is the way responsibility for maintaining equilibrium in the system is taken on by the TSO alone. The other involves the manner in which AGC systems are applied to support a form of one-way communication between suppliers and consumers. In these types of systems, one-way communication was what structured the everyday operation of the electricity system. Changes in consumption leading to variations in frequency were fed into the control system governing production. Concrete issues brought up in this context have been laid out in five related points (Schweppe et al., 1980). The five points can perhaps be most readily understood when considering that they are supposed qualities of market coordination, which the established AGC-type alternative was criticized for lacking.[6]

The first point to note is that as AGC-type systems present no framework or incentive to help predicate consumption on anything but the will of the consumer, the arrangement produces a higher than necessary need for quick load following and large spinning reserve margins. Spinning reserve is an extra capacity power plants would have to have, in order to be able to quickly ramp up and meet

[6] These ideas will thus perhaps not be at their clearest before they are seen in the light of the idea of electricity markets exerting homeostatic control (e.g. Schweppe et al., 1987). As will be apparent from the description of the functioning of Nord Pool and the EcoGrid market arrangement, AGC-type systems still play an important part in maintaining equilibrium in the Danish electricity system as they are still part of the larger homeostatic control system. Within Nord Pool, these types of control system markets are used in situations where there is a need for upwards or downwards regulation but not enough time for asking, bidding, and scheduling a reaction.

demand. A large spinning reserve margin in turn implies an inefficient use of fuel. A related issue was that the supply follows demand set-up required a large and expensive amount of often unused reserve capacity to meet peak demand. As the arrangement did nothing to influence consumption in a specific direction in the short term, the ratio between average and peak demand was deemed to be greater than necessary. The routines and decisions of electricity consumers were left uninfluenced by the state of the system, and this has been taken to lead to an undesirable degree of volatility in consumption from a systems perspective. A third aspect was that flat prices were seen as discouraging select forms of energy conservation and consumer side generation. Yet another critique was launched by pointing out that as the consumer was oblivious to the state of the electricity system, system operation became more vulnerable to short- and long-term emergencies such as blackouts and coal worker strikes or oil embargoes. Even if electricity consumers had wanted to help maintain equilibrium and avoid system breakdown, they would have had no means of knowing how to mobilize consumption. Lastly, it was stressed as problematic that decisions to consume electricity were isolated from the real costs of production, and that generation companies were isolated from the effects of competition.

When considering that the latter part of this final issue was originally raised mainly by authors from the USA, it is worth noting that utility companies there have long been privately owned. This stands in contrast to the traditionally state-owned and state-run Danish electricity system. But around the time when the Danish electricity sector was liberalized, the general argument was made to apply in a Danish context as well. The supply follows demand philosophy and AGC-type system as outlined and criticized in the very influential work on electricity markets by Fred Schweppe and his co-authors have to a great extent been replaced in Denmark. Since the liberalization of electricity in Denmark, approaching the maintenance of electricity system equilibrium has been done by a different means of regulation originally introduced under the heading of homeostatic utility control (Schweppe et al., 1980). And due to how homeostatic utility control has become the main approach to maintaining equilibrium in the Danish electricity system, it constitutes a central aspect of the framework within which the problem of wind power integration presents itself. For these reasons, the notion of homeostatic utility control and the intermittency problem will here be addressed in concert.

Homeostatic utility control

The main equilibrium control issue associated with increasing the proportion of wind power in the electricity system becomes apparent when revisiting the characteristics of electricity production by means of wind turbines. The power plant operator can only turn down electricity generation; it cannot be increased without an increase in wind speed, which has to be kept below a specified maximum. And still, a wind turbine only works within a specific wind speed spectrum. At average wind speeds, which are the most common and hardest to forecast, electricity generation is exponentially related to wind speed, which implies that relatively small changes in wind speed will lead to relatively large changes in electricity production. Considering these specific characteristics of electricity production by means of wind turbines, it becomes apparent that an increase in wind power generation requires additional resources for the maintenance of equilibrium in the electricity system. When compared with a general characterization of situations in which control becomes increasingly important, it becomes apparent that wind power pushes all the buttons:

> Control is required when a match between actual and intended performance cannot be reliably maintained. Typically because requirements change or cannot be designed-in. For example, performance might change over time due to changing inputs or outputs; it might involve processes which disproportionately amplify small differences in inputs; it might require optimization or fine-tuning in use; or performance may be too complicated to predict *ex ante*. In these instances, control systems monitor, compare and modify the inputs and parameters of various subcomponents in a coordinated way to ensure that the system behaves as intended
>
> [Italics in original] (Dorf & Bishop in Nightingale et al., 2003, p. 484)

Increasing the proportion of electricity produced by wind turbines thus conflicts with the supply follows demand philosophy by augmenting the above-mentioned problems associated with wind power production. As a larger part of electricity production becomes bound to the wind, the provision of the resources for maintaining equilibrium in the system becomes increasingly expensive and wasteful. One way to solve the control problem would be to reverse the mode of electricity system operation, and have consumption follow production by implementing a centrally run "demand follows supply" concept (Schweppe et al., 1980). By creating a frequency control system with the capacity to regulate consumption for various purposes and taking it to the extreme, equilibrium in the electricity system could be maintained by starting and interrupting the use of electricity in different instances. All power plants could by means of such an approach be run in the most efficient manner, and the system would be resilient to short-term and long-term contingencies. Such an approach would in turn present new challenges for the consumers, who would have to adapt their routines and general modes of consumption.

The current approach to frequency control in the Danish electricity system does not prescribe that supply only follows demand or vice versa. Since electricity was liberalized in Denmark, the principal method guiding frequency control has involved trying to encompass both these seemingly opposed approaches. Approaching the control problem from both sides in Denmark implies an effort to facilitate the mutual adjustment of generation and consumption by means of homeostatic control (Schweppe et al., 1987). From the perspective of the system operator, the general argument is that:

> …Homeostatic Utility Control can offer a set of advantages of both 'supply follows demand' and 'demand follows supply' while avoiding the majority of their major pitfalls. It offers a continuous accommodation of the utility and the customer to achieve stability and to minimize costs through a price-guided process…
>
> (Schweppe et al., 1980, p. 1152)

Homeostatic control implies operating the electricity system by means of an electricity market. And this in turn points to the central focus of the present inquiry. This study is about the work involved in using and enabling homeostatic control to solve the intermittency problem, as described by providing three particular empirical accounts. The three examples show how electricity markets have been introduced, changed and represented in the effort to integrate fluctuating electricity production from wind turbines into the Danish electricity system. In other words, the analysis documents three attempts to strengthen and expand the means by which homeostatic control can be exerted. Doing so implies following different efforts to change the material and conceptual infrastructure by which the Danish electricity market habitually operates the electricity system and maintains equilibrium. Doing so enables two new understandings of the performation of markets. One is made by taking into consideration the impact on market design and management made by control systems engineering in various formats. The other presents a new conception of the role of economics in market construction by demonstrating how in the context of Nord Pool, the discipline supplies measures describing the objectives applied in engineering markets for control.

In the context of electricity system control, adopting the biological notion of homeostasis implies that the equilibrium of the electricity system is displaced (Callon, 1986b) into the equilibrium of the electricity market. That is to say that the equilibrium between input and output in the electricity system resulting in the achievement of a stable system frequency was converted and inscribed into the equilibrium between supply and demand in Nord Pool, resulting in the generation of a price. Doing so involves having asking prices and bids for specific amounts of electricity at given points in time stand in and communicate on behalf of all the elements involved in production and consumption. To make the operation clear and enable an understanding of the role of control systems engineering in this first example of wind power integration by means of market construction, price-setting in Nord Pool will be discussed. Initially, emphasis is placed on how the idea of controlling power systems with price signals (e.g. Alvarado, 2005) has been implemented and actualized in Denmark. In other words, the issue is how price has come to function as a new control signal associated with the implementation of homeostatic control. For it is by demonstrating how price-setting in Nord Pool works that it becomes possible to understand how the equilibrium of the electricity system is displaced into the equilibrium of the electricity market in a way that implies that "price reflects physics" (Møller, 2006, p. 12) in Nord Pool.

Price-setting in Nord Pool

Nord Pool is owned and run by the Nordic TSOs, and in Denmark what is now known as Energinet.dk is the responsible partner. The effort to achieve equilibrium at any moment of electricity system operation starts on the Nord Pool *Spot Market*. The Spot Market is where the greater part of Nord Pool's trade takes place. Also called the day-ahead market, the Spot Market consists of a blind double-sided auction over contracts for buying and selling electricity within the 24 hours of the upcoming operating day. Every day of the year at 12:00, electricity producers and buyers make asking prices and bids for specific amounts of electricity in every one of the 24 hours of the upcoming operating day from 00:00 to 00:00. In effect, asking prices and bids are here submitted between 12 and 36 hours in advance of the moment of dispatch. For every one of the 24 hours of the upcoming operating day, buyers and sellers submit up to 62 bids, associating a specific amount of electricity with a specific price (Lykkedal, n.d.).

Asking prices and bids have to be located within a range determined by the price floor and ceiling provided by the Nord Pool administrators (e.g. Danish Energy Association, 2010). The price is set by means of the uniform pricing principle (e.g. Kahn, Cramton, Porter, & Tabors, 2010), which implies that an asking price for a specific amount functions as a seller's minimum price, and a bid serves as a buyer's maximum price for a specific amount within a specific hour. This can be illustrated with a simple example. A buyer's bid in a specific hour for 9 megawatt hours (MWh) at a price of 30 EUR/MWh implies a commitment to buy the noted amount at a price below or equaling 30 EUR/MWh, if someone is willing to sell at that price. In contrast, a producer asking to sell for example 15 MWh at a price of 29 EUR/MWh, commits to selling the noted amount at a price equal to or above 29 EUR/MWh, if someone is willing to buy at that price. When bidding closes, the merit-order calculation ensures that the producers with the lowest asking prices are prioritized as sellers in a given hour. The sorting process implies an optimization by means of running a linear program (Pinson, 2014) and continues until the aggregate demand has been met by the lowest-priced offers to sell. That is, to the extent that there are asking prices which are lower than or equal to the bids to buy (see figure 1).

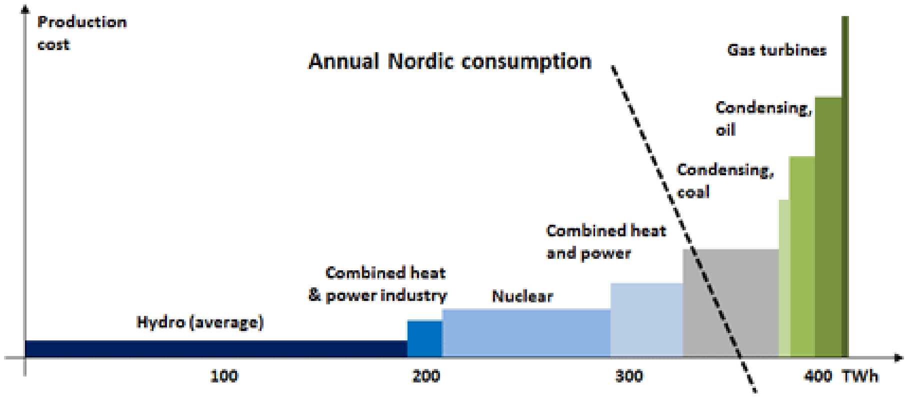

Figure 1. A stylized representation of price-setting in the Nord Pool Spot Market (Nord Pool Spot, 2015, p. 1)

The hourly price of electricity paid to all suppliers is then set by the marginal electricity producer. The marginal supplier is the producer with the highest minimum asking price, who is still 'within merit' in the sense of not asking a minimum that is higher than the highest maximum bid to buy. By 13:00, the TSO sends out information about the amounts traded and at what prices they have been traded, for the upcoming 24-hour operating day. Having the market price correspond to the asking price of the marginal producer in principle ensures that offers to sell are equal to the marginal opportunity costs of the individual supplier. Asking the costs of production makes sense in the context of a double-sided blind auction using the uniform pricing principle, because it helps to make sure that the asking price is within merit while not being so low as to imply a potential loss:

> They [the suppliers] know that if any of those bids is rejected because there are lower bids sufficient to satisfy the demand, they will be better off, because they will not have committed themselves to sales at prices that fail to cover their avoidable costs. More important, they know also that on their accepted bids they will receive the full benefit of whatever price above that level is necessary to equate demand and supply in the market, regardless of the level of their own bids, permitting them to pocket the difference between their avoidable costs and the market-clearing price as a necessary contribution toward recovery of their fixed charges and profits
>
> (Kahn et al., 2001, p. 72)

In doing the merit-order calculation to select and prioritize asking prices and bids, grid connections also have to be considered. In spite of the transmission system having been expanded over the years, the capacity for transporting electricity is not limitless. To take this factor into account, auction prices are set within 14 demarcated zones throughout the member states of Nord Pool. Thus, even though the Nord Pool arrangement presents itself as operating as a single electricity system by means of one market, limitations in grid capacity along with differences in production and consumption profiles imply that prices will vary between zones. When congestion occurs, not enough electricity is transferred in order for the market to be able to even out prices between the zones, despite the fact that reaching a single system-wide equilibrium between supply and demand could have been done if the transmission capacity was adequate. The making of multiple prices within the Spot Market of the Nord Pool exchange is called market splitting (e.g. Energinet.dk, 2013b). In this way, prices on the electricity market are dependent on more than supply and demand expressed through asking and bidding as suggested by a standard uniform-price auction.

Within Nord Pool, the arrangement of pricing zones and transmission capacity is of major importance. What is more, the fact that the material market infrastructure of Nord Pool plays a central role in the way wholesale electricity prices are produced is a key point in the understanding of how wind power has been integrated into the Danish electricity system by increasing liquidity or the ability to trade. Increasing the liquidity of electricity produced by wind turbines was accomplished by expanding the transmission capacity between the wind power-intensive electricity pricing zone named DK1 in western Denmark, and the considerably less wind power-intensive pricing zone named DK2 covering eastern Denmark. However, in order to understand how the liquidity of electricity generated by wind turbines was increased, it is important to see how a solution for the intermittency problem was constructed within the wider Nord Pool framework.

Adjacent Nord Pool markets

The Spot Market enables the making of contracts containing production and consumption schedules between 36 and 12 hours in advance of dispatch. Promises are made and equilibrium is scheduled or planned. But things do not always go according to plan, and events disrupting the contracted production or consumption schedule can easily occur in the time between the making of a contract on the Spot Market and the actual dispatch of electricity (e.g. Energinet.dk, 2013c). Hence the motto of the founders of homeostatic utility control: "The forecast is always wrong!" (Schweppe et al., 1987, p. V). Here the intermittency problem associated with volatile electricity production surfaces in the electricity market context. Considering that wind speed forecasts up to 36 hours in advance are quite uncertain (Danish Energy Agency & Danish Ministry of Taxation, 2009b), that they are the most uncertain at the most frequently occurring middle wind speeds (Ibid.), and that electricity production from a wind turbine varies exponentially with wind speed (e.g. Dong Energy, 2013) except at the very maximum and minimum wind speeds, the problem associated with an increase of wind power in an electricity market context becomes clear. It is a problem related to increasing the number of generation units where the operators have a hard time making and living up to the promises implied in their offers.

To handle deviations from the schedules agreed upon in the Spot Market, the supply and demand side can enter the intra-day market named *Elbas*. After the Spot Market closes, contracts for the scheduling of production and consumption in the same hours of the upcoming operating day can be negotiated via Elbas, which opens at 14:00 (Energinet.dk, 2013b). Asking and bidding is possible up until an hour before the operating hour, and buyers and sellers can operate in Elbas between 1 and 34 hours in advance of dispatch. The intra-day market thus enables market participants to minimize deviations from the production and consumption schedules set on the Spot Market. If for example an electricity supplier operating a wind turbine expects to be producing more or less than the original prognosis suggested, or an electricity buyer has over- or underestimated consumption by clients in the retail market, it is possible to buy or sell the difference in the after-market (e.g. Bregnbæk, 2012a). When entering Elbas, the price-making mechanism of the market changes (Møller, 2006). The uniform-pricing principle which lets the marginal power plant set a single price is changed in favor of the pay-as-bid principle (Energinet.dk, 2013b), also known as a discriminatory auction. The major change in the price-making mechanism is found in the way the market price for electricity in a specific hour is set by means of calculating an average from the asking prices circulated by the producers 'within merit' who are then paid their asking price.

Despite the fact that Elbas enables market participants to trade their way towards the obligation made in the Spot Market, it is still not sufficient to ensure equilibrium between supply and demand at any given moment of dispatch. The final steps toward equilibrium are realized through the use of a series of different price-making arrangements collectively called the *Balancing Market* (Ibid.). In contrast to the Spot and intra-day markets, the balancing market is characterized by market actors dealing only with the TSO Energinet.dk. A significant part of the balancing market is made up of what is called the *Regulating Power Market* (Bang, Fock, & Togeby, 2012). The regulating power market is where the actual final trade with electricity for balancing supply and demand takes place. In the regulating power market the TSO buys upwards and downwards regulation services from select electricity consumers and producers. The market works by means of a double-sided blind auction and the uniform-pricing principle applied within the established pricing zones, as on the Spot Market (Energinet.dk, 2008a).

The arrangement of the regulating power market has taken a number of different forms over the years, and has even simultaneously differed between pricing zones. These differences have recently been normalized, however (Parbo, 2012). In the regulating power market, the TSO obtains the required upwards or downwards regulation by buying the lacking amount of electricity or selling the excess. In doing so, Energinet.dk thus sorts and chooses the most attractive asking prices or bids for one of the two regulation services through a process of merit ordering. The markets for upwards and downwards regulation are in this way separate auctions, and are never open simultaneously for the same area. Here Energinet.dk chooses the best offers from producers to increase (upwards regulation) or decrease (downwards regulation) production, and the best offers from consumers to decrease (upwards regulation) or increase (downwards regulation) consumption (e.g. Danish Competition and Consumer Authority, 2004).[7]

[7] The way the regulating power market works will be elaborated on in chapter 2.

Suppliers of regulation services are placed in groups on the basis of their reaction times as determined by the technology used in delivering the service. The groups have been introduced due to how even small differences in the time it takes to supply regulation services are worth something in the context of equilibrium maintenance. The fastest sources are in turn switched on and off automatically by the TSO itself. This close to dispatch, the market thus shifts from scheduling to direct remote control. Providers of these resources are paid a stand-by fee in addition to the price of the regulation service supplied. The price for the service is also settled via a uniform-price auction. In this way, an AGC-type system reacting to frequency rather than price is thus still used to maintain equilibrium in the moments closest to dispatch. In real time, very small differences between supply and demand are evened out by means of the inertia of the electricity system itself (e.g. Energinet.dk, 2014b). Following the final adjustments made by consumers and producers dealing with the TSO on the markets for regulation services, balance power is traded in the *Balance Power Market*. Balance power is a 'fictive product' in the sense that the Balance Power Market is a cash-settled ex-post market dealing with the balance responsible parties (BRPs). The BRPs are obligatory legal entities representing producers, consumers, and traders in order to make sure that they are held responsible for deviations from the contracts made in the aggregate Nord Pool Market (Energinet.dk, 2013a). The market for balance power is thus a device by which the TSO redistributes the expenses for buying regulating power to the buyers and sellers who did not buy or sell the amount agreed upon.[8]

With the introduction of homeostatic utility control in Denmark, the arrangement for the economic operation of the Danish electricity system stopped relying mainly on an AGC-type system for equilibrium maintenance. In its place, a series of electricity markets constituting Nord Pool was introduced. Equating supply and demand mainly became a matter of determining a price using ongoing asking prices and bids for specified amounts of electricity in specific timeslots. And in effect, the equilibrium of the electricity system was displaced into the equilibrium of the electricity market. As the new main form of control signal, price became a

[8] For details in English on for example Balancing Market rules, contingency arrangements, and the (implied) incentives of the 'two price system' in the Balance Power Market see (Energinet.dk, 2008b).

"…mirror and a compass…" (Lingjærde, 2013, p. 150) in Danish electricity system development. Price became a mirror in the sense of reflecting the 'physics' or state of the electricity system. When prices in a pricing zone move closer to the price floor or ceiling, the extent to which extreme measures as constituted by peripheral or exceptional resources are used for maintaining equilibrium in the electricity system is highlighted. As exemplified below, the role of price as a compass here involves using prices in finding out how to expand the electricity grid. By representing differences in the economy of the production and consumption profiles of various zones along with the congestion between them, price analysis and forecasting came to supply input for decision-making with respect to infrastructure investment. This function of the price of electricity is elaborated on throughout the demonstration of how the intermittency problem has been handled by means of increasing the liquidity of electricity produced by wind turbines.

In the above, it was shown how the Nord Pool market arrangement was conceived of and implemented as a control system for ensuring equilibrium in the electricity system. In doing so, the involvement of control systems engineering in electricity market design and maintenance was introduced. Further describing wind power integration through market construction here proceeds by emphasizing the role of economics in the context of engineering markets as control systems. In providing a measure describing the outcome or state of affairs to be realized through market performation as control systems engineering, economics was used to define an objective in the form of liquidity. And in the context of Nord Pool, "A liquid market is a market with a high volume and many participants" (Lingjærde, 2013, p. 151).

It is important to note that reaching the goal of increasing the liquidity of wholesale electricity in this instance did not have an impact on the way homeostatic utility control works. Attempting to change the degree of liquidity did not involve attempting to reconfigure the control system design. Rather, increasing the liquidity of wholesale electricity is a way of increasing the means by which homeostatic utility control can and does work. Highlighting this distinction is significant as it points to how wind power integration as electricity market construction varies from case to case.[9]

To clarify the form in which economics is included in this instance of market performation for the liquidization of wholesale electricity, the notion of liquidity as presented in economics will be briefly introduced. Doing so will help to elaborate on the way wind power integration through market construction for increasing the ability to trade wholesale electricity generated by wind turbines in Nord Pool has been approached. Furthermore, it will serve as a transition into the discussion of how the material market infrastructure of Nord Pool was expanded in order to increase the amount of resources available for equilibrium maintenance by means of homeostatic utility control.

Liquidity

Having outlined the basic functioning of the Danish part of the Nordic wholesale electricity market, attention can now be turned to how the constitution of electricity system operation as the running of an electricity market involved establishing the overall framework for wind power integration in Denmark. It is here shown that the issue of wind power integration was transformed into a problem associated with the making of prices in Nord Pool. Conceiving of the intermittency problem in this particular way began as the functioning of the electricity system was described by means of market analysis. The way the equilibrium of the Danish electricity system had been displaced into the equilibrium of the electricity market implied that concepts describing the functioning of markets could be applied in order to understand the functioning of the electricity system. Integrating wind power into the electricity system was in turn approached as a matter of increasing liquidity or the ability to trade wholesale

[9] For example, in chapter 2 economics is shown to have been included in the form of the metric named price elasticity. There, the objective of increasing the price elasticity of retail electricity is part and parcel of the control system and market design. In the attempt to increase price elasticity by engineering a new control system, economics supplied a measure describing an outcome inscribed in the configuration of the new market arrangement.

electricity generated by wind turbines in Nord Pool. And in starting to clarify how this approach to wind power integration was made, the key concept of liquidity as applied in the context of Nord Pool will here be briefly described.

John Maynard Keynes introduced the notion of liquidity in *A Treatise on Money* (1930) in order to distinguish between the 'ability to trade' associated with different objects. The more "liquid" form a type of capital, asset, or good takes, the "…more certainly realisable at short notice without loss…" (Keynes, 1930, p. 67) it will be. The ability to trade a good is thus expressed in the extent to which that good can be traded immediately without having the transaction lower the market price. The term 'liquidity' has since been applied in very different ways by various writers, and the term originally coined by Keynes is now also referred to as 'market liquidity' in the sense that "…a liquid market is a market where participants can rapidly execute large-volume transactions with a small impact on prices" (Bank for International Settlements, 1999, p. 5). The definition of liquidity provided by Keynes is basically a measure of a particular quality of markets. It describes the ability to trade a good by pointing to the scope of the price-lowering effect caused by a transaction. Thus, this way of referring to the ability to trade associated with a specific good in a specific market presents no restrictions on how liquidity can be brought about. Liquidity has no *a priori* fixed sources. Here, then, the notion of liquidity can readily be understood as an outcome in the form of a feature or quality of a market STA. And while the flexibility of the concept of liquidity makes the idea straightforwardly commensurable with the position taken throughout the present inquiry, it is interesting here due to the way the openness of the metric also implies that nothing stood in the way of using it for creating an objective for the process of market construction. In the main empirical example provided in this chapter, increasing the liquidity of wholesale electricity produced by wind turbines in order to integrate wind power into the Danish electricity system implied expanding the "…infrastructure which is necessary for a well-functioning electricity market" (Nordel, 2002, p. 2).

Wind power integration as electricity valuation

The clearest example of how the intermittency problem has been approached by understanding it as an issue of increasing the liquidity of electricity produced by wind turbines is found in the report named The Future Requirements for Flexibility in the Energy System (Aarhus Municipality, 2012). The report was made for Aarhus Municipality by a Danish energy consulting firm named EA Energy Analyses. The report presents analyses of both the need for making the Danish energy system increasingly flexible and the means for achieving that end. The fact that the report embodies a widely established approach to knowledge production in relation to wind power integration was consistently confirmed by means of several different sources of data. Significantly, the idea that this approach to understanding wind power integration is widespread was confirmed in interviews with public and private stakeholders (e.g. Boldt, 2013; Østergaard, 2013; Nielsen, 2013; Lindboe, 2013). Also, various documents certify that the approach and findings of the report were endorsed by an evaluation panel consisting of representatives from the TSO Energinet.dk, utility companies, Aarhus University, The Danish District Energy Development Center, Aarhus Municipality's Climate Department, and Aalborg University (Behrmann, 2013; Aarhus Municipality, 2012). Also of significance is the fact that the same method has been used in a number of other central inputs for policy-making in Denmark (e.g. Danish Energy Agency & Danish Ministry of Taxation, 2009a). As the report is understood to give a clear idea of wind power integration in a Danish context and in part how this could be managed elsewhere, the document has also been translated into English (Kofoed-Wiuff, 2013).

A central point in the report is that having made electricity system operation equivalent with the running of Nord Pool allowed for the integration of wind power to be approached as a process of market development. It built on the fact that the equilibrium between input and output in the electricity system which enables the making of a stable frequency was displaced into the equilibrium between supply and demand in the electricity market, which facilitated the making of a variable price based control signal. The approach to wind power integration thus revolves around increasing the capacity of Nord Pool to exert homeostatic control.

Price as reflecting utility

There are two main ways in which the need for electricity system flexibility has been approached through the electricity market (not counting the need for ancillary services such as short-circuit power and voltage control as increasing with the proportion of wind power in the system, and the idea that an increased amount of fluctuating electricity generation will require a greater amount of resources for system balancing, as suggested above). One relates to securing the value of electricity produced by wind turbines at all times, and the other pertains to keeping a sufficient amount of production capacity available for periods with little or no wind. In the context of this account of wind power integration as a matter of increasing the liquidity of wholesale electricity through a process of market construction, mainly the first of these two issues is addressed. The intermittency problem was approached by considering the value, i.e. utility, of electricity produced by wind turbines as mirrored in its price. Thus, in accordance with neoclassical economics (e.g. Marshall, 1920) it was found that:

> The value of wind power will in a market-based system be expressed as the value that the market ascribes the production, directly expressed through the price of electricity. The price that the wind turbine can sell its production for in the market can be regarded as the socioeconomic value of wind turbine power production
>
> (Aarhus Municipality, 2012, p. 14)

As the price paid for wind power is taken to represent its value, it becomes an expression of how good the Danish energy system is at handling, or valuing, volatile electricity production from wind turbines. In going through the market as represented by economics and introduced in the form of the Nord Pool arrangement, it was established that the market price of wind power mirrors the system-wide utility of wind power. This means that a precise albeit hard to realize assessment of the system-wide utility of wind power can be made by comparing the average price paid for electricity sold by wind power producers over a year with the average price paid for electricity over a year. However, a simpler estimate of the electricity system's ability to utilize volatile electricity production from wind turbines as expressed through market valuation has been developed. This alternative focuses on the amount of hours during a year when the price of electricity produced by wind turbines is low, zero, or negative.[10]

Going through the market allowed the actors associated with the approach to take the position that low, zero, and negative prices paid for electricity from wind turbines were what needed to be avoided in the quest for renewable energy integration. The challenge of solving the intermittency problem was thus reconfigured into a matter of formatting the electricity market so as to prevent the making of low, zero or negative prices for electricity produced by wind turbines. The simpler estimate is made by counting the amount of hours during a year where the price paid for electricity is low, zero, or negative in a given zone (Aarhus Municipality, 2012). Wind power integration as electricity valuation is thus presented as a short-term concern. But before moving on it is worth stressing that it also has a long-term dimension:

[10] Prices of zero and below occur in a pricing zone as supply comes closer to exceeding demand while factoring in transmission capacity. Negative prices were introduced in Nord Pool in 2009 in order to incentivize suppliers to stop producing in periods when there is close to critical excess electricity in the system, and urge buyers to consume in these periods by paying them for consuming electricity. Excess electricity production resulting in a price of zero has occurred to a varying extent since 2002, with a clear majority of the instances taking place in the price zone for western Denmark (DK1). The instances were in part caused by two different arrangements which sometimes worked in concert. One was the fixed subsidy paid to wind power producers for every kilowatt hour delivered to the electricity system, regardless of the market price. The tariff implied that offloading electricity from wind power in the grid was still attractive even though the price was zero. Another driver of overproduction is the technological configuration of large conventional thermal power plants. As ramping traditional coal-fired thermal power plants up and down is both expensive and time consuming, it would periodically be more enticing to produce at a price of zero rather than have to ramp down.

With the introduction of negative prices, Spot Market prices got the ability to reflect 'physics' or the need for regulating the electricity system to a greater degree (Energinet.dk, 2010a). And the potential for producing negative prices is understood to have made electricity suppliers react by adjusting their plants in a way so as to try to avoid having to pay for offloading electricity in the grid (Lindboe, 2011). Electricity producers who were able to change their production systems were incentivized to do so in a manner helping to ensure that fewer low, zero, or negative prices were made. In this way, wind power integration was propelled forward.

> If a large part of the produced wind power electricity is sold at low or negative prices it damages the wind turbine's economy and thereby reduces the incentive to invest in new wind turbines. For this reason it is crucial to ensure the value of wind, both to maintain its socioeconomic value, and in order to preserve the economic foundation for continued wind power development
>
> (Aarhus Municipality, 2012, p. 11)

In this way, wind power integration by means of altering the conditions for valuing electricity from wind turbines also became a matter of securing investment in production capacity in the long term. The second aspect of the intermittency problem within the framework of the electricity market implies securing sufficient production capacity for periods with little or no wind power production. As an increasing proportion of electricity produced by wind turbines is put on the market, electricity prices tend to fall and thermal power plants come to produce less. The lower prices and smaller aggregate production lowers the income of conventional electricity producers, which in turn means that it becomes less attractive to run common types of thermal power plants. This suggests that an increased proportion of electricity produced by wind turbines will make it harder to ensure sufficient capacity in periods with little or no wind. The problem is thus associated with the way thermal power plants possessing the ability to increase production when needed become less attractive as objects of investment.

Problematizing wind power integration in this way begins to make sense when considered in light of how the marginal price-based auction at Nord Pool works. In windy periods, wind turbines tend to push conventional thermal power plants out of merit in the Spot Market by offering to sell large amounts of electricity at a low price. The low asking prices to sell electricity from wind power are in principle called for by the uniform pricing principle of the Spot Market auction. By paying all producers within merit a price corresponding to what was asked by the marginal electricity supplier in the blind double-sided auction, sellers should be incentivized to ask "…their marginal opportunity costs of producing electricity, which reflect variable expenses incurred in producing electricity or the foregone opportunity to sell electricity at another time or into another market" (Tierney, Schatzki & Mukerji, 2008, p. 7). Such an asking strategy should in the context of the auction help ensure to the greatest possible extent that the supplier stays within merit and is paid the market clearing price, without risking bidding so low as to suffer an avoidable loss.

When taking into account the fact that electricity production from wind turbines implies zero fuel costs, the reason why conventional electricity production is pushed out of merit becomes apparent. Adding to this is the fact that low prices related to large amounts of wind power production tend to make hydroelectric power plants pump up capacity and hold back their production until electricity prices rise. The dynamics between wind turbines and hydropower plants thus has a "…price-deflating effect even during periods when wind power production is low" (Aarhus Municipality, 2012, p. 14). As these effects are increased through the introduction of more wind turbines in Denmark, the earnings of conventional thermal power plants begin to diminish. The decreasing earnings in the Spot Market makes it less attractive to construct conventional power plants designed for delivering large amounts of electricity during long fixed periods of time. Part of this effect is also due to how ramping these technologies up and down requires relatively long periods of time and considerable expense, which in turn disqualifies them from being active in the markets temporally closest to dispatch. Renewable energy integration in this way also becomes a matter of ensuring investment in capacity which is available in periods with little or no wind, in spite of the decreased earnings associated with an increase in the proportion of electricity supply generated by wind turbines (e.g. Boldt, 2013).

In showing how solving the intermittency problem has been approached as a process of market construction, establishing the fact that wind power integration has become a matter of electricity valuation is a central step. As the main signal of the homeostatic control device for electricity system equilibrium maintenance, the way the prices of Nord Pool are made to work comes to be of great importance when wanting to understand how fluctuating electricity generation from wind turbines is handled. Wind power integration by means of electricity liquidization depends on it. Following the mobilization of liquidity as a measure provided by economics helping to describe an intended outcome of market infrastructure reconfiguration increasing the means by which homeostatic utility control can be exerted here implies a focus on the Danish transmission system. Importantly, it should be noted that in the main example taken up below, the concept of liquidity was operationalized by translating it into the notion of the 'operational utility value' of a specific transmission system interconnector.

Electricity valuation and liquidity

To see how wind power integration as an issue of strengthening the means for exerting homeostatic control became a matter of increasing the liquidity of wholesale electricity produced by wind turbines in a specific pricing zone within Nord Pool, a brief example can serve as an illustration. Recalling how price-making in a specific zone hinges on the transfer capacity to and from the neighboring zones, an example describing the production of low, zero, and negative prices can make clear the significance of liquidity or the ability to trade in relation to wind power integration. The effect is here illustrated by considering an inverted example. That is, the importance of liquidity is shown by focusing on what can happen when liquidity is drastically decreased. A central reason why Denmark's DK1 has seen a much greater amount of hours with low, zero, and negative prices than DK2 over the past several years is that western Denmark hosts a relatively large amount of wind turbine-based electricity producers (Danish Energy Agency, 2014a). The difference in the number of wind turbines in the two zones is to a large extent due to how constructing a wind power plant in western Denmark promises a better return on investment because of the higher average wind speeds in the area (Danish Nature Agency, 2011). How the liquidity of electricity produced by wind turbines impacts prices and thus the extent to which it is integrated into a market-based system such as Nord Pool can be discussed by taking up an example of the implications of a drop in transfer capacity in and out of DK1 during a windy period.

In the first hours of Friday the 4th of October, 2013, between 00:00 and 06:00, wind speeds were higher than usual on the western coast of Denmark. The fact that the event did not make it on to what is known as the storm list (Danish Meteorological Institute, 2014) means that regional wind speeds did not exceed 21 meters per second. That wind speeds were high, but not too high, is an important point here because modern wind turbines automatically shut down during periods with extreme wind in order to avoid breaking down. This meant that significant amounts of electricity were being produced by the many wind turbines in DK1 during these six hours. This was added to the production from the thermal power plants, which had not ramped down. In the same period, the ability to trade electricity between DK1 and its neighboring pricing zones as upheld by the basic market infrastructure was minimized. The decrease in liquidity was due to the transfer capacity between DK1 and its neighboring pricing zones having been temporarily limited. The TSI connecting DK1 with NO2 in the south of Norway was shut down for maintenance, as was the transmission line to northern Germany. The transmission capacity of the cable connecting DK1 to SE3 in the southern part of Sweden was reduced by 50 percent due to an accident in Sweden (Erhardsen, 2013). As production increased in DK1 and the ability to trade with the neighboring areas was significantly lowered, system balancing became an acute issue and prices dropped to around -2,75 Euro/MWh on the Spot Market throughout the period. In this period of six hours, sellers were effectively paying buyers this amount to consume electricity in that area. And that was in spite of the fact that the TSI connecting DK1 with DK2 was transmitting at maximum capacity, and that the hourly price in eastern Denmark was as high as 29,62 Euro/MWh within the same time frame (Nord Pool Spot, 2014). The clear signal in the form of the large difference in prices between the zones should ideally have made the homeostatic control system maintain equilibrium in the electricity system through mutual adjustment of supply and demand by moving electricity from one area to another. But as the transfer capacity of the grid connections was insufficient, homeostatic control could not be exerted to the extent required to even out the price differences.

Events such as the one which occurred on Friday the 4th of October, 2013, point to the importance of the liquidity associated with electricity produced by wind turbines as a feature of the market when considering renewable energy integration in Denmark. If there is a drop in the ability to rapidly execute large-volume transactions with a small impact on prices, wind power integration risks failing. In part due to how it represents a relatively simple and already established way of ensuring wind power integration, increasing transfer capacity over long distances has up until now been chosen as the central means in the effort to integrate wind power into the Danish electricity system (e.g. Energinet.dk, 2011a; 2012a, 2012c).

In order to demonstrate how solving the intermittency problem involved solving a valuation problem, focus here turns to the practical effects that displacing the equilibrium of the electricity system into the equilibrium of the electricity market has had on Danish energy system development. To do so, we must document how the general commitment to wind power integration by minimizing the potential number of instances of low, zero, and negative prices for electricity during the year was realized in a distinct case. We must also show how market development for strengthening the means of homeostatic control was approached by assessing the value of the liquidity of electricity produced by wind turbines in DK1. While not making formal analytical use of the concept of liquidity, these assessments applied the notion of the operational utility value (e.g. Energinet.dk, 2005a) and associated it with the construction of select transmission system interconnectors. Defining the operational utility value of a TSI implies addressing the systemic benefits which arise from an increase in the liquidity of wholesale electricity. Liquidity is in this way deployed as a descriptive term by the TSO, but it was not directly mobilized in the work done to establish it in this particular case. Instead, the desired and quantifiable effect of liquidity in the context of the Nordic wholesale electricity market was used. It will be described how the assessments provided a basis for constructing the first electric connection between eastern (DK2) and western (DK1) Denmark (Energinet.dk, 2013b). The TSI connected the two pricing zones, enabling homeostatic control through mutual adjustment of supply and demand by having the market move electricity produced by wind turbines over greater distances. Doing so increased the liquidity of electricity produced by wind turbines by connecting DK1 and its many wind power producers with the buyers of DK2, who are willing to buy electricity at the points in time when it is generated by wind turbines. And by following the way the making of the interconnector was approached, it becomes apparent how the concept of liquidity was operationalized in wind power integration through market construction improving the operation of an electricity system equilibrium control arrangement.

Electricity system development as market construction

In the example chosen here, increasing the liquidity of electricity generated by wind turbines has involved an expansion of market infrastructure in the form of a new TSI, which in turn required a transformation of the good of electricity itself in order to work. These two interdependent changes were part of the project leading to the construction of a TSI across the Danish strait named Storebælt (The Great Belt), completed on the 26th of August, 2010 (e.g. Energinet.dk, 2011b). The remainder of this chapter is devoted to documenting some of the work done to increase the liquidity of electricity from wind turbines by the construction of this specific connection. Doing so involves demonstrating how electricity grid development in Denmark has been approached by projecting the future values of electricity in Nord Pool in a series of electricity price scenarios involving different grid constellations. These scenarios were made in order to understand what parts of the electricity market infrastructure should be established or expanded, in part due to an increase in wind power production. It is then shown how recommendations derived from these electricity price scenarios were followed, resulting in the making of a TSI across The Great Belt and an increase in the liquidity of electricity produced by the many wind turbines of DK1. With the rise in liquidity the valuation and integration of wind power was improved, as intended.

Scenarios for infrastructure development

A central aspect of the work leading to the construction of the TSI across The Great Belt was the way the electric connection came to be understood as an infrastructure investment with a capacity to pay for itself. This understanding was established by analyzing, amongst other things, how it would help the integration of wind power into the Danish electricity system by increasing the liquidity of electricity produced by wind turbines in DK1. That is, how it would work against having the Nord Pool arrangement ascribe electricity produced by wind power low, zero, and negative prices. Coming to this understanding was to a large extent done by producing scenarios of future electricity prices. Due to how the calculations involved in the construction of these scenarios are not publicly available, in contrast to the results, describing the process here has to take a strictly discursive form.

The construction of the grid connection across The Great Belt was first discussed and analyzed in 1992, when the Danish Parliament went into dialogue with the then-two Danish TSOs about the possibility of a TSI connecting eastern and western Denmark. But at that point in time the project was not pursued, as electricity production worked along very similar lines in eastern and western Denmark in the early and mid-1990s. Both areas were generally supplied with electricity by running large coal-fired central power plants. The almost-identical technology and cost structures of electricity producers throughout Denmark meant that the cable was not deemed economically viable (Energinet.dk, 2005a). It made limited sense to transmit electricity between areas with similar production profiles and sufficient capacity. But in the later 1990s, the financial prospects for a TSI across The Great Belt began to change. The shift in potential was caused by a number of changes in the Danish energy system. Of great significance was the fact that the production profile of western Denmark was altered through the introduction of significant amounts of wind power and decentralized combined heat and power production (CHP) (e.g. Energinet.dk, 2013a). And while the amount of electricity supplied by wind turbines and decentralized CHP continued to grow in western Denmark, a number of old centralized power plants were decommissioned in eastern Denmark. Another important development was the closing of the two controversial Swedish nuclear reactors Barsebäck 1 and 2, which had supplied eastern Denmark with electricity for a number of years. The decrease in production capacity in and around eastern Denmark along with the growing amount of relatively cheap electricity produced by wind turbines in western Denmark made a TSI across The Great Belt start to seem like an economically viable infrastructural investment. Adding to these factors was the political desire to redistribute some of the pecuniary benefits in the form of lower electricity prices derived from the investments in wind turbines and decentralized combined heat and power plants. Investments in wind power and CHP were subsidized through the Danish public service obligation (PSO) tariff paid by all Danish electricity consumers (Energinet.dk, 2005a; 2005b; 2012b).

Around the time that a TSI across The Great Belt began to seem like an economically viable idea, a major blackout also occurred. Due to a chain of events starting in the grid of southern Sweden, 2.4 million people across the capital of Copenhagen and the rest of eastern Denmark were left without electricity from 12:37 in the afternoon on Tuesday September 23rd, 2003. In certain areas, the blackout lasted till after 19:00 the same day (Elkraft System, 2003). The fact that the extent of the blackout could have been contained if transfer capacity between eastern and western Denmark had been in place at the time has also been presented as one of the less economic and more political reasons for considering the construction of the interconnector (e.g. Wittrup, 2010).

An early milestone in the process leading to the construction of the TSI across The Great Belt was the introduction of ‘Nordisk systemudviklingsplan 2002’ or the Nordic Grid Master Plan 2002. The plan was made in cooperation between the Nordic TSOs, then called Nordel, which are now part of ENTSO-E (Nordel, 2002). It was the first system development plan made in a concerted effort by the Nordic countries. The project was initiated due to how cooperation with respect to energy planning was deemed relevant in light of growing international electricity exchange. Nordic Grid Master Plan 2002 was introduced in a way characteristic of contemporary Danish electricity system development in general, and wind power integration in particular: “The common Nordic electricity market is one of the central pillars of the plan…Nordic Grid Master Plan 2002 sheds light on future transport patterns in the Nordic transmission system and points out important cross-sections [existing and potential TSIs] which will later be part of more detailed analyses” [Author’s translation] (Nordel, 2002, p. 2).

The report published recommendations based in part on scenarios of future electricity flows in and between Denmark, Sweden, Norway and Finland using a piece of market-based logistics software named “Samkøringsmodellen” (Energinet.dk, 2010a). The program was originally made to model the Nordic electricity system in a coherent way by especially taking into consideration the implications of rainfall- and hydropower-based electricity production in Norway. To a large extent, the model corresponds to a stylized representation of a perfectly functioning Nordic electricity market (Nordel, 2002). Projections of electricity flows were used to predict future congestion issues in the Nordic transmission system stemming from a lack of transmission capacity between areas with differing electricity prices. In this sense, “Nordic Grid Master Plan 2002 is not an investment plan. The important cuts pointed out in the plan will be part of additional analyses in upcoming plans, where the profitability of relevant initiatives, and their alternatives, will be assessed further” (Nordel, 2002, p. 50). Quantitative calculations coupled with unexplained “…qualitative assessments by the companies [TSOs]…” (Nordel, 2002, p. 19) constituted the basis for knowing what parts of the grid to focus on in the future. Although the report did not find a TSI between eastern and western Denmark to be an important cross-section, it set a precedent for later work which applied the same method in relation to the construction of that very grid connection (Nordel, 2004).

The idea of an economically viable TSI across Storebælt first surfaced around 2004. It arose in the work following the Nordic Grid Master Plan 2002, and culminated in the Priority Cross-Sections report also made by Nordel (Lindboe, 2013). Contrary to the two-year older Nordic Grid Master Plan 2002, Priority Cross-Sections recommended starting the construction of the interconnector across The Great Belt "…as quickly as possible" (Nordel, 2004, p. 14). The difference in the recommendations in the two main reports was said to be due to how a 300 MW connection across The Great Belt was assumed as a boundary condition in the calculations made for the Nordic Grid Master Plan 2002. In assuming that a 300 MW connection was in place, adding transfer capacity in this area was deemed to be of little value (Elkraft System & Eltra, 2004). Such a result was made possible due to how the assessment of the value of a TSI involved a cost-benefit analysis figuring in the investment costs required. And that is also why an electricity market with no congestion at all is not a goal in itself. The complete absence of congestion between price zones over the long run suggests that there has been an overinvestment in market infrastructure (e.g. Lindboe, 2011; Nordel, 2002). The results and recommendations put forward in Priority Cross-Sections sparked a larger effort to document the potential implications of a TSI across The Great Belt. This work is represented in a series of documents produced mainly by the two TSOs responsible for grid maintenance and development (e.g. Elkraft System & Eltra, 2005a; 2005b; Danish Competition and Consumer Authority, 2005; Elkraft System, 2005a; 2005b; 2005c). These documents also constituted a central input for the Action Plan for the Future Electricity Infrastructure, part of the Danish government's energy plan named Energy Strategy 2025 (Danish Ministry of Transport and Energy, 2005).

In various ways these reports help to indicate the way wind power integration has been approached first and foremost as a matter of strengthening the means for having Nord pool exert homeostatic control. Constructing TSIs enables more mutual adjustment of supply and demand by using the price signal to coordinate the movement of electricity over still-greater distances and connecting still-more balancing resources with the wind turbines. They point to the need and means for negating the amount of hours where electricity from wind turbines is valued with low, zero, or negative prices. But the clearest illustration of the approach to wind power integration through an increase in the liquidity of electricity produced by wind turbines is in this context found in two separate documents. These two reports describe the utility value of the future interconnector across The Great Belt (Energinet.dk, 2005a; 2005b). The results published in these reports substantiate the overlapping advantages of the TSI between eastern and western Denmark as later described by the TSO (Energinet.dk, 2010b). These advantages are closely related to the challenges of wind power integration in a market-based system as described above.

Operational utility

One advantage of the TSI across The Great Belt is an increase in utility or Spot Market price associated with electricity produced by wind turbines in windy periods. Another advantage leading to a significant minimization of costs associated with equilibrium maintenance is the decrease in the need for reserve power which is to be mobilized in non-windy periods and accessible via power plants on standby. Because of the electric connection, DK1 and DK2 could come to share a great deal of the reserve capacity. The economic gain from sharing reserve capacity between DK1 and DK2 was in fact the most important argument for why the connection should be established (Energinet.dk, 2005a; 2005b). Benefits were also described as being a greater utilization of the cheapest electricity producers, and more similar or fair wholesale electricity prices throughout Denmark (Energinet.dk, 2010b).

The aspect of the two reports about the utility value of the TSI across The Great Belt which here makes them a central example in explaining wind power integration into the Danish electricity system is found in how they assess the value of increasing the liquidity of wholesale electricity. In addressing what is called the ‘driftsnytteværdi’ (operational utility value) of the TSI across The Great Belt, the value of increasing the ability to trade electricity between DK2 and the wind power-intensive DK1 was estimated. The aggregate utility value of the TSI across The Great Belt has been understood to take four different forms (Energinet.dk, 2005a; 2005b). But as the operational utility value associated with the interconnector ties into the notion of liquidity and is the most significant of the four forms in the context of the present argument, it is here worth isolating and emphasizing just this aspect. It is also worth recalling the fact that electricity system operation and control through Nord Pool is not in all ways different from the approach applied in the time of central planning, which here means that assessing the operational utility value of a TSI has remained largely the same procedure:

> Operational utility is the utility value which we traditionally have been able to determine in relation to new transmission links. Operational utility applies to the way the aggregate costs for producers and consumers are reduced through investment in a beneficial transmission link. The cause of the economic gain is aggregate savings on expenses for fuel because of better access to cheaper units along with a potential rise in consumption related to the lowering of prices. There can also be local operational utility for a specific area if production rises because of increased export to neighboring areas. In accordance, an area can face an economic loss if the production capacity of the area cannot compete with production facilities in neighboring areas in effect of the transmission link. Utility for producers, consumers and changes in congestion income are weighted equally
>
> [Author's translation] (Energinet.dk, 2005a, p. 5)

The notion of operational utility measures the value of an increase in the liquidity of wholesale electricity. And in the case of the TSI across The Great Belt, it describes the value of an increase in the ability to trade wholesale electricity produced by the many wind turbines in DK1. To a large extent, the operational utility value of the TSI across The Great Belt was found in the economic gain that could be achieved by connecting wind power producers in DK1 with the supply and demand side resources for equilibrium maintenance in DK2. This fact was also demonstrated in the way the operational utility value of the TSI increased drastically in scenarios taking into account an increase in the amount of wind power in Denmark. The effect was also deemed to be quite resilient to changes in the price of fossil fuels (Energinet.dk, 2005a). When electricity was generated by the wind turbines in DK1 it could to some extent be sold to the buyers in DK2, as well as those in DK1. In this way the basis for demand at critical points in time was increased. Doing so lowered the potential for producing low, zero, and negative prices. The main scenario suggested that after the establishment of a TSI across The Great Belt, every year would witness 0,1 terawatt hour (TWh) of electricity being sold from DK2 to DK1 and 2,3 TWh moving from DK1 to DK2 (Energinet.dk, 2005a). The effect was also expressed in the way prices were expected to develop in DK1 and DK2:

> In the calculations from 'Priority Cross-Sections' there is an average difference of 16,3 kr./MWh between western Denmark and eastern Denmark. In all alternative scenarios the price is higher in eastern Denmark than in western Denmark. A 600 MW Great Belt connection evens the difference in price down to 2,2 kr./MWh
> [Author's translation] (Elkraft System & Eltra, 2004, p. 1).

Again, developing the Danish energy system with the idea of operational utility value as a priority was not only ushered in with the introduction and use of the Nordic electricity market. Developing the grid with a focus on efficient use of the power plants with the lowest variable costs was also part of energy system development in Denmark before the liberalization of electricity. And in recalling the economic mode of electricity system operation and control during central planning, there is nothing to suggest that wind power integration by means of constructing TSIs should be considered an exclusive feature of the market-based system. In the case of Denmark, the need for integrating wind power and the introduction of the electricity market simply temporally coincided. But the way to operationalize this way of reinforcing the means for exerting control is not the same as it would have been if done by means of central planning. The effect of building TSIs can to a great extent be seen as having the same effect in the context of both ways of configuring the arrangement for the economic operation of the electricity system. But the difference in the way volatile electricity generation is handled is not only discursive or epistemological. The Nord Pool market STA using price as the control signal for moving electricity among specific forms of decentralized economic decision makers is still substantially different from a central planning approach as described previously.

Increasing liquidity

The TSI across The Great Belt was completed on the 26th of August, 2010 (Energinet.dk, 2011b). As projected, the TSI across The Great Belt increased the liquidity of electricity generated by wind turbines. The change in the ability to trade which altered price-making in Nord Pool also implied that wind power was integrated to a higher degree. As suggested earlier, the concept of liquidity implies that the ability to trade in a specific market has no *a priori* fixed sources. However, the idea of wind power integration by means of an increase in liquidity can still be specified by drawing on research which has pointed to sources of liquidity in other situations (e.g. Fernandez, 1999). The notion of liquidity is often presented as dependent on one or more of three dimensions:

> *Tightness* is how far transaction prices diverge from mid-market prices, and can generally be measured by the bid-ask spread. *Depth* denotes either the volume of trades possible without affecting prevailing market prices, or the amount of orders on the order-books of market-makers at a given time. *Resiliency* refers to the speed with which price fluctuations resulting from trades are dissipated, or the speed with which imbalances in order flows are adjusted
>
> [Italics in original] (Bank for International Settlements, 1999, p. 5)

In seeking to understand wind power integration in Denmark, the dimension of liquidity described as market depth is particularly relevant. This becomes apparent when recalling the examples of how an increase and a decrease in the ability to trade electricity produced by wind turbines affects price-making and wind power integration. In a Danish context, wind power integration suffers when trading large amounts of electricity produced by wind turbines results in a significant drop in market prices. And as will be made clear, an increase in the ability to trade electricity generated in the wind power intensive price zone DK1 meant that wind power integration was improved. Larger amounts of electricity generated by wind turbines, which necessarily have to be traded, could be sold without a significant drop in prices. And in this way, the tendency of Nord Pool to value electricity produced by wind turbines at low, zero, and negative prices was negated.

Increasing the depth of the Danish electricity market by connecting the wind turbines in DK1 with a larger number of buyers spread out across DK2 implied a large construction project to reconfigure both the transmission system and the electricity running through it. The result of this construction project was the introduction of an 'encountering device' (Çalışkan & Callon, 2010) integrating wind power into the electricity system by increasing the ability to trade and changing Nord Pool's price formation. Making the TSI across The Great Belt was in some ways not the same as expanding the main Danish alternating current (AC)-based transmission system, even though this new and somewhat special connection is not the only one of its kind. The TSI across The Great Belt is a 400 kV high-voltage direct current (HVDC) connection, with a transfer capacity of 600 MW (Energinet.dk, 2014c). Building and running a DC-based interconnector as part of an AC-based transmission system implies changing the way electrons flow within that specific part of the grid. Constructing the connection between DK1 and DK2 thus involved assembling a wider technical arrangement. The TSI consists of a 32-kilometer sea cable, a transformer station on each side, and 26 kilometers of land cable (Energinet.dk, 2010c).[11]

The effect on the pricing of electricity in DK1 and DK2 following from the introduction of the TSI across The Great Belt quickly showed. Shortly after the connection was activated, the price signal moved electricity between the two zones. Differences in prices began to even out as the full 600 MW transfer capacity was used to a large degree, with DK2 quickly seeing a drop in prices between 0,005 and 0,02 kr. per KWh. Since these effects were seen as demonstrating the success of the project, Energinet.dk began to consider another transfer capacity expansion in the same part of the grid shortly thereafter (Lindberg, 2010).

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[11] There were two main reasons for making the TSI in this way. One is that the transmission systems of DK1 and DK2 are not synchronized. The transmission system in western Denmark is synchronized with continental Europe, whereas the grid in eastern Denmark works synchronously with the rest of Scandinavia (Danish Energy Regulatory Authority, 2012). Building such a relatively small AC connection to directly connect two unsynchronized areas would not be possible. Furthermore, the available technologies for transporting electricity implied that an HVDC connection running underground and on the seabed over long distances would lead to significantly fewer losses than its AC counterpart (Energinet.dk, 2010c). Sending electricity across The Great Belt and transforming the way prices in Nord Pool are assembled by increasing the liquidity of wholesale electricity thus here involved a process of changing the format of electricity itself. Doing so was necessary for transmitting it between the two asynchronous systems.

Summary and concluding comments

Chapter 1 constitutes a first step in the process of answering the research question: *How have control systems engineering and economics been mobilized in the endeavor to integrate wind power into the Danish electricity system through electricity market design and management?* Answering the research question was advanced by describing the introduction and reconfiguration of the Nordic wholesale electricity market named Nord Pool as related to the integration of wind power into the Danish electricity system. It was established that the liberalization of electricity in Denmark implied changing the control system with which the crucial equilibrium between input and output in the electricity system is maintained. Shifting the means of equilibrium maintenance was done by moving from an AGC-type control system utilizing a supply follows demand philosophy, to homeostatic utility control (e.g. Tabors, 1981). Instead of maintaining a stable frequency in the electricity system by adjusting supply in accordance with demand, a largely price-based control system for mutual supply and demand side adjustment was introduced. The equilibrium of the electricity system was shown to have been displaced (Callon, 1986b) into the equilibrium of the electricity market. It was then demonstrated how the integration of fluctuating electricity generation from wind turbines was approached by going through this new system for the control and economic operation of the Danish electricity system. As price was taken to reflect the state of the electricity system, wind power integration was turned into a matter of electricity valuation. Following the reasoning that wind power would be integrated to the extent that it was not bought through Nord Pool at low, zero, or negative prices, ensuring that electricity produced by wind turbines is not periodically devalued came to characterize renewable energy integration in Denmark. The most widely used strategy of market construction to achieve this result was then described. Also known as the "export strategy" (H. Lund & Clark, 2002), the approach involves increasing the liquidity of wholesale electricity generated by wind turbines by building market infrastructure in the form of transmission system interconnectors. An electric connection was shown to link the prolific wind turbines of western Denmark with a greater number of supply and demand side resources for equilibrium maintenance. And by strengthening the means through which homeostatic utility control can be exerted by the Nord Pool market arrangement, the price difference between the zones of eastern and western Denmark was evened out and wind power absorbed into the electricity system.

Exploring how the intermittency problem has been solved through the introduction and reconfiguration of Nord Pool here leads to a novel account of the process of market performation (Callon, 2007b). And in effect, the performativity programme (Çalışkan & Callon, 2010) devoted to the study of the knowledge, know-how, and skills involved in market design and management is supplemented in two ways. First, a form of expertise not previously explored in the context of the performativity programme was highlighted as crucial to market construction. It was established that control systems engineering functioned as a generative form of expertise in the making of an electricity market. Nord Pool was conceived of and implemented as a homeostatic control device, and was also shown to include AGC-type systems utilizing frequency as the control signal in the periods closest to dispatch. Control systems engineering will also prove important to the understanding of wind power integration as electricity market construction in the next two chapters. That is, the point will be empirically elaborated on throughout the rest of the analysis. But here it should be noted that control systems engineering to a great extent characterized the design and maintenance of Nord Pool. Of course, an engineer's approach to economics has been described before (e.g. Simon, 1996). And a history of economics as a subject matter for cybernetics has been written (Mirowski, 2002). But what becomes clear from following the introduction and reconfiguration of Nord Pool is that a concrete market has here been engineered as a control system, and that market necessarily possesses the features of a control system. If equilibrium between supply and demand in another market momentarily ceases to exist, all transactions will stop. If equilibrium between input and output in an electricity system cannot be maintained, not only do transactions stop - the electricity system breaks down. And in Denmark at least, allowing brownouts and blackouts is not an option. A second characteristic of Nord Pool, which is an outcome of engineering markets as control systems, is the possibility of having features such as negative prices. When conceived of as a control signal in the above-specified electricity market STA with its peculiar technical properties, there is nothing in the way of prices becoming negative. A price of zero is in this case not a point at which a market stops working. It is simply an arbitrary point on a scale which should reflect and regulate the state of the electricity system. And as receiving a bill for offloading electricity in the grid can be economically viable in certain situations, negative prices can and do occur.

The second way in which the performativity programme is augmented relates to how economics here has a function in market performation which has remained unexplained up until this point. This second argument will be substantiated more thoroughly in the next two chapters, but should nonetheless be briefly introduced here. In the context of wind power integration by means of electricity market construction, one way in which economics was involved relates to the use of the notion of liquidity. While only being indirectly analytically mobilized through the quantified notion of operational utility value, the concept of liquidity does facilitate the description of a state of affairs in Nord Pool which has been and still is actualized by building transmission system interconnectors. The use of descriptive measures taken from economics as means of specifying an objective to be achieved by means of market construction for the introduction or improved operation of control arrangements for electricity system equilibrium maintenance is found in all three cases. In effect, one could highlight the account provided here and the accounts of market construction in chapters 2 and 3 as instances of Barnesian performativity: "Practical use of an aspect of economics makes economic processes more like their depiction by economics" (MacKenzie, 2007, p. 55). But this amounts to stating that the objective of increasing liquidity in Nord Pool became part of the method of increasing liquidity. In the context of a market engineered as a control system, this observation does not really add up to much. Barnesian performativity was the well-recognized point of engineering the electricity market in a specific way. This argument is similar to the wider point that when considering the "…professionalization of market design, performativity simply loses its radicalism" (Frankel, Ossandón, & Pallesen, 2015a, p. 8). The status of economics as part of market performation when measures such as liquidity and price elasticity are adopted in the context of Nord Pool is to facilitate the specification of objectives to be reached by means of market construction for the introduction or improvement of control system operation. What this in turn does to the state of economics in the present instances of electricity market construction is further developed in the final chapter, by considering it along the lines of Searle's (2001) conditions of satisfaction, direction of fit, and direction of causation.

Having described how wind power integration has been approached by reconfiguring the material infrastructure of Nord Pool in order to increase the liquidity of electricity generated by wind turbines and strengthen the means for exerting homeostatic utility control, analyzing how the intermittency problem is being addressed in Denmark at this point involves changing the empirical setting. Following a different case, chapter 2 documents an economic experiment named EcoGrid conducted on the Danish island of Bornholm. The endeavor of wind power integration in this context involves the construction of an experimental retail electricity market for electricity system equilibrium maintenance. In demonstrating how it was conceived of as both a Nord Pool subsystem in the form of a frequency adaptive power energy re-scheduler and an open- and closed-loop electricity consumption control system, the design and management of EcoGrid is shown to have relied on the expertise of control systems engineering. Economics is in turn shown to have been mobilized in the process of market performation by noting how the measure of price elasticity was used to describe a necessary feature of the EcoGrid design, and an outcome to be realized by implementing the arrangement.

Open- and closed-loop control | Price elasticity

Chapter 1 described how wind power integration into the Danish energy system was approached through the introduction and reconfiguration of the Nordic wholesale electricity market arrangement. It was shown that the Nordic wholesale electricity market was designed and actualized as a homeostatic control device for maintaining equilibrium between input and output in the electricity system. Nord Pool is thus both a means for the economic operation of the electricity system and an approach to making sure that system breakdown is avoided. Wind power integration was discussed as a matter of increasing the liquidity of electricity produced in a wind power intensive pricing zone of Nord Pool. Adding liquidity was exemplified by following the construction of a transmission system interconnector across The Great Belt, connecting western and eastern Denmark. It was shown that Nord Pool's capacity for exerting homeostatic control was increased by the activation of the electric connection between the price zones DK1 and DK2, as resources for equilibrium maintenance were pooled. In the process, a first step in supplementing the performativity programme was taken as control systems engineering was shown to be a generative form of expertise in the design and management of the Nord Pool market arrangement. Describing market construction here involved showing how Nord Pool was conceived and implemented as a specific kind of control system using price as the control signal. Another addition to this expansion of the performativity programme's empirical scope was then presented as economics was described as providing a means of specifying the objectives to be reached through market performation for improved or strengthened control system operation.

Chapter 2 will further describe how pursuing wind power integration in Denmark has taken the form of engineering a market for exerting control in a way that helps to maintain equilibrium in the electricity system. Doing so will involve following the experimental configuration of a new form of retail electricity market named EcoGrid on the Danish island of Bornholm.[12] Often addressed as a demonstration

[12] The present study of EcoGrid was conducted in collaboration with Trine Pallesen. This chapter thus reflects a shared research effort. Trine Pallesen should, however, not have to take any responsibility for any of it as presented here.

or prototype project (e.g. Jørgensen, Sørensen, & Eriksen, 2011), the main point of the experiment is to produce knowledge about new forms of retail market arrangements made to support the balancing of inputs and outputs in the electricity system by means of homeostatic utility control. The basic idea of the EcoGrid market experiment is to design and implement a new control system, implying an increase in the price elasticity of retail electricity as understood in the short term while having the system operator actively manage the price. Price management in this context to some extent necessarily involves correlating retail electricity prices with the prices presented in the markets of Nord Pool. As these prices reflect the state of the electricity system, the experimental control system market arrangement basically involves an attempt to move consumption to follow developments in fluctuating production. Elaborating on the process of introducing the EcoGrid arrangement involves following the making of the system, from the conception of the market design to the attempts at making it work in the large-scale experimental setting on Bornholm. Tracing the market arrangement from conception to installation provides an opportunity to show how the making of EcoGrid was largely a matter of engineering an electricity consumption control system. In order to describe the work done to make the market a success, it is emphasized how the market organizers attempt to ensure that EcoGrid participants act in accordance with their roles as 'inscribed' in the program (Akrich, 1994). Following market construction in this way involves tracing how an electricity consumer who is both willing and able to adopt the necessary patterns of behavior is 'made up' and realized. Understanding the endeavor to make EcoGrid work as intended has involved observing consumer instruction sessions, calculative equipment, and on-site consumer training, for example. The mixed reactions of EcoGrid participants to these elements are then described. To demonstrate the diversity of results produced by EcoGrid, the tendency of consumers to use the calculative devices provided by EcoGrid to realize a form of economic behavior different from the one inscribed in the EcoGrid market arrangement is then presented and discussed.

As in the case outlined in chapter 1, this analysis of EcoGrid augments the performativity programme in two ways. Control systems engineering is once again documented as being a generative form of expertise in relation to market design. In short, EcoGrid was conceived of and actualized as an open- and closed-loop electricity consumption control system. In this way, the form of control system upon which electricity market design is modelled here shifts between the cases. Analyzing the process of wind power integration as electricity market performation by means of control systems engineering here involves a shift from an emphasis on homeostatic utility control to a focus on open- and closed-loop control systems. A key aspect which adds to the importance of control systems engineering in this second case of market design and management is the fact that EcoGrid is also designed to function as a Nord Pool subsystem similar to a frequency adaptive power energy rescheduler (FAPER) (Schweppe et al., 1980). A central part of the original conception of the homeostatic utility control framework, a FAPER is a specific control arrangement enabling electricity system equilibrium maintenance by means of an electricity market. The second way the empirical scope of the performativity programme is expanded is also in some ways similar to that described in the previous chapter, as it is here once again demonstrated that economics was introduced into the process of electricity market construction to determine the intended outcomes. In the making of EcoGrid, price elasticity was used to signify an ideal outcome of market construction. There is, however, also a difference between the two cases when it comes to the way economics was mobilized. In the account of how the notion of liquidity was involved in the making of Nord Pool, economics was shown to have been included to describe an objective to be reached by means of market construction improving control system operation. The idea of liquidity was not shown to have any impact on market design. But in the case of EcoGrid, the concept of price elasticity was incorporated into the making of the control arrangement by being inscribed in the market design. In other words, economics was here included and applied to specify both a necessary feature and an outcome of the successful design and implementation of EcoGrid.

Introducing EcoGrid

The time is ready for extension of the power market system
(EcoGrid.eu, 2012a, p. 2)

EcoGrid is known as a project for the development of what is popularly called a Smart Grid (e.g. Beard, 2010; Danish Ministry of Climate, Energy and Building, 2011b). However, as the term Smart Grid has been consistently applied in referring to a number of different electrical arrangements (Energinet.dk & The Danish Energy Association, 2010), this particular wording will be avoided. The following description of the idea behind the EcoGrid project and the mission to integrate wind power into the Danish electricity system by increasing the near-term price elasticity of retail electricity while managing the price proceeds by taking a step back. This is required in order to revisit the intermittency problem and frame the second part of the inquiry.

As is apparent from the previous chapter, electricity has two qualities distinguishing it from many other goods. One of them is that electricity cannot be stored. Energy from electricity can be stored after conversion, but not without significant losses (e.g. Wittrup, 2013). The other is the way the electricity system has to be operated by constantly maintaining an exact balance between input and output if it is to not break down (e.g. Danish Energy Agency, 2001). In Denmark, electricity has historically been provided almost exclusively by means of thermal power plants, which have the capacity to turn production up and down on command. The capacity to increase or decrease generation at will meant that the crucial balance between input and output in the electricity system could be maintained by having production follow consumption at all times. But when large percentages of wind-bound electricity production were introduced into the Danish energy system, the established mode of electricity system operation was challenged. Electricity production from newer wind turbines could only be scaled down by the plant operator. Furthermore, electricity generation from wind power producers increases exponentially with a rise in wind speed when the turbine is operating at all but the highest or lowest wind speeds. As average wind speeds are both very common and hard to forecast precisely, electricity generation from wind turbines is relatively difficult to predict. These factors make it harder to maintain equilibrium in the electricity system by having production follow consumption. Since the liberalization of electricity in Denmark, as indicated in chapter 1, the main parts of electricity input and output have been equated using a homeostatic control system engineered as a series of markets and pricing arrangements in aggregate known as Nord Pool. The Nord Pool control system constitutes the Nordic wholesale electricity market. It is through the wholesale buyers on Nord Pool that smaller retail consumers buy electricity.

In this chapter the focus shifts from the wholesale to the retail area, and the differences in organization between the retail and the wholesale electricity markets need to be emphasized. Specifically, the differences in the capacity for endowing electricity with the characteristics of a price elastic economic good are highlighted. Whereas the functioning of homeostatic utility control in the wholesale market in principle implies the possibility of buyers having a price elastic relation with electricity, the vast majority of arrangements in the retail market do not. And most retail electricity consumers are largely untouched by the use of the wholesale price of electricity as a control signal reflecting the state of the electricity system. In effect, retail consumers in Denmark are generally both incapable of and uninterested in relating to equilibrium maintenance in the electricity system through their use of electricity. The organizers of the EcoGrid project sought to change this state of affairs in the retail electricity market by introducing an experimental market arrangement wherein an interested consumer is exposed to a price-based control signal and the state of the electricity system. In connecting the retail market more closely with Nord Pool, consumers are assembled so that they become more attuned to the ongoing changes in the ‘physics’ of the electricity system. To see how EcoGrid is arranged to work in this way, the notion of price elasticity will be briefly discussed before following how it has been mobilized for the making of an open- and closed-loop control system in the form of an experimental retail electricity market.

Price elasticity

An important difference between the Danish retail and wholesale electricity markets can be found in the way trade is conducted. While the liberalization of electricity in Denmark saw the supply follows demand philosophy replaced with homeostatic utility control in the wholesale market, exchange did not develop in entirely the same way in the retail market. In contrast to trade on Nord Pool, the majority of buyers in the retail market still pay a pre-specified, constant, and infrequently updated price per KWh. Buying electricity in the retail market is also most often part of household routines and many basic operations in society. The point is here that electricity tends to be price inelastic. And since the notion characterizes this account of wind power integration as market construction for the introduction of an electricity consumption control system, it is here worth briefly elaborating on the meaning of the term price elasticity.

In book III of his treatise *Principles of Economics*, Alfred Marshall undertook the task of describing what he named Wants and their Satisfaction (Marshall, 1920). In chapter III Marshall presents what is now most commonly known as the concept of price elasticity when discussing what he called the Elasticity of Wants. In also referring to the elasticity of demand, price elasticity is defined in a general form: "The *elasticity* (or *responsiveness*) *of demand* in a market is great or small according as the amount demanded increases much or little for a given fall in price, and diminishes much or little for a given rise in price" [Italics in original] (Marshall, 1920, p. 66). In other words, it is a way of addressing the sensitivity towards changes in price when settling the demand for a good in a specific market. The notion of price elasticity refers to the variation in demand associated with a change in price. By equating demand with the number of units sold in a specific market, a way of quantifying this definition is also provided in considering price elasticity to be expressed in the percentage increase or decrease in demand as efficiently caused by the percentage increase or decrease in price. In the words of Marshall:

> We may say that the elasticity of demand is one, if a small fall in price will cause an equal proportionate increase in the amount demanded: or as we may say roughly, if a fall of one percent in price will increase the sales by one percent; that it is two or a half, if a fall of one percent in price makes an increase of two or one half percent respectively in the amount demanded; and so on
>
> (Marshall, 1920, p. 513)

As is apparent, the notion of price elasticity is a measure of a particular quality of a market. And like the concept of liquidity, the idea of what is now called price elasticity as provided by Marshall does not tell us anything about how we should understand the way the elasticity of demand comes to be the way it is. It is strictly a way to measure a state of affairs in a market. Thus, just like market microstructure researchers who have worked with the notion of liquidity originally developed by Keynes (1930), when approaching issues of market structure and design (Madhavan, 2000), Marshall does not provide a formalization of the way in which the price elasticity of an economic good should change. But the topic is discussed by Marshall in *Principles of Economics*. The most recurrent explanation of how price elasticity comes to be the way it is was based in how price elasticity was found to vary with the price of the product relative to what Marshall calls 'the social classes'. To Marshall, referring to social classes effectively implies addressing variations in the resources available to buyers. It is pointed out that the elasticity of demand associated with a good can be affected by the extent to which the price of the good is high or low relative to class. If the price of a good is so low that any member of any class can buy as much as is needed for reaching the point of satiety, the elasticity of demand will tend to diminish. In this way Marshall's notion of the elasticity of demand was presented as related to the ratio between the price of a good and the total income of the buyer.

In a general sense, electricity is a textbook example of a price inelastic economic good: "Inelastic demand is a characteristic of goods that are a necessity. The substitutes for these goods are few and difficult to obtain. Power and electricity fall into this category as they are vital goods seen as essential for the existence of modern civilization" (Pöyry, 2010, p. 10). This state of affairs, which is also found in the Danish retail electricity market, has a number of efficient causes, and can be summed up by stressing the passivity of electricity consumers in the context of the electricity markets (e.g. Østergaard, 2013). Most Danish consumers have traditionally purchased electricity in patterns adapted to suit the various routines of their households or work. The aspect of this fact which has the most significance for the strain put on the electricity system is what is called the 'cooking peak', referring to the spike in aggregate demand in the period around late afternoon and early evening facilitated by the many consumers turning on their stoves and ovens to make supper (e.g. Jensen, 2009). The retail consumer's price inelastic relationship with electricity is not only based on the fact that electricity is an essential part of many activities, however. It is maintained in this form in part because of the way the structuring of transactions has not changed since the time of the supply follows demand philosophy. And despite the fact that there are examples pointing in another direction, the liberalization of electricity in Denmark generally did not do much to change the fact that most consumers receive a pre-specified, constant, and infrequently updated price per KWh. Long-term contracts with single fixed tariffs were the order of the day before the liberalization of electricity in Denmark. And in part because very few household-level retail electricity consumers have changed suppliers or products after Denmark entered Nord Pool, much remains the same in this respect (Danish Energy Agency, 2011a). The tariffs of the retail market are in principle made compatible with the varying prices of the wholesale market by having suppliers make charges based on an average derived from a longer period of time, thus evening out differences. In this way, the manner in which electricity was liberalized in Denmark implied that the practical effects of the supply follows demand philosophy were allowed to remain in the context of domestic-level retail electricity consumption.

Due to how the Danish retail electricity market continued to function in a way which was disconnected from developments in the state of the electricity system, the problematized effects of passive demand described previously were still present after the liberalization of electricity. And this is where EcoGrid comes in. The experimental market set-up basically involves an attempt to increase the means by which homeostatic control can be exerted, by introducing a new Nord Pool subsystem, which complements the established arrangement. Previously, strengthening the means by which homeostatic utility control could be exerted was handled by increasing the liquidity of wholesale electricity, enabling a larger number of buyers to absorb fluctuating electricity generation from wind turbines. Electric connections or transmission system interconnectors were built. The intended effect of EcoGrid is in turn to make domestic-level electricity consumers willing and able to partake in equilibrium maintenance through homeostatic control. Mobilizing retail electricity consumers in this way involves increasing the price elasticity of electricity as expressed in the short term. The short term has to be stressed here, as retail electricity in domestic settings might very well be slightly price elastic in some instances. But where there are pre-established, constant, and infrequently updated prices, consumer reactions to changes in price are so rare that these buyers cannot partake in equilibrium maintenance through ongoing mutual adjustment of supply and demand. As part of wind power integration by means of market construction for the introduction of an electricity consumption control system, EcoGrid constitutes an attempt to change the established set-up by getting retail electricity consumption to follow production.

Having briefly outlined the concept of price elasticity, emphasis now moves on to how increasing the near-term price elasticity of retail electricity was made relevant for integrating wind power into the Danish electricity system. Making that connection involves a description of how the EcoGrid market arrangement has been designed as an electricity consumption control system. After having addressed the ways in which EcoGrid has been conceived of as a frequency adaptive power energy rescheduler and an open- and closed-loop control system relying on and resulting in retail electricity being near-term price elastic, the account turns to describing how the arrangement was realized on the Danish island of Bornholm.

Designing EcoGrid

By heightening the price elasticity of retail electricity and managing prices, the EcoGrid market arrangement is set in place to move electricity consumption around in time. EcoGrid is intended to increase consumption when electricity production from wind power is high, and decrease consumption when production is low. In this way the construction of EcoGrid is a matter of producing a market facilitating an economic incentive to shift electricity consumption in time. And ultimately, these changes in the timing of consumption are to be done in accordance with electricity system requirements.

The concrete aspects of the EcoGrid market design were initially conceived of at the Department for Electrical Engineering at the Technical University of Denmark (DTU). DTU is a partner in the EcoGrid EU Consortium alongside other universities, privately owned companies such as Siemens and IBM, and TSOs from a number of European Union member states. The Danish TSO Energinet.dk is the formal initiator of the project (EcoGrid.eu, 2014). Apart from the contributions made by various partners, €12.7 million out of the total €21 million budget for the EcoGrid project has been provided through a grant from the 'Energy' subtheme of the European Union's seventh framework program (FP7) (European Commission, 2011). DTU is set to do much of the work involved in the first of EcoGrid's nine work packages, whilst also being formally responsible for the completion of that work package. Started in 2011, Work Package 1 revolves around the making of the EcoGrid market 'Concept and Architecture' (EcoGrid.eu, 2012b). The EcoGrid market designs were conceived of at the Centre for Electric Power and Energy, where the development process was led by the head of the center Professor Jacob Østergaard (who was also formally the leader of Work Package 1). The basic market concept was worked out in cooperation with other researchers from the department, in a process characterized by dialog and 'throwing ideas around' (Østergaard, 2013).

EcoGrid designers from the Technical University of Denmark provided several reasons for why they chose to configure an electricity consumption control system in the form of a market. But making the control system did not have to involve a market applying price as the control signal. The fact that making a market was simply one way of establishing an electricity consumption control system was highlighted in part by one of the EcoGrid designers. A technical scientist with a background in physics and wind power engineering, he had taken on the task of making the plant controllers of the EcoGrid system while also being involved in the overall design.[13] The market designer started his account of how and why an experimental retail electricity market was engineered by saying that: "Well, as I see it the market doesn't have to be there at all, well it's something we have chosen - it is a way to steer…" [Author's translation] (Larsen, 2013, 0:03:45-0:03:54). The main reason for making what is referred to as a 'market-based

[13] See chapter 1 for a description of the idea of a plant controller in a control system context.

solution' presented by the engineers behind the EcoGrid control system design was that markets have become a widely established and accepted way of organizing energy system development in Denmark:

> If you look at how the energy system has developed over the last 20 years or something like that, there has been a dramatic change and focus on using market-based solutions to optimize the system really, and to create the solutions - operating the system and making investments and so on, which are socio-economically as optimal as possible
>
> [Author's translation] (Østergaard, 2013, 0:12:01-0:12:34)

It was also underscored how the proliferation of markets in the context of electricity system development was reflected by the composition of the Department of Electrical Engineering at DTU. One of the department's six research groups is called ELMA, and is dedicated to the study and engineering of electricity markets. ELMA had also been involved in the discussions around the design of EcoGrid. The fact that a market-based solution should be pursued was also a formal requirement included in the call from the EU's FP7 - something which the DTU team members themselves had worked to get established.

> This setup is equivalent to a closed-loop control system…where the price is the control signal and the feedback is the system balance. Appropriate contracts and metering infrastructure provides settlements based on the real-time price signal, thus providing the incentives to respond to the price
>
> (Nyeng in EcoGrid.eu, 2013a, p. 3)

Understanding the work done to successfully introduce the EcoGrid market arrangement involves describing an unfolding experiment. With the large number of partners and 2000 participants, EcoGrid is known as a large-scale prototype, pilot, and demonstration project (e.g. Jørgensen, Sørensen & Eriksen, 2011; EcoGrid.eu, 2013b). And, as is apparent from the structuring of the project and its description by the organizers, most often in technically scientific circles, it is an experiment (e.g. EcoGrid Bornholm, 2013). An element of experimentation with respect to configuration is in turn also part of the making of most control systems:

> As the process will typically involve a complex division of labour between specialized components the correct way to change the starting conditions to produce a desired output can rarely be predicted from first principles. Engineers must therefore learn (principally through the trial and error analysis of prototypes and pilot plants) how to tune the characteristics and boundaries of regions of behavioral stability…
>
> (Nightingale et al., 2003, p. 484)

Bornholm thus houses a test site made for establishing how specifically to realize the overall ideas involved in the EcoGrid arrangement 'on a European scale'. EcoGrid has the purpose of moving electricity consumption away from periods of peak consumption, and towards periods of peak production resulting from significant wind speeds, among other things (e.g. EcoGrid.eu, 2012a). The most immediately apparent way in which the EcoGrid retail market was conceived of and later implemented as an electricity consumption control system can be found in how it has been modelled on both an open- and a closed-loop control system.[14] The resulting arrangement takes the form of market designs descriptively named 'open-loop and closed-loop pricing' (EcoGrid.eu, 2013a) as illustrated in figure 2 below.[15]

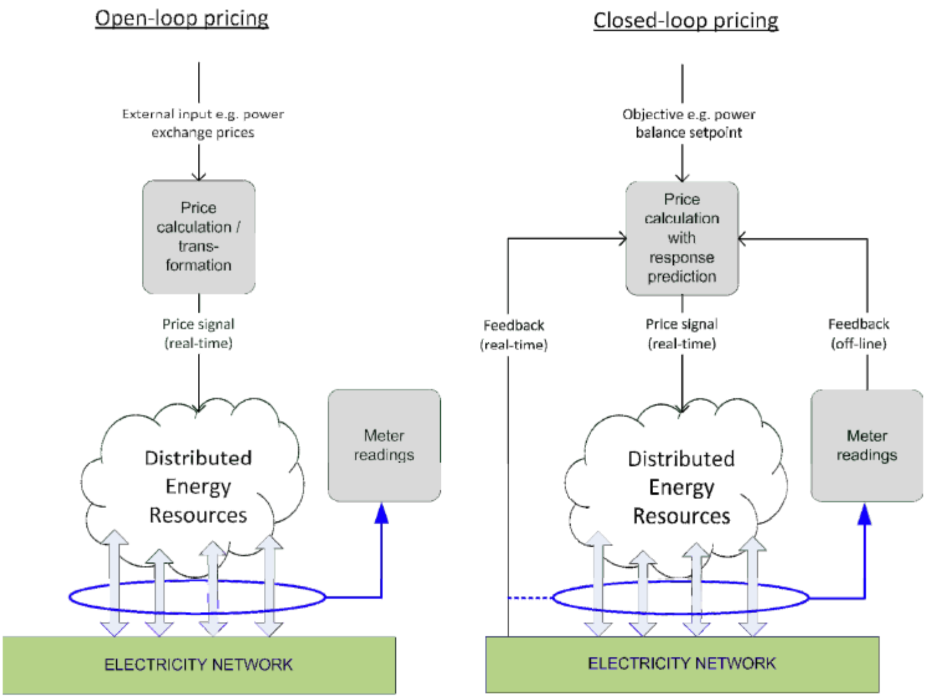

Figure 2. Open-loop and closed-loop pricing (EcoGrid.eu, 2013a, p. 4)

The functioning of the EcoGrid arrangement as an open- and closed-loop control system characterizes two different stages of the project. In the first part of the EcoGrid project, an open-loop electricity consumption control system was tested. The open-loop configuration was initially introduced to start the project with a simple means of producing data relevant for preparing the later implementation of the closed-loop set-up (Larsen, 2013). Specifically, running EcoGrid as an open-loop price based control system produces insight into consumer behavior relevant for calculating prices applied in the closed-loop set-up. An important aspect of the

[14] The main characteristics of open- and closed-loop control systems were described in in chapter 1.

[15] For a scientific journal article describing the EcoGrid market design published by the designers themselves see Ding et al. (2014).

data as part of preparing for price calculations in the closed-loop arrangement is that they imply registering changes in electricity consumption on an ongoing basis, in the context of varying electricity prices. When held up against an EcoGrid retail electricity price curve, the consumption pattern can be used in determining the relationship between changes in price and changes in retail electricity consumption. In effect, this data is used to measure the near-term price elasticity of retail electricity as found among the EcoGrid participants. And the price elasticity of retail electricity in the Bornholm setting is in turn used for assessing the price of electricity necessary for producing a relevant change in consumption (Energinet.dk, 2014b). As EcoGrid constitutes an open- and a closed-loop control system at various points in time throughout the duration of the project, making the experimental retail electricity market is in some respects different from market construction for the introduction of homeostatic utility control. Rather than collecting asking prices and bids for electricity in order to calculate a price, the control signal in the form of a price is calculated centrally and sent to electricity consumers who should then be able to react appropriately because of a negative relation between price and demand.

Closed-loop pricing works by first having the control system operator decide on the desired response or output produced by the EcoGrid electricity consumption control system. In being an arrangement introduced in order to help maintain equilibrium by adjusting system load, the input should reflect the need for system balancing. If EcoGrid was to be implemented on a national scale, determining the need for system regulation and the input for closed-loop price calculations would be undertaken by the TSO, which would also be running the EcoGrid market arrangement. Establishing the desired response would be approached by registering deviations from the system frequency set point and translating them into specific amounts of electricity. The required amount of upwards or downwards regulation would in turn need to be translated into a price expected to facilitate the equivalent change in consumption. And this is where the registered price elasticity of retail electricity needs to be mobilized. In the initial data generating open-loop pricing design of EcoGrid, varying electricity prices similar to the ones found on the Nord Pool Spot Market are applied (Larsen, 2013). As the spot market prices on Nord Pool generally reflect the state of the electricity system, this pattern of price movements is a relevant way to introduce changes in the control signal for the purpose of generating data.

The use of the open-loop market design for producing insights relevant for later market development is a concrete initial example of the experimental format (e.g. EcoGrid Bornholm, 2013) of the EcoGrid project. Wind power integration through the introduction of a control system facilitating equilibrium maintenance in the electricity system here implies doing an economic experiment for the making of a market (e.g. Callon, 2009). Thus, following the EcoGrid project is a matter of seeing how:

> These experimental activities are research activities in the sense that they aim at observing and representing economic objects, but also – and quite explicitly – in the sense that they seek to intervene on these economic objects: to seize them, to modify and then stabilize them, to produce them in some specific manner. To experiment is to attempt to solve a problem by organizing trials that lead to outcomes that are assessed and taken as starting points for further actions. Experimentation is action and reflection
>
> (Muniesa & Callon, 2007, p. 163)

In the closed-loop arrangement, the input reflecting a lack or excess of electricity goes through the EcoGrid input transducer, which converts it into a price signal. The price signal is then transmitted to the controller. But in the case of the open-loop pricing arrangement the input transducer does not convert the input. Here the input corresponds to the Nord Pool spot price of electricity, and the signal can be transmitted directly into the system without conversion. The plant in need of controlling in the EcoGrid electricity consumption control system is the electricity-consuming household taken as a single unit. In other words, the EcoGrid control system design incorporates an understanding of electricity consumption as undertaken by a composite arrangement constituted by all the elements relevant for the use of electricity. Simplified as distributed energy resources (DERs), retail electricity buyers are thus understood to act in concert with all the components partaking in electricity consumption within the domestic setting. And in accordance with the idea that electricity consumption is an activity undertaken by a DER, the design and implementation of EcoGrid addresses a number of heterogeneous elements mobilized as part of electricity consumption. Participants are trained and the use of electrical equipment in their households is connected with EcoGrid, automated, and partly remote-controlled by the market organizers. Describing how this works here requires following how the format of the controller of the DER, which receives the price signal from the input transducer, varies between the five groups of the EcoGrid experiment. And to understand the various controllers installed as part of the economic experiment, the features of the different EcoGrid groups will here be discussed.

The 2000 EcoGrid participants are divided into five groups which are variously equipped (e.g. Larsen, 2013). Group I is known as the Statistic Control Group and consists of 200 households equipped with smart electricity meters. A Smart Meter is a digital electricity meter with the capacity to register electricity consumption and transmit it in such a way as to automate the meter reading process. Within EcoGrid, the electricity seller and system operator are one and the same. The Smart Meters issued under EcoGrid register electricity consumption in five-minute intervals, and send the electricity consumption data to the project organizers via the Global System for Mobile Communications (GSM) once every hour. As the statistic control group does not receive varying prices or any additional equipment, it has strictly been introduced for reporting electricity consumption patterns over time in a way that enables statistical rigor.

Group II is called Manual Control and consists of 400 to 500 households. In addition to being equipped with the Smart Meters, consumers in this group are exposed to new electricity prices every five minutes. These prices can be viewed by means of the online EcoGrid price portal, which is accessed by the consumer through the My EcoGrid homepage when applying the password and username provided. By being exposed to price variations in five-minute intervals while equipped with a Smart Meter registering consumption in those exact same five-minute periods, the consumer is provided with the technical possibility of reducing the amount of money paid for electricity per KWh. Saving money becomes possible if the information from the My EcoGrid website is used as a guide for consuming electricity when prices are low and not consuming electricity when prices are high. If consumption in effect comes to have a negative relation with price, the electricity-consuming household is turned into a DER (e.g. Gantenbein, Binding, Jansen, Mishra & Sundstrom, 2012). In this way, the success of the EcoGrid retail electricity market depends on creating and mobilizing distributed energy resources helping to maintain equilibrium in the electricity system by reacting to an electricity price which should reflect the need for regulating the electricity system up or down.

The collective of people and devices responsible for a specific pattern of electricity consumption represents the plant or processes regulated by the controller in all the EcoGrid groups. And as no additional equipment is made available to Group II, the controller driving the plant has to be located within the person occupying the house in question. In other words, it is the person operating the electric appliances who has to receive the price signal and adjust electricity consumption accordingly. The change in consumption has to be made by the occupant of the dwelling in manually registering the change in price on the EcoGrid website and switching electrical equipment on or off. Installing a controller and letting the price signal regulate electricity consumption is here a matter of reconfiguring the electricity consumer in a way which ensures this change in behavior. With respect to Group II, the actualization of the DER thus relies on having a ready, willing, and able human present in the electricity-consuming household. In this way, the successful mobilization of the group working by means of manual control largely comes to rely on the training and motivation of the people participating.

Groups III and IV are both named Automatic Control, and have been provided with additional equipment beyond that of the Manual Control group (e.g. EcoGrid.eu, 2012b). The two groups differ by the approximately 700 members of Group III being supplied with additional equipment produced by IBM, and the approximately 500 members of Group IV receiving a series of devices made by Siemens. Group III is set to respond autonomously to price signals, whereas Group IV is planned to be able to respond to an aggregator signal at a certain point in time. The compatibility with an aggregator signal implies that the prospective DERs in Group IV are set to later be able respond to a signal which is used to optimize consumption patterns in specific areas of the distribution grid, rather than at a unified EcoGrid level. The participants in these two groups all have heat pumps or another form of electric heating installed. As the groups of participants with electricity-driven heating systems have proven to be the biggest balancing resource (Bendtsen, 2013a) while also going through a more comprehensive training program due to the larger amount of equipment they receive, much of the following will be devoted to describing electricity consumption within these two groups.

The IBM and Siemens equipment comes with access to a piece of online software for switching the specialized electric sockets supplied through EcoGrid on and off using a domestic wireless local area network (WLAN). The software enables management of the use of select forms of electric appliances, electric heating, and water heaters. A prominent feature of the software is that it can increase consumption when electricity prices are low, and decrease consumption when prices are high, by automatically switching heating on and off within temperature intervals set by the consumer, in response to fluctuations in price. The functioning of these types of programs and algorithms has also led to them being described as "energy-brokers" (Schick & Winthereik, 2013, p. 87). The controller of the DER or plant is in this case the software supplied by EcoGrid. Group V, called Smart Businesses, was planned to incorporate a similar arrangement for around 100 commercial actors. But enrolling businesses in the EcoGrid project has proved difficult (e.g. Ørberg, 2013). The lack of business participants at the time of data generation was in turn an important factor in the decision to focus on household consumption when following the implementation of the EcoGrid arrangement.

The open-loop pricing arrangement allows for testing the way the variously equipped groups react to changes in price every five minutes during the day, week, month and year. These data are used to make the input transducer for the closed-loop pricing arrangement which is introduced at a later point in the EcoGrid project. Rather than transmitting the prices from the Nord Pool spot market, the closed-loop pricing set-up consists of a publicly inaccessible algorithm based on demand response forecast models. The algorithm has been developed and tested at DTU using data from the open-loop arrangement, small-scale experiments around DTU, and synthetic data. The algorithmic input transducer converts the desired amount of electricity represented by the need for upwards or downwards regulation of the system into a price signal which corresponds to an informed "guess" of the electricity price required to get consumers to adequately adjust electricity consumption up or down (Østergaard, 2013). Again, the closed-loop arrangement differs from the open-loop version by having the characteristic feedback path between the added output measurements and summing junction. The response to the price signal in the form of the change in system balance is registered at the overall island level or from the individual meter readings (EcoGrid.eu, 2013a).

Having outlined how the experimental retail electricity market has been designed as an open- and closed-loop electricity consumption control system, the conception of EcoGrid as part of the larger Nord Pool arrangement also needs to be addressed. From the above it is apparent that as a control system, the EcoGrid market design works in a way which is quite different from Nord Pool's highest volume markets. Significantly, EcoGrid is a control system operating in intervals close to real-time. And to be able to function within moments of dispatch, it was configured as a control system implying:

> …a 'bidless' market with ex ante price announcement. This means that the final settlement price is determined by predictions of the price responsiveness rather than on explicit bids as known from conventional auction markets and published before each market interval, for which the price is valid. Furthermore each market interval is just 5 minutes, which ensures that the real-time price can follow the fluctuations of supply and demand
>
> (Østergaard in EcoGrid.eu, 2012a, p. 4)

In several respects, it is the actualized differences between homeostatic and closed-loop control which makes EcoGrid an appropriate supplement for the chain of auctions and pricing arrangements on Nord Pool. Homeostatic control works largely by means of scheduling equilibrium through ongoing price negotiation. The calculation of an electricity price by means of asking prices and bids is what signifies the maintenance of equilibrium in the high volume markets of Nord Pool. But conducting these negotiations takes time. In contrast, the open- and closed-loop control system design of EcoGrid implies that the price-based control signal is calculated centrally and then transmitted to retail electricity buyers where consumption is set to have a negative relation to price. Signaling from the demand side in EcoGrid is not facilitated by means of bids, but ultimately through changes in system frequency. The lack of active bidding and complicated price negotiation based on a large number of inputs implies that actual consumption is not necessarily always equated with the level desired by the control system and market operator, as when operating a homeostatic control system. But consistent equivalence is not a requirement in the context of EcoGrid. And closed-loop pricing here implies that consumption in principle can be changed with relatively short notice as automated and remote-controlled DERs can be made to react to a change in price every five minutes. There are thus benefits of the EcoGrid system concerning timing, for example. Running EcoGrid by means of a live auction so close to dispatch with mainly household electricity consumers as the sellers of regulating power would be difficult at best. Having household consumers produce and transmit bids which have to be included in a merit order optimized list necessarily involves an elaborate and time-consuming process.

Before specifying how the technical requirements and features of the EcoGrid design as modelled on a closed-loop control system are related to the way it was conceived of as part of the overall Nord Pool arrangement, it is worth highlighting that these characteristics imply a recentralization of electricity system operation. That EcoGrid involves a degree of centralization was also pointed at by one of the market designers in stating that they had created a monopoly (Larsen, 2013). As EcoGrid seeks to mobilize retail electricity consumers for the purpose of equilibrium maintenance in moments very close to dispatch, there is not enough time to make prices by means of the procedures applied in other electricity markets. To be able to quickly mobilize electricity consumption, EcoGrid prices are calculated by the system operator. Prices are made using an algorithm incorporating the price elasticity of retail electricity along with the need for upwards or downwards electricity system regulation. Since this approach involves one-way price-based communication between the system operator and the buyers, the organization of electricity system operation is necessarily centralized. And although the EcoGrid arrangement as implemented on a full scale would imply that the central TSO becomes an intermediary connecting actual electricity producers and retail consumers, it does not change the fact that centralization is an integral part of the market concept. Rather than trading with a retail electricity supplying company, the consumer deals directly with the TSO.

To further illustrate how the TSO would become an intermediary between electricity producers and retail consumers through the full-scale implementation of the EcoGrid control system, the way the market has been conceived of as a new part of Nord Pool will be introduced. Understanding how the EcoGrid idea has been situated within the Nord Pool context will also clarify another way in which the experimental retail electricity market was configured as a control system. It will be shown how EcoGrid was designed not only as an open- and closed-loop control system, but also as a subsystem of the homeostatic control framework introduced in the form of Nord Pool. After having described this second way in which EcoGrid was designed as a control device facilitating electricity system equilibrium maintenance and wind power integration, emphasis shifts to the use of economics in the same process of electricity market construction. As a measure addressing the relationship between changes in price and demand, the notion of price elasticity was used in the EcoGrid project to inscribe a necessary feature and intended outcome in the experimental retail electricity market arrangement. And as the concept has been used to characterize the functioning of the EcoGrid DERs, the role of the notion of price elasticity is elaborated on through a description of EcoGrid's implementation. This is in turn due to the fact that it is in implementing EcoGrid and assembling DERs that the role of price elasticity has its clearest expression.

EcoGrid as a Nord Pool subsystem

That EcoGrid has been designed to extend Nord Pool by working as a subsystem within the overall homeostatic control framework is apparent from the way it functions as a modified version of a frequency adaptive power energy rescheduler (FAPER) (Schweppe et al., 1980). Originally introduced as an important part of the homeostatic utility control concept, a FAPER is a device introduced in order to expand the means by which homeostatic control can be exerted. It does so by constituting a kind of resource supplementing equilibrium maintenance as undertaken through scheduling, in for example the day-ahead and intraday markets on Nord Pool. A FAPER implies a form of demand-side direct control for electricity system regulation accessible in the periods close to dispatch. In short, a FAPER is a device increasing the possibility of having consumers partake in electricity system equilibrium maintenance as conducted by means of homeostatic control. The team of EcoGrid market designers had experience with the FAPER concept from a previous research project named "Demand as Frequency-controlled Reserve" (Bang et al., 2013). And the notion of the FAPER as presented by Schweppe and his co-authors in the development of the homeostatic utility control concept was in turn included in the process of conceiving of the EcoGrid market architecture (Østergaard, 2015).

Importantly, the functioning of a FAPER rests on the distinction between electricity consumption as being characterized by requiring either energy or power (e.g. Tabors, 1981). 'Energy-type' electrical equipment implies a need for a certain amount of electricity over a specific period of time in order to function as intended. However, the equipment and its use imply an indifference to the exact time within the period at which electricity is consumed. Room temperature conditioning, water heating, pumping, refrigeration, melting, and grinding are examples of energy-type uses of electricity. 'Power-type' electrical equipment implies the opposite features: needing a specific amount of power at a specific point in time in order to serve its generic purpose. This second category of electrical equipment includes electrical appliances such as TV, lights, and computers. The functioning of a FAPER involves working with energy-type electricity-demanding activities by mobilizing the implied indifference to the exact timing of energy consumption. In other words, energy-type electrical equipment can help provide the possibility of distributing electricity consumption in different ways over time without compromising the output of the activity in question. As the use of electricity can be variously concentrated within a specific period, mobilizing energy-type uses of electricity using a FAPER can create effects equivalent to energy storage. A FAPER arrangement essentially consists of frequency measurement, temperature or process measurement, control logic, output actuation, and power supply:

> …consider the operation of an industrial melt pot with a FAPER. If the melt temperature lies outside of the maximum and minimum allowable range, the heating system is turned on and off accordingly. However, if the temperature is within the allowable range, the heating system operation is influenced by the measured frequency. If the frequency is below 60 Hz, the heating system operation tends to be turned off; if frequency is above 60 Hz, the heating system tends to be turned on. When supply (mechanical power out of turbines) is less than demand (electric power to costumers), system frequency decreases and vice versa. Thus, decreasing demand when frequency is low is a stabilizing action
>
> (Schweppe et al., 1980, p. 1153)

A FAPER is thus a subsystem for the overall homeostatic control system which makes it possible to have demand-side responses to system requirements. It is effectively a closed-loop control system with the same general traits as the EcoGrid retail electricity market introduced above and the room temperature control system using a thermostat described in chapter 1. In this way, the exemplary room temperature control system is relevant in the context of EcoGrid in several ways. This is in part due to how EcoGrid is intended to function along the lines of a FAPER. More precisely, the purpose of EcoGrid is to introduce devices providing FAPER functionality mainly in a household-level setting by arranging and mobilizing DERs.

As it embodies the characteristics of a control system, the FAPER concept can be scaled up and down easily. Control systems often imply subsystems, and in the case of EcoGrid, the control system arrangement can be described as implying dynamics also found in the operation of a FAPER at several levels. Indeed, finding out how to best exert control by means of defining the right aggregator level is a concern of the project organizers (e.g. EcoGrid.eu, 2012a). Their work with defining levels of control is displayed in the considerations of how demand response can be aggregated in specific areas of the distribution grid. What should be taken away from this is that EcoGrid can be and is considered a control system functioning by similar means in both a household setting and a larger pricing zone context. In short, EcoGrid is something akin to a 'meta' FAPER containing FAPERs. But as the EcoGrid arrangement implies the use of price as the control signal sent forward while maintaining frequency as the controlled variable transmitted backwards, it also constitutes a form of price adaptive power energy rescheduler.[16] And the appropriate use of price as a control signal is, in the context of EcoGrid as implemented on a national scale, not only a matter of mobilizing DERs, but also one of connecting to the other markets within Nord Pool. As a Nord Pool subsystem, EcoGrid has been designed and adjusted to fit within and connect to the markets of Nord Pool in a specific way.

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[16] Another example of the introduction of price-based FAPER-type arrangements for the integration of wind power in the Danish electricity system can be found in recent attempts to facilitate the introduction of large heat pumps in decentralized combined heat and power plants with large hot water storage tanks (e.g. Paaske, Pijnenburg, & Tang, 2013).

Connecting markets

To the EcoGrid architects and developers, making the new market arrangement is largely seen as a matter of extending the established market solutions of Nord Pool. That is, EcoGrid enables the ongoing trade with upwards and downwards regulation to move closer to the moment of dispatch (e.g. EcoGrid.eu, 2013a). When fully implemented, a solution similar to EcoGrid would be run by the Danish TSO in such a way as to complement the series of different markets which make up Nord Pool. To see how this would work, the aggregate Nordic electricity market should be approached as functioning in two different ways. The markets temporally furthest away from the moment of dispatch, not taking into account the financial markets, are the Nord Pool Spot Market and Elbas. These two are known as the day-ahead market and intra-day market, respectively. Moving closer to the moment of dispatch, the first parts of the balancing market are encountered. Here trade revolves around upwards and downwards regulation services rather than electricity. These markets function as a series of auctions with bidding going on in an aggregate period ranging from 36 hours to 15 minutes before dispatch. All these markets are part of a process of scheduling the production and consumption of wholesale electricity.

When moving even closer to dispatch, the part of the regulating power market characterized by remote control of suppliers of regulating power, rather than ongoing asking and bidding for the making of schedules, is encountered (EcoGrid.eu, 2013b). The participants in these markets use the sources of regulation services which are able to deliver with the shortest possible notice, effectively deploying a technology with a very low reaction time. So close to dispatch, there is no time for scheduling. Plants owned by the sellers of regulating power are in these instances remotely controlled by the TSO, and then paid according to the amount delivered in addition to a standby fee. The EcoGrid retail electricity market design involves an attempt to push the use of price as a control signal into periods closer to the moment of dispatch.[17] Locating a new market within Nord Pool in this way is to beundertaken by placing EcoGrid between the parts of the regulating power market which are run by live auctioning and those

[17] See chapter 1 for an introduction to the use of frequency as a control signal in AGC-type control systems within the markets of Nord Pool closest to dispatch.

involving direct remote control coupled with retrospective settlement (see figure 3).

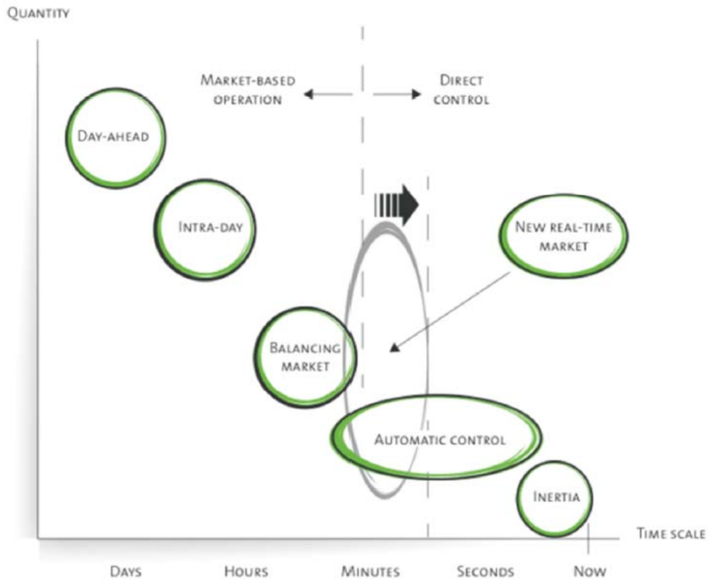

Figure 3. Placing EcoGrid within Nord Pool (Energinet.dk, 2014b, p. 39).

Introducing the EcoGrid arrangement in this way corresponds to an expansion of the number of potential sellers of regulating services in a part of the market closer to the moment of dispatch. In doing so, EcoGrid to some extent comes to overlap with established parts of the regulating power market. For this reason, a different way of adjusting the EcoGrid retail electricity price signal could involve directly transmitting the price for upwards or downwards regulation from the Nord Pool Balancing Market. These prices are found in (Energinet.dk, 2008a)) Nordic Operation Information System (NOIS) list (see figure 4).

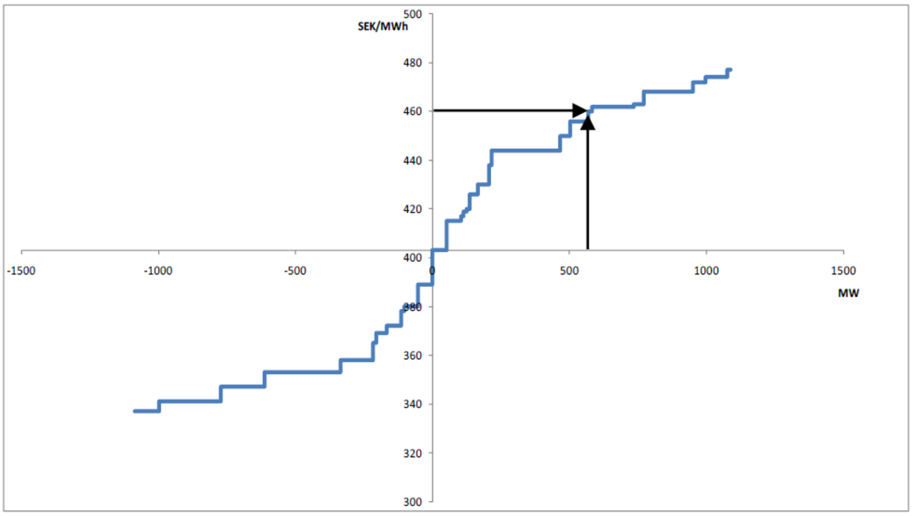

Figure 4. NOIS list, 17/6/2009, 07:00-08:00. 583 MW of upwards regulating power activated, corresponding to a price of 460 SEK/MWh (Bang et al., 2012, p. 15).

In the upwards regulating power market on Nord Pool, Energinet.dk buys the amount of electricity necessary for maintaining equilibrium in the electricity system. The prices paid for upwards regulation are set by the marginal asking price within merit to deliver a specified amount of electricity. The highest asking price still within merit thus sets the price paid to consumers using less or producers supplying more. The way upwards regulation prices are in principle directly applicable in an EcoGrid context is as follows: the greater the need for upwards regulation, the higher the price; the higher price is then also sent to retail consumers in EcoGrid, providing an incentive to reduce consumption; consumption using domestic electrical equipment is turned down, and; the state of the system is pushed towards equilibrium.

In a situation with too much electricity in the system, all trade with regulating power is undertaken in the market for downwards regulation. In the downwards regulating power market, the TSO sells the excess electricity. When one regulating power market opens and the other closes, the TSO and the market participants thus switch roles as buyers and sellers of electricity. In the upwards regulating power market, the TSO is the buyer while electricity generators and buyers are the sellers. In the market for downwards regulating power, the TSO is the supplier of electricity while the electricity generators and buyers constitute the demand side of the market. The marginal price in the market for downwards regulating power is set using the same uniform pricing principle as on the Spot Market and the Regulating Power Market for upwards regulation. But in contrast to the market for upwards regulating power, the market for downwards regulating power has to set the marginal price of electricity in accordance with the lowest bid within merit. Again, in the market for downwards regulating power, wholesale consumers make bids for increasing their consumption and producers can make bids for decreasing production. The marginal price of electricity in the downwards regulating power market thus has to be set by the lowest bid within merit to buy the excess electricity from the TSO, as this is the way to make sure that all the surplus electricity is sold. Transmitting the price from the NOIS list into EcoGrid during periods with activity in the market for downwards regulating power would thus work in the following way: as the need for downwards regulation increased, consumers would pay less for consuming more and producers would pay less for producing less; the change in price would also be transmitted to the EcoGrid consumers, providing an incentive to increase consumption; relevant energy-type electrical equipment would be switched on, and; the state of the system would be pushed towards equilibrium.

Adding EcoGrid retail electricity consumers to the Regulating Power Markets would allow for the supposed optimal sourcing of regulating services within an expanded pool of regulating service suppliers. In other words, retail electricity consumers are added to the pool of suppliers of regulating services. Doing so should lower the costs of equilibrium maintenance in the electricity system and thereby help to integrate fluctuating electricity production from wind turbines. In this way, EcoGrid "…will become an additional source of regulation capacity for the TSOs in parallel with the regulating power market. Consequently, the transmitted prices must be set in close coordination with the price development on the regulating power market" (Jørgensen, Sørensen, & Eriksen, 2011, p. 3). Put differently, the EcoGrid market design and position within Nord Pool would require that the retail electricity price signal is set in accordance with the price of regulating power. If not, an efficient allocation of resources at an aggregate level is hard to achieve. However, doing so is currently not possible due to the way in which Nord Pool market rules forbid the immediate publication of prices reflecting current system balance (e.g. EcoGrid.eu, 2013a). In this way, there is an incompatibility between the design of the EcoGrid retail electricity market and that of the established regulating power market. And introducing this new market engineered as a control system for electricity system equilibrium maintenance would thus be in conflict with the functioning of a previously established one.

Looking back on the way EcoGrid has been designed, it is possible to point out a way in which this case of wind power integration through electricity market construction serves to augment the performativity programme. The description of how EcoGrid was conceptualized at the Technical University of Denmark points to how control systems engineering has constituted a generative form of expertise in the process of market design. EcoGrid was shown to have been engineered as an open and closed-loop electricity consumption control system. Furthermore, it was made clear that the experimental retail market was conceived of as a control system or subsystem within the overall Nord Pool homeostatic control arrangement by functioning like a FAPER. In describing the way the experimental retail electricity market was configured, EcoGrid was also shown to be different from the series of established electricity markets on Nord Pool which it has been designed to complement. In EcoGrid, the price-based control signal is only sent from supplier to buyer as opposed to markets operating on the basis of transmitting asking prices and bids from the supply and demand side and negotiating prices. And it was in relation to the description of price calculation within EcoGrid that it was shown how this new form of electricity consumption control arrangement would imply the centralization of market organization.

Having clarified the use of expertise in the form of control systems engineering, focus will at this point shift to how economics has characterized wind power integration as market construction for the introduction of a new control arrangement supporting electricity system equilibrium maintenance. While drawing on the description of the way EcoGrid was designed, the following section is devoted mainly to tracing the implementation of the new market as undertaken on the Danish island of Bornholm. Following the on-site introduction of the new market helps to extract the way the metric from economics known as price elasticity was inscribed in EcoGrid as a necessary feature and outcome of the market arrangement. This highlights how economics supplied a measure describing the objective to be attained by assembling and mobilizing distributed energy resources for electricity system equilibrium maintenance. And doing so involves demonstrating a use of this form of expertise which is different from the one described in chapter 1. In the first case, the concept of liquidity was shown to have been applied when specifying the desired outcome of a process of market construction intended to improve the operation of an established homeostatic control system. In this second case, the making of the EcoGrid market arrangement for electricity consumption control is shown to have involved the notion of price elasticity as an integral part of the original market design.

Increasing the price elasticity of electricity

In EcoGrid, retail electricity is set to be made near-term price elastic. The capacity to endow retail electricity with the qualities of a price elastic good is derived from the indifference to the timing of electricity consumption implied in the use of energy-type electrical equipment. And it is mainly by managing a price signal regulating the automated use of electricity for the purposes of running domestic energy-type electrical devices that household retail electricity consumers can come to serve as DERs, helping to maintain equilibrium in the electricity system. Thus, a negative relationship between variations in price and variations in demand has to be established. Electricity consumption has to rise when prices fall, and fall when prices rise. What is more, the price elasticity of retail electricity also has to be associated with a low reaction time in order to make EcoGrid function in accordance with its intended position within Nord Pool. The change in demand as efficiently caused by a change in price has to be realized in the near term. If the EcoGrid market arrangement for controlling electricity demand is to help maintain equilibrium in the electricity system by working in the period of time closest to dispatch, consumption has to be adapted to changes in price almost instantaneously. And the requirement of being able to make rapid adjustments has also been an important factor in the decision to have EcoGrid function by transmitting a new price every five minutes. However, the choice of five-minute time intervals also constitutes a compromise between moving coordination based on a price signal closer to the moment of dispatch, and not presenting too big a computational burden. A third factor was the capacity of the equipment available (e.g. Østergaard, 2013).

Depending on the consumers and the various electricity purchasing arrangements they were part of before joining the EcoGrid project, the price elasticity associated with retail electricity will have varied. However, it will not have taken the particular form it has in EcoGrid. In order to see how such a change in the price elasticity of retail electricity was pursued through the introduction of the electricity consumption control system described above, emphasis will here shift over to the electricity consumers participating in the EcoGrid experiment. With respect to human behavior, conceiving of and later installing a system for regulating conduct in relation to the timing of electricity consumption has involved borrowing ideas from economics. These ideas are summed up in the notion of a specific kind of economic agent described by neoclassical economics. The electricity consumer inscribed in the EcoGrid market design can be described as an individual oriented towards utility maximization under conditions of resource scarcity. And developments in the demand for electricity are set to have a negative relationship with developments in price. In other words, EcoGrid seeks to mobilize 'price elasticity' (e.g. Larsen, 2014; P. Lund, 2014; Grande, 2011) in order to increase the means by which homeostatic control can be exerted and wind power integrated by placing EcoGrid in Nord Pool.

In the case of the notion of liquidity in the context of the Nordic wholesale electricity market, a measure from economics provided a way of conceptualizing what was to be achieved by means of market construction. Liquidity was increased by expanding electricity market infrastructure and providing new resources for exerting homeostatic utility control. Similarly, in the context of EcoGrid, the notion of price elasticity constitutes a measure describing a state of affairs which organizers try to change by means of a new retail electricity market configuration. Economics provides a medium for describing the objectives or ideal outcomes of making and remaking different control systems in the form of markets. The success of EcoGrid is predicated on the electricity consumer being configured in a way that implies the greatest possible price elasticity of retail electricity as expressed in the short term. The greater the degree of price elasticity realized, the greater EcoGrid's potential for contributing to electricity system equilibrium maintenance becomes.

In going about the actualization of the EcoGrid arrangement, the parties responsible did not assume that the economic agent and price elastic relation with the good inscribed in the EcoGrid design would be realized simply by transmitting fluctuating prices in five-minute intervals. As indicated earlier, this specific form of economic agent forming a crucial part of the arrangement was not a priori assumed to exist. This particular consumer is considered a central outcome of the successful introduction of EcoGrid. And a lot of work has been planned and undertaken (e.g. Bendtsen, 2013a; Jørgensen, 2013) to produce an economic agent with a price elastic relation to retail electricity as expressed in the short term. In beginning to elaborate on how a new form of retail electricity consumer is introduced, the Bornholm context will be briefly described. The island community of Bornholm constitutes the setting in which EcoGrid was inserted in 'making up' conduct for electricity system equilibrium maintenance by assembling 2000 retail electricity consumers as distributed energy resources. And for this reason it is significant for this particular exploration of "…the social relations, techniques, and forms of training and practice through which individuals have acquired definite capacities and attributes for social existence as particular sorts of 'person'" (du Gay, 2000, p. 279).

Bornholm

The island of Bornholm constitutes the easternmost part of Denmark, and has a population of around 40.000. A total of around 28.000 electricity consumers reached a peak load of 56 MW in 2007. In the same year, wind power production amounted to more than 30% of aggregate electricity production on Bornholm. The island only has one electric connection with the surroundings in the form of a sea cable running to and from Sweden. As the sea cable can be and sometimes is deactivated, the Bornholm power system can also be operated in 'island' mode. Apart from the possibility of operating the local electricity system in island mode, the Bornholm power system to a great extent possesses the characteristics of the wider Danish electricity system. The potential for running a typical system in more or less complete isolation makes Bornholm an ideal setting for electricity system experimentation (Østergaard & Nielsen, 2010).

Fishery and tourism have been important industries on the island for many years, and even though the tourism industry is still a relatively large contributor to the island's economy, the sector has been shrinking alongside the number of visitors in recent years (e.g. Thessen, 2008). On a similar note, the fishing industry in the Baltic Sea has decreased significantly in the same period (e.g. Semrau & Gras, 2013). As a way of dealing with financial downturns, in 2007 a group of 48 people representing the population of Bornholm created a 'vision' for the future known as Bright Green Island: "…Bornholm wants its future to be 100% green; a carbon-neutral community based on sustainable, renewable energy. We will supply a number of innovative green solutions for our benefit and for the benefit of the whole world" (Business Center Bornholm, 2013a, p. 1). As part of a wider process of industry development, the push for making Bornholm a bright green island attempts to touch upon many aspects of life in the community. Of particular relevance here is the notion of the 'Bright Green Test Island': "Selling and sharing sustainable innovation solutions and providing an experimental R&D playground is Bornholm's ambitious vision, which is already becoming a reality" (Business Center Bornholm, 2013b, p. 30). As part of becoming a bright green test island, Bornholm has over the years come to house a relatively large number of scientific and commercial electricity technology development projects. The island's power system has even come to be called "A Full-Scale Laboratory for Smart Grid Research" (Østergaard, 2011, p. 1). To attract development projects to the island, Bornholm has enrolled in PowerLabDK. PowerLabDK is in turn also the host of EcoGrid:

> The Bornholm power system is part of PowerLabDK, an experimental platform for power and energy. PowerLabDK is a unique research platform, ranging from flexible multi-purpose university laboratories to large-scale experimental facilities and a complete full-scale power distribution system. The facilities are interconnected and integrated experiments can be performed. Measurements from the Bornholm system are available in the Intelligent Control Lab at the university [Technical University of Denmark]
>
> (Østergaard & Nielsen, 2010, p. 5)

It is within this context that the EcoGrid market design has been actualized. And while EcoGrid itself is described as a pilot and demonstration project, it has had the possibility of drawing on the experiences obtained from smaller but related projects. However, the EcoGrid project itself did not involve a dedicated preliminary study of interests and behavior among the consumers participating in the project. Focus can thus here appropriately be turned to how the EcoGrid experiment involves an attempt to seize, modify, and stabilize retail electricity consumers in a way that effectively turns them into DERs for wind power integration or electricity system equilibrium maintenance.

Making a flexible electricity user

> …the presence of a given kind of behavior is the result of a series of social experiences during which the person acquires a conception of the meaning of the behavior, and perceptions and judgments of objects and situations, all of which makes the activity possible and desirable
>
> (Becker, 1953, p. 235)

As part of an attempt to integrate wind power into the Danish electricity system, the experimental EcoGrid electricity market has been introduced in order to produce knowledge about the potential for using closed-loop price-based control systems in adding resources for equilibrium maintenance in the electricity system. This was undertaken, as has been documented, by seeking to mobilize near-term price elasticity made available through energy-type uses of electricity at a domestic level. Again, the purpose is to transform households into distributed energy resources adjusting demand to better suit ongoing changes in the state of the electricity system. In the EcoGrid design, all elements involved in relevant types of electricity-consuming activities in a specific location are collapsed into the notion of the distributed energy resource. As a single unit, the DER encapsulates the entire arrangement of objects partaking in the ideal form of electricity consumption in the context of a domicile as laid out in the EcoGrid design. And at this point, emphasis is placed not so much on the conceptualization of the EcoGrid market and DER as formulated by technical scientists at the department for electrical engineering at the Technical University of Denmark. Rather, attention here focuses on how the control system configuration is actualized in the homes and summer houses of Bornholm.

In the context of EcoGrid, reconfiguring the market as a control system implying that retail electricity is near-term price elastic and where price can be managed as a control signal involves equipping and training consumers in a way that makes the new programme of economic action both possible and desirable. The account of how EcoGrid organizers try to assemble a flexible electricity consumer within this ‘regime of the person’ (Rose, 2000, p. 312) can thus be structured along the lines of the work needed for becoming a marihuana user for pleasure (Becker, 1953). Like in the making of a marihuana user, engineering a market for controlling consumer conduct is to a large extent a matter of making individuals both willing and able to act in new and specific ways. The attempt to have EcoGrid participants act in a manner which implies an increase in the near-term price elasticity of retail electricity was thus characterized by seeking to provide experiences and materials making price-responsive consumption both enticing and manageable. If the consumer was not sufficiently interested, participation and price elasticity would be jeopardized. Without the introduction of a series of technical devices and ideas facilitating relevant conduct, the ideal participant behavior would be unfeasible regardless of a willingness to comply. The specifically formatted fundamental economic incentive implied in the new market arrangement was thus set to be an outcome of training and equipping participants in a certain way. To clarify the attempted process of consumer agency transformation, the account here follows the path laid out for and taken by consumers in their encounter with EcoGrid.

Making a willing consumer

Depending on which experimental group the participants are part of, the selected electricity consumers on Bornholm go through a more or less elaborate introduction process coordinated by the local utility company and EcoGrid partner named Østkraft. That is, the organization of EcoGrid on Bornholm is run by a project group within Østkraft (e.g. Jørgensen, 2013). Initial contact between a potential participant and EcoGrid takes various forms. EcoGrid organizers reach out to consumers through an awareness campaign involving various types of advertisements, presence in local news broadcasts and social media, along with open house events at the demonstration site Villa Smart (C. Holm, 2012); Jørgensen, 2013; EcoGrid.eu, 2013a). A number of potential project participants also become aware of and interested in EcoGrid through word of mouth, hearing from friends and family on the island who are in some way involved in the project (e.g. EcoGrid Participant I, 2013). At this stage of the recruitment campaign, organizers try to enroll potential EcoGrid participants in the project to the extent that they are willing to sign up for learning more about what participation entails. During interviews for the present inquiry, EcoGrid participants stated various reasons for initially joining the project. Motivational factors included the potential for a financial reward, the promise of receiving free electrical equipment such as Smart Meters which could be kept when the project was terminated, helping

Denmark's transition to a sustainable energy system, and supporting a project which was seen to be 'good for the island'.

Signing up for learning more about EcoGrid is done by filling out a questionnaire on the EcoGrid Bornholm website (EcoGrid Bornholm, 2014b). Here the prospective participants provide information about the inhabitants and electricity-consuming equipment in their homes. This information enables the EcoGrid organizers to categorize the dwelling as eligible or ineligible for participation in one of the five EcoGrid groups. If relevant for EcoGrid, the consumer is then invited to an introductory session at Villa Smart. Nearly all participants initially go through this introductory session hosted by one of the two on-site EcoGrid managers from Østkraft. These sessions typically involve groups of around eight consumers. At the introductory session in Villa Smart, the reasons for participating in the project already mentioned are brought up and supplemented with arguments referring to electricity system stability. The way references to system stability were presented involved relating to the fact that there is an important electrical connection running between Bornholm and southern Sweden (Østergaard & Nielsen, 2011). Including the reference to the electric connection with Sweden is of significance as the population of Bornholm has experienced a number of blackouts over the past five years, when ships have accidentally taken the cable out of service by dropping anchor in the wrong area. The anchoring incidents were mentioned on several occasions, reflecting a collection of consumers with experiences of a fragile electricity system. During an introductory session, the accidents were used in arguments for establishing the importance of the project: "You probably all remember how the sea cable was cut! When that happens we move into island-operation mode, and in these situations it is even more important to balance the system" [Author's translation of a quote in field notes] (Bendtsen, 2013b). Participation is in this way also made into an issue of upholding electricity system stability on the island.

One widespread reason for participating consistently highlighted by both EcoGrid organizers and participants was the possibility for monetary reward. EcoGrid offers participants the chance to convert EcoGrid points into cash at the end of the project. EcoGrid points are awarded and withdrawn in accordance with the extent to which consumption takes on a negative or positive relation with price. The reward from converting these points thus corresponds to the money which would have been saved in effect of the consumer increasing the use electricity at times when the price is low and limiting consumption when prices are high. During the introductory session the expectations of the potential participants were adjusted by presenting fictive yet plausible electricity bills resulting from both the ordinary tariff-based system and from participation in the EcoGrid project. These were juxtaposed in a matrix where the total costs of electricity for a household over a period of one month were presented, making apparent a difference of around €1, which is equivalent to nine EcoGrid points. And while the potential for monetary gain varied from consumer to consumer depending on the amount of energy-type electricity consuming devices available, many households were understood to possess potential for receiving a reward substantially bigger than the €1 per month (e.g. Larsen, 2013). A guarantee against losing money was also issued. Part of the standard agreement between the consumers and the EcoGrid organizers stipulated that participants could not end up paying more than they would have done had they not used the EcoGrid system. Even though a consumer might have had consumption patterns which would in principle have led to an increase in the cost of electricity, bills could never rise above those incurred by means of a stable tariff.

Another aspect of the EcoGrid introduction session was to have consumers associate the potential for monetary gain with the behavior prescribed by the EcoGrid arrangement. The approach taken to getting consumers to associate compliance with monetary reward was to explain to them the new arrangement they were to partake in. Consumers were to learn that they now had to handle varying market prices rather than for example a fixed long-term tariff. In establishing that fluctuating market prices would be presented in five-minute intervals, it was explained to consumers how they could decrease their electricity bills. Minimizing a household's electricity costs was plainly presented as a matter of using electricity in periods where prices are low and avoiding electricity consumption in periods where prices are high. Here, de-learning the old billing system also became a key issue. Part of consumer training was a matter of detaching electricity from the routines of the household such as putting on the tumble dryer. Among the prospective and previously enrolled participants, there was not necessarily always a clear sense of the fact that the use of electricity involves making an instantaneous purchase. Electricity was nonetheless consistently considered to be worth something among the participants. It was conceived of as a resource which could be used for certain purposes, and which came at a cost. But it was often referred to mainly as a part of doing something other than consuming electricity.

In introducing the participants to EcoGrid and explaining how the new market and economic incentive was set to work, electricity was to some extent detached from its uses. Electricity, the electricity market, and the electricity system were actively discussed and presented in isolation and as things of importance in their own rights. Subsequently, electricity consumption could again be referred to as a matter of for example room temperature conditioning. But in discussing domestic electricity consumption after having detached it from and reattached it to the domestic routines of which it is part, buying electricity was presented as a service to a system which is worth something. In this way, the consumer instruction sessions in Villa Smart provide the clearest example of how the approach to realizing the economic agent inscribed in EcoGrid resembled Garfinkel's (1984) 'designed procedural demonstrations' for making commonplace scenes visible. To produce the desired conduct, training involved dialog and thought experiments seeking to estrange participants from electricity consumption in everyday routines. Doing so was coupled with a presentation of electricity as a good traded in a marketplace at varying prices and transported using a delicate infrastructure, as opposed to it being simply a resource for operating electrical equipment. Generally, willingness to comply was also reinforced by the EcoGrid organizers in picking up on and emphasizing what they learned along the way to be the motives for participating in the project. Doing so included stressing the various benefits of the equipment, and the potential for becoming an informed and environmentally friendly consumer, alongside the possibility of monetary gains through reductions in the cost of electricity.

Making an able consumer

Apart from the effort to make participation enticing, the initial session in Villa Smart also included an introduction to the various forms of equipment distributed within the different EcoGrid groups. Introducing the equipment was one of the first steps taken in order to make consumers capable of changing their relationships with retail electricity in a way which makes the good increasingly near-term price elastic. As many of the people attending an introductory session are very new to EcoGrid, the process is characterized by an effort to explain how the equipment works and how it can be operated. Even though the consumers attending the meeting can and do ask questions which often relate to concerns about what participation implies for issues such as control over their everyday lives, this part of the introductory session mainly takes on a presentation format. Instructions about the functioning of the most elaborate kit as provided by Siemens and IBM is also made available online in the form of manuals and a series of instruction videos featuring the EcoGrid Bornholm project manager (e.g. EcoGrid Bornholm, 2014b).

In some cases the work done to make consumers both willing and able to act in the way desired by the EcoGrid organizers was folded into the same process. This was not least the case with the effort to get EcoGrid participants to reconsider the patterns of use associated with their electric appliances. What is more, changing the way EcoGrid participants choose to time the use of their various electric appliances is undertaken at various sites. At the introductory session in Villa Smart, the need to change how the use of electric appliances is timed is presented at a general level as part of the presentation of how the EcoGrid system works. The issue of changing patterns of use was here also specified by taking up the concrete example of a washing machine. The degree to which it could be rewarding and manageable for the consumer to have the washing machine on at night when EcoGrid prices would typically be low, was discussed among other things as depending on what characterized other routines of the household such as family and job situation. An effort to establish a willingness to comply was promoted by urging the participant to begin to weigh the pros and cons of reacting to the price signal with regards to particular electrical appliances in specific situations. In doing so, the consumer would begin to actively relate to the price provided by EcoGrid. Establishing willingness to comply was in this respect a matter not so much of getting the consumer to react to the price, but more one of getting the consumer to enter into a situation where she can come to react to the price. Instilling the ability to comply is here supported by getting the consumer to consider how electrical appliances can be used differently, and what that change implies for everyday life.

Working out what electrical appliances and equipment can be used in a flexible way by the individual consumer was also approached by circulating a leaflet pointing out EcoGrid-compatible and non-compatible electrical appliances and equipment. The approach is effectively based on highlighting the power- and energy-type uses of electricity which can be found in a domestic setting (see Figure 5). In other words, electrical devices are color-coded and associated with a symbol in an attempt to point to the pieces of equipment which can and should be used in accordance with variations in the price of electricity.

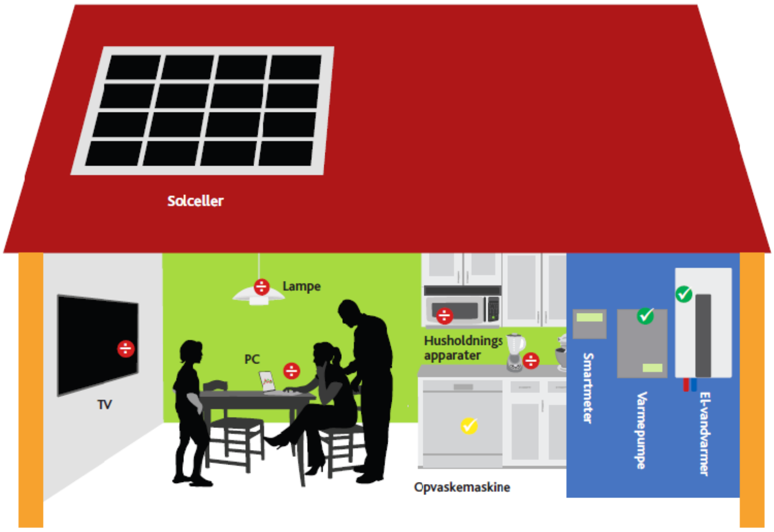

Figure 5. Cut-out of illustration (EcoGrid Bornholm, n.d., p. 3).

Red suggests incompatibility with EcoGrid and generally points to power-type uses of electricity. Yellow demarcates electrical devices which can be manually turned on or not, depending on developments in the price. Green denotes equipment running on electricity which is highly compatible with the EcoGrid arrangement. This final category of devices is characterized by including the pieces of equipment the use of which can be automated and subsequently controlled at a distance by the system operator through the Siemens or IBM equipment. In going through the supplied software-based user interface, the consumer can set the equipment to run whenever prices are low. When this is done, the system operator can more or less directly control these parts of domestic electricity consumption by means of the price signal.

If the potential participant is still interested after the introductory session, the session in Villa Smart is followed up by having an electrician from Østkraft visit the consumer in her home to set up the equipment. Apart from doing the electrical installations, the electrician here also facilitates a process of more hands-on training than was the case at the introductory session. This is in part undertaken by letting the participant experience the My EcoGrid website, which hosts the price portal and the user interface of the software running the equipment supplied by IBM or Siemens. The price portal is what immediately meets the consumer when she logs on through the My EcoGrid webpage. In addition to displaying the current electricity price, the numbers are coded green, yellow, or red to express the development in the relative cost of electricity at any given moment. If prices are on the rise, the number is coded red. If prices are falling, the number is coded green. Yellow suggests that prices have plateaued (e.g. Bendtsen, 2013a).

Apart from publishing prices in five-minute intervals, the EcoGrid terminal also shows charts of past price developments and consumption patterns. With her access to real-time prices, overall electricity consumption, appliance-specific historical consumption patterns, and past prices available through the webpage, the EcoGrid participant is also provided with the means to further train herself. This is most significant for the process of clarifying what it implies to use various household appliances in the context of EcoGrid. That is, it matters in clarifying how much electricity the different appliances use and what it costs. This information can in turn be used when weighing costs and benefits while relating to developments in the price of retail electricity. This does not, however, imply that consumers had no means of calculating the costs of electricity before the introduction of EcoGrid. The contrary was often the case, with some consumers being able to quickly make quite accurate calculations. When running the microwave oven to warm a glass of milk, for example: "…it's 20 seconds. And it's 800 watts…that is only a question of cents. But if it was running at 1000 watts, well then you can calculate it yourself – then it is one kW, which means 2,08 kroner an hour" [Author's translation] (EcoGrid Participant II, 2013, 0:45:38-0:45:57). But when electricity consumption patterns and electricity prices were displayed in this new way on My EcoGrid, they tended to have a stronger presence. The effect was most clearly illustrated in the case of EcoGrid Participant III (2013). In spite of being an electrician by training, it was not before using the EcoGrid equipment that he began to actively note and pay attention to the difference between using the oven or the toaster for heating two rolls in the morning.

The home-based consumer training sessions suggested a noteworthy degree of freedom with respect to the approach taken by the individual electrician. In addition to a dialog about which appliances could be added to the EcoGrid system and what the effect could be, the visit from the electrician here functioned in a disciplining manner by involving the consumer in setting up the devices regulating the home heating system and water heater. By going through the user interface of the software for regulating the temperature of the house step by step with the electrician, the consumer learned what it would take to adapt the use of her heating system and water heater to the new fluctuating electricity prices.

Establishing the adaptability of electric radiators, heat pumps, and electric water heaters was approached in a slightly different manner than the discussion-based format used in working out the potential of non-automated appliances. With respect to room temperature conditioning and the operation of water heaters, making retail electricity buyers increase consumption at the points in time where prices were low, and decrease consumption when prices were high, was to a large extent enabled by translating values. Take the case of going through the EcoGrid market to purchase electricity for a heat pump or an electric radiator. For most consumers this used to be a matter of adjusting a thermostat. But during the introduction in Villa Smart and the training session at home with the electrician, the consumers learn that it is now about defining a wider level of comfort. This level of comfort takes the form of room temperature intervals. The intervals are then entered into the My EcoGrid program, and an algorithm set to minimize the costs of electricity used for room temperature conditioning then takes over. For the EcoGrid organizers this transformation is crucial because no regular consumer is understood to be able to define their comfort level by accepting or rejecting prices in five-minute intervals (Bendtsen, 2013a). Rather than asking the consumer what price she is willing to pay when heating up the dwelling, she is asked to specify the room temperature intervals that she is willing to accept. When a consumer sets the interval as somewhere between 18 and 22 degrees, an algorithm and digital thermometers with WLAN access ensures that room temperature stays within that interval. The arrangement works by turning on the heating system to the extent that the maximum temperature is reached and maintained, if electricity prices are low. Conversely, the program allows the room temperature to drop to a minimum of 18 degrees before turning on only to stay at that level, if electricity prices are high.

Each of the consumers interviewed had access to a piece of interface software allowing them to define these limits for various periods of time during the week. The EcoGrid group supplied with the Siemens equipment was also equipped so as to be able to set temperature intervals for different points in time in different rooms. One participant described how the software not only allowed for, but also made her realize that she could benefit from timing the heating of the living room: "In the morning we are in the kitchen…we are not in the living room, so I have adjusted that…and at eight o'clock when I come home after having dropped the kids off at school, then it's okay to have the heating on in there because I will be in that room mostly…but that is the sort of thing I find it fun to play around with a bit" [Author's translation] (EcoGrid Participant I, 2013, 0:02:13-0:02:34). In this way, redefining the calculative agency of the consumer comes to imply getting them to deal with comfort levels in relation to room temperature rather than electricity prices, as well as the everyday routines of the household.

A significant aspect of the above configuration of the EcoGrid consumer using electricity for domestic heating is that it implies automation of decisions to buy electricity. In addition to making the above-described translation, the software provided by EcoGrid enables decisions about the purchase of electricity to be made automatically by an electricity purchasing device working within specifications set by the consumer. The automated purchase of electricity for room temperature conditioning has turned out to be the biggest contributor in moving electricity consumption in accordance with variations in price (e.g. Larsen, 2013; Bendtsen, 2013a). But automation was also important for arranging and mobilizing DERs in other instances; for example, as when water heaters are set to reach temperatures proficient for killing legionella bacteria once every week, rather than having them work at such a high and unnecessarily energy-intensive temperature non-stop. Many aspects of the EcoGrid design, such as automation, in this way rely on a series of material devices. In the case of the water heater, a power switch coupled with a waterproof thermometer which has WLAN access is introduced. After the training session with the electrician where the equipment is installed, EcoGrid participants also have a number of other means by which to learn how to adapt electricity consumption to variations in price. These include online forums for questions and answers within the EcoGrid Bornholm Facebook page and the EcoGrid Bornholm website, along with the EcoGrid Bornholm telephone hotline (EcoGrid Bornholm, 2014a). In this way, assembling distributed energy resources in EcoGrid for electricity system equilibrium maintenance and wind power integration implies realizing a particular version of *homo economicus 2.0* by carefully arranging a market *agencement* (Callon, 2007a). In order to make a certain kind of economic agent which is characterized by a near-term price elastic relation to retail electricity, the consumer is "…assisted, helped, surrounded, relayed…he is 'embedded' in assemblages endowing him with the resources, competencies, and assistance…needed for his existence" (Callon, 2008, p. 31).

In spite of all the work on behalf of the EcoGrid organizers touched upon here, the extent to which a negative relationship has been established between retail electricity prices and demand has varied. But the relation between variations in price and demand has been changed for some consumers, to some extent. Before moving on to the summary and concluding comments on wind power integration through market construction in the case of EcoGrid, emphasis is here placed on some of the outcomes of the economic experiment which were not hypothesized by the orchestrators.

Willing and able to act in different ways

A number of the consumers involved in the EcoGrid project have not conformed to the role laid out for them in the program of economic action as inscribed in the market design. Many consumers are not particularly interested in their own electricity consumption, but want the EcoGrid equipment installed. The equipment is often desired because it enables the participants to control the room temperature in their summer house from home, or to register how much the different appliances are used by the people renting a summer house (e.g. EcoGrid participant IV, 2013; EcoGrid Participant V, 2013). The equipment thus helps the participants monitor and control their houses from a distance. For example, EcoGrid participants can heat up their summer houses before arrival and monitor which appliances in the house appear to work as expected while the house is empty or rented out to strangers.

Some participants started out highly motivated to take part in EcoGrid, but ended up shutting down the system as the EcoGrid set-up intended for controlling room temperature does not take into account floor heating. Some consumers literally got cold feet. The placement of the thermometers allowing for the automated price-based regulation of room temperatures was sometimes a challenge to the EcoGrid organizers. Adding to this is the fact that floor heating very often goes hand in hand with stone floors. As heavy stone floors imply a high degree of thermal inertia and thus require a long period to warm up before being able to heat the room, comfort-oriented temperature intervals have to be narrow in order to not risk suddenly having a cold floor which would take a long time to warm up again. And narrow temperature intervals imply a lesser service in relation to electricity system equilibrium maintenance. Allowing the temperature in a room to drop too far at night would for some mean that it would take too long to reach the desired temperature needed during the day. Floor heating in this case seems to hamper the endeavor of integrating wind power into the electricity system by making retail electricity increasingly near-term price elastic and managing prices. Some consumers also found it disturbing to have others regulate the heat in their home: "…we came down one morning and it [the heating in the bathroom] had been turned off all night, so it was almost cold…So what do I do, I got hysterical almost, and then I go turn them [EcoGrid] off. Or that is to say I turn on the heating manually. Because there is no way they are going to decide whether it is cold or warm in the bathroom" [Author's translation] (EcoGrid Participant II, 2013, 0:13:24-0:14:06). One participant gave up differentiating the temperature between rooms of her house because it inhibited the movement of her cat. As the house was rented, she could not install cat flaps in the doors which would have to remain closed in order for the temperature to vary from one room to another. Yet others became annoyed with EcoGrid's equipment failing. The reasons for the lack of success are many, and often overlap.

Finally, one pattern of conduct among the participants was that the new means for monitoring and calculating the costs of consumption were used to actively save electricity, rather than move consumption around in time. In this way, an economically rational consumer different from the one inscribed in the EcoGrid design sometimes resulted from the effort of trying to make retail electricity near-term price elastic and using price as a control system. Consumers used the equipment for monitoring consumption to become aware of how much electricity was used by the various appliances. Some suddenly learned that it costs a not-insignificant amount of money to turn on the tumble dryer. By means of their new equipment, consumers began undertaking experiments to understand the quantity of electricity consumed in relation to specific routines, such as the number of KWhs consumed when warming rolls in the oven compared to heating them on a toaster. Old routines were evaluated and new ones adopted. Economic calculation thus came to center on a metric different from the one intended. Focus was on the quantity of electricity used, instead of the aggregate costs of electricity as prescribed by EcoGrid. A process for the making of a different form of economically rational electricity consumer was in this way initiated, one driven more by the consumers themselves.

Summary and concluding comments

Chapter 2 here provided the second description of how control systems engineering and economics have been mobilized in the process of integrating wind power into the Danish electricity system by means of market construction. In addressing the research question, chapter 1 focused on homeostatic utility control and the concept of liquidity in documenting the full-scale introduction of the wholesale electricity market in Denmark, and the later reconfiguration of the electricity market infrastructure. In chapter 2, the work done to solve the intermittency problem was shown to involve running a large economic experiment for the making of markets. A new form of retail electricity market arrangement was introduced in a limited part of the distribution system. As the empirical setting shifted, focus moved upstream among the efforts to integrate wind power into the Danish electricity system. In chapter 1, an effectively implemented full-scale solution was documented. In the present chapter, the work done to integrate wind power took the form of a trial conducted at more closed site.

The material presented throughout chapter 2 has augmented the performativity programme in two ways. First, control systems engineering was documented as being a generative form of expertise in the process of market construction. It was made clear that the experimental retail electricity market named EcoGrid was designed as an open- and closed-loop electricity consumption control system. Furthermore, it was documented how EcoGrid was conceptualized as a subsystem to the overall homeostatic utility control system implied in the Nord Pool arrangement. Specifically, EcoGrid was conceived of as functioning similarly to a FAPER in transmitting a price-based control signal forward and reporting on the controlled variable in the form of system frequency through the feedback path. Second, economics was shown to have provided a measure describing the objective to be achieved by means of market construction. In specifying a necessary outcome and inscribed feature of the EcoGrid market arrangement, the economic metric known as price elasticity was shown to have been mobilized in indicating the planned and ideal outcome of experimental retail electricity market construction. In chapter 1, the concept of liquidity was shown to have been used in addressing the desired outcome of building transmission system interconnectors. Heightening liquidity in turn strengthened the means through which homeostatic utility control could be exerted, and this meant that wind power could be integrated. Working in a different way, the notion of price elasticity was shown to be an integral part of the EcoGrid market design. In the case of EcoGrid, economics was not included to describe an ideal outcome of market construction improving the functioning of an existing and unaltered control system concept. Price elasticity was mobilized to depict the necessary configuration of relationships in a new electricity consumption control system.

The success of EcoGrid was described as depending on the actualization of distributed energy resources. DERs were understood as being based on the willingness and ability of EcoGrid participants to comply with the pattern of behavior laid out for them in the design of the new market arrangement. To achieve compliance, consumers were trained, equipped with a series of devices, and then continuously exposed to fluctuating prices in five-minute intervals. However, the attempt to produce a specific calculative economic agent with a near-term price elastic relation with retail electricity was countered by competing interests and rationalities among the participants. Often using the equipment provided by EcoGrid, they conducted their own experiments, followed their consumption statistics, and focused on quantity rather than the aggregate costs of electricity. Some became opposed to what they experienced as an intrusion into their homes and ended up turning off 'the system'.

In continuing the analysis in chapter 3, the empirical setting for the exploration of wind power integration by means of electricity market construction changes once again. Focus shifts to the work done by energy planners producing electricity market scenarios for the making of policy recommendations. In this final case, solving the intermittency problem is shown to have implied actualizing policy recommendations prescribing the reconfiguration of Nord Pool. These recommendations were made on the basis of techno-economic electricity market scenarios produced by means of a computer program for electricity market representation named the Baltic Model of Regional Electricity Liberalization (BALMOREL) and a data set named the Technology Catalog. As the program and data set have proved to be important in the context of wind power integration through electricity market construction, chapter 3 documents how these two elements were introduced into energy planning in Denmark. And following the making of BALMOREL and the Technology Catalog once again implies tracing the involvement of economics and control systems engineering in the process of market performation. First, it is argued that BALMOREL has been built as a particular type of control system in effect of it being based in linear programming. Second, the metrics from neoclassical economics named producer and consumer surplus are shown to have been mobilized in configuring BALMOREL so as to delineate the ideal operation and composition of electricity markets to be actualized by following policy recommendations. The empirical scope of the performativity programme is in this way expanded once again as control systems engineering is highlighted as a generative form of expertise in the making of markets. Furthermore, the findings of the performativity programme are augmented as economics is shown to have supplied metrics describing the objectives or outcomes to be reached by means of market construction for improved control system operation and electricity system equilibrium maintenance.

Linear Programming | Producer and consumer surplus

The present inquiry has explored the means through which wind power becomes integrated into the Danish electricity system. As an important part of the making of a Danish energy system which incorporates an increasing amount of renewable energy sources, understanding the way the intermittency problem is solved is instrumental for explaining how greenhouse gas emissions are limited and climate change mitigated. The accounts provided here have been structured around the empirical observation that wind power integration in a Danish context has been approached by reconfiguring an electricity market arrangement. Furthermore, all attempts at solving the intermittency problem included in the inquiry here involve the mobilization of control systems engineering and economics as forms of expertise central to electricity market construction. These observations have been coupled with an ongoing academic conversation with the so-called performativity programme as part of STS and economic sociology (Callon, 1998a). As part of a recent development within economic sociology (e.g. Mcfall & Ossandón, 2014), the purpose of the performativity programme has been to clarify the use of various forms of knowledge, know-how, and skills in designing and managing markets (Çalışkan & Callon, 2010). In connecting the subject matter of this thesis with the line of inquiry maintained by the performativity programme, the main research question is: *How have control systems engineering and economics been mobilized in the endeavor to integrate wind power into the Danish electricity system through electricity market design and management?*

Answering the research question has involved documenting three different attempts at market construction leading to the integration of wind power into the Danish electricity system. Chapter 1 documented the introduction and later reconfiguration of the Nordic wholesale electricity market. Here it was shown how the liberalization of electricity was approached by having Denmark enter the Nordic power exchange known as Nord Pool. Marketizing electricity system operation and composition was in turn described as implying a shift from one type of control system for electricity system equilibrium maintenance to another. The supply follows demand philosophy based on an AGC-type control system was to a great extent replaced with a system rooted in the idea of homeostatic utility control. It was then illustrated how the introduction of homeostatic utility control involved displacing the equilibrium of the electricity system into the equilibrium of an electricity market. After establishing how Nord Pool became the central arrangement for electricity system operation through which wind power integration would be pursued, attention was turned to how a solution to the intermittency problem came to imply electricity market construction. Wind power was integrated into the Danish electricity system by building a transmission system interconnector, expanding the material market infrastructure and increasing the ability to exert homeostatic utility control through the mutual adjustment of supply and demand in Nord Pool. In describing this first case of wind power integration as electricity market construction, the empirical scope of the performativity programme was reportedly expanded in two ways. Control systems engineering was shown to be a generative form of expertise in the process of electricity market design and management by documenting how Nord Pool was conceived of and later reconfigured as a specific type of control system for electricity system equilibrium maintenance. Economics was in turn shown to have been part of market construction in a way which has remained undisclosed by the performativity programme up until this point. Reconfiguring the Nordic wholesale electricity market implied mobilizing the notion of liquidity in order to have a measure specifying the objective to be reached by means of market construction improving homeostatic control system operation.

After following wind power integration as market construction through the full-scale introduction of a new electric connection in the Danish transmission system, chapter 2 focused on an alternate empirical setting by describing an economic experiment for the making of markets conducted on the Danish island of Bornholm. By focusing on the project named EcoGrid, an attempt to demonstrate and create knowledge about the possibility of using a new form of retail electricity market to solve the intermittency problem was depicted. In this second case, accounting for wind power integration by means of market construction putatively augmented the performativity programme in a way similar to that presented through the description of the introduction and reconfiguration of Nord Pool. In the case of EcoGrid, control systems engineering was shown to have been mobilized in two ways. It was made apparent that the experimental EcoGrid retail electricity market has been designed and implemented as an open- and closed-loop electricity consumption control system. Furthermore, EcoGrid was also shown to have been conceived of as a Nord Pool subsystem, designed to function like a frequency adaptive power energy rescheduler supporting homeostatic utility control. This second instance of wind power integration by means of electricity market construction thus pointed to how two slightly different control system concepts were simultaneously mobilized in the process of market design. Economics was then described as supplying the means to designate the desired outcome of introducing the EcoGrid market arrangement. The notion of price elasticity was used to specify the objective to be achieved by engineering an electricity consumption control system in the form of a retail electricity market. However, in the case of EcoGrid, the metric adopted from economics was not used to describe an outcome of market construction improving the operation of an already-established control system for electricity system equilibrium maintenance. Instead, the economic measure of price elasticity was inscribed in the EcoGrid design. Conceiving of EcoGrid in this way implied using the concept of price elasticity to describe the necessary relationship between developments in price and demand resulting from the introduction of the market arrangement.

Having followed both full-scale electricity market reconfiguration and an electricity market experiment conducted within a limited setting, wind power integration through electricity market construction as described in chapter 3 implies another change in empirical venue. In this third case, the exploration of wind power integration through electricity market construction takes the laboratories of energy planners in Denmark into account. As a specialty within technical science and an approach to energy system development, energy planning includes the making of scenarios describing the potential development of the energy system over time. Put briefly, such scenarios are here "…technically consistent models or pictures of the future energy supply in Denmark, incl. transportation, which respect given political objectives" [Author's translation] (Danish Energy Agency, 2014b, p. 5). These scenarios are in turn often used in the making of techno-economic policy recommendations that help to drive the development of the electricity market. Presenting this third case specifically involves describing how a widely used software program for electricity market representation in scenario building was constructed shortly after electricity was liberalized in Denmark. The program is named the Baltic Model of Regional Electricity Liberalization (BALMOREL) (e.g. Ravn, 2001a). Furthermore, it is shown how data about the qualities and costs associated with various electricity system components have been generated. Such data are necessary for electricity market modelling using BALMOREL and are incorporated in what is named the Technology Catalog (Danish Energy Agency & Energinet.dk, 2012a).

BALMOREL is a computer program for electricity market representation originally made to also include district heating. The use of the model is relatively widespread among the countries within Nord Pool, and has been growing in recent years (e.g. J. Pedersen, 2012). Since the liberalization of electricity in Denmark, the biggest energy-planning project launched by the Danish government has been conducted by an interdisciplinary group of experts named the Danish Commission on Climate Change Policy (DCCCP). The work done by the DCCCP is significant not least due to how policy recommendations from its main report called *Green Energy – The Road to a Danish Energy System Without Fossil Fuels* (Danish Commission on Climate Change Policy, 2010) were actualized in the relatively ambitious plans for sustainable energy system development introduced and carried out by the Danish government in recent years (The Danish Government, 2011a; 2011b). In generating scenarios used to derive policy recommendations, the DCCCP used the BALMOREL model (Boldt, 2013). One outcome of the DCCCP modelling effort was a recommendation to expand electricity market infrastructure in order to increase the ability to trade electricity and integrate wind power. This is apparent in the prescription of an "Expansion of the transmission grid…" (Danish Commission on Climate Change Policy, 2010, p. 65) feeding into the established "export strategy" (H. Lund & Clark, 2002) of wind power integration which continues to be of great importance in Denmark (e.g. Energinet.dk, 2014d).[18] As was also exemplified in chapter 1 when describing the making of the electrical connection between western and eastern Denmark, electricity market scenarios are very much part of wind power integration by means of electricity market construction. As three members of the Danish energy planning community put it:

> …identifying the potential of renewable energy has become a key area of interest within energy planning. A crucial element in this transfer is

[18] See Chapter 1 for a discussion and example of the importance of this established approach to wind power integration where electricity is moved over increasing distances in order to find buyers interested in purchasing electricity at the point in time at which it is produced by means of wind turbines.

> often to show coherent technical analyses of how renewable energy can be implemented, and what effects renewable energy has on other parts of the energy system. Such analyses require computer tools that can create answers for these issues by modelling defined energy systems
>
> (Connolly, Lund, Mathiesen, & Leahy, 2010, p. 1060)

The Technology Catalog is a best available technology (BAT) list of energy system components such as power plants and grid connections. Related to the national energy planning effort introduced in reaction to the oil crisis in the 1970s, the Technology Catalog has become a mandatory reference for public Danish energy-planning projects. The Technology Catalog has provided basic data for electricity market scenario-based reports set to inform Danish energy policy such as *Energi 2050* (Energinet.dk, 2010d), and *The Future Requirements for Flexibility in the Energy System* (Aarhus Municipality, 2012). Significantly, the DCCCP background report named *Fremtidsbilleder og virkemidler: Sektoranalyse – El- og varmeforsyning* (EA Energianalyse, 2010) containing the data about the qualities and costs of energy system technologies as applied by the commission, was based on the data specified in the Technology Catalog (Boldt, 2013). And having stable data that capture the qualities and costs associated with the components included in the modelling effort is a prerequisite for producing meaningful insight by means of calculations such as those performed when using BALMOREL (e.g. Andersen, 2013). Understanding wind power integration through electricity market construction thus here implies describing the making of two specific "market devices" (Callon, Millo, & Muniesa, 2008; Pallesen, 2013). Due to the fact that the Technology Catalog and BALMOREL are important to Danish energy planning for electricity market development and wind power integration, they are market devices in the sense that they constitute central "…material and discursive assemblages that intervene in the construction of markets…" (Callon, Millo, & Muniesa, 2008, p. 2). Focusing on the making of BALMOREL and the Technology Catalog in this way brings with it the possibility of documenting how electricity market construction for wind power integration takes on different forms and is distributed across various sites.

Following wind power integration by means of electricity market construction through the making of these two market devices involves documenting how "…objects are transported from the 'exterior' to the 'interior' of the laboratory.

But this movement is an operation of transformation and reduction: objects are 'purified' in order to make them fit for manipulation and production of controlled information" (Muniesa & Callon, 2007, p. 170). And in demonstrating how the objects represented by BALMOREL and the Technology Catalog enter into the laboratories of energy planners, chapter 3 seeks to augment the performativity programme in two ways. First, it is shown how control systems engineering constituted a generative form of expertise in the making of a software program mobilized in energy planning for wind power integration by means of electricity market reconfiguration. Doing so demands illustrating how BALMOREL has been built to represent electricity markets such as Nord Pool by means of linear programming (Ravn, 2001a), and how it in effect is set to function as a 'higher order' control system (Dantzig, 1957).[19] It is thus demonstrated how coming to represent Nord Pool by means of BALMORAL involved taking the merit order optimization method used to sort bids and asking prices on Nord Pool (e.g. Pinson, 2014) and devising an electricity market modelling program around it. Linear programming was used for the marginal cost-based dispatch of power plants under a central planning regime in Denmark and then similarly applied in setting prices on Nord Pool after the liberalization of electricity. And in a similar vein, the linear programming method was moved into electricity market representation with the making of BALMOREL. The Baltic Model of Regional Electricity Liberalization is in this way not a traditional example of the application of linear programming. The way linear programming was developed and proposed independently by the Soviet planner Leonid Kantorovich prior to its development in the USA is

[19] It is important to note that the categorization of linear programming as a form of knowledge developed within control systems engineering can be challenged. Without going too much into "…'boundary work' between artificially distinguished academic disciplines" (Mirowski & Nik-Khah, 2007, p. 198), a few points should here be noted. Linear programming constitutes a central part of the conceptual material produced by the cybernetics movement. Cybernetics is in turn intimately interrelated with what is now known as control systems engineering. And, significantly, a great milestone in the history of the discipline of economics was when it became intertwined with cybernetics around World War II (Mirowski, 1989; 2002). As with other products of cybernetics - such as the computer - the interdisciplinary character of the early cybernetics discipline makes the academic origins of linear programming somewhat of a 'historical chameleon' (Cf. Mirowski, 2002). However, for an account of how linear programming was developed chiefly by a mathematician in the RAND corporation as an applied mathematics approach to production system optimization and control, see Dantzig (1982).

suggestive of how the origin of linear programming is one of planning for production system optimization and control.[20] What is more, the making of linear programming as undertaken within the US Air Force think tank named the RAND Corporation was specifically oriented towards planned production system operation found in, for example, oil refineries and military training programs (Dantzig, 1982; 1957). In this way, getting to understand the making of BALMOREL comes to involve a description of how linear programming was adapted for electricity market representation and optimization. In short, the transition was made possible by conceiving of electricity generation and transportation as activities within a centrally operated production system in need of optimization through higher order control. What makes for a representation of an electricity market in BALMOREL is in turn that the optimized generation and transportation of electricity is coupled with developments in the representation of a demand system which is "…elastic [so as] to identify the responsiveness of demand to changes in supply prices" (Ravn, 2001b, p. 28).

The making of scenarios using BALMOREL implies specifying the ideal choice of elements such as types of power plants and connections in conjunction with the ideal way of operating them in order to meet demand at all times. And it is this ideal format of energy system composition and operation which is used to guide decisions influencing the way electricity is produced, transported, and consumed in Denmark. Following the account of how a higher order control for production system optimization was adapted for the purposes of electricity market representation, it is shown how economics was mobilized in specifying the objective to be reached by means of ideal electricity market operation and composition in scenarios built using BALMOREL. It is described how the maximization of producer and consumer surplus (Marshall, 1920) has been introduced as the guiding principle for the making of scenarios used in actualized policy recommendations prescribing the way the electricity market should be developed. Also designated as socio-economic value, the aggregate consumer and producer surplus has been explicitly specified as the factor guiding the making of

[20] Leonid Kantorovich received the Sveriges Riksbank Prize in Economic Sciences in Memory of Alfred Nobel in 1975 along with Tjalling Koopmans for his work with linear programming. For more on the subject and how it relates to operations research and control systems engineering, see Mirowski (2002).

scenarios when using BALMOREL. Inquiring into the making of the model thus underscores how control systems engineering as combined with economic metrics has a wide scope within the context of wind power integration through electricity market construction in Denmark.

Before explaining how the Technology Catalog was made as part of the development of a national Danish energy planning scheme, it should be noted that this account also provides an empirical example of how elements from the central planning regime have remained in the Danish electricity sector after liberalization. Such an example was also provided in chapter 1. In chapter 1, it was described how the marginal costs-based merit order optimization of power plants for dispatch was adapted from electricity system operation as done by means of central planning and used for price setting in Nord Pool. The mechanism for doing the merit order optimization in the context of both Nord Pool and the central planning regime for electricity system operation is known as linear programming. In the present part of the analysis, linear programming as originally introduced for economic electricity system operation by means of central planning is shown to have been adapted once again. Specifically, it is demonstrated how linear programming was used for electricity market representation through BALMOREL.

Both energy planning and the use of linear programming thus persisted after Denmark's entry into Nord Pool. As electricity was liberalized in Denmark, Nord Pool was set to organize energy system development. Instead of centralized economic decision making about aspects such as investment in the appropriate amounts and forms of production capacity, the market price of electricity was set to provide the information and incentive needed to coordinate these activities. But as Denmark entered Nord Pool, energy planning simply began to take into account the new framework for electricity system operation and composition. Rather than being made redundant by the electricity market, energy planning for the introduction and integration of renewable energy sources in the Danish energy system came to incorporate the idea of Nord Pool as an organizing factor.[21] Doing

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[21] Several potential reasons could be provided to explain why the introduction of Nord Pool did not replace energy planning within the electricity sector. One plausible explanation is market failure. Denmark's entry into Nord Pool has, for example, brought with it a relative increase in

so was in part accomplished through the launch of BALMOREL. Building scenarios for policy making came to involve producing scenarios of electricity market development. As a framework for energy system operation and composition within which energy policy would have to function after the liberalization, energy planning came to relate to the development of the electricity market in various ways.[22]

The Technology Catalog

The term energy planning has several meanings in a Danish context. One noteworthy application of the concept can be found in the way it signifies a specific field within technical science. As an academic specialization and research topic, energy planning tends to combine various disciplines in the study of how to rationally optimize energy system configurations and the policies conducive to these arrangements (e.g. Aalborg University, 2014). But when it was formally introduced in Denmark, the term energy planning did not denote a position within technical science as much as it referred to an activity conducted by the Danish state. And to see how energy planning was established as a public undertaking that brought with it the predecessor of the Technology Catalog, among other things, attention is here turned to the oil crisis of 1973. As 95 percent of the total national energy supply took the form of oil (The Danish Government, 2011b), the drastic rise in oil prices caused by a 25 percent reduction in supply from OPEC member states in 1973 had a large impact on life in Denmark. When the price of oil had increased substantially, energy planning surfaced as a term summing up a series of

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household-level retail electricity prices in part due to a lack of actual competition among suppliers (e.g. Danish Energy Agency, 2011a). Furthermore, Nord Pool has not facilitated the necessary investments in production capacity (e.g. Boldt, 2013). Thus, leaving the organization of the electricity sector up to the decentralized agents in the electricity market does perhaps not seem to be a uniformly good idea.

[22] An example of how energy planning came to imply electricity market development can be found in chapter 1. Here it was shown how the liberalization of electricity in Denmark facilitated how the expansion of the transmission system was approached as a matter of developing electricity market infrastructure.

initiatives launched to remedy the implications of the rising cost of oil and to prevent a similar energy crisis from developing in the future.

Before the oil crises of the 1970s, treating energy provision as a subject for central planning was unheard of in industrialized countries (Meyer, 2000). Supported by the governments of the countries in which they were based, the major North American and European oil companies were responsible for obtaining the amount of oil necessary for supplying the buyers close to home by means of oilfields abroad (Mitchell, 2011). In Denmark the national electricity companies would simply buy the amount of oil necessary for meeting demand, while also being responsible for planning the necessary development of the grid. In the early 1970s, 90 percent of the electricity produced in Denmark was generated using oil-based thermal power plants. Almost all buildings were heated using individual oil furnaces. When oil prices began to soar as supply was reduced, the Danish government quickly went to work on realizing what was presented as the primary goal of a new energy policy: "…to achieve the greatest possible reduction in the dependency on oil by means of savings in energy consumption and through a conversion to other sources of energy" [Author's translation] (Danish Ministry of Commerce, 1976b, p. 71). One very important outcome of this effort was the first official Danish energy plan named Danish Energy Policy 1976 (Danish Ministry of Commerce, 1976b) and the Danish Law on Energy Policy Measures of 1976 (Danish Ministry of Commerce, 1976a). Danish Energy Policy 1976 marked the beginning of almost 40 years of long-term national energy plans for Denmark. The practice of energy planning was tightly bound up in the making of energy policy, which in turn has been instrumental in the country's effort to lower greenhouse gas emissions (e.g. Lindboe, 2011; Clausen, 2010).

To realize the ambitions behind Danish Energy Policy 1976 and the Danish Law on Energy Policy Measures of 1976, a range of policy measures in the form of legislation and incentives were set in place (Danish Energy Agency, 2012b; 2014c; 2014d). Energy taxes on oil and electricity were introduced in 1977, and new subsidies for the introduction of combined heat and power plants (CHP) and district heating systems were established. Using the excess heat from electricity production as input for district heating systems resulted in efficiency gains relevant for exploiting the energy in each unit of fuel. Later, energy taxes also came to apply to natural gas and coal, and have been raised several times since being introduced. Adding to the events of 1977 was the tightening of requirements for heat savings in new buildings, originally introduced in 1961. The new requirements were followed by state subsidies for the insulation of existing buildings in 1978. These factors added to the previously oil price-driven incentive to insulate the very large proportion of buildings heated by oil furnaces.

Two central changes were initiated in 1979 when Denmark introduced the Heat Planning Law and adopted a bill on the establishment of a natural gas system. Prior to 1979 there had been no law directly focused on the way buildings were heated in Denmark, and around 50 percent of energy consumption in Denmark was dedicated to the heating of buildings (H. Ø. Pedersen, 2007). One significant implication of the introduction of these two legislative measures was the way they marked "…the beginning of new public planning" (Danish Energy Agency, 2012b, p. 16). To facilitate the transition away from oil and towards coal and natural gas as fuels for running new and more energy-efficient technical arrangements such as CHPs in a district heating context, a new approach to infrastructure planning was established by law. In combination, the two bills regulated the introduction, content, and form of energy planning in Denmark.

The planning process was to a large extent rooted in local government, and involved three overall phases (Danish Energy Agency, 2012b; 2014c; 2014d). Initially, local authorities were set to produce reports about each municipality's heat requirements, the applied heating methods, the amounts of energy used for heating, and the possibility of establishing heat supply. These reports were then passed on to the county councils and used to make regional heat supply summaries. The second round involved the local authorities presenting a report on the potential future configuration of heat supply in their area, with the county councils producing regional summaries. A third phase then involved the county councils using the material from the first two phases to lay down a definitive regional heat plan.

The regional heat plan would have two main aspects. One was the demarcation of zones, which involved pairing geographical areas with one of the two new public energy supply systems for room heating. Establishing the zones determined whether buildings had to be connected to the natural gas grid for heating by means of individual furnaces, or to a local district heating system run by means of a CHP.

The other main aspect of the definitive regional heat plan was the specification of the location of future heat supply installations and pipelines for natural gas and warm water. After having negotiated with the energy utilities, the local authorities would prepare a municipal heat plan complying with the regional heat plan. To help ensure that the plans were carried out, the municipalities were given the authority to oblige the owners of new and existing buildings to allow for the establishment of a connection to either the natural gas grid or a local district heating system. They were also given the authority to oblige building owners to stay connected. Furthermore, the municipalities were given the authority to collect a tax for the establishment of the connection. However, one thing the regulations did not do was to bring with them an obligation to actually use the installed district heating or natural gas connection (Danish Energy Agency, 2014e). All changes in the district heating system and natural gas grid, such as their establishment, alteration, and expansion had to be approved by the local authorities as being in line with the municipal and regional heat plans. Ultimately, the making of the zones and the appointment of an obligation to connect to either the natural gas grid or the local district heating system would be based on an assessment of which solution would incur the lowest aggregate costs.

To support assessments and analyses within this new large-scale decentralized planning effort, a series of documents making up what was called *Forsyningskataloget* or the Supply Catalog were produced throughout the 1980s in several editions (e.g. Styregruppen for Forsyningskataloget, 1988). And there is good reason to consider the introduction of the Supply Catalog a defining moment in the process of establishing the contemporary source of stable technology data called the Technology Catalog, which in turn has constituted a basis for recent electricity market modelling undertaken by the DCCCP. What started with the creation of the Supply Catalog was a practice of applying a widely accepted and often mandatory reference stipulating the qualities and costs associated with the components included in energy system representation. The Supply Catalog and the documents which have later replaced it have supplied data on energy system elements in ways which helped to alleviate large errors, created a shared data platform for comparison and evaluation, and served to dampen controversy in energy planning (e.g. Andersen, 2013; H. Ø. Pedersen, 2012).

Cataloging qualities and costs

Work on the first Supply Catalog began in 1979, and the first edition was published six years later (Styregruppen for Forsyningskataloget, 1985). Making the Supply Catalog was facilitated by establishing what is known as a *samordningsgruppe* or coordination committee. The coordination committee was one out of a number of new "…untraditional and intensive organizational forms…" [Author's translation] (Poulsen, 1986, p. 359) applied widely in the new energy planning scheme. The heat planning coordination committees consisted of representatives from the municipalities, counties, the new regional natural gas companies, electricity companies, the Danish Energy Agency, and the district heating companies. Apart from being responsible for the creation of the Supply Catalog, the coordination committees pushed the heat planning effort forward by providing concrete examples of zone demarcations, and training the staff of the regional authorities, municipalities, and supply companies, while also hosting a series of public meetings providing information to citizens who had to adjust to the heat planning program (H. Ø. Pedersen, 2007).

Work in the coordination committee for the making of first Supply Catalog involved a form of consensus planning. All contributors from the coordination committee responsible for creating the Supply Catalog had to agree about the final content. And getting experts with specific interests and orientations from for example the natural gas, district heating, and electricity companies to agree about the qualities and costs of the various energy system components turned out to be difficult. But after long and intense negotiations, a list of prices and qualities was drawn up and fixed (H. Ø. Pedersen, 2012). The Supply Catalog was updated and republished in 1988. And like the Technology Catalog which later replaced it, the Supply Catalog served to "…establish a uniform, commonly accepted and up-to-date basis for energy planning activities…the framework conditions for the development and deployment of certain classes of technologies" (Danish Energy Agency & Energinet.dk, 2012b, p. 5). And if public energy planning includes values different from those stipulated in the catalog, the exception has to be explicitly justified (e.g. Kofoed-Wiuff, 2013). The Supply Catalog was especially made to help planners avoid major mistakes when doing calculations for deciding what energy supply format was to be chosen for a specific area of the country, as this was an issue when the planning program was initially introduced in the southwest of Denmark (H. Ø. Pedersen, 2012).

The energy planning effort culminated in 1990 when all of Denmark had been zoned in a way stipulating that buildings should be connected to the natural gas or district heating system. Some zones included both natural gas and district heating, while buildings in scarcely populated parts of the country were exempted from having to connect to either type of supply system. As the overall heat plan was in place at this point, the legal arrangement requiring ongoing heat planning was replaced with what is known as the 'project system' (Danish Energy Agency, 2007). This new approach to changing the national room heating arrangement involved the municipalities approving projects for the alteration of the heat supply system on the basis of the established national heat plan. In this way, heat planning in Denmark in the 90s was characterized by the municipalities working to ensure that projects for the expansion of production capacity, grids, and the geographical areas supplied by the various heat-producing companies corresponded to the heat plan and the prerequisites laid out by the government. The same applied to alterations like changes in fuel format. As with the energy planning scheme, the catalogs published during the 90s were less extensive and were only reissued by the Danish Energy Agency in relation to the making of larger policy documents (Boldt, 2013) such as *Energy 21* (The Danish Government, 1996). The transmissions system operator Energinet.dk has participated in the making of later editions, which are now known as the Technology Catalog (e.g. Danish Energy Agency & Energinet.dk, 2012a).

Both the Supply Catalog of the 80s and its replacement Technology Catalog have aided energy planning in Denmark by constituting an obligatory reference specifying the qualities and costs associated with different technologies. Apart from helping planners avoid applying inaccurate figures, the catalogs have also proved to be practical by providing a kind of common platform for evaluation and debate among planners doing energy system modelling. As one energy system modeler and BALMOREL user from the consulting company Ea Energy Analyses put it, when it comes to the making of scenarios, the Technology Catalog is:

> …the starting point for technology data when you're – in a planning context. It is obvious that when an actor has to go and do calculations on his own plant, then they won't stick to the Technology Catalog, then they will go and say: how well can we do this – right'…but it is the point of departure. But then that means that if I see somebody else who has made analyses and I know the model, and I say what data

> have you used? ‘We have used the Technology Catalog’ – okay, with my experience I can then have an idea of how they have ended up with these numbers…
>
> [Author’s translation] (Bregnbæk, 2012b, 01:08:00-01:08:08)

As the Technology Catalog serves a mandatory list of values, a number of practical advantages thus begin to materialize. A central effect of the data being obligatory is that it allows for the simplifications included in the technology catalog to stand in for and serve some of the same purposes as data which are true in a general sense. In this way, regardless of the variations and uncertainties in the actual and future qualities and costs associated with energy system components, core tasks of energy planning such as analysis, modelling, comparison, evaluation, and prescription can still be completed. Were it not for the agreement or convention around the use of the data included in the Technology Catalog, many of these tasks would become significantly more difficult as different datasets and ideas would proliferate. As these data are widely used, the possibility of acts such as comparison, evaluation, and prescription, which are usually reserved for instances where objectively general statements exist, is attained.[23] Even though the contents of the Technology Catalog are not objectively general or recognized as being objectively general, by means of convention they still allow analysts to apply the data from the list to any of the specified technologies when making scenarios for energy planning. Furthermore, in containing a negotiated compromise of knowledge about the qualities and costs associated with different energy system technologies, data from the Technology Catalog are widely applicable in energy system modelling. And as several interviewees put it, having common data is a huge advantage when the time comes to argue over results (e.g. Boldt, 2013; J. Pedersen, 2012).

[23] To clarify this idea, one can consider the definition of generality provided by Peirce. In contrast to the quality of vagueness, “A sign (under which designation I place every kind of thought, and not alone external signs,) that is in any respect objectively indeterminate (i.e. whose object is undetermined by the sign itself) is objectively *general* in so far as it extends to the interpreter the privilege of carrying its determination further” [Italics in original] (Peirce, 1905a, p. 487).

In 2004, the Danish Energy Agency and Energinet.dk decided to publish a new version of the Technology Catalog focusing on electricity-producing technologies. However, the liberalization of electricity in Denmark which had begun around 1999 implied that the formal consensus-based approach to the negotiation of technology data as established in the 1980s and practiced in the coordination committees was no longer an option. One reason was that the liberalization of electricity had implied that data regarding the performance of electricity producing technologies had become either trade secrets or products sold at a price exceeding the budget available for updating the Technology Catalog (Boldt, 2013). Adding to this was a series of changes in the way the public sector was run (Ibid.), which were mainly introduced by the government elected between 2001 and 2011. In a wider effort to realize a specific ideal state (A. F. Rasmussen, 1993) by means of, among other things, the introduction of New Public Management, the organizational setup and steering of Danish universities underwent significant changes in this period. The transformation was marked most clearly by the Danish university reform of 2003, manifest in the university law of 2003 (Ministry for Science, Technology and Development, 2003) and the action plan named *Nye veje mellem forskning og erhverv – fra tanke til faktura* (The Danish Government, 2003). One outcome of the rearrangement of the Danish university sector was that the abilities to allocate state funding to publicly employed researchers were taken away from the universities. Instead, research funding was to a growing extent to be funneled towards select research projects with more immediate applicability in select and often commercial settings by a new set of funding bodies. This initiative came at the expense of broad, basic research activities (e.g. Richter, 2009). And key Technology Catalog stakeholders such as Risø at the Technical University of Denmark could no longer work on the compilation of the catalog as their funding was now allocated by separate external bodies and earmarked for specific projects.

A new method for making the Technology Catalog had to be introduced, and a former employee of the Danish Energy Agency named Jørgen Boldt, who had turned into an independent energy consultant, was hired to compile the new catalog in a way which would be practically and financially viable. From this point, the Technology Catalog was produced by Boldt, initially with the aid of an assistant, by arranging a ‘pseudo-consensus’ (Boldt, 2013). And once again it becomes apparent that elements from the central planning regime for Danish energy system development and operation were adapted rather than discarded as the electricity sector was liberalized. As with the use of linear programming for the marginal cost-based merit ordering and dispatch of power plants, the liberalization of electricity here implied that elements from the central planning regime were adapted to the new setting. The transformation of the approach to negotiating the qualities and costs associated with buying and operating energy system technologies was summed up concisely during an interview with the consultant:

> …when I then took over in 04…it became sort of a pseudo-consensus right. Because I couldn't have a meeting with – if you just take the two big companies Vattenfall and DONG Energy right, I couldn't invite them to a meeting and say 'let's agree about what is the best technology thermal efficiency of a coal-fired power plant today, and what do we expect it to be in 2015, 25, and 35'. You can't do that because they simply won't share the information with each other. They would've in…1980 or 81 and so on, right. At that point they had no problem sharing the information, but they won't anymore. So what I call pseudo-consensus, that is - I invite myself to an interview with DONG and asked what they thought, and after that I went out to Vattenfall and asked what they thought, and then they thought a little differently and then I extracted a common denominator. I took the square root of something, right. So I created consensus, but there wasn't consensus – right? So I interviewed all the parties about what things would cost and how they would work. And then I had to – not in a meeting, but I had to in my head say like 'okay then I think it will be approximately thereabout', and then maybe sometimes make an interval which covered both. And then we did a hearing…we typically had a hearing for about a month or two where we sent it out to all the interested parties, saying 'This is what we have come up with so far. Do you have any comments?' So we tried to do a consensus process. And then our logic was that if you didn't protest, then you agreed
>
> (Boldt, 2013, 0:33:30-0:35:03)

To make sure that sensitive information such as trade secrets was not made public, the bilateral discussions between the consultant and the contributors to the Technology Catalog were sometimes followed up with formal agreements. Here it would be stated what data the contributor could and could not be referenced for having provided (Boldt, 2013).

One result of the most recent major revision of the catalogs was that two were published in May 2012. One covers the qualities and costs of various forms of individual heating plants and energy transportation; the other includes generation technologies in electricity and district heating systems, energy storage, and energy carrier generation and conversion (e.g. Danish Energy Agency, 2014f). July 2013 saw the publication of a new form of Technology Catalog about technologies for the conversion of biomass to biofuel (Danish Energy Agency, 2013a). The core of the Technology Catalog is a series of datasheets. In the case of the catalog about the generation of electricity and district heating, energy storage, and energy carrier generation and conversion, the typical datasheet will include three categories of data associated with each technology. The first category encompasses Technical Data such as generation capacity per unit in MW, construction time and technical lifetime measured in years, availability over time due to planned and forced outage, and electrical efficiency. The second data category is named Environment, and presents different emissions measured in grams per gigajoule of fuel processed. Finally there are financial data including nominal investment costs alongside fixed and variable costs, costs of operation, and maintenance costs per MW produced. The values associated with each subcategory are outlined for the years 2015, 2020, 2030, and 2050 (Danish Energy Agency & Energinet.dk, 2012b).

In specifying how the Technology Catalog has been developed, a description of the making of a market device containing requisite technology data for electricity market modelling was put together. These technology data were in turn involved in electricity market representation for the formation of actualized policy recommendations regarding electricity market reconfiguration. Constituting an obligatory reference for the qualities and costs of energy system technologies in a public Danish energy planning context, the Technology Catalog co-developed alongside energy planning in Denmark in response to the oil crisis of 1973. Currently, the Technology Catalog plays just as big a part in energy system modelling and electricity market representation as the Supply Catalog did in the initial cost calculations for zoning decisions in the first national energy planning efforts of the early 1980s (e.g. Andersen, 2013). The specific values associated with electricity market components are only one of the central kinds of input needed for electricity market representation and the making of scenarios, however. Another is the software program named the Baltic Model of Regional Electricity

Liberalization (BALMOREL). Having outlined the making of the Technology Catalog containing data about the qualities and costs of energy system components necessary for energy system modelling using BALMOREL, focus now shifts to the making of the computer program. For it is by following the configuration of BALMOREL that it can be demonstrated how economics and control systems engineering have been mobilized in the making of a market device intervening in electricity market construction and wind power integration. And in this way, a further putative augmentation of the performativity programme is presented in two parts. First, it is shown that control systems engineering in the form of the linear programming concept constituted a generative form of expertise upon which BALMOREL was built. Second, it is described how economics supplied a metric for creating the objective that steers the making of scenarios produced by BALMOREL.

BALMOREL

> …the equilibrium conditions may be elegantly expressed as equivalent conditions in a linear programming
>
> (Ravn, 2001b, p. 36)

Describing the introduction of BALMOREL in a Danish energy planning context here involves showing how this second market device was made by mobilizing two forms of expertise. And as they were central to the development of BALMOREL, these two forms of conceptual input are shown to have been instrumental in the making of scenarios forming the basis of actualized policy recommendations for electricity market development in Denmark. Specifically, attention is here turned to the use of control systems engineering and economics. When configuring BALMOREL, the input provided by control systems engineering took the form of linear programming.[24] Being a 'higher order' control

[24] Developed at the US Air Force think tank the RAND Corporation, linear programming got its name from how "The military refer to their various plans or proposed schedules of training,

system for the optimization of production system operation (Dantzig, 1957), linear programming constitutes the conceptual basis of the model.[25] Economics is in turn shown to have been applied in the configuration of BALMOREL through the introduction of producer and consumer surplus. The metrics known as consumer and producer surplus are here shown to have been used to stipulate the way in which the model is set to represent optimal electricity market operation and composition in scenarios used for prescribing electricity market reconfiguration.

Getting to see how control systems engineering provided a central conceptual input in the form of linear programming has two main aspects. First, it is made clear how linear programming constitutes a specific type of control system dedicated to the steering and optimization of production systems. After having introduced this particular control system concept, the making of BALMOREL is then described as a particular instance of applied linear programming. To clarify how an electricity market can be represented using linear programming, emphasis is put on the way in which the generation and transportation of electricity in Nord Pool was transformed or 'reduced' to a linear programming model (Dantzig, 1957). For it is when the supply side of the electricity market is represented in this particular format that it can be virtually optimized and controlled using a generic equation solver such as the one applied in BALMOREL. In this way, it is shown how the electricity market is moved into the laboratories of energy planners by representing it as a linear programming model when working with BALMOREL.

As in all other instances of linear programming, making BALMOREL by transforming part of Nord Pool into a linear programming model involves making a number of changes in the way the object to be modelled is conceived (Dantzig, 1957). Accordingly, the making of BALMOREL is here explained by describing

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logical supply and deployment of combat units as a *program*" [Italics in original] (Dantzig, 1982, p. 47).

[25] Constituting a specific higher order control arrangement for the optimization of production system operation, linear programming has also been used for electricity system operation within the earlier central planning regime in Denmark as well as in price setting on Nord Pool after the liberalization of the electricity sector. See chapter 1 for a description of how the use of linear programming for electricity system operation was adapted to the liberalized electricity sector.

how the supply side of Nord Pool was converted into a linear programming model by following the steps outlined by George Dantzig in *Thoughts on Linear Programming and Automation* (1957). It is here important to note that the way BALMOREL was built, by reducing the supply side of Nord Pool to a linear programming model, involves representing supply and demand in distinct ways. And before demonstrating how BALMOREL was made by following the various steps as formalized by Dantzig for reducing a production system to a linear programming model, this fundamental distinction in the way supply and demand are represented has to be made clear. As linear programming is a method for implementing a higher order control system for the optimization of production system operation, BALMOREL represents the electricity market by optimizing the production and transportation of electricity in accordance with a variable representation of demand. In this way, demand is not optimized. BALMOREL was configured to represent an optimally functioning Nord Pool by conceptualizing the supply side of the electricity market as one centrally planned system reacting to a dynamic demand (e.g. Ravn, 2001b; 2013).[26] Conceiving of the supply side of the electricity market in this manner made it possible to introduce linear programming for production system optimization in a way that corresponds to the use of linear programming for electricity system operation under a central planning regime. And by showing how this works, it is once again demonstrated how the expertise used to operate the Danish electricity system under a central planning regime was adapted rather than discarded as the electricity sector was liberalized.

After having outlined the involvement of expertise from control systems engineering in the form of linear programming, the role of economics in the making of BALMOREL is then taken up. Focusing on the application of economics is undertaken by describing how producer and consumer surplus were introduced to steer the way electricity market operation and composition are represented in the scenarios produced by the model. BALMOREL has been made

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[26] Electricity generation and transportation are set to meet a representation of a price elastic, cross-price elastic, and income elastic demand at all times. In other words, demand for electricity as represented in BALMOREL can vary in response to changes in the price of electricity, changes in the price of other goods such as district heating, and changes in the incomes of electricity buyers.

to work by producing scenarios describing the configuration and operation of the electricity market maximizing the total producer and consumer surplus under a series of constraints. In other words, the model describes how to compose and operate the electricity system so as to produce the highest possible consumer and producer surplus, or socio-economic value.[27] And in showing that BALMOREL works in this manner, it becomes evident how consumer and producer surplus have been used to describe the objective of electricity market representation when producing electricity market scenarios for policy recommendations regarding electricity market reconfiguration and wind power integration.

By initially considering actualized policy recommendations such as those found in *Green Energy* (Danish Commission on Climate Change Policy, 2010), BALMOREL and the Technology Catalog were shown to have been central to energy planning for wind power integration through electricity market construction. In effect, the making of these two market devices is a significant part of electricity market performation and wind power integration in Denmark. And by outlining the use of linear programming and consumer and producer surplus in the making of BALMOREL, the empirical scope of the performativity programme is effectively expanded in two ways. On one hand, it is shown that BALMOREL is based on a specific kind of production system control arrangement in the form of linear programming. This implies that control systems engineering constituted a generative form of expertise in electricity market construction. On the other hand, consumer and producer surplus are shown to have been mobilized in describing the objective set to guide electricity market representation when using BALMOREL. By accounting for the use of consumer and producer surplus it is made apparent how economics supplied metrics driving the making of scenarios which have constituted the basis of actualized policy recommendations for electricity market reconfiguration. To begin to see how BALMOREL was configured by means of conceptual input from both control systems engineering and economics, describing the making of BALMOREL will start with a brief outline of the original BALMOREL project.

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[27] Within marginal analysis or neoclassical economics and in the context of BALMOREL, the maximization of socio-economic value is a logical outcome of producing a price at the intersection between the marginal costs of production and the marginal utility of consumers.

Funded by the Danish Energy Agency (Boldt, 2013), the original BALMOREL project was completed in 2001 and headed by freelance consultant Dr. Techn. Hans Ravn. Making the model began some time before, as BALMOREL is a further development of two studies documenting the possibilities for establishing the trade of electricity and gas among the countries around the Baltic Sea. In this way, the making of BALMOREL started as part of a series of initiatives in part sparked by the dissolution of the Soviet Union at the beginning of the 1990s (Ravn, 2013). Before the liberalization of electricity and introduction of BALMOREL, one of the main modelling programs used in the Danish electricity sector was the Norwegian software named Samkøringsmodellen. As pointed out in the description of making the decision to build the TSI connecting DK1 and DK2, Samkøringsmodellen was developed in Norway with a focus on accurately representing the large proportion of hydropower generation in the Norwegian electricity system. That Samkøringsmodellen was developed with this emphasis highlights how the configuration and functioning of such programs tend to reflect the context of use they have been made for, as characterized by the traditions and priorities involved in solving different tasks (e.g. S. L. Pedersen, 2012). A central purpose of the BALMOREL project was to construct a program for electricity market representation in reaction to the liberalization of electricity in Denmark and many other European countries (e.g. Ravn, 2001b). But an equally important aspect of BALMOREL was that it was built with an international focus through unbiased modelling of technology mixes and established energy system configurations. Finally, BALMOREL was intended to function as a shared modelling platform for discussing the exchange of electricity among the countries in close proximity to the Baltic Sea (S. H. Jacobsen, 2003).

After having explored and discarded the option of adapting existing software, BALMOREL was developed in a collaboration between Elkraft System, Risø National Laboratory, Danish Institute of Local Government Studies, the Estonian Stockholm Environment Institute, the Latvian Institute of Physical Energetics, the Lithuanian Energy Institute, the Polish PSE International, and the Russian Kaliningrad State University. In accordance with the ambition to establish a common modelling platform for electricity market representation, BALMOREL was developed as an open-source program coded using the General Algebraic Modelling System (GAMS). GAMS is a widely used modelling system originally developed in the Washington, DC-based R&D center of the International Bank for Reconstruction and Development (Bussieck & Meeraus, 2004). As BALMOREL is open source and based on the generic equation solvers in GAMS, the program is relatively pliable in character. In other words, it is possible to add to the code and represent other aspects of the energy system, such as parts of the transportation sector (e.g. Bregnbæk, 2012b).

To see how this collaborative project implied mobilizing expertise from control systems engineering, emphasis here shifts to the use of linear programming in the making of BALMOREL. Developed specifically for production system optimization and control, linear programming is part of the tradition of 'bottom-up' design and modelling found within the technical sciences (e.g. Capasso, Grattieri, Lamedica, & Prudenzi, 1994). When doing bottom-up modelling or design "…you start from the components, develop circuits, and then assemble a product. In *top-down* design, a high-level picture of the requirements is first formulated; then the functions and hardware required to implement the system are determined" [Italics in original] (Nise, 2004, p. 9). As they are central concepts in recent approaches to production system optimization, linear programming and bottom-up modelling share a history with the central planning regime for energy system operation and development in Denmark.[28] Given its configuration as a bottom-up model, based on a higher order control arrangement for production system optimization, BALMOREL thus "…has its root in the optimisation of the operation of the electricity system, as performed in the electricity companies. Models within this tradition emphasise the description of the generation units, the electricity network and other technical elements of relevance for…economic operation…" (Ravn, 2001b, p. 9).

Seeing how BALMOREL represents the electricity market by optimizing and controlling the production system for generation and transportation of electricity in accordance with changes in demand is significant to understanding how control systems engineering in the form of linear programming constitutes a generative form of expertise in the making of this market device. Again, a key characteristic

[28] See chapter 1 for a description of the use of linear programming for the marginal cost-based merit order-optimized dispatch of power plants when operating the electricity system by means of central planning and after the liberalization of the electricity sector.

of BALMOREL which comes from its roots in control systems engineering for production system optimization is that the model represents the electricity market by conceiving of the generation and transportation of electricity as if they were centrally planned, so as to meet a variable or elastic demand and establish a price.[29] In order to see how this works, focus here shifts to the way linear programming functions as a method of production system optimization. That is, it is shown how linear programming constitutes a particular type of control system arrangement.

Linear programming for production system control

> …programming constitutes a higher order control. It is not a feedback device for holding a boiler at a fixed temperature or pressure but a method for deciding what the temperature or pressure settings should be and for how long
>
> (Dantzig, 1957, p. 139)

The name chiefly associated with linear programming is that of George B. Dantzig. In 1947 Dantzig introduced what is called the simplex method, which has proved important for quickly solving linear optimization problems (e.g. Mirowski, 2002). And Dantzig's widely used textbook *Linear Programming and Extensions* (1963) still constitutes a central reference in the GAMS Corporation’s introduction to the modelling system (Rosenthal, 2014). The way linear programming has been conceived of and functions as a higher order control was made clear in Dantzig’s

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[29] In this way, the making of BALMOREL resembles the making of Nord Pool. In both cases, the use of a concept for the economic operation and understanding of the electricity system as part of the central planning regime, i.e. linear programming, was adapted to the new circumstances. The making of BALMOREL involved transmitting part of the price-setting mechanism found in Nord Pool into to a computer programme set to represent Nord Pool. And in effect, the construction of both Nord Pool and BALMOREL revolved around building a marginal cost-based merit order optimization for the dispatch of power plants as mutually adjusted with demand through a varying price, rather than production being adjusted to meet demand as understood through system frequency.

(1957) paper entitled *Thoughts on Linear Programming and Automation*. Using this understanding of linear programming as constituting a particular form of control system, the following will describe how representing Nord Pool using BALMOREL involved setting up a higher order control optimizing a virtual version of the production system in Nord Pool. To illustrate how this works, focus will be on the way the electricity market representation has been arranged so as to allow the GAMS equation solver to do the optimization by means of iteration (Ravn, 2013). Put differently, what is traced here is the way the electricity market was conceived of in order to make it eligible for optimized representation using linear programming. This approach to understanding the application of linear programming in the context of BALMOREL is in line with the general definition provided by Dantzig:

> "To many the term "linear programming" refers to mathematical methods for solving linear inequality systems. While this may be the *central mathematical problem* it is not its definition. Linear programming is a technique for building a model…for describing the interrelations of the components of a system"
>
> [Italics in original] (Dantzig, 1957, p. 132)

Following in this vein, it is shown how the making of BALMOREL involved conceiving of the generation and transportation of electricity in Nord Pool as a programming problem similar to the economic problem faced by system operators under the central planning regime, and then working "…to reduce the programming problem to…the linear programming model" (Dantzig, 1957, p. 133). The linear programming model implied in BALMOREL is in turn shown to have been set to work in cooperation with a representation of electricity demand as elastic in several ways (e.g. Ravn, 2001b), in order for it to constitute a market simulation.

Dantzig's conception of linear programming as a higher order control rests on a number of distinctions signifying a progression in the potential for exerting control. The levels or steps are manifested in the notions of mechanization, automation, and super automation. Super automation is what is of interest here, as it implies the delegation of higher order controls to machines, in the way implied in the introduction of linear programming using computers. In brief, "Mechanization's purpose is to relieve man of certain duties using *human energy* for power; automation's purpose is to relieve him of certain *mental tasks* and the related physical tasks necessary for their expression" [Italics in original] (Dantzig, 1957, p. 131). In other words, automation is the mechanization of a special category of human activities denoted as mental tasks. Mechanization thus implies a transition towards having machines complete human energy tasks, whereas automation refers to a situation where a machine replaces a human in conducting a simple control task. Super automation in turn denotes the mechanization of higher order control tasks. That is, super automation is a process whereby machines replace humans doing complex control tasks, "*…particularly those mental tasks involving selection from among alternative courses of action…*" [Italics in original] (Ibid.). The higher order control tasks of interest to Dantzig are captured in the notion of the making of a linear program which is "…defined as a schedule of actions by means of which an economy, organization, or other complex of activities, may move from one defined state towards some defined objective – and their physical realization known as *production control*" [Italics in original] (Ibid.).

Higher order control by means of linear programming is thus a matter of modelling a production system in such a way that it depicts optimal operation in accordance with selected criteria. The approach to engineering a control system thus takes on a special form, one also known from operations research. Significantly, this approach implies that "Operations are considered as an entity. The subject matter studied is not the equipment used, nor the morale of the participants, nor the physical properties of the output, it is the combination of these in total as an economic process" (Hermann & Magee in Dantzig, 1957, p. 131). Operations conceived of as the course of action implied in the concerted functioning of the components of a complex production system are in effect the objects being controlled. In other words, control by means of linear programming implies drawing together the desired and actual modes or states of production system operation.

As in all instances of linear programming, getting to represent the electricity market through the making of BALMOREL involved specific ways of conceiving of the system in question. An important initial conceptualization of Nord Pool was made when the supply side of the electricity market was understood as a centrally operated production system for the generation and transportation of electricity. Production system operation was in turn conceived of as the marginal cost-based merit order-optimized generation and transportation of electricity for constantly meeting a representation of an elastic demand. Conceptualizing the supply side of the electricity market as a centrally operated system responding to a variable demand was what enabled control systems engineering in the form of linear programming to work as generative form of expertise in the making of BALMOREL. That is, by understanding the supply side of Nord Pool as a centrally operated production system, the generation and transportation of electricity could be modelled by means of linear programming while still being part of a market representation.[30]

Conceiving of the supply side of Nord Pool as a centrally operated production system for the generation and transportation of electricity thus enabled the use of control systems engineering in the form of linear programming for electricity market modelling. It meant that the generation and transportation of electricity as part of the wholesale electricity market could be approached as a programming problem in the development of BALMOREL. To clarify how control systems engineering in the form of linear programming was introduced into the configuration of this market device, it will be demonstrated how this programming problem was reduced to a linear programming model (Dantzig, 1957). Following the steps for the reconceptualization of a production system outlined by Dantzig indicates how the generation and transportation of electricity in Nord Pool were made eligible for virtual optimization using the generic equation solver in GAMS. Accordingly, focus here shifts to documenting the way in which the programming problem was established and then reduced to a linear programming model.

[30] Chapter 1 demonstrates how Nord Pool functions by means of linear programming in a similar way by showing how price setting in Nord Pool is designed to work by doing the same marginal cost-based merit order optimization for the dispatch of power plants as before the liberalization of electricity. A significant difference in the way the electricity system has been operated since the introduction of Nord Pool is in turn found in the fact that the responsibility for calculating and submitting the costs of electricity production has been decentralized.

Making a higher order control system

In configuring the BALMOREL model for the optimized representation of electricity generation and transportation in response to demand, all aspects of the electricity market apart from demand have to be abstracted into a number of 'activities' as part of the linear programming process. To see how it is done, one is asked to:

> Suppose that the system under study (which may be one actually in existence or one which we wish to design) is a complex of machines, people, facilities, and supplies. It has certain overall reasons for its existence. For the military it may be to provide a striking force or for industry it may be to produce certain types of products. The linear programming approach is to consider the entire system as decomposable into a number of elementary functions called "activities"; each type of activity is abstracted to be a kind of "black box" into which flow tangible things such as supply, money, and out of which may flow the products of manufacture or trained crews for the military. What goes on inside the "box" is the concern of the engineer or the educator, but to the programmer, only the rates of flow in and out are of interest
>
> (Dantzig, 1957, p. 132)

At the most general level, the activities set up in BALMOREL pertain to the generation and transportation of electricity. Or as pointed out by one interviewee, if one was to take away all the additional features of BALMOREL such as the capacity for representing investments and demand-side reactions to various changes, a basic merit order optimization for electricity system operation is what will be left (Bregnbæk, 2012b). As a result of being based on linear programming in this way, the supply function or "generation cost function" (Ravn, 2001a, p. 6) is central to the functioning of BALMOREL. And using linear programming to control the operation of arrangements for generating and transporting electricity under an assumption of perfect competition "…implies that for any total output (*e*, *h*) [of electricity and heat] the generation is constituted such that it is done the cheapest possible way, and in the same way as if it had been centrally planned" [Italics in original] (Ibid.). What count as activities in the context of linear programming according to the definition provided by Dantzig and as realized in BALMOREL are exclusively found in the representation of the generation and transportation of heat and electricity. Demand does not qualify as an activity in the sense that it is not included as an element eligible for optimization. While the model still "…represents [the] generation, transportation and consumption of energy" (Ravn, 2001a, p. 28), it does so by optimizing the generation and transportation of electricity in accordance with demand. Demand as represented when running the model will change, for example in accordance with fluctuations in the price of electricity. Demand is thus a parameter that the ongoing optimization of the generation and transportation of electricity has to take into account, due to how the generation and transportation of electricity are set to influence demand and demand is set to be influenced by the production and transportation systems. But demand is not optimized using linear programming. Demand as defined within specific geographical areas and for specific periods throughout the year is represented in BALMOREL by introducing nominal consumption figures from historical data. Building on the data about past consumption patterns, the dynamics of demand are modelled by representing changes facilitated by the maximization of utility within a budget constraint in accordance with "…price elasticity, the cross price elasticity, and the income elasticity" (Ravn, 2001a, p. 12).

Having encompassed the electricity market in generation and transportation activities responding to an elastic demand-side, another significant step in the process of getting to represent Nord Pool in BALMOREL using linear programming involves quantifying the activities in question:

> For a production type activity it is natural to *measure* the quantity of the activity by the amount of some product produced by it. This quantity is called the *activity level*. To increase the activity level it will be necessary of course to increase the flows into and out of the activity. *In the linear programming model the quantities of flow of various items into and out of the activity are always proportional to the activity level*. Thus it is only necessary to know the flows for the unit activity level. If we wish to *double the activity level* we simply *double* all the corresponding flows for the unit activity level
>
> [Italics in original] (Dantzig, 1957, p. 132)

In BALMOREL, the measure for the activity level is the MW, which in the model can be specified by means of the often more familiar MWh (e.g. Ravn, 2001a). As a quantitative measure, MW is used to denote the activity level of both the generation and transportation of electricity. That is, the measure of MWh is applied in referring both to the amount of electricity produced and the amount of electricity moved. The activity level involved in electricity production is specified for a time and place while factoring in the technologies applied. These technologies will initially include the established generation capacity as constituted by, for example, wind turbines. Power plants are in turn grouped according to type (a thermal power plant is defined as a condensing plant, for example) with each type of generator associated with "…a number of physical and economic parameter values, describing the fuel types, efficiency, environmental characteristics, [and] economic parameters (operation and maintenance cost, and investment costs for new units)" (Ravn, 2001b, p. 32). Again, in public energy planning projects the Technology Catalog is often an obligatory reference when it comes to ascribing these qualities and costs to the various units involved in the generation and transportation of electricity. And in accordance with the prescriptions of the linear programming method "All the characteristics of a unit are represented by a set of linear relations" (Ravn, 2001a, p. 5). The activity of electricity generation, for example, has an inflow of items such as fuel and maintenance costs and outputs of items such as electricity and CO_2, SO_2, and NO_x emissions. The representation of electricity transportation works in a similar manner. The main item flowing both in and out of the activity is electricity, with both transmission and distribution implying a loss of electricity and a cost proportional to the amount of electricity entering the transportation activity from the generation side (Ravn, 2001b).

Another step involved in reducing the operation of the supply side of the electricity market to a linear programming model involves finding the item or product flowing in the system around which the optimization should revolve. That is, there has to be an object within the representation guiding the optimization:

> One of the items in our system is regarded as *precious* in the sense that total quantity of it produced by the system measures the payoff. The contribution of each activity to the total payoff is the amount of the precious item that flows into or out of each activity. Thus if the objective is to maximize profits, activities that *require money* contribute negatively and those that *produce money* contribute positively to total profits
>
> [Italics in original] (Dantzig, 1957, p. 133)

As is the case in the application of linear programming for economic electricity system operation under a central planning regime and in an electricity market arrangement, the precious item flowing in the system representation when making scenarios using BALMOREL is set to be money. In this way, electricity system operation becomes a matter of meeting demand by relying on the patterns of activities for generating and transporting electricity which come at the lowest possible costs:

> As minimizing total generation costs become a main aim in an integrated and liberalised power market generation technologies having low generation costs will be preferred to technologies having high generation costs. In a short term perspective facing existing generation capacities priority in generation will be based on short run marginal costs. In a long term perspective facing the need for investments in new generation capacity priority will be based on long run marginal costs, which take into consideration investment costs
>
> (Ravn, 2001b, p. 20)

The last step needed to reduce the generation and transportation of electricity to a linear programming model format as found in BALMOREL is the introduction of the requirement of a material balance equation. Put briefly, this requirement is the idea that "…for each item it is required that the total amount on hand equals the amount flowing into the various activities minus the amount flowing out" (Dantzig, 1957, p. 133). The idea of having a material balance equation characterize the way the items can be accounted for when flowing in the abstract system implies that the arrangement of activities has to be complete. In other words, getting a complete overview of the flows of various items in the model has to be possible by means of following the activities included. Characterizing the items in the system by a material balance equation in this way ensures that there can be no 'gaps' in the model.

To recount, configuring BALMOREL for the making of electricity market scenarios involved a series of steps reducing the electricity market to a programming problem in the form of a linear programming model. Initially, an important reconceptualization of the electricity market implied treating supply and demand in different ways. Supply was considered as equivalent to centrally planned electricity generation and transportation, while demand was conceptualized as price-, income-, and cross-price elastic electricity demand by building on historical consumption data. Making this fundamental distinction implied that Nord Pool could be modelled utilizing the higher order control of linear programming by having a marginal cost-based optimization of the generation and transportation of electricity meet the representation of a dynamic demand at all times.

At the highest or most general level, the generation and transportation of electricity came to constitute the activities of the production system to be optimized and controlled in accordance with variations in demand. These activities were in turn quantified in providing a measure of the activity level in the form of MW or MW/h, and the item flowing in the system regarded as precious was configured as money. Finally, the idea that the items in the abstracted system would have to be made completely accountable by following the activities inscribed in the system was introduced. As the supply system has been reduced to this form, the equation solver built into GAMS can be put to work. Having transformed the supply of electricity into this virtual system, GAMS can solve the programming problem "…which consists in determining values for the activities levels which are positive or zero such that flows of each item (for these activity levels) satisfy the material balance equations and such that the value of the payoff is maximum" (Dantzig, 1957, p. 133).

In outlining the making of a market device for the production of electricity market scenarios used in actualized policy recommendations for Danish electricity market development, the role of linear programming in wind power integration through electricity market construction was established. In doing so, it was illustrated how expertise in the form of a higher order control for production system operation and optimization was mobilized in the process of market construction. Having established the significance of control systems engineering for the making of BALMOREL, focus here shifts to a description of one of the central ways in which economics was mobilized in the making of the model. Through the metrics named producer and consumer surplus, economics was used to describe the objective guiding the making of scenarios made by means of BALMOREL in conceptualizing how the optimized marginal cost-based operation of the electricity system intersects with demand side marginal utility. In other words, arranging for equilibrium between the marginal costs of production and the marginal utility of consumers corresponds to a maximization of socio-economic value understood as the total producer and consumer surplus (e.g. Marshall, 1920; Ravn, 2013). It is thus possible to see how economics was mobilized in wind power integration through electricity market construction by making a market device set to produce scenarios conceived of as implying the maximization of producer and consumer surplus.

Consumer and producer surplus

As an instance of applied linear programming, BALMOREL represents the making of an equilibrium between the consumers' marginal utility and the producers' marginal costs by covering "…the two types of agents (producers and consumers), the two products (electricity and heat), the various relevant geographical entities (electrically divided regions), and the various temporal entities (short terms (within the year) and long terms (between years))" (Ravn, 2001a, p. 29). One significant implication of making such a representation is that the model works in accordance with neoclassical economics by producing a virtual equilibrium between the marginal costs of production for suppliers and the marginal utility of consumers. Within the realm of marginal analysis or neoclassical economics, this move corresponds to maximizing the total amount of consumer and producer surplus. To understand how this works, the definitions of producer and consumer surplus as provided by Alfred Marshall (1920) are briefly outlined.

The consumer surplus consists in the difference between the market price for a specific amount of a specific good and the aggregate utility associated with buying that amount of that good. In the same situation, the producer surplus is the difference between that very same market price for the specified amount and the total costs associated with supplying that quantity of the good. Marshall's *Principles of Economics* introduces the idea that "Utility is taken to be correlative to Desire or Want…[which] cannot be measured directly, but only indirectly by the outward phenomena to which they give rise…the measure is found in the price which a person is willing to pay for the fulfillment or satisfaction of his desire" (Marshall, 1920, p. 61). An immediate implication of the idea that the price a buyer is willing to pay reflects her want or utility is that the price the consumer is willing to pay will decrease with a diminishing utility, as for example when an increase in the consumption of a good implies that the buyer moves closer to the point of saturation. Marginal utility here decreases, while total utility still increases until the point of saturation is reached.

To see how the consumer surplus is derived from the difference between the price for a specific amount of a good and the total utility associated with the possession of that amount of the good, one can take the example of the utility of an electricity buyer. Picture, for instance, an electricity buyer with a utility curve which can be expressed by means of an exponential equation. The buyer might be willing to pay a very high price per MWh for only a small amount of electricity, in order to not go entirely without it. The consumer might also only be willing to pay a very low price per MWh when having bought enough electricity to meet more or less all her needs. If buying only one MWh, the consumer might be induced to pay €5000/MWh. When buying two, the number falls to €1500/MWh, then again to €450/MWh when buying three, €135/MWh when buying four, €40.5/MWh when buying five, €12.15/MWh when buying six, and so forth. To figure out the consumer surplus when buying a specific amount of electricity, the difference between the aggregate utility associated with the purchase of that amount of electricity and the price paid for it is what has to be clarified. In other words: "The excess of the price which he would be willing to pay rather than go without the thing, over that which he actually does pay, is the economic measure of this surplus satisfaction. It may be called consumer's surplus" (Marshall, 1920, p. 78). Take the instance where the buyer purchases two MWh of electricity, for example. As price should reflect utility, the total utility associated with the purchase of two MWhs is 6500, or 5000 plus 1500. But since the price in this instance is 1500 per MWh, the total price is 3000, or two times 1500. As the consumer surplus consists of the difference between the aggregate utility associated with buying a specific amount of electricity and the total price of that amount of electricity, the consumer surplus would here come to be 3500, or 6500 minus 3000.

In describing how the producer surplus is constituted by the difference between the price paid for a certain amount of a good and the total costs associated with supplying that amount of the good, marginal analysis suggests that:

> When different producers have different advantages for producing a thing, its price must be sufficient to cover the expenses of production of those producers who have no special and exceptional facilities; for if not they will withhold or diminish their production, and the scarcity of the amount supplied, relatively to the demand, will raise the price. When the market is in equilibrium, and the thing is being sold at a price which covers these expenses, there remains a surplus beyond their expenses for those who have the assistance of any exceptional advantages
>
> (Marshall, 1920, p. 288)

An example of the exceptional advantage mentioned by Marshall in the context of Nord Pool would be found in the fact that wind turbines have no fuel costs. A producer's surplus thus depends on how far removed the total costs of supplying a good are from the price of the good. And as the price of the good is set at the intersection between the marginal utility of the consumers and the marginal costs of production among suppliers in a way ensuring that the producers with the appropriate costs and the consumers with the relevant degree of utility partake in exchange, the maximization of the consumer and producer surplus is an implicit feature of achieving equilibrium.

The idea is that the price of a good is set by the producer with the highest costs of production, which is still within merit. And that is thus how both Nord Pool and BALMOREL come to operate: "The guiding principle for the determination of the endogenous variables is that there should be a balance between consumers' and producers' surplus…" (Ravn, 2001a, p. 29). BALMOREL involves the same coupling of an aggregate demand with a merit order-optimized supply side as does the operation of the Danish electricity system by means of Nord Pool. When running BALMOREL, the supply side is represented in the form of asking prices for specific amounts of electricity which can be derived from the marginal costs of production associated with various forms of power plants. And again, an often obligatory reference for such costs is the Technology Catalog.

Running the generation cost function in BALMOREL as an instance of linear programming thus serves to complete a marginal cost-based merit order optimization of eligible power plants and produce a dispatch schedule. And doing so is similar to the operation involved in setting prices on Nord Pool. But another aspect of the scenarios which can be produced by means of the model is the composition of the facilities for producing and transporting electricity to be operated as prescribed by means of the generation cost function. This feature is known as 'endogenous investment' (e.g. Bregnbæk, 2012b) due to how it effectively implies that BALMOREL represents the optimal pattern of investments in new power plants and electrical connections required for meeting demand. In this way, endogenous investment is a significant part of the way in which BALMOREL is associated with wind power integration through electricity market construction by means of scenarios forming the basis of actualized policy recommendations. The way BALMOREL makes endogenous investments implies that the maximization of consumer and producer surplus not only guides the operation of the electricity system in the making of electricity market scenarios, but it also comes to steer the way electricity supply and generation are configured. Following how the model works with endogenous investment is thus required in order to clarify how the concepts of producer and consumer surplus are mobilized in specifying what guides the making of electricity market scenarios for wind power integration through electricity market construction.

Endogenous investments

Configuring BALMOREL so as to be capable of making endogenous investments was undertaken by including investments in generation and transportation capacity as endogenous variables alongside the generation of electricity and heat as distinguished by technology and fuel, consumption of electricity and heat, electricity transmission and distribution, emissions, and the prices of electricity and heat (Ravn, 2001b). When running BALMOREL, the option of introducing new generation or transportation capacity is bound up with a specific period of time, typically one or several years. It is possible to invest in new capacity in the beginning of each period or year. The capacity introduced as a result of the investment is then made available in the beginning of that same year. This function has also led to the observation that the model eagerly erects power plants overnight (S. L. Pedersen, 2012). The total generation capacity for one year is thus the sum of capacity from the previous year which is not set to be decommissioned, plus the sum of new capacity as introduced in the beginning of the year.

Significantly, the way investments in energy system components become guided by the prices produced in representing the operation of the electricity market involves including the potential costs associated with investing in and operating energy system technologies for the transportation and generation of electricity. Potential costs present possibilities for generating and transporting electricity in such a way as to lower the costs associated with meeting the elastic demand for electricity. If investing in and operating a specific transportation or generation unit leads to an increase in the total producer and consumer surplus by lowering the costs associated with having supply meet demand, the investment is made as part of the scenario. In this way "…the long term aspects, covering future years, is represented by the possibility of performing investments. Therefore long term marginal costs [factoring in the costs associated with investment in capacity] may become price setting in periods with capacity shortage. In periods with sufficient capacity the short term marginal costs prevail" (Ravn, 2001a, p. 19). Endogenous investments made by BALMOREL thus come to influence the representation of the generation and transportation of electricity in a given scenario. And as the operation of this system representation further guides endogenous investments, the operation and composition of the electricity system co-develops in electricity market scenarios produced using BALMOREL.

Even though BALMOREL in a practical way mimics the outcome of a perfectly functioning electricity market by directly incorporating a specific part of the price-setting mechanism found on Nord Pool, the means of producing the final production and consumption schedules are not identical. BALMOREL does not reflect the string of auctions enabling market participants to trade their way towards fulfillment of their original obligations to produce or consume electricity.[31] In this virtual version of the electricity market, there are no deviations from the production and consumption schedules agreed upon by means of a single auction. There are no unexpected changes in weather or breakdowns in equipment. This feature is related to the notion of the use of BALMOREL as involving 'perfect foresight' (e.g. Bregnbæk, 2012b; Boldt, 2013). In other words, optimization is undertaken and control exerted under conditions which are deprived of uncertainty. As all relevant factors are pre-specified, the effects of occurrences such as sudden variations in weather or breakdowns in the transmission system are not included in the representation of the functioning of the electricity market.[32] One example can be found in the way exogenous variables such as precipitation data are specified before running the equation solver.

Finally, it should be noted that the way BALMOREL comes to construct electricity market scenarios that prescribe and describe the operation and composition of the electricity system as guided by the maximization of producer and consumer surplus will involve a series of constraints. Constraining the way the model optimizes the generation and transportation of electricity in accordance with demand is most often necessary in order to conform scenarios to the specific political objectives involved in the process of energy planning. Objectives such as, for example, that of having a specific proportion of electricity generated by wind turbines at a specific point in time can be reflected in a constraint associated with scenario production specifying a minimum degree of wind power penetration in the electricity system.

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[31] Rather than representing ELBAS or the Intraday Market, the subdivisions of the Regulating Power Market, and the Balancing Market for retrospective settlement, BALMOREL typically chooses the producers with the lowest costs as established by means of knowledge of the installed capacity in an area and the qualities and costs of the various units as stipulated in the Technology Catalog. In this way it is assumed that all initial promises to produce and consume electricity are always fulfilled using only the original contract. When representing the electricity market using BALMOREL, nothing stands in the way of having suppliers and buyers fulfill a contract formed in a setting corresponding to the Nord Pool Spot Market. Buyers and suppliers live up to their spot market obligations all the time. Thus, there is no need to represent adjacent markets when running the program.

[32] This does not mean, however, that they cannot be taken into account in other ways when operating the model.

Modelling constraints can take several forms and apply in several different contexts with respect to the making of scenarios. Constraints are introduced to ensure that generation or transportation quantities associated with potential and existing units will always be equal to or higher than zero, and equal to or lower than the stated capacity of the unit (e.g. Ravn, 2001a) as stipulated in for example the technology catalog. And as is also the case with many other aspects of the model, investments can be subjected to constraints reflecting elements such as resource restrictions and political commitments. The central physical constraints of BALMOREL include consistency, i.e. equilibrium, between demand and supply in every sub-period and in each geographical entity (Ravn, 2013), while taking into account distribution losses; consistency between differing regions in accordance with transmission constraints and losses in each sub-period; a reflection of the availability of specific fuels and generation units; emission limitations, and so on. But the principle which guides the optimization within the array of possible energy system compositions and modes of operation allowed for by these overall physical constraints corresponds to the joint maximization of consumer and producer surplus in the sense that BALMOREL works towards an "Equilibrium between electricity and heat consumers' marginal utilities and producers' marginal costs in each sub period and each geographical entity…" (Ravn, 2001b, p. 37). And it is by coupling modelling constraints such as requirements for specific amounts of installed wind power capacity at specific points in time and requiring that supply meets demand at all times in all areas that wind power integration necessarily materializes in a virtual form when optimizing the operation and composition of the electricity system in scenarios produced by BALMOREL. In this way, wind power integration in scenarios specifying the optimized composition and operation of the electricity system becomes inevitable in the sense that equilibrium maintenance becomes a prerequisite feature (e.g. Ravn, 2013).

Against the backdrop of the description of the origins of the prerequisite technology data and energy planning tradition found in the account of the Technology Catalog, the two ways in which the account of the making of BALMOREL putatively augments the performativity program became apparent. First, control systems engineering can be shown to constitute a generative form of expertise in wind power integration through market construction for the improvement of homeostatic utility control system operation and electricity system equilibrium maintenance. Taking the form of linear programming, this form of expertise is shown to be central to the making of scenarios forming the basis of actualized policy recommendations for electricity market development as found in reports such as *Green Energy* (Danish Commission on Climate Change Policy, 2010) and *The Future Requirements for Flexibility in the Energy System* (Aarhus Municipality, 2012). The significance of linear programming was made clear by showing how this method for production system optimization and control constituted core conceptual content of the Baltic Model of Regional Electricity Liberalization applied when making these scenarios. The second way in which the scope of the performativity programme is putatively expanded is apparent from the fact that economics was shown to have supplied a metric used in formulating the objective guiding the making of scenarios when using BALMOREL. Taking the form of consumer and producer surplus or socio-economic value, economics was demonstrated to have been applied when inscribing the way electricity system composition and operation functions in BALMOREL.

Summary and concluding comments

Following the making of the Technology Catalog and BALMOREL was undertaken in order to provide an answer to the research question: *How have control systems engineering and economics been mobilized in the endeavor to integrate wind power into the Danish electricity system through electricity market design and management?* Answering this question required documenting the introduction and infrastructural reconfiguration of the Nordic wholesale electricity market in chapter 1, and an economic experiment for the making of a new retail electricity market arrangement in chapter 2. In this final case, wind power integration as electricity market construction was shown to have been based on energy planning involving the making of scenarios and policy prescriptions. It was made clear how actualized policy recommendations for wind power integration by means of electricity market reconfiguration have been made using BALMOREL and the Technology Catalog. In the case of the work done by the Danish commission on climate change policy, the BALMOREL program and the Technology Catalog data set were used to make scenarios outlining ideal electricity market development which formed the basis for policy recommendations applied by the Danish government. Mitigating greenhouse gas emissions by introducing and integrating renewable energy sources in the Danish energy system was in this way shown to involve electricity market construction through energy planning using two ‘market devices’ (Callon et al., 2008). In effect, attention was turned to the making of the Technology Catalog and BALMOREL as a matter of establishing the means by which electricity market scenarios are made in order to inform energy policy decisions.

The Technology Catalog was described as a product of the national Danish energy planning scheme which started as a reaction to the oil crisis in 1973. Originally named the Supply Catalog and made to help energy planners make decisions as part of the heat planning initiative, the Technology Catalog was described as constituting an obligatory reference for technology data used in public energy planning projects. The Technology Catalog’s status as a mandatory reference is in this way on par with that of the prerequisites for socio-economic analyses of the energy sector found in *Forudsætninger for samfundsøkonomiske analyser på energiområdet* also published by the Danish Energy Agency (e.g. 2011b; 2014g). If scenario construction as part of public energy planning in Denmark is based on values and methods not stipulated in these publications, the decision to not include the Technology Catalog and prerequisite methods has to be explicitly justified by describing why a different approach constitutes the better alternative (e.g. Kofoed-Wiuff, 2013). Both before and after the liberalization of electricity in Denmark, the catalogs have provided technology data for energy planning by specifying the qualities and costs associated with introducing and operating various energy system components such as power plants and electrical connections. Following the way stable data on the qualities and costs of energy system elements were produced to provide the practical advantages usually associated with general facts involved tracing the transition from a consensus based approached to the making of the Supply Catalog in a coordination committee, to the ‘pseudo-consensus’ method developed to accommodate the new actors and interests of a liberalized electricity sector. By being included in scenario building leading to actualized policy recommendations for the alteration of the Danish electricity market, the Technology Catalog provided technology data necessary for deploying the second electricity market device named BALMOREL. In this way, the significance of the Technology Catalog stems from the fact that it is an integral part of the making of electricity system scenarios in a Danish context. Without such a stable source of data regarding the qualities and costs of electricity system components, scenario production and market performation for wind power integration using BALMOREL would be difficult (e.g. Andersen, 2013).

As a computer program for the making of electricity market scenarios, the introduction of the Baltic Model of Regional Electricity Liberalization was here described as significant not only in the context of wind power integration through wholesale electricity market reconfiguration, but also as a way for energy planners to incorporate Nord Pool as an organizing factor in contemporary energy system analysis. To understand the way BALMOREL was made, the configuration of the model was approached by emphasizing its roots in linear programming. And by considering the model as a framework for making electricity market scenarios using linear programming, it became possible to see how the functioning of BALMOREL involved the introduction of a higher order production system control (Dantzig, 1957) for the optimization of electricity supply. The task of outlining the configuration of the model in turn came to revolve around a description of how part of Nord Pool in the modelling context has been reduced to a linear programming problem, which can be solved using the General Algebraic Modelling System. Seeing the way Nord Pool was moved into the laboratories of energy planners involved following the method provided by Dantzig for transforming a production facility into an abstract system representation, which can be optimized using generic equation solvers such as those found in GAMS. In highlighting the various steps involved in producing an electricity market representation implying a linear programming problem, it was noted how BALMOREL works by conceiving of the electricity market as operated by optimizing the generation and transportation of electricity along with investments in these capacities as if it had been centrally planned. This representation of the supply system was in turn shown to have been set to meet an elastic demand at all times.

As part of a bigger picture, the account of the making of BALMOREL demonstrates how linear programming has been variously applied in the context of the Danish electricity system. Linear programming has been used in the marginal cost-based optimization of electricity system operation under a central planning regime, and in a similar fashion when setting prices on the auctions of Nord Pool after liberalization. And it was here made clear how the configuration of BALMOREL for the making of electricity market scenarios using linear programming to some extent mirrored the events taking place in the electricity sector at the point when Denmark entered Nord Pool. Around the time linear programming was put to use in the Nordic wholesale electricity market, it was set to work in a similar way in a program representing that same market. Part of Nord Pool was thus transmitted into BALMOREL, which in turn was made to produce scenarios specifying ideal market composition and operation. Such scenarios have then been used to create policy recommendations prescribing how the electricity market can be put on the path of optimal development.

Accounting for the construction of BALMOREL, which was made relevant and possible by the prerequisite technology data and energy planning tradition outlined when describing the making of the Technology Catalog, putatively augments the performativity programme in two ways. By showing how the making of a market device in the form of a computer program for electricity market representation, along with the market itself, was based on the higher order control system concept of linear programming, control systems engineering was demonstrated to have been a generative form of expertise in the process of market performation. Engineering a control arrangement for production system optimization proved to be of importance in renewable energy integration by enabling electricity market design and management. The empirical scope of the performativity programme was also widened by giving consideration to the role of economics in the making of BALMOREL. Through exploring how the maximization of consumer and producer surplus has been used to guide the making of scenarios when running the model, economics was shown to have been mobilized by providing a metric describing the state of affairs to be attained in electricity market scenarios, and thus also in Nord Pool. In the process of energy planning as part of electricity market design and management, economics was here deployed in the form of these metrics in order to specify the ideal outcome achieved by means of electricity market construction.

Having described three cases of wind power integration in the form of electricity market construction, the analysis of how the intermittency problem has been approached in a Danish context can at this point be brought to a close. To follow up on the findings, the final chapter will highlight and elaborate on the implications of the present study. Apart from summing up the argument of the thesis as a whole, the discussion and concluding comments will be structured around three main arguments. Importantly, the topic of representation as conceived of in the performativity programme will be taken up. Having stressed how the notion of performativity is trivialized in a setting where markets are engineered as control systems for the purpose of electricity system equilibrium maintenance as specified by means of economic metrics, the functioning of these forms of expertise in the context of market construction is considered. When economics was mobilized through measures describing objectives of market construction for the introduction or improvement of control system operation, the state of economics was changed. In being used as part of an engineering approach to the making of control system electricity market arrangements, the direction of fit and direction of causation (Searle, 2001) originally associated with economics were reversed.

After having clarified some of the implications of engineering electricity markets and mobilizing economics in the description of ideal outcomes of market construction, the findings from the analysis are used as a springboard to start comparing and discussing the empirical stance taken in the present inquiry and a somewhat different stance found in the performativity programme as exemplified in the work of Michel Callon. By demonstrating how these stances differ, a third way in which the present study supplements the performativity programme begins to surface. Addressing the performativity programme in this way implies suggesting a reorientation in the attitude or approach towards empirical experience on one hand, and the development of concepts and theory on the other. The point is to stress that the performativity programme could benefit from adopting an empirical stance. Doing so would enable it to more fully commit to a pragmaticist position and thus genuinely submit to the requirements which can reasonably be expected to apply to a research program proclaiming to constitute a "…'pragmatic turn' in the study of markets and economic activities…" (Callon et al., 2008, p. 1).

Finally, the practice of energy system development in Denmark is addressed. By giving consideration to the outcomes of market construction for continued electricity system equilibrium maintenance, the discussion comments on the wider approach to wind power integration in Denmark. And in highlighting the fact that several additional forms of market arrangements for electricity system equilibrium maintenance and wind power integration are being considered by the central authorities on behalf of the government (e.g. Energinet.dk, 2014e), while also stressing the absence of alternative ways of thinking about the intermittency problem and its solution, the uniformity of the official approach to wind power integration in Denmark is questioned.

Discussion and concluding comments

Motivated by concern about the implications of climate change as caused by greenhouse gas emissions from the burning of fossil fuels, the present study involves an inquiry into the making of a Danish energy system based on renewable energy sources. Focusing specifically on one of the major barriers to the introduction of renewable energy sources in the Danish energy system, emphasis has been put on how fluctuating electricity generation from wind turbines has been integrated into the Danish electricity system. In taking an empirical stance (van Fraassen, 2002) as part of a pragmaticist inquiry (Peirce, 1905a), the study came to revolve around the fact that the integration of wind power in Denmark involved the introduction and reconfiguration of electricity markets. Significantly, these electricity markets are engineered as control arrangements for electricity system equilibrium maintenance while using metrics from economics to describe the ideal outcome or objective to be attained through market construction. Coupling these empirical observations with a line of inquiry about the use of knowledge, skills, and know-how in market design and management as found in the performativity programme (Çalışkan & Callon, 2010) led to the following research question: *How have control systems engineering and economics been mobilized in the endeavor to integrate wind power into the Danish electricity system through electricity market design and management?* Answering this research question involved an analysis of electricity market construction made by means of inquiry into three different empirical settings. Chapters 1 through 3 thus document the introduction and reconfiguration of the Nordic wholesale electricity market Nord Pool, the making of the experimental retail electricity market EcoGrid, and the reconstruction of Nord Pool through scenario building and energy planning.

The presentation of the discussion and concluding comments will proceed in three stages. Initially, a summary of the analysis will be provided. Here, the main findings and conclusions from the three cases explored in the analysis will be outlined. After reviewing the main points made throughout the thesis, emphasis shifts to highlighting and discussing implications of the present study in the context of the performativity programme. This second section starts by revisiting the role of economics in the making of markets. Specifically, it seeks to indicate how the state of economics has been changed in adapting its metrics for the description of objectives to be attained as part of wind power integration through market construction for the introduction or improvement of control systems operation. The concepts derived from economics touched upon in the three cases of the analysis are shown to have been initially developed as a representation of an empirical state of affairs. In other words, these economic metrics were originally analytical in character. This feature of economics is then shown to have been a central part of what was changed when mobilizing liquidity, price elasticity, and consumer and producer surplus in the engineering of electricity markets functioning as control systems. That is, the direction of fit and direction of causation (Searle, 1983; 2001) of economics was reversed as part of the wider approach to making control systems engineering and market construction one and the same.

By highlighting the centrality of intention on behalf of market designers, demonstrating that the direction of fit and direction of causation of economics have been reversed when engineering electricity markets as control systems serves as a first step in directing critical attention to previous studies of Nord Pool. These previous inquiries into the making of the Nordic wholesale electricity market have applied the notion of Barnesian or strong performativity to explain a planned and intentional process of market construction. However, in light of the discussion of the direction of fit and direction of causation of economics, it is clear that the notion of Barnesian performativity becomes superfluous when dealing with instances of market construction which involve intentional market development.[33]

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[33] The point here is that the relevance of concepts is not independent of the context, history, and particularity of the circumstances of an empirical setting. Addressing the work done by professionals dedicated to market design and management, and then treating as a finding the fact that their knowledge, skills, know-how, models, or tools make a difference in the construction of a market to the extent of making the object more similar to its format as inscribed into these concepts or models, implies a redundant and trivial conclusion. By analogy, it amounts to stating that the expertise of engineers building bridges or configuring particle accelerators is instrumental in making such arrangements in specific instances. The risk associated with such an emphasis is in turn that it can render market construction opaque by drawing attention away from the relevant empirical state of affairs and towards academic concepts which have little analytical relevance when trying to understand the making of markets in specific situations.

Nonetheless, questions and answers centered on the idea that economics at large is performative have been deployed in addressing the work done by professionals dedicated to the design and management of Nord Pool. Significantly, this scholarly undertaking found within the performativity programme not only brings with it the risk of producing redundant statements about market construction; it also implies the risk of making our ideas about the object of inquiry unclear. This is due to how rendering market construction opaque is an occupational hazard when conducting research ranking empirical experience and description second to the task of transmitting concepts and explanations from one setting to another. To understand this problem, the stance (van Fraassen, 2002) involved in research conducted within the performativity programme and which has contributed to blurring Nord Pool as an object of inquiry is tentatively discerned and exemplified with reference to the work of Michel Callon.[34] The unfortunate effects of this stance in relation to empirical inquiry as found in the performativity programme are then described as manifest in recent studies of Nord Pool (Karlstrøm, 2012; Silvast, 2015). In completing the second section, it is made evident that one way for the self-proclaimed 'pragmatic' research programme (Callon et al., 2008) to avoid redundant statements about market design and management along with the risk of rendering the object of inquiry opaque when doing empirically oriented research, would be to live up to the demands of an 'empirical stance' (van Fraassen, 2002).

The third section ends the discussion and concluding comments by addressing the practice of wind power integration in Denmark. By considering the findings from the analysis along with the current plans for solving the intermittency problem presented by the central authorities, it is noted that the introduction and reconfiguration of market arrangements is intended to remain a central approach to wind power integration in Denmark. In also noting that the results achieved through the use of market-based solutions have been mixed, the uniformity in the approach to solving the intermittency problem in a Danish context is questioned. Here the discussion takes a step back and questions the current widespread

[34] This stance is discussed as appropriate depending on the undertaking in which it is involved. Thus, the approach is highlighted as appropriate to the work of Michel Callon. However, it is demonstrated that problems begin to materialize when this particular stance is taken up within the performativity programme as part of inquiry into an empirical state of affairs.

commitment to market-based solutions and the general lack of alternative ways of thinking about wind power integration.

Revisiting wind power integration in Denmark

In noting the importance of increasing the use of renewable energy sources in order to reduce greenhouse gas emissions and mitigate climate change, the present inquiry has explored the ways in which wind power is currently being integrated into the Danish electricity system. Documenting the way the intermittency problem has been approached in a Danish context initially involved outlining how wind power integration became a matter of concern. And to see how electricity generation by wind turbines became an infrastructural problem in Denmark, a description of the system in which wind turbines have recently been introduced on a large scale was provided.

To describe the setting in which the patterns of electricity production associated with wind turbines was problematized, two aspects of key importance to electricity system operation were highlighted. First is the fact that in order to avoid planned outages and breakdowns in the form of brownouts and blackouts, running the electricity system requires carefully balancing input and output at all times. If the production and consumption of electricity is not equated, the system stops working. Second, electricity cannot be stored. Energy from electricity can be stored after conversion, but the process of transformation is associated with a significant loss of energy. When considered in concert with the fact that the grid itself has no storage capacity, these features imply that active equilibrium maintenance is a crucial aspect of electricity system operation.

As with many other activities and arrangements falling under the auspices of technical science, maintaining equilibrium between input and output as part of electricity system operation has traditionally been performed by engineering control systems (e.g. Nise, 2004; Nightingale et al., 2003) ensuring that supply follows demand.[35] Importantly, the supply-follows-demand approach to equilibrium maintenance was made possible as the generation of electricity was sourced to thermal power plants. In a system relying on thermal power plants, the production of electricity could be made to correspond to consumption by burning more or less fossil fuel. It is in the context of this method of electricity system operation that electricity generation by means of non-thermal renewable energy sources such as wind turbines has been problematized. While electricity generation by modern wind turbines can be reduced at will by power plant operators, it cannot be increased without higher wind speed. Adding to this is the fact that electricity generation by means of wind turbines is exponentially related to wind speed at all but the very highest and lowest wind speeds. Finally, wind speeds not located at the extremes of the spectrum are the norm in Denmark, and are the most difficult to forecast in a precise way. Due to these characteristics, electricity generation by means of wind turbines is less well suited for an arrangement where the equilibrium between the generation and consumption of electricity is maintained by having supply follow demand. And as the proportion of electricity produced by wind turbines continued to grow, finding means of equilibrium maintenance under these new conditions became an increasingly pressing issue (e.g. Danish Energy Agency, 2001).

In order to understand how the intermittency problem has been solved in Denmark and thus see how a substantial barrier to the making of an energy system based on renewable energy sources has been overcome, the present inquiry has followed the efforts to increase the means by which equilibrium in the electricity system can be maintained while a growing portion of Danish electricity generation is derived from wind turbines. This has involved following attempts to introduce and improve the operation of control systems engineered for electricity system equilibrium maintenance. Significantly, wind power integration became a pressing issue around the time that the Danish electricity sector was liberalized. And understanding Denmark's entry into the Nordic wholesale electricity market and the way Nord Pool has been constructed and later reconfigured is central to seeing how wind power integration has been approached. This is in turn due to the fact

[35] Actively maintaining the equilibrium between supply and demand by adjusting the generation of electricity so as to follow consumption has been done in Denmark as well as many other industrialized countries (e.g. Schweppe et al., 1987).

that Nord Pool was engineered as a control system set to maintain equilibrium in the Danish electricity system.

As Nord Pool was introduced and the established actors of the Danish electricity sector were reconfigured as part of the unbundling process, the supply-follows-demand approach to electricity system equilibrium maintenance, functioning similarly to a 'automatic generation control' system (Imthias Ahamed et al., 2002), was to a great extent replaced with the notion of 'homeostatic utility control' (Schweppe et al., 1980). A particular type of control system taking the form of an electricity market, equilibrium maintenance by means of homeostatic utility control implies the mutual adjustment of supply and demand rather than having generation follow consumption. In other words, the control system model upon which electricity market design was based took the form of a self-stabilizing system relying on the interdependent parts of the system themselves in order to maintain equilibrium. And, as the equilibrium of the electricity system was displaced into the equilibrium of the electricity market, the main control signal for equilibrium maintenance constituted by system frequency was replaced by transitioning to "controlling power systems with price signals" (Alvarado, 2005). In this way, the electricity market became the overall framework for maintaining the crucial equilibrium between generation and consumption in the Danish electricity system. And since the issue of wind power integration is essentially a matter of endowing the electricity system with the capacity to maintain equilibrium between input and output in spite of a growing portion of fluctuating electricity generation coming from wind turbines, solving the intermittency problem has become a matter of electricity market construction for the introduction and improvement of control system operation.

In addition to explaining how Nord Pool was introduced in Denmark and outlining some of its most significant implications with respect to the prevailing approach to wind power integration, chapter 1 also described a later reconfiguration of the wholesale electricity market. Doing so involved tracing a process of market construction strengthening the means by which homeostatic utility control can be exerted via Nord Pool. Specifically, it was documented how a piece of electricity market infrastructure in the form of a transmission system interconnector straddling The Great Belt was built in order to improve homeostatic utility control system operation. As the two different production and consumption profiles of eastern and western Denmark were connected, a greater number of electricity buyers were linked with the wind power producers predominantly found in the western part of Denmark. In effect, the basis for buying electricity at the points in time when it is generated by wind power producers was strengthened. This meant that the price of electricity was heightened in western Denmark, which has a large proportion of wind power producers, and lowered in eastern Denmark, which has relatively few wind turbines. That prices were evened out across the two zones implied that wind power was integrated into the Danish electricity system. This was due to how the introduction of Nord Pool mandated that the degree of wind power integration in the Danish electricity system could be derived from the price of wholesale electricity produced by wind turbines. As the price of electricity now mirrored system-wide utility in a Nord Pool context, wind power was integrated and the intermittency problem solved as the transmission system interconnector operated in such a way that there were fewer instances in which electricity generated by wind turbines was sold at low, zero, or negative prices (Cf. Aarhus Municipality, 2012).

Making Nord Pool and building the transmission system interconnector across The Great Belt was described as involving a particular approach to market construction. This method of wind power integration by means of market construction for the introduction or improvement of control arrangements for electricity system equilibrium maintenance is a central theme of the three different cases explored in the present study. Documenting the way it works in turn expands the empirical scope of the 'performativity programme' (Çalışkan & Callon, 2010) in two ways. One important aspect is that this approach to wind power integration involves control systems engineering as a generative form of expertise in market design and management. In this first case, the introduction of Nord Pool was shown to have implied the engineering of a system exerting homeostatic utility control. The other significant component of this approach to solving the intermittency problem through market construction is the particular use of economics, which up until now has remained ignored by the performativity programme. Through the measure of liquidity, economics was applied in creating the objective for the process of market construction, improving the means by which homeostatic utility control could be exerted. In other words, by operationalizing the metric describing the desired 'ability to trade' and its implications, the ideal outcome to be realized by changing the material infrastructure of Nord Pool was produced by mobilizing economics.

This specific approach to wind power integration through market construction using expertise in the form of economics and control systems engineering was also made evident in chapter 2, which described an economic experiment for the making of a new form of retail electricity market. Named EcoGrid and implemented on the Danish island of Bornholm, the experimental market arrangement was introduced in order to create knowledge about the potential for using a new retail electricity market format to integrate wind power in the electricity system. The purpose of EcoGrid was to replace the previous retail electricity market which to a great extent functioned by means of a pre-specified, constant, and seldom updated price. Instead, the EcoGrid market arrangement was introduced in order to provide varying electricity prices presented in five-minute intervals, and to encourage around 2000 retail consumers to react to them in a specific manner. By being conceived of as using prices closely coordinated with the ones found in the Regulating Power Market within Nord Pool, the successful introduction of EcoGrid would imply that retail electricity consumers could be mobilized for electricity system equilibrium maintenance in periods of time close to the moment of dispatch.

In tracing the design and management of EcoGrid, it was apparent that the market arrangement had been modelled on two slightly different control system concepts. First, EcoGrid was conceived of as both an open- and closed-loop electricity consumption control system, which in contrast to the case of electricity market design found in chapter 1, utilized predictions in the making of a control signal in the form of a retail price for electricity. Furthermore, the feedback in the closed-loop EcoGrid arrangement was designed to take the form of the quickly accessible system frequency rather than a negotiated price of electricity. In this way, the control system concept upon which the EcoGrid market arrangement was modelled is different from the one used in conceiving of Nord Pool as a homeostatic control system functioning by means of the mutual adjustment of generation and consumption. In this case, where a closed-loop electricity consumption control system was configured in the form of the EcoGrid retail electricity market, the focus was on designing an arrangement for having consumption follow generation. Second, it was made clear that the EcoGrid market design was based on the notion of a frequency adaptive power energy rescheduler, which is a specific type of control arrangement constituting a subsystem for exerting homeostatic utility control. It was then demonstrated how economics was used in the design of EcoGrid. Taking the form of price elasticity, economics was mobilized in conceiving of a necessary feature of the market design. The functioning of EcoGrid depended on the actualization of near-term price elastic retail electricity consumption. Simultaneously, the concept of price elasticity was used to denote a central objective to be attained through the introduction of EcoGrid. Price elastic retail electricity consumption was to be a key outcome of a well-functioning EcoGrid.

With reference to this second case of electricity market construction, chapter 2 reportedly augmented the empirical scope of the performativity programme once again. By showing how the notion of a frequency adaptive power energy rescheduler and the concepts of open- and closed-loop control systems were central inputs in the process of electricity market design, control systems engineering was emphasized as a generative form of expertise in the process of market construction. Furthermore, by tracing the use of the metric known as price elasticity, the analysis brought forward an application of economics in market construction which has remained unaddressed by the performativity programme up until this point. In the case of EcoGrid, economics was used to conceive of both a necessary feature of the market design and the objective to be attained by implementing the system.

Chapter 3 described wind power integration as undertaken by energy planners in Denmark. Attention was turned to electricity market modelling for the making of scenarios informing energy policy and electricity market reconfiguration. In this case, the making of the Danish Commission on Climate Change Policy's main report named *Green Energy – The Road to a Danish Energy System Without Fossil Fuels* (Danish Commission on Climate Change Policy, 2010) was deployed as an example because it has constituted a key reference in recent Danish energy policy. Making the electricity market scenarios which informed the policy recommendations from *Green Energy* and several other reports was then shown to have been approached using a specific computer programme known as the Baltic Model of Regional Electricity Liberalization (BALMOREL) (Ravn, 2001b). Furthermore, it was demonstrated that the necessary data regarding the qualities and costs of energy system components which were applied when making *Green Energy* were taken from the best available technology list named the Technology Catalog (Danish Energy Agency & Energinet.dk, 2012b). Against this backdrop, chapter 3 documented the making of BALMOREL and the Technology Catalog as two significant 'market devices' (Callon et al., 2008) which have proven to be central for actualized policy recommendations leading to wind power integration through electricity market construction.

The effort to augment the performativity programme was undertaken in chapter 3 by highlighting the way control systems engineering and economics were mobilized in the making of BALMOREL. Explaining the use of control systems engineering in the configuration of BALMOREL was undertaken by demonstrating how the model has its roots in linear programming. As linear programming constitutes a form of 'higher order' control system (Dantzig, 1957), the making of BALMOREL was in this respect described as a matter of getting to do electricity market representation by reducing the supply side of the electricity market into the linear programming model for production system optimization and then coupling it with a representation of a dynamic demand for electricity. Finally, it was shown how economics was applied in specifying the guiding principle for scenario building through electricity market representation by means of BALMOREL, via the metrics named consumer and producer surplus. In aggregate also known as socio-economic value, consumer and producer surplus were used to describe the defining feature of scenarios produced by means of BALMOREL. In other words, electricity market composition and operation were represented by maximizing the producer and consumer surplus under a number of constraints.

Having emphasized the arguments and findings of the analysis, the implications of the inquiry in relation to the performativity programme can now be further elaborated. Doing so here involves specifying some of the implications of mobilizing economics and control systems engineering when engineering markets as control systems. Specifically, there is a change in the state and status of economics as a representation of actual economic processes, which will be addressed. The metrics known as liquidity, price elasticity, and producer and consumer surplus were mobilized so as to make economic processes more like their depictions in economics, as they were used to describe the objectives or ideal outcomes of electricity market construction. But rather than dealing with how or to what extent economics became 'performative' (MacKenzie, 2007) or was actualized through market 'performation' (Callon, 2007b), the idea is here to discuss how economics in the form of descriptive concepts was used by professional market designers when conceiving of and managing electricity markets. In short, it is shown how economics as an analytical form of expertise was mobilized by actors working within approaches taken from the sciences of design and engineering (e.g. Simon, 1996).[36] Significantly, doing so involved reversing the direction of fit and direction of causation (Searle, 2001) of economics. Clarifying these matters not only provides a more detailed understanding of the state and status of economics when engineering control systems in the form of electricity markets; it will also make it possible to thoroughly appreciate why instances of market construction coupling the use of economics with elaborate planning and intention are poorly understood using the concept of performativity. And in this way, discussing how the direction of fit and causation of economics was reversed in the engineering of electricity markets also serves as a foundation for elaborating on how what we might describe as 'the theoreticist stance' found within the performativity programme has had adverse effects when included in previous inquiries into the making of Nord Pool.

Economics reversed

> Ainsi l'économique est sinon la mécanique elle-même appliquée à l'équilibre et au mouvement de la richesse sociale, comme l'hydraulique est la mécanique elle-même appliquée à l'équilibre et au mouvement des liquides, du moins une science analogue à la mécanique
>
> (Walras in Vatin, 2008, p. 133)

[36] See Roth (2002) for a case of the once-analytical discipline of economics becoming a 'science of the artificial' (Simon, 1996) in its own right. See Mirowski (2002) for a historical account of how this development started mainly around World War II. For a consideration of what this shift in the state and status of economics implies with respect to, for example, the commercialization of economic expertise, refer to Guala (2007) and Mirowski & Nik-Khah (2007).

In *More Heat than Light* (1989), the historian of economic thought Philip Mirowski described the development of modern economics as an attempt to make a ‘social physics’ modelled on the concepts and mathematical formalisms of classical mechanics. And as the present study shows, when integrating wind power into the Danish electricity system by engineering markets as control systems, economics was indeed applied as a social physics. In a mainly implicit way, economics constituted a theory describing the ‘laws’ governing the elements of the setting in which the control system market arrangement was to function. While the notion of say, a utility maximizing agent subjected to resource scarcity was not explicitly referred to, such conceptualizations functioned as assumptions for the introduction and improvement of electricity markets. But as was apparent from the discussion of the implementation of EcoGrid, for instance, engineering a control system as a market involves a task which is not found in the making of control systems which only regulate the behavior of material arrangements governed by the laws of physics. When engineering a market as a control system, one aspect is of course the matter of configuring the arrangement in a way that ensures the desired functionality in a setting governed by principles of economics. But another and equally important undertaking when engineering a control system which takes the form of a market, is to make sure that the general laws governing the setting in which the system is inserted actually apply. This is due to the fact that the objects studied in the discipline of economics have throughout history tended to act less steadily and have proved more difficult to measure consistently than those of the natural sciences which economics has tried to emulate (e.g. Marshall, 1920).

If it is to become an accurate representation of an empirical state of affairs and provide the requisite laws for control systems engineering, economics has to be endowed with the quality of truth (James, 2009). If not, the foundation upon which the control system is set to function does not exist. A relevant example of how this works was provided through the description of the elaborate training programs and large amounts of equipment deployed in the making of a specific form of economically rational electricity consumer as part of EcoGrid. Accordingly, emphasis is here put on what it means to mobilize economics when market design and management become a matter of engineering. And to see how this works, the conditions of satisfaction, direction of fit, and direction of causation (Searle, 2001) associated with economics are introduced. The main point of doing so is to stress that in the ongoing construction of the Danish electricity market as outlined in the present analysis, economics as a form of expertise was used in the engineering of markets by referring to the conditions of satisfaction of economics. Simultaneously, the direction of fit and direction of causation of the originally descriptive body of knowledge were reversed.

Conditions and directions

It should initially be noted that objects which include an element of representation can be understood to have conditions of satisfaction, a direction of fit, and a direction of causation.[37] Consider a globe which serves as a representation of the planet Earth, for instance. Let the globe have a circumference of one meter. The conditions of satisfaction associated with the globe as a representation of planet Earth require an accurate translation of the 1:1 planet into a scale 1:40 million model, since the circumference of the earth is 40 million meters. Thus, when it comes to the conditions of satisfaction, a model can be considered analogous to a belief as both a model and a belief have conditions of satisfaction which are satisfied if the entailed representation of a state of affairs is true. In a wider sense, it is worth noting that "A belief is satisfied if true, not satisfied if false. A desire will be satisfied if fulfilled, not satisfied if frustrated. An intention will be satisfied if carried out, not satisfied if not carried out" (Searle, 2001, p. 37).

The globe has a 'model-to-world' direction of fit as a result of being made to represent the earth in a smaller and simplified form. Another example can be found in a mental state involving a specific desire. A desire to go to Provence has conditions of satisfaction stipulating that the person with that desire would have to be located somewhere between the Rhône River, the Mediterranean, and the French Alps. The desire to go to Provence has the 'world-to-mind' direction of fit. If fit is achieved, the relevant state of affairs or 'the world' (Searle, 2001) is changed to match the desire as a result of that person relocating to Provence. Finally, there is the notion of the direction of causation. Keeping with the same

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[37] Note that the notion of representation is here broadly construed. Representation can thus apply to an actual as well as potential state of affairs or arrangement; that is to say that both real objects as well as figments can, of course, be represented.

example, the idea is here that if a person successfully acts on the desire to go to Provence, the direction of causation between the mental state of desire and the state of affairs is 'mind-to-world'. The desire in the mind is part of causing a change in the state of affairs it refers to. An example of the opposite can be found in a sense-based experience such as when smelling cinnamon. If the experience matches the world, i.e. if there is fit, this instance of a sense-based experience will involve a 'world-to-mind' direction of causation. A state of affairs in the world involving cinnamon here efficiently causes the experience of the smell of cinnamon.[38] In this last example the 'world-to-mind' direction of causation is paralleled by a mind-to-world direction of fit. That is, the change needed to attain fit is made in the mind by recognizing the smell of cinnamon through an experience of the world. Having briefly outlined what is implied in the concepts of the direction of fit, direction of causation, and conditions of satisfaction, emphasis can now be put on the relevance of these terms to understanding the use of economics in creating objectives for control systems engineering as market construction.

Reversing the direction of fit and causation

In the neoclassical thinking of Alfred Marshall, among others, economics was an analytical or descriptive discipline comparable to the natural sciences in the sense that it was "…the business of economics, as of almost every other science, to collect facts, to arrange and interpret them, and to draw inferences from them" (Marshall, 1920, p. 23). In line with the introductory statement by Walras, Marshall made clear that "Thus best may we obtain sound generalizations as to the past and trustworthy guidance from it for the future" (Ibid.). Here, then, the extent to which the conditions of satisfaction implied in economics were satisfied, i.e. the

[38] Following (Searle, 2001), the only form of causation understood to exist here is "efficient causation" (p. 41). Furthermore, by not taking the use of the term 'efficient cause' to imply the attribution of the status as the single primary change agent in a given situation, the idea of an efficient cause here simply refers to a source of stability or change. An example would be included in stating that 'the earthquake efficiently caused the collapse of the building'. Formal, final, and material causation as also originally presented by Aristotle are not considered.

extent to which the model was true, was an outcome of the ‘model-to-world’ direction of fit. Attaining fit between economics and an empirical state of affairs was conceived of as requiring an adjustment of the model in accordance with empirical observation. Furthermore, the idea of economics as an analytical science had implications for the direction of causation. As an effect of having empirical observation influence the state of the model, economics had a ‘world-to-model’ direction of causation. Attaining fit between economics and the objects it described was done by having facts about markets influence their conceptualization in economics.

To Marshall, significant aspects which set economics as a discipline apart from the natural sciences it tried to imitate were to be found in the lesser accuracy and potential for use in prediction implied in economic ‘laws’ as compared to the law of gravitation, for instance:

> It [the law of gravitation] is a very exact statement—so exact that mathematicians can calculate a Nautical Almanac, which will show the moments at which each satellite of Jupiter will hide itself behind Jupiter. They make this calculation for many years beforehand; and navigators take it to sea, and use it in finding out where they are. Now there are no economic tendencies which act as steadily and can be measured as exactly as gravitation can: and consequently there are no laws of economics which can be compared for precision with the law of gravitation
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> (Marshall, 1920, p. 24)

When engineering a market in a way which presupposes that the laws of economics characterize the setting in which the control system is supposed to work, unsteady and hard-to-measure economic tendencies can constitute a significant barrier to achieving the goal of regulating conduct. The fact that the ideal type *homo economicus* does not exist *a priori* also helps point to why so much work went into making market actors behave as intended, be it through ‘unbundling’ as witnessed in the making of the wholesale electricity market (e.g. Bach, 2013; Thostrup, 2013) or the training and equipping of retail electricity consumers in the context of EcoGrid (e.g. Bendtsen, 2013a; Jørgensen, 2013). Integrating wind power into the Danish energy system by constructing electricity markets as control systems for electricity system equilibrium maintenance thus involved two overlapping tasks. One was to design, implement, and reconfigure electricity market arrangements functioning as control systems. Another was to make sure that the setting in which these control arrangements were inserted could be described using the economic concepts inscribed in the system designs. And it is the implications for the state of economics caused by the latter undertaking which is of most interest here.

The market organizers followed in the present inquiry were not blind to the fact that economics does not necessarily provide statements which are true and objectively general. However, they were also well aware that the successful operation of control system market arrangements depended on having people act in accordance with the inscribed programs of economic action. And as market construction for the introduction and reconfiguration of control systems evidently contained efforts to make economics an increasingly true representation of conduct in a market setting, the direction of fit and direction of causation originally associated with economics was reversed.

Originally introduced as measures of a state of affairs in a market, the concepts of liquidity, price elasticity, and producer and consumer surplus were in this context used to set objectives to be achieved through a process of market construction. And in this way, these formerly analytical concepts were endowed with a direction of fit and a direction of causation usually associated with other objects, such as that of the mental state of desire. Take the case of the use of price elasticity in the making of EcoGrid, for instance. As a metric describing the relationship between the price and demand for a specific good, the concept of price elasticity had a direction of fit which was 'model-to-world'. The measure was made to represent an empirical state of affairs. This was changed in the engineering of EcoGrid. As the concept of price elasticity was used to conceive of and describe a necessary feature and the ideal outcome to be achieved by introducing the experimental market arrangement, the direction of fit associated with the concept of price elasticity was reversed. The fit between economics and the object in question was to be attained by reconfiguring retail electricity consumption into a format conceived of and accurately described through the notion of price elasticity. Rather than 'model-to-world', the use of economics in the engineering of a control system in the form of a market thus implied a 'world-to-model' direction of fit.

The direction of causation between the measure named price elasticity and the object it represents was also reversed. Originally, empirical observations forming part of an analytical science guided and influenced the conception of the metric now known as price elasticity. In this way, the notion of price elasticity had a 'world-to-model' direction of causation. But when used for conceiving of and describing the way retail electricity consumption was to be carried out after having introduced a specific electricity market, the configuration of the object was to be influenced by the model. In other words, the direction of causation associated with the potential fit between the concept of price elasticity and the object in the form of retail electricity consumption became 'model-to-world'.

Having outlined the way the direction of fit and direction of causation of economics were reversed when engineering electricity markets as control arrangements for electricity system equilibrium maintenance, a more detailed picture of the use of economics in market construction begins to materialize. Providing a more intimate understanding of the use of economics in electricity market construction is intended to add to the performativity programme by including a novel combination of conceptual and empirical material. However, emphasizing the fact that the state and status of economics were changed as the direction of fit and direction of causation reversed in the engineering of electricity markets also serves as the starting point of an argument for subtracting or excluding elements from the performativity programme. In essence, it will be argued that what can be called the 'theoreticist stance' should be taken out of empirical inquiry as conducted by the performativity programme. To lay down the foundation for this argument, the following section will further describe the implications of the fact that the direction of fit and direction of causation originally associated with economics were reversed when engineering electricity markets in Denmark.

Intention in market construction

Significantly, the approach to using economics by reversing the original direction of fit and direction of causation when engineering electricity markets implies an element of intention. That is to say that the use of expertise in the form of control systems engineering and economics in this particular approach to market construction involves ‘intentional causation’, which implies that “…an intentional state either causes its conditions of satisfaction, or the conditions of satisfaction of an intentional state cause it” (Searle, 2001, p. 41). The notion of intentional causation can in turn be exemplified by once again considering the desire to be in Provence. Intentional causation exists if the desire to go Provence, which here includes an element of intention, causes the person with the desire to relocate to Provence. However, intentional causation is also present if being located in Provence causes the desire to be somewhere between the Rhône River, the Mediterranean, and the French Alps. Returning to the example described in the EcoGrid case, it is apparent that the mixed results with respect to consumer compliance produced by the experiment only merit reference to a certain degree of intentional causation. Nonetheless, the retail market on Bornholm was intended to take the form of the arrangement designed in the Department of Electrical Engineering at the Technical University of Denmark. And to a great extent, EcoGrid did just that.

The intentional aspect of market construction as explored in the present inquiry in turn denotes a central difference between the three cases documented here and the markets which have fruitfully been understood using the concept of Barnesian performativity (MacKenzie, 2007, p. 55).[39] In a situation such as that described by Donald MacKenzie, highlighting the fact that an aspect of economics was used in a way that made the market more like the depiction of it in economics proved insightful. One reason why one can learn something from that observation has to do with the idea that in that particular empirical setting, economics was introduced for analytical purposes by the actors under study. In that particular situation, there was never the intention that economics would be anything but analytical. In other words, economics was conceived of as having its original direction of fit and direction of causation. A central part of MacKenzie’s significant observation was exactly that this turned out not to be the case. For a limited period of time, achieving fit between the Black-Scholes formula and a market for options was done by unintentionally reversing the model’s direction of fit and causation. For this reason, Guala (2007) named the phenomenon described by MacKenzie

[39] Note that reference is here made to MacKenzie’s types of ‘performativity’ and not to Callon’s (e.g. 2007) notion of ‘performation’.

‘spurious performativity’. But in the engineering of the electricity markets described here, economics was consistently applied in market construction in a way which implied actively working with the reversed directions of fit and causation. And when observing empirical settings such as electricity markets and focusing on situations in which intentional causation is the order of the day, the notion of performativity becomes trivial.

Remarkably, in spite of the fact that it amounts to presenting a pleonasm when stressing the finding of Barnesian performativity in a situation where market design and management is evidently handled by dedicated professionals working with economic concepts in a prescriptive way, it is still being done. To the extent that the aim of inquiry is to produce empirical and conceptual findings which are different in character from statements such as ‘backing backwards’, understanding market construction by means of the concept of Barnesian performativity in a situation where the use of economics blatantly involves intentional causation requires critical attention. Providing due scrutiny is briefly undertaken here in three steps. Initially, the ‘stance’ (van Fraassen, 2002) involved in previous studies of the making of Nord Pool is tentatively outlined. While this particular stance has been taken up by representatives of the performativity programme in several instances, it is here discerned from the exemplary work of Michel Callon. Again, it has to be stressed that exemplifying the stance in question through the work of Callon is undertaken in order to direct critical attention to attempts at inquiry into the construction of markets made by other members of the performativity programme. In other words, discerning the theoreticist stance in this way is not meant to form a critique of Callon’s authorship. Accordingly, the following clearly testifies to the fact that inquiry into a specific empirical state of affairs is not a feature of the work of Callon included here. Nonetheless, the stance is exemplary of that which is also found in previous studies of Nord Pool. And it is when this particular stance has been adopted as part of inquiry into market construction as an empirical phenomenon that adverse effects have materialized.

Having traced some of the features of this stance, emphasis shifts to demonstrating its presence and effects in specific studies of Nord Pool emanating from within the performativity programme (Karlstrøm, 2012; Silvast, 2015). What will be clarified is the way such a stance can contribute to rendering Nord Pool opaque. In the two examples taken up here, it does so through two moves. First, it makes the transmission of explanation and production of redundant statements a worthy undertaking. Second, it draws focus away from the object of study and towards academic concepts of little relevance to the empirical situation. Specifically, it is described how the theoreticist stance has led to the idea that finding Barnesian performativity in instances of market construction characterized by intention on behalf of professional market designers and managers constitutes a valuable and worthwhile product of inquiry. But as has already been demonstrated, such a finding is trivial. Before moving on to addressing the practice of wind power integration in Denmark, it is suggested that taking an empirical stance (van Fraassen, 2002) implies an alternative approach which would eliminate the risk of prioritizing the making redundant statements and making them findings in their own right. Expanding this into a wider point, it is underscored that taking up an empirical stance would be an appropriate move for the performativity programme to make in becoming an increasingly data-driven research agenda.

The theoreticist stance

To outline central aspects of the stance found in the performativity programme which has been conducive to redundant conclusions and rendering Nord Pool opaque, a number of examples clarifying this approach to the study of markets will be drawn from the work of Michel Callon. It is initially worth noting that the two central aspects of the stance which will be discussed here were touched upon by du Gay when stressing a twofold tendency characterizing Judith Butler's and Michel Callon's work with the concept of performativity:[40]

[40] It should be noted that this particular formulation as presented by du Gay was introduced with reference to the work of Judith Butler. However, the argument was also applied to the work of Michel Callon.

> First…the specificities of empirical and historical circumstances are subordinated to transcendent truth claims, and second…the politics deemed to flow from this theory programme has little obvious connection to (minimalistically) practical politics and considerably more to do with the ways in which politics is identified with the intellectual operations of certain sorts of theory
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> (du Gay, 2010, p. 177)

The point here is to highlight the stance, or attitude, occupied by Callon when studying markets, and which is tied in with these tendencies observed by du Gay. The stance in question is here presented as having two main features. One is a primary commitment to or prioritization of the development of generally applicable conceptualizations of markets. The other is a lack of concern with the object of study as constituted by an empirical state of affairs. Examples from the bibliography of Callon have been sampled from the point at which the notion of economy as broadly construed began to be emphasized. Tentatively outlining the stance in question here implies initially focusing on the development of the notion of techno-economic networks (Callon, 1991; 2007a), with the text named *Techno-economic networks and irreversibility* (Callon, 1991) constituting an early milestone for STS in the journey into economic sociology. Another significant feature of the publication is that it is helpful for discerning the stance in question because it concisely exhibits both a commitment to the development of a general theory of techno-economic networks and an overt willingness to neglect empirical reference.

Put briefly, a techno-economic network is presented as "…a coordinated set of heterogeneous actors which interact more or less successfully to develop, produce, distribute and diffuse methods for generating goods and services" (Callon, 1991, p. 133). This statement or understanding and its implications are based on the observation that:

> Life is complicated. But I will start with a heuristic simplification and assume that TEN's [techno-economic networks] are organized around three distinct poles: *First* there is a *scientific pole* which produces certified knowledge. This is where scientific research is practiced: for instance, in independent research centres, universities and relatively basic industrial laboratories. *Second* there is a *technical pole* which conceives of, develops and/or transforms artefacts. Its products

> include models, pilot projects, prototypes, tests and trials, patents, norms, and technical rules, and it is found in industrial technical laboratories, research associations, and pilot plants. *Third* there is a *market pole* which refers to users or consumers who more or less explicitly generate, express or seek to satisfy demands or needs…*In principle* they are as different as chalk and cheese…*In practice*, however, they are linked
>
> [Italics in original] (Callon, 1991, p. 133-134)

This way of deriving the notion of something called techno-economic networks in simply noting that 'life is complicated' while drawing on an undescribed 'heuristic simplification' is exemplary of the stance in question. It displays the inclination towards making wide generalizations and a lack of concern with the object of study as an empirical phenomenon. Note that in the context of the present argument, it is unimportant whether or not the statement made about techno-economic networks possesses the quality of truth. What matters here is the attitude or approach taken towards the making of generalized statements and empirical experience as part of inquiry.

Manifestations of the stance in question, in the form of a commitment to the making of general statements to which empirical experience is ranked second, are also discernable from another milestone publication, *The Laws of the Markets* (Callon, 1998a).[41] Take the way in which the now-canonical analysis of the making of a strawberry auction (Garcia-Parpet, 2007) has been taken up by Callon as documenting the performativity of economics, for instance. Using this piece of work as an empirical cornerstone for the performativity thesis as presented in the introduction to *The Laws of the Markets*, it is stressed that the study documents "…the constitution of a market with characteristics corresponding to those described in political economy manuals" (Callon, 1998b, p. 20). Upon consulting

[41] See du Gay (2010) for a discussion of the conception of the 'framing and overflowing model' (Callon, 1998c; 2007b) originally introduced by Callon in *The Laws of the Markets*. Here the stance in question is apparent in the sense that the conception of the model is shown to imply accepting as legitimate the production of general statements without the use of empirical reference. It is here stressed that "philosophical reconstruction" (du Gay, 2010, p. 177) as a form of simulacrum has knowingly and willingly been made to replace empirical experience in the inference of universal statements.

the text in question, it becomes clear that this particularly important empirical account demonstrating the performativity of economics suggests that:

> The creation of the computer-assisted descending-auction market seems to have been the result of a meeting between an economic advisor to the Chambre d'Agriculture and a number of local producers who shared an interest in promoting this new method of buying and selling…This advisor had more educational capital than other members of the Chambre d'Agriculture including the director. He had studied at the Ecole Supériure d'Agronomie at Nancy and had two degrees, in biology and law. It was doubtless as a result of his training in economics, which he had received as a law student, that he was familiar with the neoclassical theory that was to guide his actions
>
> (Garcia-Parpet, 2007, p. 31)

Taking an empirical stance (van Fraassen, 2002), one can come to wonder if the consultant educated as a lawyer and biologist had applied skill, knowledge, and know-how significant to introducing the market which would not qualify as economics. What were the other more, equally, or less significant knowledge-based inputs for this case of market design and maintenance? As also pointed out in the introduction to the present study, the way these questions are dealt with in the work of Callon is clear. Through concepts such as 'economics at large' and 'economics in the wild' (e.g. Callon, 2007b) all forms of knowledge come to qualify as economics if they participate in the making of a market. While at this stage not considering the consequences this has for inference, what can be discerned from observing this way of approaching the study of markets is the theoreticist stance. Empirical experience along with particularized, contextual, and historically situated understandings are neglected or negated (Cf. Mirowski & Nik-Khah, 2007) as part of the overarching effort to produce a tautology or universally true statement about the construction of markets.

A final example in which the stance in question is expressed can be found in the manifesto *Economization Part 2: a research programme for the study of markets* (Çalışkan & Callon, 2010). In this case, a research agenda is based on the idea that markets are produced by means of five different processes of "framing" (e.g. Callon, 1998c). The point of interest here is in turn the approach taken to the conception of markets, i.e. the approach taken to understanding and defining the object which is to be constituted by framing its various dimensions in five different ways. The way markets are conceived of or the manner in which the object of study has been demarcated in order to then progress to discussing the way in which it should be studied, is apparent from the introduction:

> The study of marketization would be altogether too difficult if it were not for an agreement in contemporary societies on the characteristics of markets, this particular organizational form for economic activities…As such, the notion of a market can be treated as though it encompasses a set of significations, realities and practices whose content and expected outcome has become a matter of widespread agreement...The academic literature as well as a survey of 'popular' meaning of markets sees these as institutions that favour the creation and the production of values by organizing competition between autonomous and independent agents. This conceptual coherence leads us to define markets as sociotechnical arrangements or assemblages (agencements)…Our definition is consistent with the academic literature. It is coherent with our comments on the family resemblance of markets and on the role of economics and social science in enacting this resemblance. And it is also compatible with the 'popular' meanings of markets as institutions that favour the creation of values by organizing competition between autonomous and independent agents
>
> (Çalışkan & Callon, 2010, p. 2-3)

In presenting how the object around which the conceptual research agenda revolves has been defined, appeal is made to number of sources: 'characteristics agreed upon in contemporary societies', 'family resemblance', 'widespread agreement on realities and practices', 'the academic literature',[42] and the 'popular meaning' of the term market constitute the supposed points of contact with reality through which markets have been understood. Again, how or to what extent the beliefs and research programme derived from this approach to the conceptualization of markets resonates with empirical observations of markets is not the concern at this point. The central point is that the reader is once again

[42] See (Çalışkan & Callon, 2009) for the literature review which preceded the introduction of the research agenda.

confronted with the attitude, commitment, and approach characteristic of a theoreticist stance. And this particular stance implies, among other things, a satisfaction with general explanations derived from a simulacrum based on theoretical reconstructions, along with a willingness to neglect empirical experience.

Having provided an outline of two of the central features signifying the particular stance found in the work of Callon and the wider performativity programme, some of its implications can be tentatively discussed. Initially it can be noted that taking a stance such as that outlined here is not inappropriate if one is in the business of say, making concepts to think with when inquiring into the making of markets. This stance is thus not unsuitable for theorizing upon theory as sometimes done in the work of Callon. But one type of situation in which such a stance is wholly inappropriate is when research seeks to produce findings about markets by means of inquiry. A preoccupation with concepts and generalization coupled with a willingness to rank empirical experience second can and does help to blur Nord Pool as an object of study. And it is in this latter respect that discussing the theoreticist stance is important. This is due to the fact that it is by taking this stance as part of an approach to inquiry into the making of Nord Pool that the finding of pleonasms has become possible and conceived of as relevant or worthwhile. Occupying this stance enables and legitimates the understanding that the concept of performativity adds to rather than hinders the analysis of market construction involving intentional causation. That is, taking a theoreticist stance as part of inquiry into an empirical state of affairs has led to a trivial and redundant focus on performativity in situations where markets are carefully designed and managed by dedicated professionals. To demonstrate how this problem unfolds and indicate why taking an empirical stance as part of inquiry into the design and management of markets would help to prevent it, two recent papers on the configuration of Nord Pool named *Design, Deregulation, and Reregulation of the Nordic Power Markets in Finland: An Empirical Exploration of the 'Performativity' Thesis* (Silvast, 2015) and *Empowering Markets? The Construction and Maintenance of a Deregulated Market for Electricity in Norway* (Karlstrøm, 2012) are briefly discussed. These two examples are particularly relevant as they involve exemplary expressions of the potential effects associated with taking a theoreticist stance when inquiring into market construction, in the context of Nord Pool.

Blurring Nord Pool

To show how the theoreticist stance taken up within the performativity programme has contributed to hindering the understanding of market design and management as an empirical object of study, attention is here turned to a concrete example: a study of Nord Pool in which such a stance is taken. And in doing so, it is shown how taking such a stance can be instrumental in producing a situation in which stating a pleonasm about market design and management can come to be considered a satisfactory product of inquiry.

Discerning the effects associated with the theoreticist stance implied in *Design, Deregulation, and Reregulation of the Nordic Power Markets in Finland: An Empirical Exploration of the 'Performativity' Thesis*, can be approached by initially considering the research question driving the inquiry. The theoreticist stance here manifests itself in the sense that the notion of Barnesian performativity is treated as important in and of itself. Instead of empirically oriented inquiry, the stance motivates the 'empirical exploration' of Barnesian performativity:

> Have energy market mechanisms become 'performative' for the electricity infrastructure? That is to say, does energy market design shape the electricity infrastructure to operate in a way that corresponds more closely with economic theory than before?
>
> (Silvast, 2015, p. 7)

As also suggested in the title of the paper, emphasis is put on transmitting a concept and explanation of processes involved in market construction from one setting to another. And when considering the contents of the questions, the extent to which the stance is misplaced in the context of inquiry becomes striking. Early on in the text it is established that economics has been "…a tangible part of how energy markets were established and how decisions such as financing were made and communicated on these market places" (Silvast, 2015, p. 5).[43] This point is

[43] That this point is made also serves as a good illustration of the fact that the inclusion of empirical details such as formulas for pricing and cost calculations, statements made by expert market managers and so on does not constitute a safeguard against the effects of taking a theoreticist stance as part of the empirical study of markets. Again, it is *how* such details are approached and prioritized in the process of inference that is the point of focus here.

fairly well documented and seems plausible considering the character and history of electricity markets such as Nord Pool, which by necessity have been carefully designed and managed. One wonders: What can be learned from searching for Barnesian performativity in a context evidently characterized by intentional causation on behalf of engineers and economists mobilizing economics in a prescriptive manner for the configuration of markets? From what sense of priority can such a situated question stem, if not from a preoccupation with concepts and the transmission of explanation as coupled with lack of concern for accurately describing the market and taking seriously its context, history, and particularity? In getting back to the effects of taking such a stance in the context of inquiry, it should be noted that the answer to the research question seems to be a 'yes'. Barnesian performativity can be detected in the context of Nord Pool. It is concluded that:

> …regulation works by supporting markets rather than by preventing their functioning and this seems to be more generally the case…What emerges here is not a regulator that governs risks and uncertainties through some kind of centralized command and control. Instead, regulation merely channels risks and uncertainties and creates possibilities for the markets to function
>
> (Silvast, 2015, p. 16)

In focusing on the stance and its effects rather than the contents of the argument, what should be noted here is what is supposed to be learned from asking this type of question and providing this type of answer. The prescriptive concepts used by experts in the construction of markets are found to have taken part in making market arrangements or processes more like those inscribed in the same concepts. One can of course argue that "Indeed, with markets for energy…evidence pertains that performativity is rather an appropriate characterization of what transpires in the marketization of energy infrastructures" (Silvast, 2015, p. 4). But while such a conclusion is not strictly incorrect, it attains its legitimacy or relevance from being coupled with an understanding of the concept of Barnesian performativity as being worth applying and 'exploring' in and of itself. And as the notion of Barnesian performativity was developed in the effort to describe a process of market construction deprived of intentional causation, the normative endeavor to transmit the concept into the context of Nord Pool here results in a trivial finding. And to the extent that trivial abstract statements come to be the central products of studies of market construction instead of accurate empirical description, the object of inquiry is necessarily rendered opaque.

For an example of how the theoreticist stance found within the performativity programme can help produce different but similarly redundant statements, consider *Empowering markets? The construction and maintenance of a deregulated market for electricity in Norway* (Karlstrøm, 2012).[44] To understand the construction of Nord Pool in a Norwegian context, the idea here has been to "…turn to work done within science and technology studies (STS) and economic sociology regarding the way scientific expertise influences the production of politics, exemplified by the recent work on the concept of performativity" (Karlstrøm, 2012, p. 8). Remarkably, and as the author also notes, a lot of work regarding the notion of performativity was developed by studying financial markets. This is especially true for the strong or Barnesian form of performativity that once again is of special interest. But as in the previous example, the theoreticist stance as manifested in a preoccupation with concepts or theory along with a tendency to rank empirical experience second implies that the defining differences and characteristics of Nord Pool as opposed to a specific financial market are ignored at crucial points in the discussion. Primacy is given to understanding Nord Pool in terms that are determined by the demands of the theory. These empirical differences which are related in part to the presence or non-presence of intentional causation disappear as they are trumped by the wider sense of priority associated with this stance or approach to inquiry, and a situation once again arises in which it is supposedly satisfactory to present a pleonasm as a finding:

> Doubtless, the performativity perspective developed by Michel Callon and others introduces a research agenda well worth exploring. On the other hand, the analysis in the four papers in this dissertation shows that the performativity perspective, especially the strong version where theory is taken to do all the work on its own, cannot account for the observations related to the deregulation of the Norwegian electricity market. When deregulation is framed from the point of

[44] In part due to the fact that *Empowering markets?* has not been available in full length, the following comment takes on a more speculative character.

> view of (strong) performativity, each of the four papers observe a particular form of overflow – to use Callon's…own term – that critically questions the framing
>
> (Karlstrøm, 2012, p. 33)

Not being concerned with the applied understanding of 'strong' performativity or the general truth value of these statements, what is worth noting here is the implications of taking a theoreticist stance as part of inquiry into an empirical state of affairs. Specifically, there is a sense of priority implying that the existence of Barnesian performativity is regarded as non-trivial, regardless of the fact that Barnesian performativity is an acknowledged and intended outcome on behalf of market designers and managers. In this way, findings in the form of pleonasms are attributed merit. But it is hard to learn anything new about an empirical phenomenon through conclusions such as 'engineers do engineering' or 'market makers make markets'. What seems to be presented in the above quote is a critique or address of a trivial concept after it has been made so by transmitting it into the context of an electricity market which is simultaneously described as arduously designed and managed, i.e. a setting signified by intentional causation. Again, this sort of result is characteristic of research incorporating the attitude, commitment, and approach in question. The notion of performativity which is "…the now canonical bread-and-butter of social studies of finance…" (Pardo-Guerra, 2013, p. 1) was developed as part of inquiry into an empirical setting and situation which is fundamentally different from Nord Pool. However, taking a theoreticist stance can lead to a lack of concern about the implications of such differences when transmitting concepts and explanations from one setting to another. The point here is not that it is wrong to state that:

> Performativity theory should be credited for making economic theory into an object that – together with a host of other material objects – is part of the socio-technical construction of markets. Deregulation is clearly an effort to redesign exchanges of for example electricity, and thus may be considered to be a socio-technical development
>
> (Karlstrøm, 2012, p. 37)

But is the notion of performativity necessary for building such an understanding? And is the concept the right choice for analyzing situations characterized by intentional causation? While helping to vanish fundamental differences between empirical phenomena such as the presence or non-presence of intentional causation in market construction, the stance also legitimizes the introduction of the concept of performativity when demonstrating "…how the profession of economists and their political machinery played a vital role in making a theoretical economic design into an actually deregulated electricity market" (Karlstrøm, 2012, p. 33).

In order to avoid ending up in a situation where stating a pleonasm is considered a satisfactory outcome of inquiry, taking an empirical stance or least trying to do so could be a valuable first step. This change in stance would imply shedding the prioritization of conceptual development along with the willingness to disregard empirical experience as part of inquiry into the making of markets. And it would in turn imply privileging empirical experience by treating "…science as practice, as search, as rational form of inquiry par excellence" (van Fraassen, 2002, p. 63).[45]

Having outlined the theoreticist stance and some of its implications for the performativity programme, attention now turns to the practice of integrating wind power into Denmark by means of market construction for the introduction or improvement of control systems for electricity system equilibrium maintenance. In finalizing the discussion and concluding comments, a selection of the wider implications of constructing markets for the improvement or introduction of control arrangements as part of electricity system equilibrium maintenance as documented in the analysis will be briefly addressed. The discussion of the practice of integrating wind power into the Danish electricity system includes two main topics. First, the current and planned use of market-based solutions for the integration of wind power into the Danish electricity system is discussed as bringing with it issues which require the attention and involvement of affected parties, to the extent that there is a desire to increase participants' control of their lives. These issues pertain to the distribution of rights and privileges when combining economics, engineering, markets, and policy in novel ways. Finally, the section is brought to a close by considering and questioning the currently widespread use of markets for dealing with matters of public concern such as the

[45] The particular empirical stance occupied as part of the present study and described in the introduction to the present volume would be a relevant starting point for the reorientation of parts of the performativity programme.

integration of wind power when trying to establish an energy system based on renewable energy sources.

Practicing wind power integration

A point initially worth noting in addressing the practice of wind power integration in Denmark, is the way in which the notions of what a market is and what a market can be change fundamentally when considering how electricity markets have been engineered as control systems. And as stressed repeatedly throughout the analysis, it provisionally augments the performativity programme by highlighting control systems engineering as a generative form of expertise and economics as the supplier of metrics for the creation of objectives for market construction. But beginning to understand the engineering of electricity markets as control systems also enables a number of reflections and questions which are more practical in character.

One issue which surfaces as markets are shown to be control systems designed and managed to maintain equilibrium in the electricity system is that they are markets introduced in part to deal with matters of coordination traditionally handled by the state. As opposed to many other objects which go under the name 'market', entities such as EcoGrid are designed specifically to solve societal problems. It is a market for dealing with 'collective concerns' (Frankel, Ossandón, & Pallesen, 2015b). The fact that the electricity markets described in chapters 1 through 3 have been designed and managed as a form of policy by mobilizing economics and control systems engineering in turn has a number of implications.

As a 'policy device' (Ibid.) Nord Pool was set to ensure security of supply, investment in capacity for electricity production, equilibrium maintenance and so on. Far from being a spontaneous or emergent market, Nord Pool has been carefully designed and managed for specific purposes. Nord Pool was configured using specific forms of expertise, enabling the functioning of the market through an accommodation of the characteristics of electricity systems and their functioning. But by combining markets, policy, economics, and engineering in this way, a number of challenges regarding the administration or management of these disparate components begin to materialize. (Central issues include deciding on the privileges associated with the evaluation and management of the market arrangement, for instance.) As markets are introduced and tailored in order to serve higher purposes, such matters become increasingly important. By what type of actor or authority are these control-system markets to be judged a success or failure? What kind of expertise should form the basis for formulating evaluation criteria and for deciding how these criteria are to be applied?

Even though energy planners have pointed out the striking lack of interest in, and actual evaluation of, the large infrastructural change which the introduction of Nord Pool brought about (Boldt, 2013; Hvelplund & Meyer, 2007), these questions are not motivated by a lack of attempts at establishing assessment criteria or claims of expertise and authority. Such efforts are indeed being undertaken (Energinet.dk, 2014e). But if there is a sufficiently strong desire to increase the electricity consumers' control of their lives, the conversation and potential debate around these issues should be prioritized, formalized, and brought out into the open, rather than folded into highly technical reports made by the incumbents of the electricity sector (Cf. Callon et al., 2009). Doing so could perhaps even help facilitate the questioning of a central premise for wind power integration and energy sector development in Denmark, which is the use of and trust in Nord Pool. But it could also contribute to a number of smaller or incremental and potentially beneficial changes for electricity consumers.

Distributing rights and privileges

One instance in which wind power integration could potentially benefit from openness in the conversation around the privilege of market management and the evaluation of the functioning of Nord Pool and its subsystems, relates to the distribution of roles and interests in the liberalized electricity sector. Take the case of *Elpristavlen*, for example. *Elpristavlen* was set up to be a central ‘market device’ (Callon et al., 2008) when the retail electricity market was introduced in Denmark. *Elpristavlen* is a website which has been designed to act as the entry point to the Danish retail electricity market. The website, which enables access to relevant information in an organized format, was set up to help retail electricity consumers complete economic calculations in order to then choose a specific product delivered by a specific supplier at a specific price. One benefit for the process of wind power integration following from *Elpristavlen* could surface if consumers were able to use the website to make informed choices involving a solution enabling flexible electricity consumption. The format of such a retail electricity product would in an overall sense be similar to that implied in EcoGrid. However, the website has been criticized repeatedly for hampering the mobility of retail consumers and hindering competition among suppliers (M. Pedersen, 2012). And the non-functioning of this central calculative device of the retail electricity market in Denmark is no trivial issue.

In an investigation of the developments in electricity prices and their causes within the period between 1995 and 2009, the liberalization of electricity which started in 1999 was shown to have led to a net rise in retail electricity prices of 21 percent. In the same period, industrial-scale electricity buyers taking part in the wholesale market saw net savings in the cost of electricity of 16 percent (Danish Energy Agency, 2011a).[46] The difference between price developments in the wholesale and retail electricity markets has been attributed to two overall issues. One is the fact that subscription fees have been heightened as a result of the electricity companies' unbundling. The other pertains to two overlapping developments characterizing the retail electricity market (Ibid.), and is significant when considering the case of *Elpristavlen* as suggestive of the need for conversation about the relevant roles and interests in market management in the context of markets designed to serve the public interest. And these issues relate specifically to the price of electricity rather than the costs of the subscription fee.

The first of the two overlapping issues which are related to the increase in the price of retail electricity is that the mobility of consumers and competition among suppliers was never really established in the Danish retail electricity market. A significant recommendation made by the Danish Energy Agency was in this respect to improve the basic functionality of *Elpristavlen*. The other aspect of the retail electricity market which has contributed to this development in prices is what is known as *forsyningspligten* (Danish Energy Agency, 2013b). *Forsyningspligten* implies that a default product was provided to electricity

[46] These figures are 'cleaned' of the implications of rising fuel prices, taxes, the emissions trading scheme and so on.

consumers who did not react to the fact that electricity was liberalized. In other words, it was an arrangement made to make sure that electricity would still be provided to retail consumers, regardless of whether they could or would choose to be active in the retail electricity market from 2003 onwards. Around 90 percent of all household consumers relied on *forsyningspligten* for the delivery of electricity in 2009. Through *forsyningspligten*, these consumers were assigned a supplier of retail electricity on the basis of geographical areas or zones which ties together buyers and suppliers in close proximity to each other. But relying on *forsyningspligten* means paying a tariff for electricity called *forsyningspligtafgiften*, which is set by the Danish Energy Authority. And this tariff has proved instrumental in producing a cost of electricity which is significantly higher than what could have been attained if a supplier and product had been actively chosen using *Elpristavlen*. This state of affairs was made possible in part because *forsyningspligten* was never intended to imply a low price (Danish Energy Agency, 2011a).

As the head of the Danish Competition and Consumer Authority put it, when it comes to the retail electricity market in Denmark, "Competition is weak, and the consumers are passive. They can't comprehend the market. So things aren't going too well" [Author's translation] (Gersing in Bredsdorff, 2011, p. 1). In this context, one thing is to point out the fact that *Elpristavlen* needs to be improved (Danish Energy Agency, 2011a; 2013b). But it is also worth noting the fact that *Elpristavlen* is operated by the Danish Energy Association, the interest group working on behalf of the electric utility companies in Denmark. While entities such as the Danish Energy Authority are also partly responsible for the functioning of *Elpristavlen*, the fact that the interest group representing the electric utility companies is operating the central market device for consumers begs critical reflection. *Elpristavlen* is supposed to foster competition between suppliers and enable consumer mobility in a way that potentially facilitates wind power integration, while also lowering retail electricity prices. The point is not to suggest that the Danish Energy Association has helped its members obtain an unduly high price of electricity through the arrangement known as *forsyningpligten* by hampering retail consumer mobility and supply-side competition through the non-functioning of *Elpristavlen*. But one might ask how the Danish Energy Association ended up being responsible for the functioning of *Elpristavlen* in the first place? And especially when considering the state of the retail electricity market in Denmark, it seems relevant to ask whether it is a good idea to rely on the utility companies themselves to look after the economic interests of the consumers? If nothing else, it now implies an unfortunate symbolic gesture given the development of the Danish retail electricity market.

It is of course hard to say how many consumers would consider the distribution of authority and privilege implied in the Danish retail electricity market a good idea. However, the point is here to stress that there are ideas, conventions, and interests involved in the distribution of rights and obligations in the context of these markets which are made for the purpose of dealing with collective concerns. And as economics, engineering, markets, and policy come together in a different and specific form in Nord Pool and its subsystems, it becomes relevant to consider how and to what extent established ideas, conventions, and interests need to be debated and adapted when distributing rights and privileges as part of market design and management. And that is a task which needs to be undertaken. As pointed out before, these reflections refer to incremental changes in the established arrangement. But the reliance on Nord Pool in much of the work done to integrate wind power into the Danish electricity system and develop the energy system in a wider sense can also be discussed.

Is there really no alternative?

Finally, the uniformity of the approach to the integration of wind power into the Danish electricity system will be briefly addressed. As is apparent from the three cases of wind power integration in Denmark outlined above, the Nord Pool framework has become an integral part of the way the intermittency problem and its solutions have been approached. Not only has wind power integration become a matter of strengthening and expanding the market as shown in chapters 1 and 2, it has also come to occupy a central place in finding out what can and should be done about wind power integration in the future, as shown in chapter 3. Still, it is acknowledged that Nord Pool has significant weaknesses, for instance when it comes to ensuring investment in appropriate capacity for electricity production. Furthermore, while it is recognized that established markets can be hard to undo, new markets are still a top priority. This is not least the case when it comes to further dealing with wind power integration in Denmark (Energinet.dk, 2014e). In many ways, the use of markets for wind power integration and wider energy system development in Denmark has thus been locked-in or 'irreversibilized' (Callon, 1991). New markets are expected to solve the problems which are created or remain unaddressed by the markets being set in place (Cf. Mirowski, 2013).

Considering the tendency for markets to fail, only to then be supplemented by other markets as if there genuinely were no alternatives, this approach to regulation on behalf of the state as of now possesses the potential to produce an open-ended number of markets.[47] With a view to the spiraling production of markets, it is thus here appropriate to take up a point made by José Ossandón in his exchange with the recipient of the Sveriges Riksbank Prize in Economic Sciences in Memory of Alfred Nobel - market designer Alvin Roth. In commenting on the optimism associated with market design and management for dealing with societal challenges, it was asked:

> …shouldn't we also be experimenting with other ways of doing things? I am not saying that markets are always bad, but that the same brilliant ideas currently oriented at designing better markets could also be spent devising other forms of solving our common problems. In my opinion market civilizers and engineers will become fully respectable technicians the day they are also able to advise something like: 'thank you for contacting me, but here you don't need a market'
>
> (Ossandón, 2013, p. 1)

The belief in and commitment to markets, along with the alternatives to markets and the possibility of introducing these alternatives after markets have been put in place, are issues which also need to be both researched and debated as part of a nuanced and informed approach to wind power integration in Denmark.

[47] See Guala (2007) on the notion of 'third way economics' for a description of market construction on behalf of the state as an approach to the making of policy which can accommodate both the believers in regulation of the left and the market enthusiasts on the right.

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