Large scale wind power penetration in Denmark – breaking up and remixing politics, technologies and markets*

Peter Karnøe

The Danish electricity generating system prepared to adopt nuclear power in the 1970s, yet has become the world's front runner in wind power with a national plan for 50% wind power penetration by 2020. This paper deploys a sociotechnical perspective to explain the historical transformation of "networks of power" via the interactions of politics, the techno-physics of electrons, and the market setting. The Danish case is about how an assemblage of new agencies has reorganized and reshaped society by building a new sociotechnical network. This has rendered developments highly unpredictable and highly experimental. The transformation process can be followed through the way successive technical engineering reports have represented the challenges associated with the penetration of wind power. The iteration shows how novel technical phenomena emerge and are assimilated, and how new engineering expertise evolves and contributes to the normalization and large-scale penetration of wind power in the electricity generating system. The analysis teaches us how technological paths become locked-in, but also indicates keys for locking them out.

The new Danish government succeeded in October 2012 to assemble a broad political coalition behind a new national Energy Plan with the ambitious 50%-target for wind power penetration in the electricity-energy system by 2020[1]. The Minister for Climate, Energy and Buildings said: "Denmark will again be the leading country in the world when it comes to transition to green energy. It will help us in a future where oil and coal prices will go up".

To give wind power such a strong role in the future electricity-energy system is the final recognition and acceptance of an energy technology that many from the 1970-1990s saw as marginal, as alien, or as museum object from the past. The practical experiments with and discourse of wind power developed in an environment of an already strong discourse on nuclear power as the next natural step in the Danish electricity system. Further, the first wind turbines met an already-existing technological environment characterized by a centralized system of electricity production and distribution. Given this context, wind power went in Denmark from a completely marginal source of energy in the late 1970s to dominant position in today's Danish energy strategy.

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[1] The notion electricity-energy system is used here because the recent technical expert Road Map report to the Ministry of Climate, Energy and Buildings from January 2013 on the challenges with the transformation of the energy system cannot work with a distinction between the electricity and energy system. With fossil fuels on their way out larger shares of the energy for heat and transportation is generated from electricity.

What happens when such political support of wind power (as opposed to support coal or nuclear power) leads to increasing penetration with wind power in the existing electricity and energy system arrangements? Is wind power just smoothly feeding electricity to the grid or is disruptive in the sense that the dominant technical standards and operational routines for load balancing must change? These questions are worthwhile asking in the light of the Danish experience, as the country (with Germany) stands as a particularly exciting real large-scale experiment in energy policy and energy system transformation.

1. Sociotechnical networks and networks of power

The lessons from studies of path dependence and the social construction of technology have shown that no technology is born dominant or born to be successful. Their failure or success is produced in their contingent and particular historical development that may lead to dominant standards that are relatively locked-in. The lesson is that the winning technologies do not result from optimal or perfect market processes, because learning effects result from the entrepreneurial actions and contingent timing of actions stemming from political intervention, strategic maneuvering (marketing and lobbying), producer-user inter-action, and (enactment of) historical circumstances (Utter-back, 1996, Pierson, 2001). Studies shows that way the US electricity industry developed "was only one of possible outcomes and not necessarily the most technically or economically efficient" (Granovetter and McGuire, 1998:149).

To conceptualize the dynamics of maintaining and breaking sociotechnical lock-ins, new studies puts a stronger emphasis on the work of existing and new actors, and includes increasingly architectures of markets (Garud and Karnøe, 2003; Karnøe and Garud, 2012). The emergence of the US electricity system involved entrepreneurial action that simultaneously made political and technical "networks of power" (Hughes, 1983). Further, the boundaries between political, the technical and the economical were constantly crossed as they were mixed as the entrepreneurial agencies (Mitchel, 2008) struggled to make the resources realized one of the competing visions for the centralized electricity system by Edison, Tesla, and Westinghouse (Jonnes, 2003).

The relative sociotechnical lock-in (Callon, 1991; Unruh, 2002) has strong exclusion effects on alternative technological designs. This exclusion effect is made by the sociotechnical bundling of mutual reinforcing translations of expertise and practices linked to operational routines and training, to operating equipment and industry standards, to user-socialization and cultural preferences, to legitimate criteria for efficiency, as well as to the organization of knowledge-expertise used for defining ministries as resort areas for political regulation. Another term for a sociotechnical lock-in and the possible exclusion effect is "networks of power" as it is built from these heterogeneous elements. The French nuclear power can be also considered a strong "network of power" because of its massive sociotechnical configuration of sunk cost in existing nuclear plants and infrastructure, skills and competencies, norms of calculation, legitimate claims on efficiency, the political support and customized regulation, and a socialization of people into a (till now) passive public accepting nuclear power (Hecht, 2009).

What happens when such political support of wind power leads to increasing penetration with wind power in the existing electricity and energy system arrangements?

The ideas of sociotechnical lock-in are very useful for studying the centralized electricity systems.

Here I use the sociotechnical networks of power and out emphasis the blurred boundaries and intertwining of actions originating in political-regulative, technical-physical domains of electricity generation, and economic value of wind power. These papers departs in an overview of the political support of wind power, but follow mainly the transformation of the electricity system by looking at the engineering expertise mobilized in some critical reports on the problem of adding wind power. New technologies require specific knowledge of the subject and are related to the participants' professional activities. The co-production (Jasanoff, 2004) of expertise and destiny of the project is highly important since the expertise and the knowledge frames enact, represent and give reality to the new.

> **The French nuclear power can be also considered a strong "network of power"**

2. Political dynamics of networks of power for wind power and nuclear power

The Danish wind power activities as discourse and practical technological experiments emerged in 1970s. It was an alternative to the dominant discourse of nuclear power as the dominant vision of future energy supply, and an alternative to the established dependency on expensive imported fossil energy to the centralized power plants. A key to understand wind power in Denmark is to look into how the two different "networks of electricity power" (in both senses of the word) evolved.

The energy crisis 1974 was used by the network coalition behind nuclear power to advocate nuclear power as the "natural response". This stimulated counteraction from the anti-nuclear groups and 1974-1980 they joined forces with groups experimenting with and advocating renewable energy, concerned scientist-activist, and forged a patchwork type movement or assemblage with many linked points of activity and not one center. Determination in favor of nuclear power was the main response to this movement (the following based upon Karnoe and Garud, 2012). The Director of the Electrical Utility Association in Denmark famously claimed at that time: "You may discuss as much as you like but nuclear power you will get". The first official Danish energy plan of 1976 focused on a shift from oil to coal dependency, with an emphasis on nuclear power, energy efficiency and domestic energy sources. The new coalition of groups contested the "established networks of centralized power" and managed to penetrate the technical and political network, in a mostly experimental manner. For example Riisager, a carpenter became the first wind turbine hacker, as he in 1976 without permission connected his home-designed wind turbine to the grid. Based on strong political coercion the Danish Electrical Association of Utilities developed a set of guidelines that granted Riisager, and the many other emerging users of wind turbines, the right to be connected to the grid – and to pay the power producer a modest price for the electricity, equivalent to fuel savings. This price was not enough to make wind power investments an economically attractive investment for the early buyers, and the state offered an investment subsidy from 1979, and a production subsidy from 1983. These combined market instruments stimulated entrepreneurial action in companies that fostered the Danish wind turbine industry. These market instruments was the invention of the so-called *Feed-in Tariff* that has become the dominant model in Europe, USA and China for stimulating the development of wind power and other renewable energy technologies.

Rather than being the outcome of grand political initiatives, this network of power for wind power resulted from a patchwork technical experiments, political struggles and mobilizations that evolved in the 1980s and the 1990s with new key concerns, new forms of coalition, new regulatory initiatives (Karnøe and Buchhorn, 2008). I will refer to some of these political developments in the sections, but obviously, the new Danish energy Act pointing at 50% wind power by 2020, shows that the network of power supporting wind power won out, while the network for nuclear power and other centralized electricity production lost out.

3. The sociotechnical making of electrical power

The network of power for wind power did not only involve political support and regulations. The network of power happened to involve the physics of electricity and the skills and operational routines used to control the movement of electrons in the grid.

Text-books in power engineering and most technical reports emphasize that the defining characteristic of AC (alternate current) electricity is that the frequency must be kept stable at any level of "load", which means that for any consumption level there must be a corresponding level of production into the grid. If we open these sentences further, we see electricity is characterized by stability in movements of charged electrons generated by the rotation speed of electromagnetic rotors, which are driven by steam made from fossil fuel, nuclear or wind turbine rotations. The stability of the movements of "electrons" is measured with the terms frequency and voltage (power). Agreeing of one particular movement was critical in the AC-system, and as the standard of 50 Hz in Europe and 60 Hz in the US movements became socially accepted (Granovetter and McGuire, 1998). Electrical systems work through the connected components that make up a system that operate compatibly with one another. *Thus, in this way generating and maintaining frequency stability defines electricity*. The founding fathers of centralized electricity systems Edison and Tesla did not know how to do that from the outset. Artificially fabricated, electricity was a flow, highly sensitive, a living dynamic difficult to control. Control emerged in a historical learning process over several decades before load-balancing in the centralized electricity system had become an organizational routine (Hughes, 1983). For example, centralized power systems evolved and created a new actor, The System Operator TSO, who was responsible for maintaining load balance at all load levels, Based upon a day ahead planning process the TSO coordinated power plants to make sure that "load follows demand" by turning on/off centralized power plants in a linear fashion. Also, the classification of power plants into base-load and peak-load power, and reactive power, and forms of reserves, was invented and used to organize and classify forms of power regulation in a way that was linked to their physical response time of the power plants. For frequency stability the time-scale of response time is divided in three 1) seconds, 2) 10 minutes, and 3) hourly response time. Fluctuations in load generation happen mainly because of contingencies due to power plant failures, component break down, and other unexpected events. The time-scales and response times were and are crucial to prevent black-outs that are likely to happen if load balancing is not well coordinated. The frequency standard and time-scales in Denmark is monitored from the TSO control room where the frequency is kept stable when the TSO makes sure that generators followed the planned production in order to maintain the load balance at a second-to-minute level.

The network of power happened to involve the physics of electricity

Centralized power systems evolved and created a new actor, The System Operator

4. Adding wind power to the Danish electricity grid

Riisager connected his wind turbine to the grid about the time when the Danish model of centralized electricity production peaked with 98% (1980) of the Danish generation. While the Danish utilities were waiting for nuclear power, their research department was asked by the Ministry of Energy to evaluate the consequences of integrating wind power in the electricity system (as part of the official Danish large scale wind power demonstration program that did not include the small wind turbines of Riisager). Wind power had less than 0.2% of Danish electricity production, but the national Energy plan form 1981 depicted a possibility for 10% wind power by 2000. The report from 1983 made a simulation of 600 MW wind power in the electricity system and concludes that because of the unpredictability of wind power it is not a reliable source of power, and wind power would result in "certain operational disturbances, whose solution requires extra expenses (my translation)" (DEFU, 1983:2.a). Further, the current technical design of the power plants cannot balance the shorter (second and 10 minutes) variations in frequency, whereas the power plants are adequate to balance the power generation on an hourly basis. This inflexibility in the existing electricity system was aggravated due to increased co-production of heat and power, as district heating systems linked to electrical power plants was part of the national program for increasing energy efficiency.

"Nuclear units are assumed to run on full load"

The report evaluates and calculates the technical integration of wind power based upon the current time-scale standard 1) seconds, 2) 10 minutes, and 3) hourly response time that has evolved in the centralized electricity system world-wide) used to organize and classify forms of power regulation directly linked to the physical response time of the power plants. The technical and operational problems are related to the particular technical equipment used to generate electricity: "The production from a wind power generation system will be characterized by limited predictability (contrary to the electricity load (the demand, my insert, PK)), and frequent and often strong variations. When the regulation on the power plants happens with some inertia, can there be difficulties in balancing the production of the power plants in relation to the wind power production and the electricity demand (my translation)" (DEFU, 1983: p. 2.3).

The existing electricity system was made primary as it is stated: "It is assumed that combined heat and power generation at any time is technically linked, and production units cannot be down-regulated than their minimum by coal-fuel. Nuclear units are assumed to run on full load" (DEFU, 1983:3.13).

Evaluated against these technical conditions the economics of wind power becomes problematic, as the "Solution of the regulation problems can result in such significant expenses, that the value of the wind power production is reduced significantly" (DEFU, 1983: p. 2.5). The economic value of wind power was calculated as the saved fuels in power plants, as wind power can hardly be attributed any positive value for supplying power effect, as back-up always is needed.

These particular representations of technical and economic conclusions of increasing the share of wind power were based upon state-of-the-art technical expertise linked to an unchanged model of the centralized electricity system, and one where nuclear power still was expected to become an active component.

Such 1983-claims about wind power in centralized electricity system seem to have continued till today. It is a conclusion in many studies, that wind power is problematic because "unlike conventional capacity, wind-generated electricity cannot be reliably dispatched or perfectly forecasted, and exhibits significant temporal variability" (DeCarolis and Keith, 2005, p. 70). The study by Hoogwijk *et al.* (2006) keeps, like DEFU 1983, the large power plants in the centralized electricity system constant and investigates the challenges for load balancing and economic consequences of increasing wind power to 50% by 2050. The study concludes that the *mismatch coefficient* increases, which "accounts in a generalized way for (problems in, my insert, pk) interconnection, transmission capacity and the load following capacities" (Hogwijk *et al.*, 2006, p. 1400).

The load-following capacity of the generation mix is an important factor. Large numbers of quick-start plants such as gas turbines and/or hydropower or storage plants with high load-following capacity can absorb larger amounts of intermittent supply than typical base load units such as large nuclear and coal-fired plants (Hoogwijk *et al.*, 2007, p. 1401).

The load-following capacity of the generation mix is an important factor

Holding the existing electricity system constant results in a dramatic increase in discarded "electricity from intermittent sources that with given tech-mix, storage and demand-flexibility cannot be absorbed in the system" (Hoogwijk *et al.*, 2006, p. 1400).

Thus, this restates the conclusion from the Danish 1983-report. That amounts to saying that wind power is technically problematic and will lead to increased share of discarded electricity, or excess electricity that either is system critical or of little economic value. However, this knowledge and claim is the standard talk, based upon technical knowledge where wind power penetration is evaluated in the context of an unchanged electricity-energy system.

5. Engineering expertise departing from status quo of the electricity system

However, also other representations and conclusions began emerging. By 1990 when wind power generated 2% of the Danish electricity production, and the ambitious national Energy Plan from 1990 associated wind power and renewable energy as solutions to the climate and environmental problems. New knowledge was needed, and some of it came from a technical report titled "Large-scale Renewable energy for electricity and heat production" (Nielsen, 1994). The work was headed by Risø, the National renewable energy research center, and involved experts from the electrical utilities. The main question was formulated as "whether technically well-functioning electrical supply systems that are capable of providing the same quality of electric service as exists today can be developed in the period up to year 2030, based mainly on fluctuating electricity inputs from renewable energy sources such as wind power photovoltaic, and biomass" (Nielsen, 1994, p. 5). Again a stable load balance (quality of electricity service) is fundamental, but now with large integration of renewable energy. One conclusion is that in order to avoid load balance violating "excess electricity", the thermal power plants are mainly to deliver regulation capacity to the increased shares of wind power (p. 15), and it is discussed how load following capacities require technical designs of power plants that can respond faster, and wind turbines with frequency converters. This report is one of the first to suggest a new role for the old electricity power plants.

6. From "excess electricity" in reports to "excess electricity" in the grid

After 1993 the positive political support of wind power, and the adjusted feed-in tariff, there were massive investments in wind power. By 2000 wind power increased the material presence in the electrical grid from 2-13%; it was indeed becoming a "large-scale" penetration. A new phenomenon emerges, as witnessed by articles in the Danish media and engineering journal *The Engineer* stating that "Denmark is flooded with excess electricity". Flooded with electricity means that the total power generation within an area is larger than the consumed power, and it may drive prices down or has to be exported to low prices or for free.

To address the new technical issue the Danish Energy Agency commissioned in 2001 a report from the involved stakeholders – among them the wind turbine owners, electric utilities, TSOs, the Organization for Renewable Energy, and experts – to analyze the problem and come up with solutions to excess electricity ("El-overløb" [excess electricity], Energistyrelsen, 2001). The experts invented the term *critical excess electricity* which happens when "the electrical load cannot be consumed within a given area – and other power plants have difficulty in reducing further, therefore export is the only option to avoid critical system failure" (Energistyrelsen, 2001).

Excess electricity was linked to the technical phenomenon labeled “technically bounded electricity generation”. Technically bounded electricity generation occurs when heat and power generation is combined in power plants as they will produce electricity when there is need for heat, and wind power owners will use their right to generate power when there is wind. As the timing of heat demand and high wind speeds is occurring in the winter months there is a problem of too much electricity in the grid, because power plants cannot regulate their power generation down, and since wind power owners has priority right to generate this threatens grid load balance. There are two types of “Excess Electricity”. Exportable excess electricity can be exported if there is capacity in transmission lines out of the load balancing area. The other type is Critical Excess Electricity, which is defined as excess electricity that theoretically would occur and result in system break down *if an actor did not step in and regulate the generation or demand* (Energistyrelsen, 2001:8). Thus, Critical Excess Electricity is threatening but must not occur, but as this imbalance must be dealt with within very short notice (less than an hour), the TSO must buy or sell electricity in the regulation and reserves market. The report recommends that a technical instrument is developed that can handle the problem, but at the same time it is noticed that the instrument is only efficient if the TSO has a mandate to activate the instrument. However, it is also pointed out that since this problem enacted to become “critical excess electricity” is defining a completely new situation, the category did not exist in the Danish Electricity Supply Law, and consequently there are no legal provisions that allow the TSO to take that role in relation to “critical excess electricity” (Energistyrelsen, 2001:81). Such provisions should make it possible for the TSO to cut off power producers that threatens load balance stability, but at present it violates the rule that provides renewable electricity generation first priority.

There are two types of “Excess Electricity”

Following the proposal from the report the political majority was able to make a supplement in the Electricity Supply Law in 2004. It stated that Decentral Combined Heat and Power plants shifted role in the “dispatch hierarchy of power generators”, as these plants were now required to stop production to give space for wind power generated loads in the system. The advantage of capacity bottlenecks in transmission lines to Norway, Sweden and Germany are mentioned, but since the price for “excess electricity” will always be low investing in transmission lines may not be preferred to solving balancing problems internal in the Danish system.

What we see in this new situation is where the political valuing of wind power leads to a technical overflow of electrons, that is system threatening, and this triggers the opening of the boundaries between the political support of wind power, the technical world of electrons, the legal mandate for organizational actors, the legal regulations and the political need to sanctioning changes in the Danish Electricity Supply Law. Also re-design of the market mechanisms are mentioned as the fully liberalized electricity market was opened around 2003. Indeed, in 2009 a negative price was introduced in the market design, which means that any power generator that cannot stop production in situations of excess electricity must pay for the production (Karnøe, 2010). In December 2012 the negative price was 200 Euro per MW for some production hours. So many aspects of the sociotechnical arrangement are being transformed to foster the large-scale unlocking and transformation of the Danish electricity-energy system.

7. What to do with the real “excess” electricity? New engineering expertise enacting new realities!

A government driven by environmental skepticism could not completely stop wind power in the 2000s (Karnøe and Buchhorn, 2008), and wind power reached a 20% share of electricity generation in 2008. One result was that Critical Excess Electricity increased from

0-hours in 2002 to about 250-hours in 2012 in the West Denmark. New techno-economic reports began enacting new political realities and discourses of "50%-wind power in the electricity system". They shaped and were shaped by various Danish and EU political commitments to move towards a low-carbon or even CO_2-free energy system. In 2006 the influential Association of Danish Engineers (IDA) commissioned a research report for how to make a 100% CO_2-free energy system by 2050. IDA announced 2006 to be an "Energy year" involving 1,600 engineers in nation-wide workshops. In 2007, the government commissioned a Climate Commission that should look at how the Denmark energy system could become 100% free of fossil fuels by 2050, and 50% wind power was part of the solution. "50% wind power" was now becoming a new norm and not a fantasy, for example the respected electricity-energy system consultancy AE-Energy Analysis published with the Electrical Utilities a report commissioned by the Association of the Danish Wind Turbine Manufacturers (EA, 2007, p. 6).

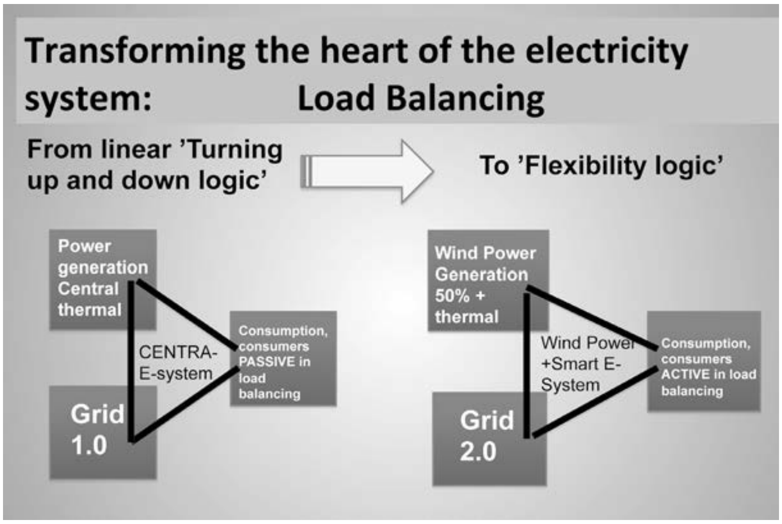
The new reports represented a shift in engineering expertise, even though they differ in their approaches to load balancing with contributions from "all load influencing entities on the supply and demand side", and the role of transmission lines. However, the existing electricity system was no longer taken for granted or seen as having one order role in load balancing. For example, the IDA-work was carried out by a group of energy system researchers from the core group of alternative energy systems at the University of Aalborg. The 2007-report was unique as it demonstrated an energy model that on an hourly basis could provide the heat and electricity needed in the Danish system (Lund *et al.*, 2009). Due to load balancing all the problems of integrating fluctuating wind power are not over in one step, but linked to a step-by-step sociotechnical re-building of the electricity-energy system to become flexible enough to handle the fluctuations on the generation and demand side, and even making it more interactive as in the Smart Grid concept. The concrete steps of re-configuration from 2008 towards 2030 were based upon 1) introducing thermal heat storages at D/CHP plants, which creates a buffer so they can adjust electricity production by increasing or lowering the water temperature; 2) large scale heat pumps at D/CHP plants, which allows wind power electricity to generate heat for district heating; 3) flexible demands for 15% of demand for industry and households; 4) smart charging EV batteries. The 15% load following demand is one factor in the load-responsive demand side.

The more official recognition of the revolution in the discourse came when the Danish TSO in an official 2009-report (Energinet.dk, 2009) stated that 50% wind power is possible, and depicted a flexible energy system, based upon conversion of electricity to heat in heat pumps, thermal storages, and electrical vehicles.

8. Step-by-step into a revolutionary transformation!

What began with Riisager hacking his small wind turbine to the grid has now evolved into a real-time large-scale integration of more than 20% and stepping the share of wind power up to 50% by 2020. That is an about 25% increase in 7 years. This challenges the old load balancing "turning-up-and-down" logic, with a sociotechnical configuration of centralized power generation, with consumers/consumption made passive in load balancing. Figure 1 shows the old model "Grid 1.0 turning power plants up and down model", which developed historically in most countries with a "load follows demand dictum". As we have seen from the technical reports, the "Grid 1.0" model is a hostile territory to wind power, which cannot avoid being costly and difficult to integrate due to the *particular* standard-model of load generation and preserving load balance because of the inflexibility of the existing large power plants.

The "Grid 1.0" model is a hostile territory to wind power



Transforming the heart of the electricity system: Load Balancing

From linear 'Turning up and down logic'

To 'Flexibility logic'

Power generation Central thermal

CENTRA-E-system

Consumption, consumers PASSIVE in load balancing

Grid 1.0

Wind Power Generation 50% + thermal

Wind Power +Smart E-System

Consumption, consumers ACTIVE in load balancing

Grid 2.0

Figure 1. Transforming the electricity system from a "Grid 1.0" to a "Grid 2.0" flexibility model.
(source: Karnøe, 2010)

The movement towards the new Danish model of the "Grid 2.0 flexible energy system" model introduces a paradigm-shifting load balancing, a "flexibility" logic. In this flexibility logic, load balancing calls upon as many load interactive or responsive elements as possible, and the "challenge is to realize the steps to the new path without violating the quality of electricity. This "flexibility logic" is based on a power generation mix with 50% of wind power and on smart complementary generation, interactive storage and consumption technologies, which also enhance consumer/consumption agency in load balancing.

This learning implies that many experiments are still to happen. For example, besides from the experiments with the technology mix of load generation, the flexibility model relies greatly on a responsive demand and consumption side, which may include a reflexive consumer. It therefore opens the black box of the kind of citizen-consumer that needs to be configured, and, with this, the condition of energy as a public service in a common world. The technically disruptive experiment is therefore also an anthropological experiment and a political one, and definitely a necessary one. And the experiment ought to be an open one. The ways of configuring an "active" consumer are manifold. You can rely on an exacerbation of the culture of consumer choice, exposing users to all sorts of signals, in particular price signals that demand decision-making. But you can also rely on automation protocols that shift decision making to collectively assessed rules embedded in appliances and apparatuses.

In countries like Denmark, Germany, Spain and US engineers working with the challenge to transform the electricity system to build upon large-scale fluctuating sources like wind power are now learning new operational routines for handling load balancing. A recent report from US National Renewable Energy Laboratory writes in the summary "*Systems today have developed their rules and practices based on a long-standing history of operations. Many systems are even now learning new ways to change these rules and practices where high penetrations of variable generation are becoming apparent*" (NREL, 2011).

This learning implies that many experiments are still to happen.

9. From Smart Grid to Smart Energy Systems

The momentum is here and new expertises emerge, for example the research report

Coherent Energy and Environmental System Analysis (Lund, 2011) continued the IDA-project, and coined the phrase “smart energy system”. It was done to expand the question “what to do with the excess electricity” to include fully the transportation sector, and not only the small EV-cars. Critical here is that reserving biomass for bio-fuel for transportation that cannot be electric, uses of biogas, electricity used to make hydrogen as fuel for transportation,

By January 2013 a recent Road map on research commissioned by the Ministry of Climate and Energy confirmed this new reality with its central figure representing the new reality (see Figure 1). For the first time the two concepts Smart Grid and Smart Energy Systems were together, and hopefully assist the navigation of the energy system transformation. Identification of new issues and objects for research emerge out of this “path” to this new electricity-energy system.

However, even if there is consensus about the 50% wind power and the transformation, there are still unsolved problems and controversies regarding *how* to establish the economic and regulatory architecture of roles and incentives that support the realization of complementary technical assets like heat pumps, thermal water storages, decentral heat and power capacities etc. Further, there is a controversy about how much, if any extra transmission capacities are needed to maintain a high quality load balancing capacity. Neither the Danish state nor the TSO, Energinet.dk has made this clear. Denmark does not have the full formula for making this transition, but has already in an experimental way moved further into new techno-economic territory than many other countries.

10. A network of wind power in the making

The Danish case clearly shows that large-scale wind power integration in the electricity systems is possible indeed it is happening. The making of the path and associated networks of power involved and involves real life technical experiments, political actions, and the co-production (Jasanoff, 2004) of expertise and the new project since the expertise and the knowledge frames enact, represent and give reality to the new. The making of the path involves still heterogeneous engineering and crossing boundaries between political support of wind power, the increased real world

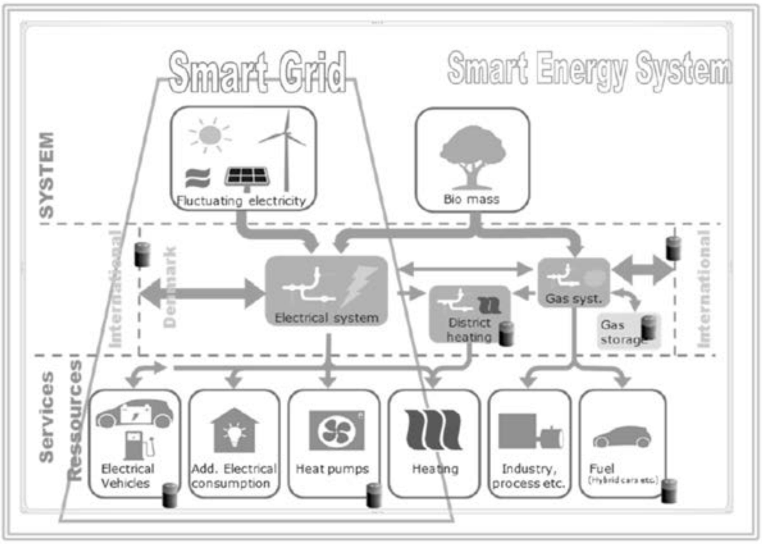


Figure 2. The combination of Smart Grid and Smart Energy System in Danish energy system research.
(source: Smart Grid Research Network, 2013)

technical-physical flow of electrons from wind power in the grid, and re-making of the market architecture for pricing.

Political commitment to favoring wind power has disruptive consequences and these disruptive consequences have to be assumed at face value and organized in a responsible manner. However, regarding responsibility, there are also “limits to wind power” as concerned groups protest against new wind power installations just like for nuclear power facilities in Denmark. Wind power moved from being marginal to becoming the central actor in the energy system, but does that give the right to “run over smaller actors”. There is evidence that shows how democratized co-ownership of large-scale on-shore and off-shore wind farms in Denmark may transform interests of concerned people. Does this mean that the technical and economic value of wind power is politically malleable and socially constructed? Yes, if you take into account the material, technical aspects of that malleability and that experimental construction. There is nothing fixed structural that makes a sociotechnical network stronger in principle, but it surely becomes stronger and more irreversible as it is undertaken by various actors and possibly institutionalized in “networks of power”. This teaches us about how technological paths are locked-in but it also indicates keys for locking them out. The Danish case is also about how an assemblage of new agencies reorganized and re-shaped society by building a new sociotechnical network. This makes evolutions highly unpredictable. We are in a highly experimental terrain. ■

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