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SuperGrid or SmartGrid: Competing strategies for large-scale integration of intermittent renewables?

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HIGHLIGHTS

- Compares SuperGrid and SmartGrid strategies for integrating intermittent renewables.
- Identifies technological and socio-economic conflicts of interest between the two.
- Proposes a strategic zoning strategy allowing for both strategies to evolve.
- Presents a paradigmatic case study showing that strategies are mutually exclusive.
- Proposes dedicated SmartGrid innovation zones and SmartGrid investment trusts.

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ABSTRACT

This paper defines and compares two strategies for integrating intermittent renewables: SuperGrid and SmartGrid. While conventional energy policy suggests that these strategies may be implemented alongside each other, the paper identifies significant technological and socio-economic conflicts of interest between the two.

The article identifies differences between a domestic strategy for the integration of intermittent renewables, vis-à-vis the SmartGrid, and a cross-system strategy, vis-à-vis the SuperGrid. Policy makers and transmission system operators must understand the need for both strategies to evolve in parallel, but in different territories, or with strategic integration, avoiding for one strategy to undermine the feasibility of the other. A strategic zoning strategy is introduced from which attentive societies as well as the global community stand to benefit.

The analysis includes a paradigmatic case study from West Denmark which supports the hypothesis that these strategies are mutually exclusive. The case study shows that increasing cross-system transmission capacity jeopardizes the feasibility of SmartGrid technology investments.

A political effort is required for establishing dedicated SmartGrid innovation zones, while also redefining *infrastructure* to avoid the narrow focus on grids and cables. SmartGrid Investment Trusts could be supported from reallocation of planned transmission grid investments to provide for the equitable development of SmartGrid strategies.

1. Introduction

Policies aimed at increasing the penetration rates of intermittent renewables, thus reducing atmospheric emissions and the dependence on fossil fuels, has led to simultaneous efforts in the United States and Europe to modify the architecture of the energy system (Coll-Mayor et al., 2007; Hammons, 2008; Bayod-Rújula, 2009; Kaldellis and Zafirakis, 2007).

During the 2008 U.S. presidential election, the future Obama administration's "New Energy for America" presented a vision for a US SmartGrid with intelligent metering and distributed storage technologies (Obama and Biden, 2008). In consequence, Department of Energy (2009) announced the single largest grid modernization investment in US history to "spur transition to SmartGrid". The equivalent of €2.4 billion in public funding, matched by €3.5 billion in private funding, were awarded to 100 programs in three categories; Integrated SmartGrid systems (63%), Smart meters, pricing programs, appliances (27%), and Grid automation, sensors, two-way communication (10%). The awarded programs are dedicated SmartGrid efforts and do not include budget allocations for grid extensions.

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Europe is choosing a different strategy that focuses on strengthening cross-border transmission infrastructure. In November 2010, the European Commission (EC) presented EU's energy infrastructure priorities for 2020 and beyond (European Commission, Directorate-General for Energy, 2011). Called a "blueprint for an integrated European energy network", the strategy defines priority corridors for the transport of gas and electricity. The EC estimates that the total cost towards 2020 for expanding the electricity infrastructure will amount to €100 billion. Earlier, in March 2010, the EC allocated €0.9 billion for transnational transmission lines as part of the European Energy Programme for Recovery (European Commission, 2010).

The EU strategy also mentions a SmartGrid but does not include an allocation of funds for SmartGrid investments. Others have estimated that European SmartGrid investments could attract €80 billion in investments towards 2020 (Pike Research, 2011). In fact, some are confident that SmartGrid developments could replace the internet as a key economic driver; Cisco (2009) announced their strategy for providing services to the SmartGrid development expecting that the Information and Communication Technology (ICT) market in SmartGrids will average USD 20 billion per year between 2010 and 2015.

Related power system developments are observed in China (Yuan and Hu, 2011) and the Middle East (Brand and Zingerle, 2011), which tend to focus on expanding the cross-border transmission infrastructure, and in Japan, which tends to focus on intelligent metering and distributed generation (Duffield and Woodall, 2011).

It appears that efforts to upgrade the electricity architecture are working along two tracks: SuperGrid and SmartGrid. But should policy makers expect SuperGrid and SmartGrid markets and technologies to develop well alongside each other? Or are these strategies possibly competing within common markets thus undermining the feasibility of one another? If so, does the current market structure provide an even or equitable basis for competition, or is one strategy de facto in need for policy support and intervention due to the dominant influences of the other?

This paper defines and investigates SuperGrid and SmartGrid pathways for modernizing the electricity architecture focusing on their ability to support increasing penetration rates of intermittent renewables. Potential conflicts of interest between SuperGrid and SmartGrid are addressed, and a cost-effective policy strategy for energy infrastructure innovation is proposed. In a paradigmatic case-study, the paper investigates how electricity markets have responded to the August 2010 transmission cable between wind-rich West Denmark and a wind-poor East Denmark. The case-study contributes with empirical evidence to discuss to what extent different infrastructure strategies should be considered mutually exclusive in the short to medium term.

2. Strategies for an intermittency-friendly energy system

Fig. 1 illustrates the integrated nature of an energy system with intermittent renewables. The basic elements of an energy system provide four basic services (heat, cooling, electricity, and mobility) and are divided into five categories: resources, conversion, relocation, exchange and storage, and demand. An important evolution in intermittency-friendly energy systems is the relocation column, which hosts the mechanism of coupling energy carriers; for example coupling electricity and heat using electric boilers, coupling electricity with both heat and cooling using vapor-compression heat pumps, or coupling electricity and mobility using vehicle-to-grid technologies (electrochemical storage). Relocation by coupling electricity with heating and cooling allows for utilizing thermal storage rather than electrochemical or mechanical storage for handling the balancing problem. Relocation by coupling electricity with mobility allows for utilizing existing electrochemical or mechanical storage.

Understanding the basic layout of the energy system is important as it allows us to identify the balancing options, particularly the balancing role of storage and relocation technologies as well as the balancing role of cross-system electricity exchange.

The long-term energy system design is likely to combine all of these balancing mechanisms in what we term the SuperSmartGrid. However, we will argue the existence of two different pathways towards this end vision that needs individual attention: SuperGrid and SmartGrid.

The SuperGrid relies on the mechanism of cross-system electricity exchange (export and import) across systems with different intermittency sources, balancing technologies, and demand patterns. This mechanism makes it theoretically possible to handle large-scale penetration of intermittent resources without any short to medium-term need for storage or demand flexibility, for example

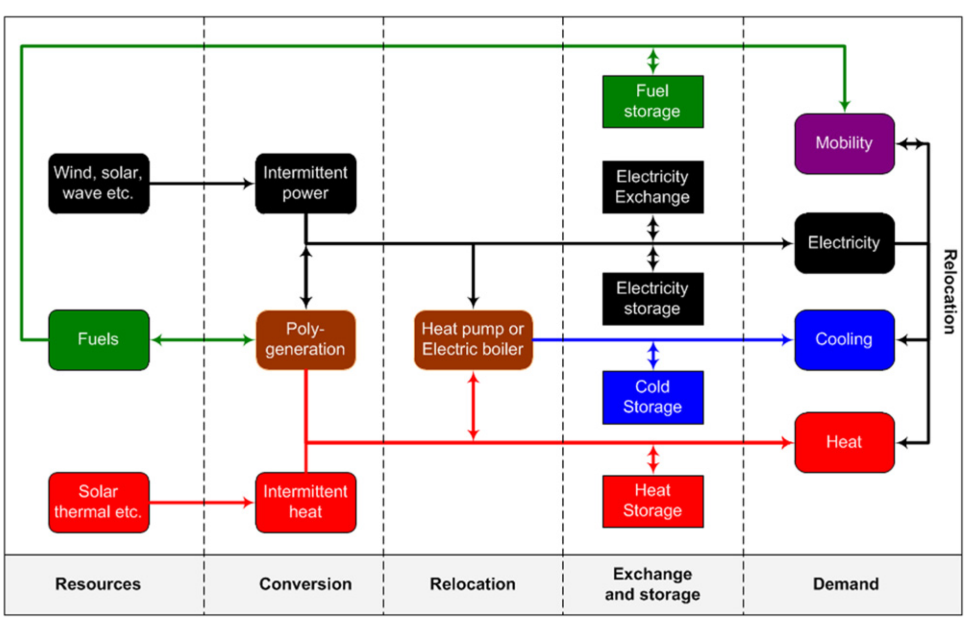

Fig. 1. The intermittency-friendly energy system.

as speculated for the case of Sardinia (Purvins et al., in press).

The SmartGrid relies on the mechanism of storage and relocation (coupling of energy carriers) under constraint of strict system boundaries. Storage and relocation makes it theoretically possible to handle large-scale penetration of intermittent resources without any excess electricity transmission and distribution capacity, for example as speculated for the case of Denmark (Lund and Mathiesen, 2009).

Our point of departure is that the existing energy system is actually already both “super” and “smart”. While we acknowledge that the current understanding of what SuperGrid and SmartGrid implies often focuses on electricity transmission and distribution grid planning, our understanding is that these terms are defining modern energy policy, the future of the energy system, and the energy economy, and that their definitions must reflect that.

SuperGrid and SmartGrid are different and possibly conflicting technological, institutional, economic, and social pathways for the design and organisation of the energy system. While they may converge into SuperSmartGrids in the long term, the path leading there and the end result will differ in terms of agents and assets.

2.1. The SuperGrid

In academic literature, reference to a SuperGrid was first made when naming the high voltage transmission grid in the UK (Argent and Ryan, 1985; Croxton and Fleming, 1970), although the concept was described earlier in a global context by Fuller (1981). More recently, the term is used for various specific initiatives or concepts: including a common European transmission grid (Wito et al., 1994), nuclear-based superconducting grids with hydrogen (Starr, 2002), the North Seas Countries Offshore Grid Initiative (MacIlwain, 2010), Desertec's vision for solar thermal power plants located in desert areas (Desertec Foundation, 2009), and numerous current research projects (Rohrig et al., 2010). In recent efforts, the SuperGrid theme is raised for handling the geographical uneven distribution of renewable resources.

The industry-driven Friends of the SuperGrid (2010), which promotes electricity grid developments in EU, defines the SuperGrid as “an electricity transmission system, mainly based on direct current, designed to facilitate large-scale sustainable power generation in remote areas for transmission to centres of consumption, one of whose fundamental attributes will be the enhancement of the market in electricity”.

From this definition, we understand that the current transmission grid is already “super”, but with capacity constraints. Modern notions of a SuperGrid basically refer to a model for expanding and merging existing transmission grids. As such, the SuperGrid could more appropriately be referred to as the MegaGrid.

A SuperGrid strategy implies increasing the capacity of existing transmission and distribution grids and establishing new cross-system transmission capacity, and will result in technology innovations in high-voltage transmission, particularly HVDC technologies, as well as in market and institutional developments that supports transnational integration of existing national and local energy systems. Furthermore, as the SuperGrid is intended to address the intermittency of generation from wind and solar, it also implies increased built-in redundancy in capacity (but at a lower capacity factor).

As such, the SuperGrid is based on a centralized supply model similar to what dominates today's national and regional energy systems, the nature of which already requires significant transmission capacities due to the long distance between centres of supply and demand, and significant built-in redundancy in capacity. In the short to medium term, a SuperGrid will continue to provide support for large-scale conversion facilities, such as large-scale fossil/nuclear power-only plants and large-scale wind farms or solar-power fields in combination with heat-only boilers, electric chillers, and other conventional end-use technologies.

In result, the SuperGrid will depend more on innovations in large-scale power transmission (e.g. high temperature superconductors) and less on technological innovations in distributed supply for handling the intermittency challenge, which would also reduce the redundancy in capacity. In fact, the SuperGrid may even be a threat to technology innovation in this area.

2.2. The SmartGrid

Reference to a SmartGrid was first made to define a “Self-Managing And Reliable Transmission Grid” that would use ICT to conduct “an automated system of monitoring, control, and protection” (Vu et al., 1997).

Recent literature tends to refer to the control and communication technology dimension of the SmartGrid, notably Katz et al. (2011) who proposes an “information-centric energy infrastructure” where pervasive information is suggested to be the key to the integration of intermittent resources.

The “SmartGrid Dictionary” (Hertzog, 2010) defines SmartGrid as a “bi-directional electric and communication network that improves the reliability, security, and efficiency of the electric system for small to large-scale generation, transmission, distribution, and storage.” The US Department of Energy furthermore offers a definition that identifies seven characteristics of the SmartGrid (NETL, 2007):

(1) Enables active participation by consumers.
(2) Handles all generation and storages possibilities.
(3) Handles new products, services, and market models.
(4) Delivers power quality.
(5) Operates efficiently and optimizes assets.
(6) Self-heals in the course of any system disruptions.
(7) Functions with resilience in natural and man-made disasters.

These SmartGrid characteristics closely resemble the qualities of distributed energy systems. Marnay et al. (2011) describes distributed micro-grids as “electricity distribution systems containing loads and distributed energy resources, (such as distributed generators, storage devices, or controllable loads) that can be operated in a controlled, coordinated way either while connected to the main power network or while islanded.”

As such, a distributed energy system is seemingly also a SmartGrid. But is a SmartGrid necessarily a distributed energy system?

The world's largest full-scale SmartGrid experiment certainly is. With a population of 43,000, the Danish island of Bornholm receives 50% of its annual electricity supply from distributed renewables, wind power making up for 60% of the installed distributed capacity. A coalition of partners from EU and US, including Energinet.dk (the Danish TSO), Energy Research Centre of the Netherlands (ECN), Siemens, IBM, and several others, are implementing a variety of programs, under a funding budget allocation of €60 million, intended to establish a system for handling the intermittency issue without additional cross-system transmission capacity, ultimately also allowing for operating in islanding mode.

While establishing flexible demand response to real-time price signals for all end-users is a central component that also involves installing Smart Meters (Faruqui et al., 2010; Hargreaves et al., 2010; Jackson, 2010; Olmos et al., in press), Bornholm's SmartGrid program holds all the elements of a distributed micro-grid, including integration of both wind and photovoltaics, integration of EVs, integration of micro CHP units and heat pumps in distributed generation, development of residential demand response appliances, e.g. frequency controlled refrigerators, and the development of real-time markets that allows for both households and distributed operators to provide balancing and ancillary services.

The close relationship between SmartGrid and distributed micro-grids is supported by a recent survey among representatives in US power engineering and industry of the perceived importance of selected SmartGrid attributes (Brown et al., 2010). The survey found that the two highest ranking perceived attributes were the optimization of distributed assets and the integration of distributed energy resources.

We will define SmartGrid as a distributed energy system that does not rely excessively on the capacity of the transmission and distribution grid. This definition reaches beyond the conventional policy focus on control and communication technologies as it also relies on other micro-grid characteristics, including technology options for balancing distributed generation in heating and cooling supply, options for integrating storage and relocation technologies, engagement of hybrid consumers and producers (prosumers) (Toffler and Toffler, 1981), options for utilizing local renewable energy resources, the development of real-time markets and tariffs, as well as on regulatory and institutional change.

While current institutional and policy focus in SmartGrid programs is often focusing on the role of ICT and Smart Meters, SmartGrid is much more than adding a two-way communication protocol to the existing energy system. SmartGrid could be a paradigm shift in favour of a network of distributed and intermittency-friendly micro-grids. SmartGrid policies and initiatives must therefore consider the need for developing a wide range of technology areas as specified above, while preparing for new institutions and markets.

2.3. *SuperGrid and SmartGrid are competing market options on uneven terms*

The definitions above tend to suggest for SuperGrid and SmartGrid to be nothing more than modern terms for the long-debated and possibly opposing supply regime candidates: centralized versus distributed. But is there a need for making any essential distinction between SuperGrid and SmartGrid strategies even with definitions that involve wider aspects of energy system generation and end-use? It could be argued that SuperGrid and SmartGrid should complement each other to provide cost-effective integration of renewables, and that also distributed operators, micro-grids, and prosumers in SmartGrids would benefit from a large transmission grid, allowing for them to compete with central generation facilities. Such notion suggests the existence of a level playing field between new and existing operators, between incremental and disruptive/radical innovation.

But even the basic market mechanism suggests that both strategies should not be expected to develop fully in common markets. The basic control strategy in modern markets is based on price settlements between producers and end-users, and the subsequent cost-effective commitment of production units and end-uses. This control strategy would apply for both SuperGrid and SmartGrid. As low net requirements correlate with high production from intermittent renewables, and market prices are observed to correlate strongly with net requirements, this least-cost control strategy is in fact effectively supporting the integration of intermittent renewables. Net requirements are here defined as electricity demands minus intermittent electricity supplies.

In the SuperGrid, a constrained transmission and distribution capacity will affect markets towards greater volatility and cause price differences between market regions. Such constraints will support the feasibility of investments in new transmission and distribution capacity as a result of which price volatility and market area differences will be dynamically reduced.

In the SmartGrid, a constrained storage and relocation capacity will affect markets towards greater volatility and relatively low average price levels reflecting the low short-term marginal costs of operating intermittent renewables. Similarly, this market will provide investment opportunities for storage and relocation technologies. Once in operation, these technologies will similarly result in reduced price volatility.

SuperGrid and SmartGrid technologies benefit from similar market conditions, and produce similar dynamic impacts that are, ceteris paribus, reducing the feasibility for subsequent investments. As a result, SuperGrid and SmartGrid technologies are competing for similar markets, and produce similar dynamic feedback effects into those markets, reducing the feasibility of future investments. The paradigmatic case-study below will further investigate this hypothesis.

It could be argued that allowing for SuperGrid and SmartGrid to compete in common markets would be a reasonable strategy assuming that policy makers should not take responsibility for choosing technology winners. But as it turns out, the playing field is uneven. It must basically be appreciated that while SuperGrid involves technology innovations in already well-established areas such as high-voltage transmission as well as market and institutional developments that are supported by developments already taking place towards transnational integration, SmartGrid involves innovation in a wide range of less established technology areas and markets, and change in support of decentralized and local control.

3. Comparing strategies by pathways, technology, and interests

Understanding that SuperGrid and SmartGrid are different technology paradigms, and that SuperGrid implies incremental innovation (at least in system design although materials innovation may be substantial) while SmartGrid involves radical or even disruptive technology change, we appreciate the challenges for engaging in comparative techno-economic analysis. For example, an assessment should never be confined to the energy system alone, but should involve an evaluation of the long-term consequences for the structure of the economy. These consequences will depend on a multitude of unknowns such as scientific and technological breakthroughs, the success rate for bringing new technologies to the global market, local job creation, and social stability.

While numerous energy system studies have attempted to assess the techno-economic differences between various scenarios for future energy systems in both the EU and the US, some scenarios involving SuperGrids, others involving SmartGrids or similar, the methodological problems associated with comparing fundamentally different paradigms and assumed successes in disruptive technology change should cause for policy analysts to be reluctant to engage in, let alone refer to, such studies. The involved uncertainties render these so-called system analyses pseudo-scientific by nature.

Rather, we find it relevant to offer a more fundamental discussion of pathways, technology, and interests.

3.1. *Pathways*

From the perspective of technology change theory, Verbong and Geels (2010) argue the existence of three possible pathways for modernizing the electricity infrastructure: transformation, reconfiguration, and alignment.

The transformation pathway is driven by current stakeholder policies within national or state domains, and describes the process of gradual adjustments within existing regimes. Some would call it the business-as-usual scenario. Under this pathway, infrastructure investments are channelled towards co-firing of coal and biomass, CCS, large wind farms, smart meters, and transnational interconnections.

The reconfiguration pathway is driven by over-national or federal policies for integration, and describes how markets tend to become dominated by a few large utilities and operators. The reconfiguration pathway basically describes a supra-national transition to SuperGrid (or MegaGrid). Infrastructure investments will target large offshore wind farms and large-scale PV and CSP plants, connecting these with hydropower plants and coal-fired power plants with CCS for balancing. While this may seem to be a narrow vision for generation options in the SuperGrid – SuperGrid could theoretically also be allowing for wide-scale interconnection of micro-grids – the reality of this scenario is supported by current developments. Basically, it reflects the technology focus and investment strategies with existing large-scale utilities, operators, and their organisations (Friends of the SuperGrid, 2010; Vattenfall, 2010; Macalister, 2009). This is come as no surprise, as the institutional and technological capacity of existing large-scale utilities, operators, and their organisations, would suggest a technology structure that allows for intermittent renewables while maintaining a centralised and fossil-based supply system with large-scale generation units, thereby protecting the business models and markets on which these stakeholders rely.

The alignment pathway is driven by local, municipal, and national policies that favour decentralization over integration. Under this pathway, infrastructure investments will focus on end-use technologies and distributed generation, which are connected in regional grids, which may be operated in island mode utilizing various storage and balancing technologies, including thermal storage. The alignment pathway leads to SmartGrid.

Verbong and Geels (2010) argue that the alignment pathway (vis-à-vis the SmartGrid) will be marginalized under the reconfiguration and transformation pathways. Not only will both SmartGrid and SuperGrid suffer if competing in common markets, jeopardizing the feasibility of one another, SmartGrid will suffer due to an uneven playing field. A technology analysis allows us better to understand the nature of the playing field.

3.2. Technology

Müller (2003) suggests that the assessment of technological change must compare technologies by elements of knowledge, organisation, technique, and product. Our analysis of SmartGrid and SuperGrid in Müller (2003) conceptual framework is summarized in Table 1.

With respect to *knowledge*, the discussion above suggests that SuperGrid builds on existing power-rationality relationships in energy supply and transmission, while SmartGrid requires new power-rationality relationships in local governance, distributed generation and end-use. From a Foucauldian perspective, the stakeholders that drive the SuperGrid are powerful enough to define and exercise reason and rationality in order to protect their vested interests. This puts SmartGrid in an uneven position for reasoning its case.

With respect to *organization*, SuperGrid is driven by existing institutions manageable within existing regulatory frameworks, while SmartGrid requires new solutions, markets, institutions, and framework that engage local governments, individuals, and new businesses. This puts SmartGrid in an uneven position for organising its case.

With respect to *technique*, SuperGrid is based on refining existing techniques for large-scale expansion and merging of transmission and distribution infrastructures, while SmartGrid relies on a variety of new technical solutions in distributed generation, local grid control, end-uses, and in markets and tariff systems. This puts SmartGrid in an uneven position for proving the necessary skills.

With respect to *product* (vis-à-vis the service provided by each strategy), Verbong and Geels (2010) suggest that priority objectives for SuperGrid (the transformation/reconfiguration pathways) are reliability, environment, and cost efficiency. While these priorities are also in place for SmartGrid (the alignment pathway), higher priority is given to local control and reduced external dependence. Basically, SmartGrid provides a product similar to SuperGrid, but introduces a new priority objective in terms of local interests and independence. According to this, SuperGrid and SmartGrid are in fact competing options for the energy system infrastructure, with SmartGrid offering the added value objective of local control and reduced external dependence. Could this particular objective be a threat to dominant SuperGrid interests?

Our interpretation suggests that even while fulfilling the same basic objectives, the alignment pathway (SmartGrid) is likely to be marginalized when competing with SuperGrid in common markets. The SmartGrid "technology" – in terms of knowledge, organisation, technique, and product – is facing an uneven match.

3.3. Interests

The energy sector is a playing field of conflicting interests and policy researchers have long understood the purposefulness of defacing commercial and political efforts to suppress conflicts. In fact, an expert on planning theory, Flyvbjerg (2004) suggests that the most important question for policy researchers to ask is

Table 1
Technology analysis framework.

Technology components	**SuperGrid**	**SmartGrid**
Knowledge	Builds on existing power-rationality relationships in energy supply and transmission	Builds on new power-rationality relationships in distributed generation and end-use.
Organization	Centralized top-down initiative and implementation manageable within existing regulatory frameworks	Decentralized bottom-up implementation required engaging individuals and small-scale companies. New solutions, markets and institutions required.
Technique	Large-scale expansion of T&D cable infrastructure, potential innovations in materials.	A variety of technical changes in distributed generation, grids, end-use, as well as in markets and tariff systems
Product	Priority objectives (Verbong and Geels, 2010): (1) reliability. (2) environment. (3) cost efficiency.	Priority objectives (Verbong and Geels, 2010): (1) local control and reduced external dependence. (2) reliability. (3) environment. (4) cost efficiency.

"who wins, and who loses?", rather than only focusing on rational criteria, the definition of which strongly correlates with the interests of those in power.

In his comparative analysis of Habermas and Foucault, Flyvbjerg (1998) finds evidence that social conflicts are the true pillars of democratic society. This means that ignoring or suppressing conflicts serves anti-democratic interests. Conflicts must be expressed, addressed and managed in order to develop social interests and values.

Neglecting conflict potential and opposing interests would in this case be a particular disadvantage to SmartGrid, as it is representing a relatively greater deviation from the current path of development, and thereby depends relatively more on political and institutional support.

It is our understanding that SuperGrid and SmartGrid represent a potential conflict of interests between large-scale industry and national or supra-national governance and system operation on one side, and local governance, civil society, and small-scale operations on the other.

With the SuperGrid pathway, the winners will be existing large-scale utilities, big industry, and national – possibly supra-national – governance systems.

With the SmartGrid pathway, the winners will arrive from a large variety of medium-scale and small-scale projects and technology developments in supply and end-use, and will in particular be distributed operators, end-users, and local governance systems.

While the outcome is unlikely to be as categorical as suggested here in terms of served interests – the struggle for social and technological development is continuous and interests will adapt – our hypothesis is that SuperGrid and SmartGrid imply a shift in the balance of served interests towards centralized (SuperGrid) or distributed (SmartGrid) technologies and operators. Again, it could be hypothesised that SuperGrid could serve the interest of distributed technologies and operators, but such suggestion ignores the stronghold that existing large-scale operators and technologies already have and are already extending into SuperGrid developments. Under such stronghold, distributed operators and technologies are easily overpowered by the manoeuvring capacity of interests shared by large-scale operators and end-users. Furthermore, such hypothesis loses the perspective of the substantial economic costs involved in establishing the SuperGrid and how those funds could alternatively be used for SmartGrid developments providing potentially radical benefits for local economies and distributed technology development. This includes the potential benefits for communities and states of both keeping and controlling monetary flows between service providers and consumers. Also, it will be more difficult to hold consumers accountable for the environmental and social consequences of energy demand due to the large distance between supply and demand centres that SuperGrid allows for.

Assuming the suggested conflict of interest, what are the options for managing the conflict? While some frameworks for conflict analysis focus on the need to negotiate consensus and peace by communicative action as formulated by Habermas (1984), Flyvbjerg (2004) applied Foucault and Aristotle to formulate the need for more stringent political and institutional control systems based on practical wisdom.

4. Zoning strategy towards a SuperSmartGrid

The analysis of SuperGrid and SmartGrid technology components and the power-rationality (Flyvbjerg, 2009) structures they represent, in combination with our observations of utility investment plans as well as national and supra-national policies, lead to a hypothesis that SmartGrid may be less likely to happen than for SuperGrid to happen, and that SmartGrid is more dependent on external developments and strong policy intervention. This is also suggested by Verbong and Geels (2010). We also hypothesise that SmartGrid efforts and interests will suffer under a SuperGrid strategy due to the opportunities that SuperGrid provides for upholding the centralization paradigm's current dominance, possibly leading to both over-investments and the less fair distribution of wealth.

This hypothesis holds significant policy and regulatory implications. With SuperGrid and SmartGrid representing important socio-economic positions for technology development in the energy sector, and furthermore competing in similar markets with similar feedback effects into those markets, but on uneven terms, we propose for policy and regulatory systems not only to appreciate the potential benefits arriving from fast and effective development in both areas, but also realize the need for shielding SmartGrid developments.

The solution could be a strategy that separates these two important areas of innovation. In fact, a zoning strategy is supported by modern innovation theory which suggests that a common set of people, ideas, and objects tend to come to dominate the larger community. Based on surveys involving product development within a wide range of companies, Hargadon concludes that it is better to embrace the boundaries in order to ensure focus within each zone and a variety of best practice. "Divided we innovate", Hargadon (2003) concludes.

A three-zone strategy for SuperGrid and SmartGrid technology systems could allow for both systems to innovate while maintaining a high level of continuity. The three zones are SuperGrid, SmartGrid, and the transformation pathway (or business-as-usual, as defined by Verbong and Geels (2010)). Fig. 2 illustrates the relationship between the three zones. Over time, the transformation pathway will be effectively eliminated by successful SuperGrid and SmartGrid experiments. At this point, as SuperGrid and SmartGrid have both matured, options are open. We envision a SuperSmartGrid that intends to minimize the excess supply capacity, which will be a likely result of zoning, by combining the strengths of matured SuperGrid and SmartGrid technology. Alternatively, perhaps the power-rationality behind SmartGrid will challenge SuperGrid on even terms at this point.

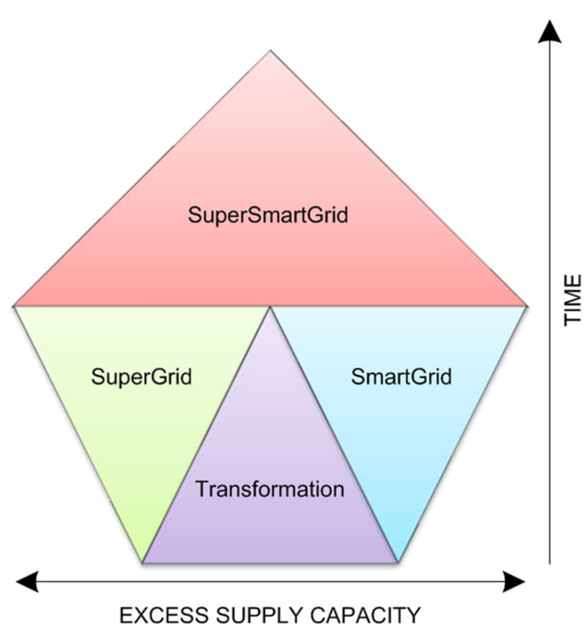

Fig. 2. A zoning strategy that allows for both SuperGrid and SmartGrid to effectively innovate and mature.

In the US, we see a limited window of opportunity for full-scale SmartGrid experiments in California and Texas. In the EU, we see a very limited window of opportunity for cost-effectively shielding potential full-scale SmartGrid experiments in West Denmark, Northern Spain, and Ireland.

5. A paradigmatic case study: Wind power integration in West Denmark

Facing critical penetration levels – in 2010, 26% of West Denmark's annual electricity production came from wind power with plans for increasing penetration levels further in the future – the Danish TSO, Energinet.dk, is responsible for securing the necessary balancing options and infrastructure.

In handling this challenge, East and West Denmark were electrically connected by a 600 MW HVDC cable over Great Belt on August 26, 2010. The Great Belt Link (GBL) is a step in the planned integration of West Denmark's transmission system with neighbouring transmission systems, which Energinet.dk is instigating. Energinet.dk's plans for increasing new cross-system transmission capacity is also an element of EU's infrastructure policy for establishing so-called priority corridors in gas and electricity transmission, and therefore also partly financed by EU funds.

Including the GBL, plans are in place for investing a total of €1.57 billion for expanding West Denmark's cross-system transmission capacity. In addition to GBL, the Skagerrak IV connection to Norway is already under construction. Furthermore, there are plans for a second link to East Denmark, an extension of the connection to Germany, and a new connection to Holland (Tables 2 and 3).

In order to investigate whether the GBL has made conditions for SmartGrid technologies better or poorer in West Denmark, electricity markets in the two price areas, DK-West and DK-East, are compared. The focus is on how the GBL may have affected electricity markets in West Denmark, being perhaps the World's most obvious full-scale SmartGrid innovation zone candidate.

5.1. Physical exchange

Markets are analysed for two periods of operation before and after GBL. The first period is from January 1, 2009 up to August 25, 2010, i.e. before GBL. The second period is from August 26, 2010 to July 2011, i.e. after GBL.

Table 2
Existing transnational connections for West Denmark excl. GBL.

Project	Connects to	Capacity (MW)
Skagerak I–III	Norway	1000
Kattegat	Sweden	600
Kassø Germany	Germany	1000
Total	–	**2600**

Table 3
Planned transnational cable projects for West Denmark incl. GBL.

Project	Connects to	Status	Capacity (MW)	€ million
Great Belt Link I	East Denmark	Completed	600	175
Great Belt Link II	East Denmark	Planned	600	160
Skagerrak IV	Norway	Decided	700	375
Kassø-Tjele-Germany	Germany	Planned	2500	405
COBRA Esbjerg	Holland	Planned	700	455
Total	–	–	**5100**	**1570**

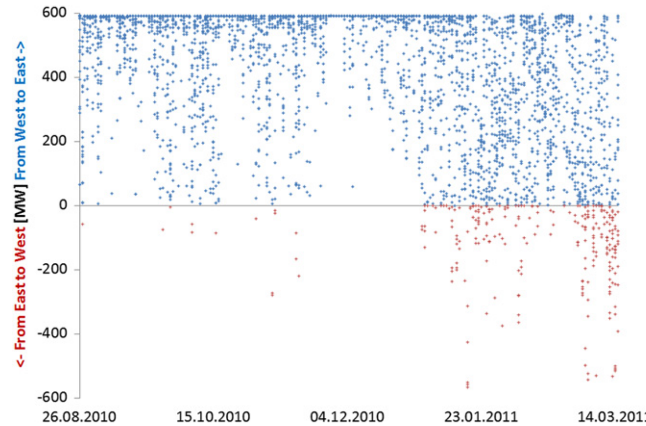

Fig. 3. GBL physical exchange during the period 26/8–2010 to 15/3–2011. Top (blue): West to East (98.5% of period total). Bottom (red): East to West (1.5% of period total). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Table 4
Pre-GBL and post-GBL spot market analysis for DK-West and DK-East.

Result	Unit	DK-West		DK-East	
		Pre-GBL	Post-GBL	Pre-GBL	Post-GBL
Mean	€/MW h	38.89	52.96	45.46	57.46
Variance	–	119	139	1592	1395
Feasible electric boiler operation	Hours	1772	400	1304	297

Fig. 3 illustrates the physical exchange over GBL between East and West Denmark. It appears that the GBL is almost entirely used for exporting electricity from West Denmark. In fact, 98.5% of the total electricity exchange is due to export from West to East. This is initially the result of the price differences between the two markets, DK-West having significantly lower prices than DK-East, partly due to the high penetration of wind power in DK-West.

5.2. Statistical means and variance

Table 4 shows the results for statistical means, variance, and wind as a marginal producer before and after GBL for the two market areas, while Fig. 4 illustrates hourly electricity spot market prices and linear price trends.

It is found that while natural gas and coal prices for Danish producers are 25–30% higher in the recorded period after GBL compared to the period before GBL (Dong Energy, 2011; Argus Media 2011), mean electricity spot market prices have increased by 36% in DK-West and only by 26% in DK-East.

This shows that spot market prices in wind-rich West Denmark have increased above what can be related to fundamentals. Our hypothesis is that the additional increase is caused by the GBL. Alternatively, the increase could be caused by developments in neighbouring markets. However, our analysis shows that the net income for exchange between DK-West and the neighbouring Norway, Sweden, and Germany has increased by 34%, which indicates that DK-West has been the more expensive market area, driving up spot prices.

It is furthermore found that the linear price trend in DK-West is upwards, while the linear price trend in DK-East is downwards, converging towards the end of the period. This shows that the GBL has resulted in markets converging towards DK-West having higher price levels for electricity.

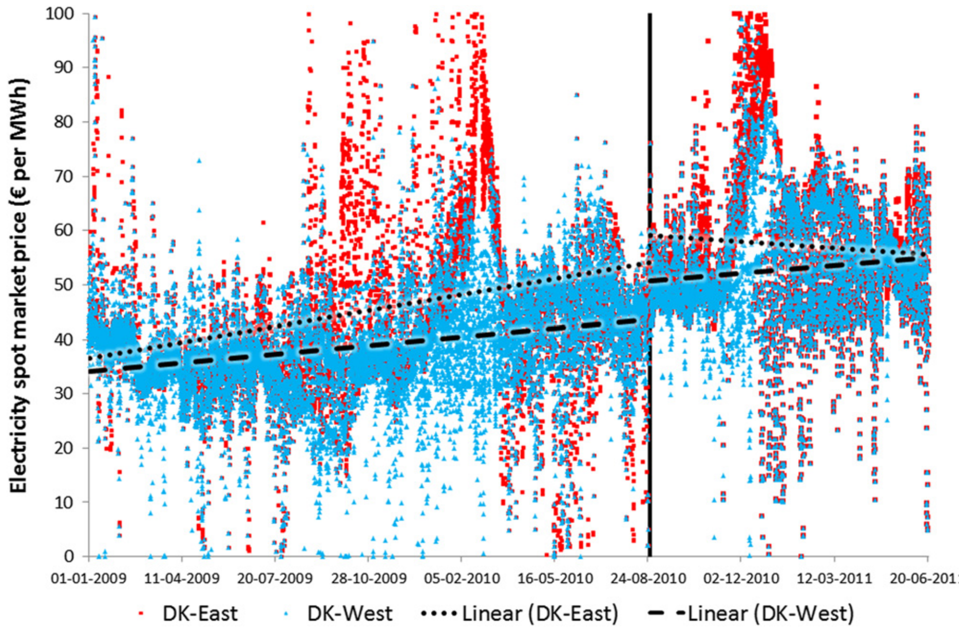

Fig. 4. Electricity spot market prices and linear trends before and after GBL (vertical line) for the period 1/1–2009 to 21/6–2011.

With respect to statistical variance after GBL, the variance in spot prices has increased in DK-West and decreased in DK-East. We had expected for the variance to decrease in both areas. A likely explanation for the increase in variance in DK-West is a 36% increase in average wind production compared to the period before GBL. Had it not been for GBL, the variance increase would likely have been greater.

5.3. The feasibility of electric boilers in distributed co-generation

As a consequence of the above impacts on DK-West's electricity markets due to GBL, West Denmark is now less favourable for SmartGrid technology investments.

We have looked more closely into the case of electric boilers in district heating, which has been one of the most notable Smart-Grid investment areas in Denmark. Over 20 district heating plants have installed electric boilers since 2008 varying in capacity from about 5 to 20 MW. With increasing gas prices and low electricity prices, and policy plans for increasing penetration rates for wind power, policy makers and system operators have made it attractive for operators in distributed generation to invest in electric boilers for substituting gas-fired co-generation.

From techno-economic analysis, the spot price under which electric boilers will substitute gas-fired engines was found to be on average €29.5 per MW h before GBL and an average €37.6 per MW h after GBL. Combining this result with recorded spot market prices, the number of hours during which it will be feasible to substitute gas-fired engines in distributed co-generation with electric boilers in DK-West has dropped by 77% from 1772 to 400 h (Table 4), rendering recent investments in electric boilers infeasible.

5.4. Problem: SmartGrid investments are jeopardized

The results show that GBL has jeopardized the feasibility of SmartGrid investments. While GBL supports the intended higher penetration levels for intermittent renewables by increasing the value of electricity production during periods of high wind production, SmartGrid investments could have had a similar impact. But unfortunately, GBL has moved us further away from being able to bring evidence to the hypothesis that SmartGrid technology could have served such purpose, as the electricity market is now a less interesting market for SmartGrid innovation and investments than before GBL. This makes the path to market more difficult for EVs, heat pumps, electric boilers in district heating, electro-chemical and mechanical storage technologies, thermal storage, and other SmartGrid technologies.

The GBL link has effectively levelled price differences in the two markets with wind-rich DK-West now featuring higher electricity prices, and a significant reduction in the number of hours where spot market prices previously had been supporting one significant first generation SmartGrid technology: electric boilers in distributed cogeneration. Consequently, existing SmartGrid investments are now less feasible, and new investments in SmartGrid technologies are less attractive.

In perspective, it should be acknowledged that data availability for GBL is limited due to the recent start date of operations.

5.5. Solution: Redefine infrastructure and reallocate funds

Like other European TSOs, Energinet.dk's ownership is limited to gas pipelines and electricity transmission cables. They are not allowed to invest in and own SmartGrid infrastructure technologies due to unbundling regulations. This prohibits the TSOs from investing in SmartGrid infrastructure, while they are in fact committed to investing in SuperGrid infrastructure.

A core element of the TSO's business model is so-called bottleneck income generation; TSOs in connected market areas share the price differential between markets for each interconnection. Since 2006 and up until March 15, 2011, Energinet.dk has earned a total of €888 million from this scheme. But according to current regulations, the TSO must reinvest these funds in transmission infrastructure. This is a critical flaw in the current policy design, providing a prescriptive standard rather than a performance standard. The principal objective must be *balancing*, not transmission. Before anything, the regulatory design must come to reflect this, thereby opening up to TSO investing in balancing infrastructure other than grid infrastructure, rather than prescribing continuous investments in the transnational transmission grid.

An associated technological lock-in is found in EU's policy on energy infrastructure priorities for 2020 and beyond, as referenced in the introduction. While EU has allocated €100 billion for investments in the electricity transmission infrastructure, SmartGrid is not formally acknowledged as infrastructure and therefore not included in this effort.

A first step in preparing for a zoning strategy that supports SmartGrid developments will be for policy makers and TSOs to redefine infrastructure towards its primary objectives, which could be local control and reduced external dependence, reliability, environment, and cost efficiency (Table 1).

The second step that would enable effective SmartGrid developments could be to reallocate a significant part of the SuperGrid infrastructure funds currently assigned to transmission infrastructure to SmartGrid infrastructure within dedicated strategic SmartGrid innovation zones. SmartGrid Investment Trusts could be supporting R&D and investments in SmartGrid infrastructure, such as storage, heat pumps, EV-to-grid infrastructure, smart meters and appliances, as well as a range of other technologies that would contribute towards the primary infrastructure objectives, including the support for integrating intermittent renewables.

In SmartGrid innovation zones, national funds which are currently allocated for grid investments would be reallocated to SmartGrid Trusts. In Denmark and elsewhere in the EU, these funds should arrive from bottleneck income and EU infrastructure funds. In the US, funds should be reallocated from cross-state transmission investments and possibly also involve obligations by wind farm and solar field investors.

5.6. The result for West Denmark: From wind power success to wind system success

The current situation in Denmark resembles the situation in the period from 1985 to 1995 when power utilities were unable to make an effective effort to stimulate higher end-use efficiencies. Utilities were experienced in building coal-fired and other large central station power plants, and mostly did so well. But when they engaged in end-use efficiency programs, the results were meagre. At the same time new coal-fired power plants were planned for and built; plants that are not needed today.

In response to this situation, policy makers established the independent “Danish Electricity Saving Trust” (in Danish: Elsparefonden) in 1997. The trust has turned out to become a major economic success. In 2004, an independent study found that the trust's activities had resulted in savings worth €1 billion returning every amount invested in “nega-watt” (Lovins, 1989) 10-fold, easily making it one of the most profitable investments in the history of Danish energy policies (Rambøll Management, 2004).

This could be the strategy for SmartGrid Trusts in dedicated strategic SmartGrid zones. Billions are to be made from “nega-grid” investments, especially when the associated effects from fulfilling the added objective of local control and reduced external dependence – vis-à-vis local governance and social stability – are internalized. Early movers in SmartGrid technology furthermore stand to gain significantly from creating new global technology businesses and jobs.

For SmartGrid innovation zones, SmartGrid Trusts could be the financial basis for exploring the process of transition into independent, reliable, cost-effective, and environmentally-friendly distributed energy systems and strengthened local economies. The objective for these zones and funds would be to enable a most-needed and potentially very profitable development from the current global successes for wind and solar power *technologies* to future global successes for wind and solar powered energy *systems*.

6. Conclusion

The study identifies significant technological and socio-economic conflicts of interest between SuperGrid and SmartGrid policy strategies, and suggests that these conflicts are opposing short to medium term strategies for integrating intermittent renewables into the energy system. In the long term – for example post 2050 – we see opportunities for allowing these energy system experiments to merge into a SuperSmartGrid, taking advantage of mechanisms in both regimes, while preferably continuing to facilitate local control and independence, and local accountability for demand.

The hypothetical suggestion that SuperGrid and SmartGrid are also competing in common markets and induce similar feed-back effects into those markets is supported by a paradigmatic case-study for West Denmark. The study shows that increasing cross-system transmission capacity jeopardizes the feasibility of SmartGrid technology investments. The large capacity HVDC GBL is supporting increasing penetration levels for intermittent renewables in West Denmark in applying the mechanism of export and import between systems with different penetration levels. The GBL has resulted in increasing electricity prices in West Denmark during periods of high wind production. This has a negative effect on the feasibility of SmartGrid investments in West Denmark. Also, it undermines the need for understanding how energy systems may approach extreme penetration levels. West Denmark may still be an obvious candidate for offering such knowledge to the global knowledge base.

In order for generating such knowledge, our case study research in combination with results from technological pathways research and modern innovation research, leads us to conclude that policy makers and TSOs must be mindful about the conditions under which to expect SmartGrid innovation to take place. The analysis suggests that SmartGrid technology innovation is at present more dependent on external developments and strong policy intervention than SuperGrid is, and that for SmartGrid innovation to be timely and effective, SmartGrid innovation zones must be shielded.

Attentive societies as well as the global community stand to benefit greatly from a strategic zoning strategy that allows for SuperGrid and SmartGrid to evolve in parallel, but in different territories or with well-defined strategic overlap, thereby avoiding for one strategy to undermine the feasibility of the other. Without strategic zoning, policy makers will be running a serious risk of society over-investing in meeting policy objectives, operators and investors will face critical uncertainties associated with future electricity markets, and SmartGrid technology areas stand to be marginalized and under-developed.

Current policies and regulatory frameworks hold a critical flaw leading to a prescriptive standard rather than a performance standard for energy infrastructure developments. Rather than supporting a technological lock-in on grid investments, policy makers and TSOs must redesign and reallocate investments to comply with real infrastructure objectives, which could be local control and reduced external dependence, reliability, environment, and cost efficiency. This should result in funds being reallocated from cables and pipelines to SmartGrid Investment Trusts in zones dedicated thereto.

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