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Smart meter deployment in Europe: A comparative case study on the impacts of national policy schemes

Shan Zhou*, Marilyn A. Brown

School of Public Policy, Georgia Institute of Technology, 685 Cherry Street, Atlanta, GA 30332, USA

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ABSTRACT

While low-carbon energy technologies are often regarded as a key solution to climate change mitigation, the successful transformation to a clean energy economy requires a solid scientific understanding of the technological change process and the role of public policies. To better support effective policy making, we conducted a comparative case study to investigate how the choice of policy bundles has led to the cross-national variation in smart meter deployment in Sweden, Finland, Denmark, Germany and the Netherlands. We found that countries with a combination of policy measures that address multiple barriers to smart meters tend to be leaders, while laggards often overlook or fail to adopt policies to overcome key barriers. This research builds on technology diffusion and policy impact assessment literature and provides valuable insights on the design of effective policy tools to promote clean energy innovations.

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1. Introduction

There is a growing consensus among scholars about the immense risks of global climate change and the urgent need to promote clean energy technologies to address this challenge (Brown and Sovacool, 2011; Mowery et al., 2010). Neoclassical economists think that markets alone are insufficient and government policies are required to internalize externalities associated with the diffusion of sustainable innovations (Jaffe et al., 2005). How to design policy schemes that effectively promote clean energy technology has become a central problem in climate change and energy policy discussions.

Our research uses comparative case studies to investigate how policy bundles have shaped clean energy technology deployment in five European countries: Sweden, Finland, Denmark, Germany and the Netherlands. We focus on the advanced metering infrastructure (AMI), commonly known as "smart meters" or the "cornerstone of smart grids" (Palacios-Garcıa et al., 2015), which measure and record energy usage data at hourly or more frequent intervals and can provide usage data to both consumers and energy companies (FERC, 2012). Smart meters not only reduce costs associated with meter reading, grid monitoring and maintenance, improve billing accuracy and outage management, they also enable other important functions of smart grids, such as demand response programs, time variant pricing, and distributed renewable generation (EPRI, 2007; Leeds, 2009).

Smart meters in Europe offer an interesting case to explore because of the large variation in policy contexts and market penetration across countries (see Appendix A). and both recommend large-scale smart meter deployment to enhance energy efficiency (European Commission, 2006; 2012). The European Commission. 2009b Electricity Directive (2009/72/EC) requires EU member countries to roll out smart meters based on economic assessments and to have at least 80% of consumers equipped with smart meters by 2020 (European Commission, 2009a). Countries have adopted smart meter pilots, demonstration programs, and policies both before and after EU directives. As of 2014, smart meter penetration rates of most EU member states are below 10%, including the UK, France, Germany, and the Netherlands (European Commission, 2014a). Sweden, Italy and Finland have achieved more than 90% smart meter market share, ranking the highest in the EU (European Commission, 2014a). The goal of this paper is to understand why smart meter diffuses faster and to a greater extent in some pioneering countries than in others, focusing on the policy impact.

This paper is organized as follows. We first explain case selection and research methodology. We then describe results of five

* Corresponding author.
E-mail addresses: zhoushanbnu@gmail.com (S. Zhou), marilyn.brown@pubpolicy.gatech.edu (M.A. Brown).

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case studies. In the following sections, we discuss policy implications, and offer conclusions.

2. Methodology and Case Selection

The dependent variable of interest here is smart meter penetration rate. The independent variable is domestic policy context. The case study approach is chosen because of the descriptive and explanatory nature of our research question: what policy bundles have been adopted and how they have shaped countries' smart meter deployment status? Besides policy interventions, a group of confounding factors may also affect smart meter penetration, such as national economic strength, domestic energy market liberalization, energy research, demonstration and development budget, economic competitiveness and clean technology innovation. To minimize any confounding effects, we select and compare cases that are similar with respect to these confounding factors (Kitchenham et al., 1995). We also choose contrasting cases that include both successes and failures in smart meter deployment (Yin, 2011).

Based on the above criteria, five countries are selected: Finland, Sweden, the Netherlands, Germany and Denmark. They vary in both policy contexts and technology deployment status, but are similar in important confounding factors (see Appendix B). In particular, Finland and Sweden are leaders in smart meter deployment, the Netherlands and Germany are laggards, and Denmark falls in between (see Fig. 1). More details about their energy statistics are presented in Table 1. After controlling for confounding variables, we can then evaluate the policy impacts on smart meter deployment without suffering the effects of omitted variable bias (King et al., 1994).

3. Results

This section compares and contrasts five case studies to identify policy bundles adopted and how they have shaped countries' smart meter deployment. A summary of policy milestones is presented in Fig. 2.

3.1. Finland

Finland sees smart grid deployment as an important opportunity to reduce carbon emissions at all levels and to gain competitive advantages in the global clean technology market (MEE, 2014). In 2008, an economic analysis of Finland's demand side response potential concluded a positive outcome based on a national smart meter rollout scenario (European Commission, 2016). The Finnish government then adopted the Government Decree on Determination of Electricity Supply and Metering (66/2009), aiming to obtain a smart meter penetration rate of at least 80% and cover 3.2 million energy consumers by the end of 2013 (Smartregions, 2013b).

The Decree (66/2009) sets metering responsibilities for energy market participants (Finnish Energy Industries, 2010). Distributed system operators (DSOs) are responsible for installing metering devices and data transmission connections at the electricity

Fig. 1. Smart meter penetration rates by country as of 2014.

consumption and production sites (Finnish Energy Industries, 2010). They must arrange electric metering for balance settlement and billing, and for reading, verification, registration and reporting of metering data to electricity market participants (Finnish Energy Industries, 2010). DSOs are also responsible for data security and protection; however, customers and authorized third party are entitled to access metering data (Finnish Energy Industries, 2010). DSOs should also facilitate the installation of in-home displays (directly or through a third party) when requested by customers (Finnish Energy Industries, 2010).

The Decree (66/2009) defines smart meters minimum functional requirements and obligations for data transmission and storage (Finnish Energy Industries, 2010). Smart meters should be able to send hourly data to customers once a day and record distribution interruptions that exceed three minutes. They should also have remote reading, disconnection and reconnection facility, and at least six-year and two-year storage time for metering data and interruption time data respectively. Moreover, data protection, storage and processing system need to be verified before the meter can be used.

Since 2005, DSO regulation in Finland has combined the ex-ante revenue cap model and incentive based model (NordREG, 2011). Regulators set an allowed return on investment for DSOs and compute realized adjusted profit based on companies' financial, accounting and regulatory performance. Incentive to improve quality is provided, but it may not exceed 20% of the reasonable return (NordREG, 2011). DSOs can adjust their price setting in the following regulatory period to compensate the surplus or deficit, which equals to the difference between the allowed return and the realized adjusted profit.

Under this regulatory model, smart meter roll out in Finland is financed by a rise of electricity prices, which was for instance about 2.8% in 2012 (Energy Market Authority, 2013). Consumers are generally supportive, as smart meters have enabled them to better control their energy usage and eased the supplier switching procedures (European Commission, 2014b). Privacy and data security have not been a great concern to the general public in Finland (Smartregions, 2013a).

3.2. Sweden

Sweden is one of the first countries in Europe to carry out metering reform and large-scale smart meter roll out. The main goal is to increase consumer awareness and activity with more accurate electricity bills, simplified supplier switching processes and better energy consumption information (Swedish Energy Agency, 2012). Before the reform, electricity consumption data for small customers were read on a yearly basis and billing was estimated based on previous year's consumption, instead of actual meter reading. This had been the major source of customer complaints (Mannikoff and Nilsson, 2009). Consumer demand for timely and correct billing were the main driver for smart meter deployment in Sweden (Morch et al., 2007).

In May 2002, a cost-benefit analysis (CBA) concluded that monthly metering reading can reduce energy usage by 1–2%, and lead to a net annual benefit of around €60 million (KEMA, 2010). The Swedish Parliament then passed Government Bill 2002/03:85, which mandates monthly meter reading for large customers (>8000 kWh) from July 1st, 2006, and for all other customers from July 1st, 2009. The bill also requires hourly metering for customers with larger than 63A fuse from July 1st, 2006.

In Sweden, smart meter deployment is considered as network upgrading and led by DSOs. Although the law does not mandate the replacement of traditional meters, many DSOs decided to introduce smart meters (especially AMIs) because of the costly manual meter

Table 1
Energy statistics of the five countries.

	Netherlands	Germany	Denmark	Sweden	Finland
GDP per capita (€ in 2013)	35,900	33,300	44,400	43,800	35,600
Population (million in 2013)	16.8	82.0	5.6	9.6	5.4
Gross inland energy consumption in 2013 (Thousand tonnes of oil equivalent)	81,171	324,272	18,101	49,134	33,926
Electricity use per capita in 2011 (kWh)	7036	7094	6122	14,030	15,738
Electricity price for domestic consumers (2014S1)(€/kWh) – including taxes and levies	0.1821	0.2981	0.3042	0.1918	0.1563
Electricity generated from renewable in 2012 (%)	10.5	23.6	38.7	60.0	29.5
Installed wind net capacity at the end of 2012 (MW)	2434	31,332	4163	3607	257
Total connected and cumulated PV capacity at the end of 2012 (MWp)	365	32,698	399	24	11
Total small hydraulic net capacity (<10 MW) in 2012 (MW)	–	1780.0	9.0	953.0	315.0
Gross electricity production from urban municipal waste in 2012 (GWh)	2235.0	4951.0	892.1	1662.0	333.8
Renewable energy target by 2020 (% of final energy)	14%	18%	50% of electricity from wind	At least 50%	38%

Sources: Eurostat, IRENA, and EurObserv'ER

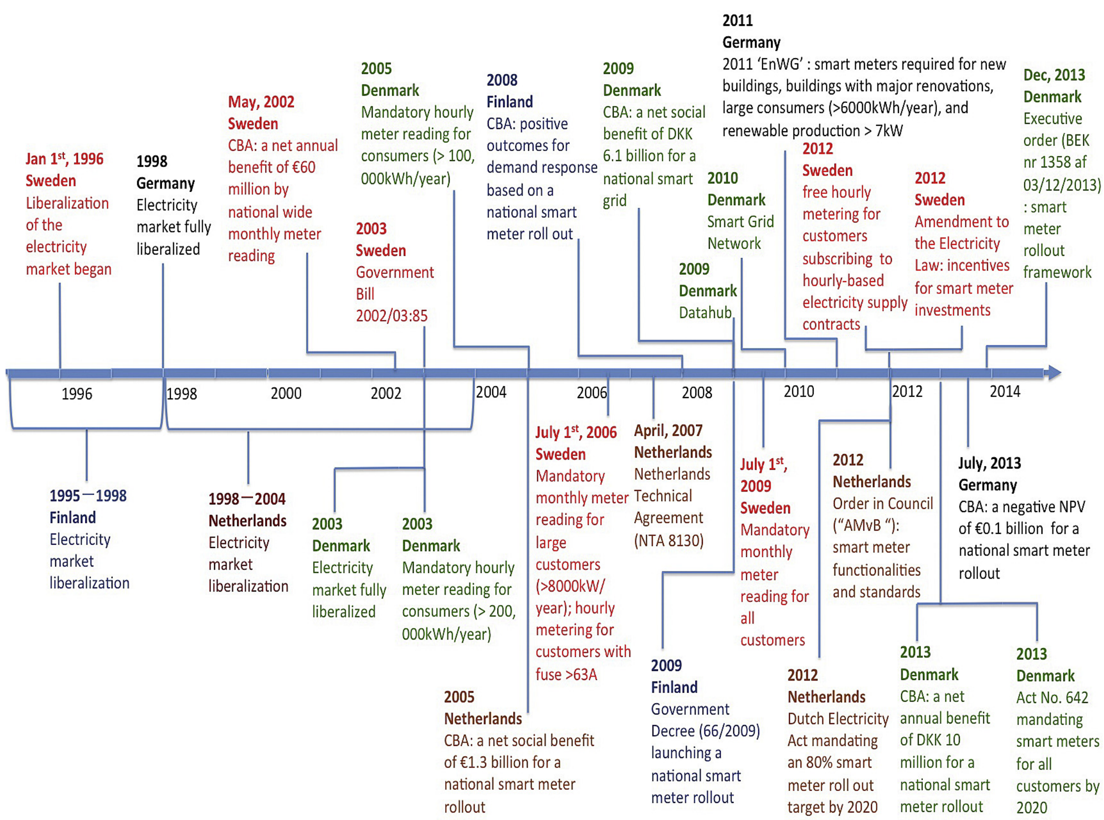

Fig. 2. Smart meter policy milestones.

readings (World Energy Council, 2010). No rules have been adopted to regulate functionalities, data usage, or interoperability of smart meter systems (KEMA, 2010). There has been low-levels of public opposition to the technology (Widegren, 2013).

Meter replacement in Sweden was estimated to cost €1.5 billion (Swedish Energy Agency, 2012), which is borne by DSOs and ultimately by consumers (Energy Markets Inspectorate, 2011). Before 2012, there were no strong financial incentives for DSOs to invest in smart meters. The Amendment to the Electricity Law in 2012 allows returns on investments as long as they are necessary to support core activities of DSOs (i.e. electricity distribution and metering) (Energy Markets Inspectorate, 2011). According to the Amendment, a revenue cap that covers reasonable operational costs and a reasonable return on capital will be decided for each DSO in advance for each regulatory period. This new regulation also provides quality incentives, allowing DSOs to raise electricity prices if they modify their grids and provide more intelligent services to consumers (NordREG, 2011). To further increase customer awareness and activity in the retail market, the Swedish government adopted "Hourly Metering for Active Electricity Consumers" in 2012, requiring the enforcement of hourly metering at no extra cost for customers who subscribe to hourly-based electricity supply contracts[1] (Swedenergy, 2013).

3.3. Denmark

Denmark aims to have 50% electricity consumption from wind

[1] The hourly-based electricity contract represents dynamic electricity pricing that varies from hour to hour, with the goal to give customers more information to make informed decisions about their energy consumption.

power by 2020, and 100% of total energy consumption covered by renewables by 2050 (IRENA, 2013). A smart grid is considered to be the most effective strategy to accommodate the significant changes in electricity consumption and production, and to achieve the ambitious climate and energy targets set by the Danish government (Energinet.dk & Danish Energy Association, 2009).

Denmark mandated hourly electric meter-reading for customers with an annual consumption larger than 200,000 kWh from January 1st, 2003, and 100,000 kWh from January 1st, 2005 (Morch et al., 2007). In April 2009, the Datahub was established to provide consumers with easier access to their own energy data and easier switching between electricity suppliers (KEBMIN, 2013). In 2010, the Smart Grid Network was set up to collect recommendations from stakeholders and authorities to promote smart grid deployment.

An economic analysis in March 2013 showed that a full smart meter roll out would generate a net annual benefit of DKK 10 million for Denmark (Danish Energy Agency, 2013b). The Danish Parliament then adopted Act No. 642 in June 2013, mandating smart meter installations for all customers by 2020. In December 2013, an executive order (BEK nr 1358 af 03/12/2013) was adopted, which sets out the smart meter rollout framework (Danish Energy Agency, 2013a). The Order also sets minimum functional requirements for smart meters: it should be able to record energy consumption data every 15 min or at shorter intervals; be able to store and transmit metering data; have remote control settings for meter frequency; and be able to adjust intervals for data transmission to the grid company to adapt to its settlement and billing routines (Danish Energy Agency, 2013a).

DSOs in Denmark are responsible for smart meter deployment (European Commission, 2014b). Regulation on DSOs was changed from an ex-post rate-of-return policy to the combination of a revenue cap and a maximum rate of return in 2005 (NordREG, 2011). DSOs are free to set distribution tariffs as long as they do not violate revenue caps and the maximum rate of return on network assets. The allowed revenues will be lowered for companies that have poor quality of supply. In Denmark, smart meter investments do not result in a corresponding expansion of DSOs' revenue caps (Energinet.dk & Danish Energy Association, 2009; 2012). However, some DSOs found it profitable to invest in smart meters under the incentives of demand response programs. Danish policy makers are planning to adopt regulations to encourage time variant pricing in the future (Energinet.dk & Danish Energy Association, 2012).

3.4. Germany

Germany envisions that smart meters can help integrate renewable energy and encourage consumer participation in the energy market, when data protection and security is strictly guaranteed (BMWi, 2015b). Before 2011, there was no policies except several demonstration and pilot projects (Hierzinger et al., 2012). The 2011 amendment of the German Energy Act ('EnWG') was a major regulatory effort in recent years. It requires smart meters to be installed for new buildings and buildings with major renovations, final consumers with consumption over 6000 kWh/year, newly installed renewable energy production larger than 7 kW, and other cases if technically and economically acceptable (BMJV, 2005). However, following a negative CBA outcome in July 2013, the German government decided not to fully roll out smart meters in the country. The German CBA had the lowest expected energy savings (1.2%) and the lowest peak load shifting (1.3%) assumptions among the five case study countries, leading to the conclusion that costs exceeded benefits.

The metering sector was completely liberalized in Germany. DSOs are responsible for smart meter installation and ownership, but consumers can also choose a third party as their preferred metering point operator (MPO) (European Commission, 2014b). There are deep public concerns about smart meter privacy and data security (Alejandro et al., 2014). The government is authorized to adopt minimum smart meters technical requirements and certification criteria under the German Energy Act (BMJV, 2005). However, very limited progress had been made by far.[2]

Currently, each DSO has an authorized revenue cap, which is determined by benchmarking operators sharing the same characteristics against each other (Ernst & Young, 2013; NordREG, 2011). The goal is to encourage cost reduction – both at the individual company level and across the whole group. New investments are taken into account by adjusting the authorized revenue through an expansion factor that is dependent on the number of new connections to the grid and the size of DSO service area. While costs are decoupled from revenues, there is often a delay of three to seven years between new investments and the integration of resulting capital expenditures within the revenue cap (Eurelectric, 2011). Therefore, the achievable rate of return for German DSOs is often significant lower than the expected regulatory rate of return, resulting in a strong barrier to smart meter investment (Eurelectric, 2011).

3.5. The Netherlands

Based on a positive CBA outcome, the Dutch government first envisioned a national smart meter roll out in 2006 to ensure the smooth operation of it retail energy market (Dutch Parliament, 2006). In April 2007, the Netherlands Technical Agreement (NTA) 8130 "Minimum Set of Functions for Metering of Electricity, Gas and Thermal Energy for Domestic Customers" was adopted. According to NTA 8130, DSOs are responsible for smart meter installation, operation and management, as well as the implementation of security measures to ensure system safety, while energy suppliers can access and manage smart metering data through central access servers (Netherlands Normalization Institute, 2007).

In 2008, two mandatory smart meter roll out bills were submitted to the House of Parliament (Dutch Parliament, 2008a; 2008b). The bills set smart meter technical standards and infringement penalties[3] for consumers who refuse to install a smart meter. The bills were alleged to have violated the Dutch Data Protection Act, and there was a lack of consent regarding data access (Dutch Data Protection Authority, 2008). With amended proposals, both bills were passed in the House of Parliament in July 2008 (Dutch Parliament, 2008c). However, in October 2008, concerns were raised about the potential invasions of privacy by smart meters (Cuijpers and Koops, 2008). Along with objections from the public and campaigns of civil society organizations, the Senate declined to approve both bills in April 2009 (Dutch parliament, 2009).

The amendment proposal which improved privacy protection and data security finally passed the Dutch House of Parliament in November 2010 (Dutch Parliament, 2010b), and the Senate in February 2011 (Dutch Parliament, 2011). This Dutch Electricity Act requires DSOs to offer all households and small businesses an electric smart meter from 2012, and to achieve a penetration rate of at least 80% by 2020. The Order in Council ("Algemene Maatregel van Bestuur" or "AMvB"), which came into effect on January 1st,

[2] After several years' discussion and preparation, the Measurement and Verification Act finally became effective on January 1st, 2015, which sets detailed minimum technical requirements for smart meters and their operation (BMWi, 2015a).

[3] Consumers who refuse to install a smart meter can be sanctioned with a fine of up to €17,000 or imprisoned for a maximum of 6 months.

2012, determines smart meter functionalities and standards (IEADSM, 2012). The Dutch Electricity Act provides great flexibility for technology implementation: customers can refuse smart meters; customers can install a smart meter, but opt out of sending meter data automatically ("administrative off") or have a limited set of automatic meter reading capabilities ("standard meter readings"); customers can also have a smart meter installed with explicit consent given to more data measurement and reading than the standard meter reading regime ("detailed meter readings") (Dutch Parliament, 2010a).

In the Netherlands, DSOs are regulated by a system of yardstick competition: the allowed revenue of a DSO is adjusted annually taking into account the consumer price index, a quality factor, and the efficiency incentive (Energiekamer, 2011). An objective (or a yardstick) in the final year of a 3–5 year regulatory period is determined ahead of time and is equal for all DSOs (Energiekamer, 2011). The system of yardstick competition provides incentives to increase productivity; however, DSOs may invest less than the socially optimal level in order to reduce costs and increase profits (Energiekamer, 2011). In order to maintain the quality of the grid, Dutch regulators introduced the quality factor into the system of yardstick competition in 2011.

4. Discussion

4.1. Driving forces

Driving forces of smart meter deployment differ across countries. Consumer demand for timely and accurate electric billing was the main driver in Sweden, which indicated less public opposition to the technology. Its low population density and high cost of manual meter reading served as another cost driver. Swedish government leveraged these drivers and adopted the mandatory monthly meter reading target. The Swedish case confirms previous findings that customer demand is an important factors driving clean innovation adoption (Veugelers, 2012).

Finland, Denmark and Germany see smart meters as a useful technology to reduce carbon emissions. Smart meters in Finland were deployed to promote demand response, electricity storage, and the competitiveness of domestic clean energy sector. The smart meter rollout mandate adopted by Finland has successfully driven smart meter deployment. Although Denmark did not have any mandates before 2013, its ambitious goals in carbon reduction and renewable energy development have placed great pressure on the power grid system, which accelerated smart meter rollouts. Germany has clear motivations in smart meters, but few policy efforts have been made so far. In the Netherlands, smart meter deployment was driven by the need to ensure smooth operation of the retail energy market. The Dutch government had a high expectation for the technology, but there was a large gap between policy objectives and social acceptance, resulting in slow policy adoption and technology implementation.

4.2. Institutional barriers and regulatory measures

Institutional barriers may arise from a lack of regulatory framework, institutional inertia, and a lack of interests and capacity in clean energy deployment (Painuly, 2001). Complying with regulations is one of the most important motivations for eco-innovation adoption (Arundel et al., 2010). The case studies in this paper also confirm the positive role of regulations: countries with mandatory regulations tend to be leaders in smart meter deployment.

In all five cases, the adoption of smart meter roll out mandates is based on CBA outcomes, which differ substantially across countries due to different local conditions, meter functionalities, and CBA methodologies used. Fig. 3 shows that only Germany had a negative NPV, which resulted in the absence of a national smart meter rollout mandate. This may be because the expected energy savings and peak load shifting used in the German CBA are at the low-end compared to those used by the others (see Table 2). As more countries are likely to consider smart meter CBA and regulatory measures, standardizing CBA methodologies may help ensure that CBA results are based on sound assumptions and that policy decisions are made to maximize social benefits. In 2012, European Commission Joint Research Center (JRC) published a CBA assessment framework that provides guidelines to tailor CBA assumptions to local conditions, to identify and monetize benefits and costs, and to perform sensitivity analysis. However, the European Commission has not released official guidelines or standards in that regard.

Two types of regulatory measures can overcome regulative barriers and drive smart meter deployment. The first is the mandatory target that requires full-scale smart meter rollout within a specified time horizon, such as Finland's 66/2009 Decree. The second is the mandatory monthly meter reading target, which has indirectly but successfully driven smart meter installations in Sweden. These policies are compulsory and stable, with consistent policy objectives. They also send out clear signals about the need for smart meters, hence reduce uncertainties faced by DSOs about future grid investment. This confirms the literature that consistency and clear time frames for policy implementation enhance the effectiveness of energy policies (Auld et al., 2014; Veugelers, 2012).

4.3. Financial barriers and cost recovery mechanisms

Diffusion of clean energy technology needs to be justified on economic grounds. For smart meters, financial barriers are often huge as meter replacement involves a significant capital investment, but there are few incentives for utility (Depuru et al., 2011). While benefits of smart meters might be shared among different stakeholders in society, the investment burden solely on the shoulders of DSOs can create a barrier to smart meter deployment. It is also important to note that financial barriers in each country are vastly different heights, since the investment decision is largely driven by how old or ineffective the current meters are.

Fig. 4 compares the financial regulations of DSOs for the five

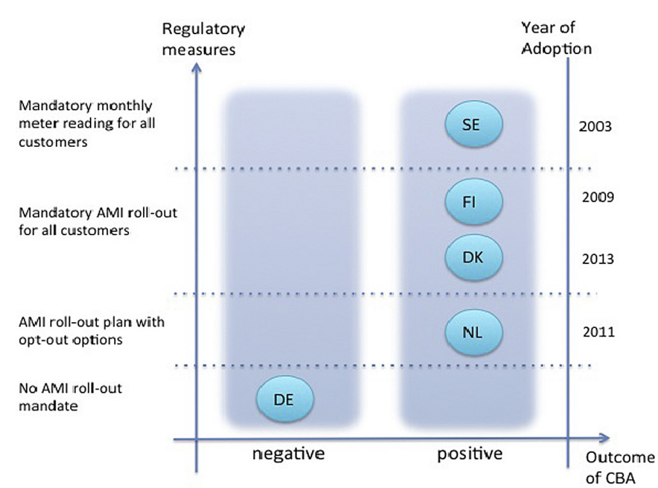

Fig. 3. Regulatory measures for smart meter deployment.
Source: Authors, based on CBA results published in Energinet.dk, & Danish Energy Association (2009); KEMA (2010); Ernst &Young (2013); European Commission (2014a,b); and European Commission (2016)

countries. Only Sweden and Finland allow DSOs to gradually recover costs of smart meters through increased distribution network tariffs. In Denmark, only traditional grid components are included in the revenue caps. Regulations in Germany and the Netherlands encourage cost reduction rather than social optimal investment; hence smart meters that incur additional costs are often in an unfavorable position.

Quality incentives allow DSOs to set tariffs to fund grid investments that maintain high-quality deliveries to consumers. DSOs often choose to invest in smart meters and smart grids to deal with increased loads and distributed generation. Therefore, including the "quality" factor in revenue caps encourages smart meter deployment. All case study countries provide quality incentives, except Germany.

The metering sector in Germany is competitive. DSOs are responsible for meter installations and are allowed to pass metering services to the market through the tendering process. In that case, smart meters are financed by metering operation fees, for which maximum cost thresholds have been set by the government (BMWi, 2015c). German regulators expect the competition between metering service providers to drive down metering costs and encourage smart meter deployment; however, this has not yet proved effective in Germany.

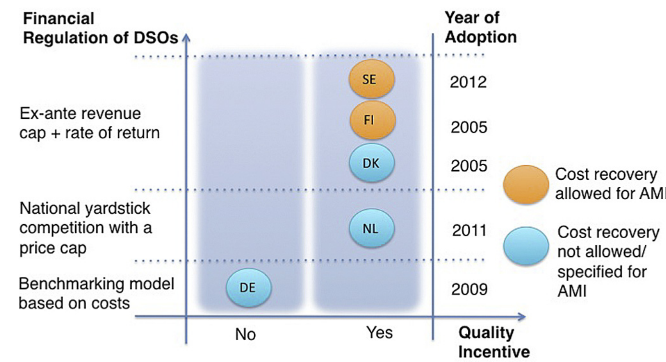

Fig. 4. Financial regulation of DSOs.

4.4. Technical risks and minimum functional requirements

Technical risks are associated with data management, storage, and the interoperability of devices (Depuru et al., 2011). One main challenge for DSOs is to choose a technical solution that is cost-effective but also meets future market and legislative requirements (Morch et al., 2007). Without clear regulations on minimum functional requirements, meter manufacturers and DSOs may use different communication solutions and protocols, and DSOs might be locked into suboptimal technologies and limited economies of scale in sourcing (Giglioli et al., 2010). DSOs may also postpone their investment to get cheaper and more advanced meters in the future.

As of 2014, Finland, Denmark and the Netherlands have adopted smart meter minimum functional requirements (see Fig. 5). The German government was required by law to adopt minimum functional requirements; however, no progress has been made by the end of 2014. Sweden has not adopted its own national standards, but has chosen to wait for the final results of several ongoing EU projects on smart meter functional requirements and standards (Energy Markets Inspectorate, 2011). Although literature points to the importance of standards in ensuring long-term technological development (Cavoukian et al., 2010; McHenry, 2013), we do not find enough evidence to claim that it is a prerequisite for high smart meter penetration rates. However, it is noteworthy that the generalizability of this conclusion may be limited to developed countries with liberalized energy market and innovative clean technology sector.

4.5. Social acceptance

The introduction of new technology to society often faces opposition due to traditional norms and values. When issues surrounding the societal embedding of new technologies are not addressed, resistance by societal groups may slow implementation (Verbong and Geels, 2007). Successful technology deployment hence depends on the widespread adoption by a diverse range of individuals and sectors. Social acceptance is particularly important for large-scale technologies, such as wind (Wüstenhagen et al., 2007) and carbon capture and sequestration (Huijts et al., 2007; Van Alphen et al., 2010).

Consumer acceptance of smart meters is dampened by fears regarding privacy violations, increased electricity bills and loss of control over electricity usage (Krishnamurti et al., 2012). It is important to change public perception and build public trust. Three types of social acceptance policies are prominent based on our case studies.

4.5.1. Privacy protection and data security policies

Collection and transmission of energy consumption data by smart meters creates privacy and security risks, as these data can be used to determine the presence and activities of people at their residence (Depuru et al., 2011).

The proposed Dutch laws in 2008 set a high technical standard for smart meters, which imposed great privacy and data risks and triggered widespread public opposition (Cuijpers and Koops, 2013). To enhance social acceptance, the Dutch legislation provides great flexibility for consumers, including options to opt out and to turn off smart meter functions. This flexibility reduces compliance costs for consumers, but may have slowed technology deployment due to more complex administrative challenges for governments.

Table 2
Smart meter roll-out CBA assumptions and results.

	Number of Metering Points (mn)	Investment (€ mn)	Total Benefit (€ mn)	Discount Rate	Smart Metering Lifetime	CBA horizon (years)	Energy Savings	Peak Load Shifting
Finland	3.3	692	NA	NA	15–25	15	1-2%	2%
Sweden	5.2	1500[a]	1677	NA	10	NA	1-3%	NA
Denmark	3.28	310	322	5.0%	10	10	2.0%	8.4%
Germany	47.9	6493 by 2022; 14,466 by 2032	5865 by 2022; 16,968 by 2032	3.1%	13	20	1.2%	1.3% in 2022; 2.9% in 2032
Netherlands[b]	15.2	3340	4108	5.5%	15	50	3.2%	2.8%

[a] Only capital expenditures are included.
[b] Joint rollout of electric and gas meters.
Sources: (European Commission, 2014a, 2014b)

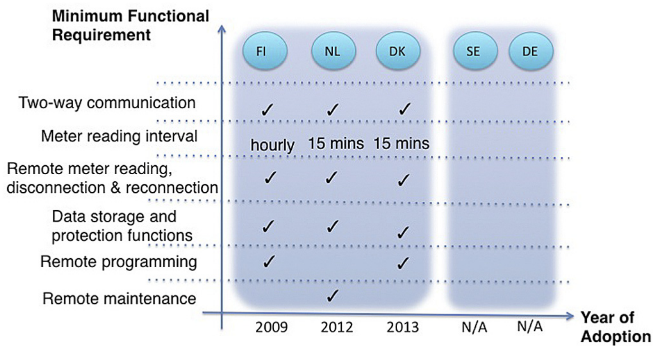

Fig. 5. AMI minimum functional requirements.

German regulators are cautious about data security and privacy protection, as these issues are even more critical and urgent in order to ensure a well functioning liberalized metering market (Vasconcelos, 2008). However, no data management and protection rules have been adopted by the end of 2014. In Sweden, there has been little discussion about potential privacy infringement of smart meters (KEMA, 2010). This might be due to the fact that only monthly meter reading is compulsory, while smart meters are not (KEMA, 2010). In Finland, privacy and data security is not a common concern for the general public, but the Government Decree (66/2009) has set data security requirements for smart meters.

4.5.2. Regulations regarding smart meter ownership and liability

Clear regulation about ownership and liability is crucial to gain public trust for clean technology deployment (Van Alphen et al., 2010). All countries have designated meter ownership and liability, except Germany. The unclear separation between regulated DSOs and independent metering operators in the liberalized metering market in Germany may have led to inefficiencies and inertia in smart meter deployment (Bergaentzlé, 2012).

4.5.3. Policies that realize the benefits of smart meters

Social acceptance may be enhanced if consumers perceive smart meters to be useful for society and the environment (Broman Toft et al., 2014). Regulators can adopt policies that encourage the usage of smart meters. Examples include Sweden's law that mandates the provision of hourly electricity pricing to customers who subscribe to hourly-based electricity supply contracts, Finnish legislation requiring DSOs to provide consumers with in-home displays upon request, and the Danish DataHub which allows easier access to energy consumption information and more transparency for supplier switching.

4.6. Smart meter manufacturers

Compared to the other four countries, Germany has a great advantage in smart meter manufacturing capabilities. Major smart meter producers, including Sensus, Landis + Gyr, GE Energy and Elster, all have manufacturing facilities in Germany (see Table 3). However, Germany's frontrunner position in smart meter manufacturing does not seem to drive the technology penetration. No policies exist to encourage domestic smart meter manufacturers to develop a customer base in Germany. This supports prior findings that top deployers of renewable energy may not always be the same as the top exporters (Jha, 2009). It is likely that factors driving the deployment of clean energy technology in exporting countries are unrelated to those that determine their domestic manufacturing capacity and exports.

4.7. Summary

Table 4 provides a summary of barriers and policy measures identified in the five cases. It shows that leaders in general have been better at systematically addressing multiple deployment barriers, while laggards have often failed to adopt policies to address key obstacles. In particular, leading countries such as Finland and Sweden have adopted policies that overcome institutional and financial barriers, and enhance social acceptance of the technologies. Countries that failed to address these barriers tend to be laggards, such as Germany and the Netherlands.

A clear regulatory push accelerates smart meter deployment. Countries with mandatory regulatory measures are often leaders, such as Finland and Sweden. Countries with partial or conditional smart metering roll out policies tend to progress more slowly, as in the cases of Germany and the Netherlands. Although Denmark currently is lagging behind with 50% smart meter penetration rates, the mandatory roll out target adopted in 2013 will likely drive the technology deployment in the future. We consider the Dutch case to be conditional roll out as the legislation allows consumers to opt-out or to turn off the smart meter functions. This increased flexibility in smart meter implementation may reduce the policy effectiveness of the Dutch rollout target.

Financial regulations on DSOs affect smart meter deployment. DSOs are more incentivized when costs of smart meters are considered in the pre-determined revenue caps, or when quality of service is taken into account in the ex-ante revenue cap.

Based on our case studies, minimal functional requirements are not a prerequisite for high smart meter penetration rates. Technical standards are more important for liberalized metering markets (i.e. Germany) to ensure interoperability. In regulated metering markets, metering service is a monopoly business carried out by DSOs. They may invest in advanced metering before the adoption of technical standards (i.e. Sweden), as AMI is often cost-effective and attractive in the long-term in expectation of future regulatory requirements (NERA, 2008).

Social acceptance of technology needs to be properly addressed by a range of measures, such as privacy and data protection rules, polices for meter ownership and liability, and policies encouraging consumer involvement. As shown in the case of Germany and the Netherlands, social acceptance policies often grant more flexibility

Table 3
Locations of smart meter manufacturing facilities.

	Sensus	Landis + Gyr	Itron	GE Energy[a]	Elster
Finland	–	Jyskä	–	–	–
Sweden	–	–	–	–	–
Denmark	–	–	–	–	–
Germany	Laatzen; Ludwigshafen	Nuremberg		Ahrensburg; Alzenau; Huerth; Odelzhausen; Wunstorf; Neumunster	Mainz-Kastel
Netherlands	–	–	–	Rheden; Haaksbergen	–

[a] Locations of GE Energy manufacturing facilities are for energy services in general. GE's Energy Services provides cleaner, smarter and more efficient solutions to address climate change and energy security challenges, including smart grid products and technologies.
Sources: company websites of Sensus, Landis + Gyr, Itron, GE Energy, and Elster; (Alejandro et al., 2014)

Table 4
Smart meter policy measures adopted to address barriers.

Barriers	Policy measures	Countries				
		Finland	Sweden	Denmark	Germany	Netherlands
Institutional barriers	Mandatory smart meter roll out target	X		X		
	Mandatory monthly meter reading		X			
	Partial/conditional smart meter roll-out				X	X
Financial barriers	Cost recovery for smart meters	X	X			
	Quality incentive	X	X	X		X
Technical risks	Minimum functional requirements	X		X		X
Social acceptance	Privacy and data security policies	X				X
	Regulation regarding smart meter ownership and liability	X	X	X		X
	Policies that maximize consumer benefits from smart meters	X	X	X		

to consumers and involve more time consuming legislative procedures, hence they may be less effective in driving smart meter installations than regulatory mandates and financial regulations. This confirms with previous finding that privacy and data security policies do not directly affect smart meter penetration rates (Zhou and Matisoff, 2016).

5. Conclusions

This paper conducts comparative case studies of Sweden, Finland, Denmark, Germany and Netherlands to evaluate how policy bundles have been adopted to leverage drivers and address barriers to smart meter deployment.

Finland and Sweden are frontrunners in smart meters and their rollouts were mainly driven by regulatory mandates, favorable financial regulations for DSOs, and policies enhancing social acceptance. Although Denmark did not adopt any mandatory smart meter rollout plan until 2013, Danish DSOs have been actively pursuing smart meter trials and pilot programs to meet the government's ambitious carbon mitigation and renewable energy development targets. Smart meter roll out triggered public opposition in the Netherlands due to concerns about privacy infringement and data security. Low social acceptance has greatly hindered smart meter deployment till the adoption of a smart meter roll out mandate in 2011. Germany has been lagging behind due to a lack of regulatory push and financial incentives. While German government and the public are cautious about data security and privacy, no protection profiles or technical standards has been adopted so far.

This paper shows that smart meter deployment is highly influenced by government interventions. Policy measures that address regulatory, financial and social acceptance barriers tend to be more effective in facilitating smart meter diffusion. Pioneering countries in general have addressed the multiple barriers in a more systematic way, while laggards have often overlooked some barriers and failed to provide policy interventions. The case selection of this research may limit the generalizability of our findings to developed nations with liberalized energy markets and innovative clean technology sector. Additional case studies on the diffusion of smart meters, including larger countries with high levels of penetration such as Italy (see Appendix A), could also be valuable to identify drivers, barriers, and policies in large markets, since the countries examined here that had successful smart meter policies and penetration were all relatively small markets.

This analysis also sheds light on the relationship between clean technology deployment and domestic clean technology industry. On the one hand, smart meters do not necessarily diffuse more rapidly in countries with a more robust manufacturing capability, such as in the case of Germany. On the other hand, countries that have successfully adopted smart meters have not developed into large exporters, i.e. Finland. This might be due to the high labor cost and the decline of manufacturing jobs in the Nordic over the past decade (Iris Group, 2015). Future research may be needed to investigate how technology-driven regulations affect the clean technology production industry.

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Appendix A. Smart Meter Deployment Status of EU Member Countries

Country	Total Meters (million)	Deployment Status	Penetration Rate (As of 2014, or otherwise indicated)
Austria	5.7	Mandatory smart meter roll-out started from 2012	< 10%
Belgium	9.1	No roll-out yet	<10%
Czech Republic	5.7	No roll-out yet	<10%
Denmark	3.28	Voluntary roll-out has been carried out with 1.63 million smart meters already installed. A law introduced in June 2013 mandates the full smart metering roll-out.	Around 50%
Estonia	0.709	Mandatory roll-out from 2013 to 2017	23% As of July 2014
Finland	3.3	Voluntary roll-out started in the early 2000's. The Finnish government then mandated a smart meter roll-out.	97% by the end of 2013
France	35	The government mandates the smart meter roll-out from 2014 to 2020. The universal deployment of smart	<10%

(continued on next page)

(*continued*)

Country	Total Meters (million)	Deployment Status	Penetration Rate (As of 2014, or otherwise indicated)
		meter system in France will entail the installation of 35 million meters.	
Germany	47.9	The government hasn't decided on the roll-out plan.	<4%
Greece	7	Mandatory roll-out between 2014 and 2020.	<10%
Ireland	2.2	Mandatory roll-out between 2014 and 2019.	<10%
Italy	36.7	The government defined the legal framework for mandatory roll-out to all metering points in the country in 2006.	95% as of 2011
Latvia	1.1	No roll-out yet	The CBA suggests a penetration rate of 23% by 2020.
Lithuania	1.6	No roll-out yet	The CBA suggests a penetration rate of 80% by 2020.
Luxembourg	0.26	Roll-out will start on July 1st, 2015	National law requires at least 95% penetration rate by the end of 2018
Malta	0.26	Smart meter deployment is expected to complete in 2014. Currently around 0.18 million smart meters have been installed.	69%
The Netherlands	15.2	Mandatory roll-out but customers can choose to opt-out. Smart meter roll-out will occur between 2012 and 2020.	<10%
Poland	16.5	Mandatory roll-out to cover 80% of electricity consumers. Smart meter roll-out will occur between 2012 and 2022.	Penetration rate is around 4% as of 2014.
Portugal	6.5	No roll-out yet	<10%
Romania	9	An official smart metering roll-out plan has yet to be endorsed.	<10%
Slovakia	2.625	Mandatory roll-out for supply points with annual consumption of over 4 MWh.	A 23% penetration rate in 2020
Slovenia	Not available	No roll-out yet	<10%
Spain	27.77	Mandatory roll-out for all domestic meters with contracted power lower than 15 kW between 2011 and 2018.	Penetration rate by the end of 2014 will be around 35%.
Sweden	5.2	Voluntary roll-out between 2003 and 2009	100%
UK	63.8	59.6 million meters will be replaced between 2012 and 2030.	<10%

Source: European Commission (European Commission, 2014b).

Appendix B. EU Country Statistics

Country	GDP 2013 (Euro per inhabitant)
Luxembourg	83400
Norway	75900
Switzerland	61100
Denmark	44400
Sweden	43800
Austria	37000
Netherlands	35900
Ireland	35600
Finland	35600
Belgium	34500
Iceland	34000
Germany	33300
France	31300
United Kingdom	29600
Italy	25600
Spain	22300
Cyprus	19000
Malta	17200
Slovenia	17100
Portugal	15800
Czech Republic	14200
Estonia	13900
Slovakia	13300
Lithuania	11700
Latvia	11600
Croatia	10100
Poland	10100
Hungary	9900
Romania	7100
Bulgaria	5500
Greece	–

Source: Eurostat.

Country	Energy RD&D budgets (million 2013 Euro)
France	1142.92
Germany	740.466
Spain	736.799
Norway	460.231
United Kingdom	428.892
Italy	403.176
Finland	266.427
Switzerland	190.295
Denmark	174.286
Netherlands	155.227
Sweden	151.117
Poland	150.553
Austria	125.282
Hungary	92.079
Belgium	78.628
Luxembourg	26.216
Slovak Republic	25.736
Ireland	20.988
Greece	6.144
Portugal	1.113
Estonia	0
Czech Republic	–

Source: IEA.

Europe Top 10	Global Competitiveness Index 2014–2015 (Global rank)
Switzerland	1
Finland	4
Germany	5
Netherlands	8
UK	9
Sweden	10
Norway	11
Denmark	13
Belgium	18
Luxembourg	19

Source: World Economic Forum.

Country	Global Cleantech Innovation Index 2014
Finland	4.04
Sweden	3.55
Denmark	3.45
UK	2.84
Switzerland	2.8
Germany	2.78
Ireland	2.73
Netherlands	2.64
Norway	2.41
France	2.38
Austria	2.34
Belgium	2.23
Hungary	1.88
Portugal	1.8
Spain	1.7
Italy	1.54
Slovenia	1.5
Czech Republic	1.35
Romania	1.19
Poland	1.03
Bulgaria	1.01
Greece	0.97

Source: Cleantech Group and WWF.

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