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Global sustainability, innovation and governance dynamics of national smart electricity meter transitions

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ABSTRACT

Smart electricity meters are a central feature of any future smart grid, and therefore represent a rapid and significant household energy transition, growing by our calculations from less than 23.5 million smart meters in 2010 to an estimated 729.1 million in 2019, a decadal growth rate of 3013%. What are the varying economic, governance, and energy and climate sustainability aspects associated with the diffusion of smart meters for electricity? What lessons can be learned from the ongoing rollouts of smart meters around the world? Based on an original dataset twice as comprehensive as the current state of the art, this study examines smart meter deployment across 41 national programs and 61 subnational programs that collectively target 1.49 billion installations involving 47 countries. In addition to rates of adoption and the relative influence of factors such as technology costs, we examine adoption requirements, modes of information provision, patterns of incumbency and management, behavioral changes and energy savings, emissions reductions, policies, and links to other low-carbon transitions such as energy efficiency or renewable energy. We identify numerous weak spots in the literature, notably the lack of harmonized datasets as well as inconsistent scope and quality within national cost-benefit analyses of smart meter programs. Most smart meters have a lifetime of only 20 years, leading to future challenges concerning repair, care, and waste. National-scale programs (notably China) account for a far larger number of installations than subnational ones, and national scale programs also install smart meters more affordably, i.e. with lower general costs. Finally, the transformative effect of smart meters may be oversold, and we find that smart electricity meters are a technology that is complementary, rather than disruptive or transformative, one that largely does not challenge the dominant practices and roles of electricity suppliers, firms, or network operators.

1. Introduction

Smart electricity meters constitute perhaps one of the great success stories for the diffusion of new household energy devices of our time. In this study, we construct and utilize a novel and original dataset to assess the economics, deployment, management, sustainability, and transformative potential of smart electricity meters. We examine a wide range of features including diffusion, deployment, and energy savings, as well as other non-technology factors including governance patterns, design of programs, and links to other ongoing electricity transitions. In doing so, we analyze 102 national and subnational smart meter programs in 47 countries, targeting 1.494 billion households and with a collective program cost (for a subsample of 39 programs) estimated at $138.16 billion USD (updated for inflation to 2020US$).

Smart meters—which we define as devices that can measure electricity consumption (often in real-time or close to real-time) and communicate the information back to energy suppliers and/or households—have become central in recent discussions of energy data as well as energy savings and energy transitions (International Energy Agency, 2019; Serrenho and Bertoldi, 2019). Webborn and Oreszczyn (2019: 624) state that “smart metering has the potential to revolutionize access to energy consumption data.” Smart meters can engender “unprecedented insights into energy use behavior” with a plethora of other advantages as varied as the the avoidance of fraud and theft, better energy

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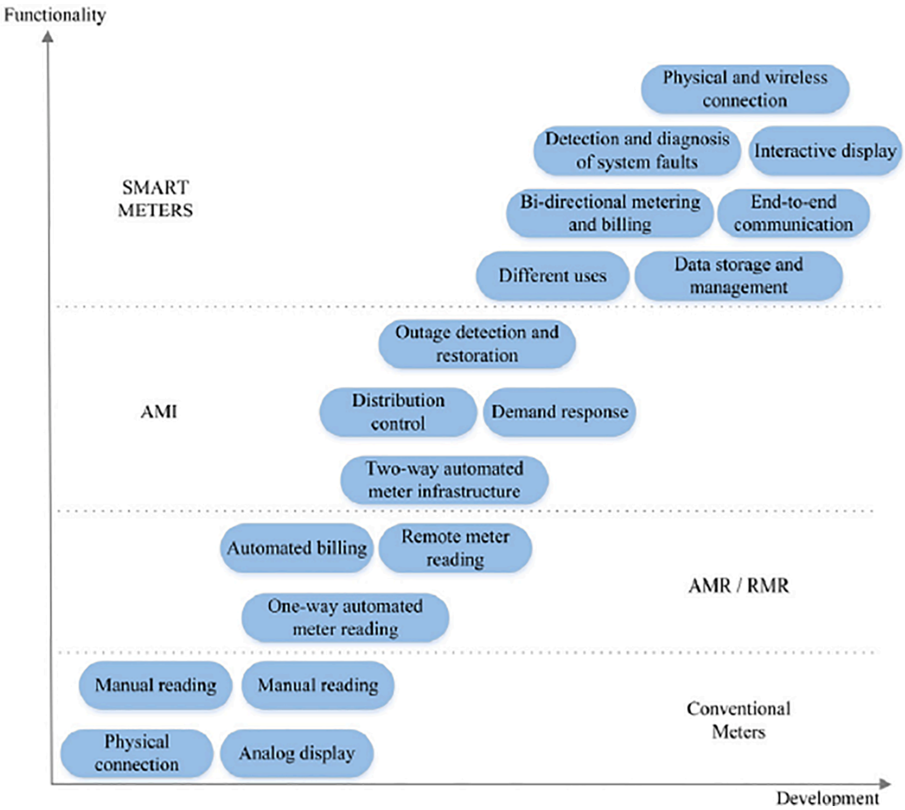


Fig. 1. Classes of Automated Meter Reading devices (AMR meters), Advanced Metering Infrastructure (AMI), and Smart Meters by Functionality. *Source:* Avancini et al., 2019.

management, and innovative business models and pricing tariffs (Véliz and Grunewald, 2018). In the extreme, smart meters could even contribute to a "Smart Earth" whereby information and communication technologies become coupled with digitization and the Internet of Things (IoT) applications to transform both environmental monitoring and governance as well as consumer behavior (Bakker et al. 2018).

Given that smart meter data can be displayed on in-home displays, web portals etc., which may be used for behavioral interventions such as goal setting or competition (Vine and Jones, 2016), their deployment is also routinely linked with sustainable household energy transitions (Martin et al. 2019). In their formal collection of cost-benefit analyses for smart meter programs within the European Union, the European Commission (2015) identified no less than 11 different categories of benefits alongside 27 sub-benefits. Looking only at the smart meter program in the United Kingdom, Sovacool et al. (2017) identified 67 anticipated benefits spread across the shorter-term and longer-term. The International Renewable Energy Agency (IRENA, 2019) states that because smart meters can enable real-time pricing and help shift demand to times when electricity supply is plentiful, there is a need to install smart meters in at least 80% of all households worldwide so that they can take advantage of improved pricing regimes or demand management programs.

Despite the scale and importance of this technological transition, neither the International Energy Agency (IEA) nor IRENA tracks annual smart meter installations by country. This renders systematic comparison difficult. The European Union (EU) compiles sporadic reports, with five-year updates, and limited to EU member states. Consequently, it remains difficult to generalize from a wave of fragmented smart meter trials with small convenience samples (Tiefenbeck et al. 2018), rather than a broader, more representative dataset about this rapid technological diffusion. At the time of drafting, research on smart meters appeared only once in this particular journal, and with a single national case study of Great Britain's program (Sovacool et al. 2019). A detailed global analysis like ours can therefore contribute considerable value, both to characterize recent progress and to inform future governance of this massive and rapid – but uneven – global transition.

Our study seeks to address the above gap head on, examining the lessons learned from global smart meter programs with original data from every country we could find reliable data on. Based on a novel state-of-the-art dataset (explained in greater detail in Section 2) and analytical protocol rooted in relevant interdisciplinary literature (Section 3), we explore:

- **Deployment**: a granular analysis of adoption/installation rates across space (countries and subnational regions) and time (during 2007–2019);
- **Economics**: the costs of smart meter diffusion, including a critical look at costs and benefits (via formal cost-benefit analyses) as well as program costs per unit;
- **Governance**: programmatic designs of smart meter rollouts, their targets, and the actors involved in management;
- **Sustainability**: whether smart meters are linked to energy savings or carbon emissions reductions, as well as the robustness of that evidence; and
- **Transformation**: whether smart meters result in the transformation of user behavior (via energy efficiency or enhanced/automated demand response) or the uptake of more renewable energy and the shaping of other energy infrastructures.

Interestingly, when coupling our data on economics and deployment, we see that rapid diffusion is not necessarily more costly, but that there are possible tradeoffs between scale (degree of adoption or installations) and speed (rate of adoption or installations). In addition, our data suggests that fossil fuel regimes and larger electricity markets are more likely to have greater shares and volumes of smart meters, not fewer, and that complexity and fragmentation across multiple energy

Table 1
Description of national and subnational electricity smart meter programs covered in our analysis (in alphabetical order).

No.	Location	Type [a]	Installation target [b]	Budget [c]	Date of launch	Primary data source	Smart meters including [e]
1	Alabama (AL)	S	1,200,000		2010	U.S. Energy Information Administration (2019)	R, C, I
2	Alaska (AK)	S	250,000		2014	U.S. Energy Information Administration (2019)	R, C, I
3	Argentina	N	N/A		2015	Demartini (2017), Smart Energy International (2017), Smart Energy International (2018a)	R
4	Arizona (AZ)	S	1,625,117			U.S. Energy Information Administration (2019)	R, C, I
5	Arkansas (AR)	S	700,000		2012	U.S. Energy Information Administration (2019)	R, C, I
6	Austria	N	5,730,000	5,620,336,464	2012	European Commission (2014, 2018, 2019)	R
7	BC Hydro, Canada	S	2,000,000		2015	IT World Canada (2014)	R
8	Belgium	S	3,450,000		2019	European Commission (2014, 2018, 2019)	R
9	Brazil	N	63,000,000	101,534,905	2019	Bnamericans (2019)	R
10	California (CA)	S	15,690,609	2,878,143,580	2008	U.S. Energy Information Administration (2019)	R, C, I
11	Chile	N	6,500,000	1,971,057,621	2010	Smart Energy International (2018a), Bnamericas (2019a)	R
12	China	N	5E + 08		2018	Smart Energy International (2018b)	R
13	Colombia	N	11,000,000	753,722,213	2012	Smart Energy International (2018a)	R
14	Colorado (CO)	S	2,400,000		2010	U.S. Energy Information Administration (2019)	R, C, I
15	Connecticut (CT)	S	1,685,276	554,242,249	2012	U.S. Energy Information Administration (2019)	R, C, I
16	Croatia	N	2,187,648	234,093,348	2019	European Commission (2014, 2018, 2019)	R
17	Cyprus	N	543,910			European Commission (2014, 2018, 2019)	R
18	Czech Republic	N	5,712,550			European Commission (2014, 2018, 2019)	R
19	Delaware (DE)	S	438,000		2011	U.S. Energy Information Administration (2019)	R, C, I
20	Denmark	N	3,280,000		2019	European Commission (2014, 2018, 2019)	R
21	Estonia	N	710,000	334,834,00	2014	European Commission (2014, 2018, 2019)	R
22	Finland	N	3,500,000	140,856,000	2013	European Commission (2014, 2018, 2019)	R
23	Florida (FL)	S	9,500,000		2011	U.S. Energy Information Administration (2019)	R, C, I
24	France	N	35,000,000	1,222,762,312	2020	European Commission (2014, 2018, 2019)	R
25	Georgia (GA)	S	4,400,000		2013	U.S. Energy Information Administration (2019)	R, C, I
26	Germany	N	47600000[d]	4,918,820,000	2016	European Commission (2014, 2018, 2019)	R
27	Greece	N	7,500,000	1,748,910,000	2017	European Commission (2014, 2018, 2019)	R
28	Hawaii (HI)	S	550,000		2018	U.S. Energy Information Administration (2019)	R, C, I
29	Hungary	N	7,500,000	1,584,950,000	2020	European Commission (2014, 2018, 2019)	R
30	Idaho (ID)	S	730,000		2015	U.S. Energy Information Administration (2019)	R, C, I
31	Illinois (IL)	S	5,400,000		2010	U.S. Energy Information Administration (2019)	R, C, I
32	India	N	3E + 08			U.S. Energy Information Administration (2011)	R
33	Indiana (IN)	S	2,900,000		2015	U.S. Energy Information Administration (2019)	R, C, I
34	Iowa (IA)	S	1,500,000		2015	U.S. Energy Information Administration (2019)	R, C, I
35	Ireland	N	N/A			Commission for Regulation of Utilities (2017)	R
36	Israel	N	2,540,000			Israeli Electricity Authority (2018)	R
37	Italy	N	41,000,000	1,202,380,000	2006	European Commission (2014, 2018, 2019)	R
38	Japan	N	80,000,000		2015	Smart Energy International (2015); U.S. Energy Information Administration (2011)	R
39	Kansas (KS)	S	1,200,000		2012	U.S. Energy Information Administration (2019)	R, C, I
40	Kentucky (KY)	S	2,000,000		2015	U.S. Energy Information Administration (2019)	R, C, I
41	Lithuania	N	1,800,000	4,264,573,554	2016	European Commission (2014, 2018, 2019)	R
42	Louisiana (LA)	S	2,100,000		2015	U.S. Energy Information Administration (2019)	R, C, I
43	Luxembourg	N	300,500	379,936,538	2018	European Commission (2014, 2018, 2019)	R
44	Maine (ME)	S	750,000		2007	U.S. Energy Information Administration (2019)	R, C, I
45	Malaysia	N	9,100,000		2018	Cheong (2019)	R
46	Malta	N	315,000	51,924,691	2018	European Commission (2014, 2018, 2019)	R
47	Maryland (MD)	S	2,625,830	511,521,751	2012	U.S. Energy Information Administration (2019)	R, C, I
48	Massachusetts (MA)	S	3,276,275	379,298,208	2012	U.S. Energy Information Administration (2019)	R, C, I
49	Mexico	N	38,000,000	1,620,160,000	2007	Binz and Brancho (2019) Binz and Brancho (2019)	R, C, I
50	Michigan (MI)	S	6,600,000		2010	U.S. Energy Information Administration (2019)	R, C, I
51	Minnesota (MN)	S	2,500,000		2012	U.S. Energy Information Administration (2019)	R, C, I
52	Mississippi (MS)	S	1,500,000		2015	U.S. Energy Information Administration (2019)	R, C, I
53	Missouri (MO)	S	3,000,000		2015	U.S. Energy Information Administration (2019)	R, C, I
54	Montana (MT)	S	1,200,000		2015	U.S. Energy Information Administration (2019)	R, C, I
55	NB Power, Canada	S	350,000	46,255,878	2011	CBC (2018); Fortnum (2020)	R
56	Nebraska (NE)	S	1,000,000		2017	U.S. Energy Information Administration (2019)	R, C, I
57	Netherlands	N	7,600,000	57,907,300	2011	European Commission (2014, 2018, 2019)	R
58	Nevada (NV)	S	1,500,000		2010	U.S. Energy Information Administration (2019)	R, C, I
59	New Hampshire (NH)	S	700,000		2010	U.S. Energy Information Administration (2019)	R, C, I
60	New Jersey (NJ)	S	3,500,000		2018	U.S. Energy Information Administration (2019)	R, C, I
61	New Mexico (NM)	S	1,000,000		2018	U.S. Energy Information Administration (2019)	R, C, I
62	New York (NY)	S	8,319,807	1,798,757,807	2012	U.S. Energy Information Administration (2019)	R, C, I
63	New Zealand	N	2,000,000	850,080,573	2014	Electricity Authority (2016)	R
64	North Carolina (NC)	S	5,000,000		2010	U.S. Energy Information Administration (2019)	R, C, I
65	North Dakota (ND)	S	400,000		2010	U.S. Energy Information Administration (2019)	R, C, I
66	Norway	N	2,500,000	3,286,742,399	2018	NVE (2016)	R
67	Nova Scotia Power, Canada	S	N/A		2015	Fairclough (2019)	R

(*continued on next page*)

Table 1 (*continued*)

No.	Location	Type [a]	Installation target [b]	Budget [c]	Date of launch	Primary data source	Smart meters including [e]
68	Ohio (OH)	S	5,500,000		2015	U.S. Energy Information Administration (2019)	R, C, I
69	Oklahoma (OK)	S	1,750,000		2010	U.S. Energy Information Administration (2019)	R, C, I
70	Ontario, Canada	S	4,800,000	2,180,614,693	2015	Ministry of Energy (2014)	R
71	Oregon (OR)	S	2,000,000		2010	U.S. Energy Information Administration (2019)	R, C, I
72	Pennsylvania (PA)	S	6,147,243		2013	U.S. Energy Information Administration (2019)	R, C, I
73	Poland	N	17,700,000	5,270,656,785	2013	European Commission (2014, 2018, 2019)	R
74	Portugal	N	6,500,000	1,018,741,359	2011/2013	European Commission (2014, 2018, 2019)	R
75	Quebec, Canada	S	3,800,000	2,100,000,000	2020	Hydro Quebec (2017)	R
76	Rhode Island (RI)	S	500,000		2019	U.S. Energy Information Administration (2019)	R, C, I
77	Romania	N	9,200,000	2,388,492,407	2015	European Commission (2014, 2018, 2019)	R
78	Russia	S	N/A		2014	Smart Energy International (2014); Reuters (2012)	R, I
79	SaskPower, Canada	S	380,000			SaskEnergy (2016), Smart Energy International (2018a), Smart Energy International (2016)	R
80	Singapore	N	1,400,000		2018	Tan (2019)	R
81	Slovakia	N	2,625,000	1,009,295,779	2017	European Commission (2014, 2018, 2019)	R
82	Slovenia	N	930,000		2018	European Commission (2014, 2018, 2019)	R
83	South Africa	N	N/A	281,728,750	2006	Sustainable Energy Africa (2015)	R
84	South Carolina (SC0	S	2,658,050		2012	U.S. Energy Information Administration (2019)	R, C, I
85	South Dakota (SD)	S	485,315		2012	U.S. Energy Information Administration (2019)	R, C, I
86	South Korea	N	22,000,000			T&D World (2011), KEPCO (2018), U.S. Energy Information Administration (2011)	R, C, I
87	Spain	N	28,000,000	228,155,535	2012	European Commission (2014, 2018, 2019)	R
88	Sweden	N	5,300,000	1,438,774,761	2011	European Commission (2014, 2018, 2019)	R
89	Tennessee (TN)	S	3,000,000		2013	U.S. Energy Information Administration (2019)	R, C, I
90	Texas (TX)	S	12,000,000		2012	U.S. Energy Information Administration (2019)	R, C, I
91	Thailand	S (Cities)	N/A		2018	Smart Cities World (2018); Chu (2016)	R, C
92	United Kingdom	N	53000000[d]	17,850,589,144	2012	BEIS (2013)	R
93	Uruguay	N	1,500,000	100,043,346	2021	Smart Energy International (2018a)	R
94	Utah (UT)	S	1,000,000		2015	U.S. Energy Information Administration (2019)	R, C, I
95	Vermont (VT)	S	376,994	147,016,986	2012	U.S. Energy Information Administration (2019)	R, C, I
96	Victoria, Australia	S	2,800,000	1,766,121,412	2008	Department of Treasury and Finance (2011); Victorian Auditor-General's Report (2015)), Victorian Auditor-General's Report (2009)	R
97	Virginia (VA)	S	3,500,000		2008	U.S. Energy Information Administration (2019)	R, C, I
98	Washington (WA)	S	3,300,000		2015	U.S. Energy Information Administration (2019)	R, C, I
99	West Virginia (WV)	S	1,020,239	759,734,869	2012	U.S. Energy Information Administration (2019)	R, C, I
100	Western Australia	S	238,000		2020	U.S. Energy Information Administration (2011); Smart Energy International (2019)	R
101	Wisconsin (WI)	S	2,750,000		2018	U.S. Energy Information Administration (2019)	R, C, I
102	Wyoming (WY)	S	300,000		2012	U.S. Energy Information Administration (2019)	R, C, I

Source: Compiled by the authors. *Note:* [a] N refers to national, S to subnational. [b] Refers to number of meters, not households. [c] Updated to 2020US$. [d] does not disaggregate between electricity and gas smart meters. [e] R refers to residential (often including small businesses), C to commercial, and I to industrial.

suppliers and transmission and distribution operators has no significant effect on diffusion rates. Our comprehensive coverage catapults smart meter research into a broader field of play, because the expanded range of data opens up scope to examine aspects of this rapid global transition that have hitherto been limited to single-country or small-group analyses.

2. Research methods

This section describes our research methods, including details about how we defined smart meters and differentiated types of smart meters, built our global dataset, and conducted our data analysis techniques.

2.1. Key definitions and terms

We began by defining a smart meter as any device that measures real-time electricity consumption and communicates the information back to energy suppliers and/or households, often in an automated or digital manner. This is consistent with recent definitions in the academic literature (Biresselioglu et al., 2018; Brown et al., 2018). Such smart meters sit within an entire sociotechnical system including data communication, energy supply, policy and regulation.

For classification purposes, this means our dataset was intended to include the three most general classes of smart meters: Automated Meter Reading devices (AMR meters), AMR meters with enhanced capability, and Advanced Metering Infrastructure (AMI) meters.

AMR meters utilize a connection channel between a customer (a business, a household) and its energy supplier. They automatically send digital information to energy suppliers, usually once a month, for more accurate billing and also give households or consumers a chance to review their energy usage data, eliminating the need for manual meter reading. AMR meters are sometimes classified as RMR, for remote meter reading.

Some AMR meters also meet Smart Metering Equipment Technical Standards (known as SMETS), giving them further enhancements so that they can offer more granular feedback (e.g., once an hour rather than once a month) or offer visualization of data (e.g., connecting to an in-home display or smart energy display).

AMI meters are almost always SMETS classified, and generally refer to those capable of fully measuring and collecting energy consumption data, and reporting it both to energy suppliers as well as consumers. These usually rely on a dedicated communication network and enable two way communication. Perhaps confusingly, AMI meters may also come with optional "in-home displays" or "smart energy displays," showing energy use in real time.

Our dataset therefore includes all three of the main "classes" of smart meters including AMR and RMR, AMI, and enhanced AMI smart meters shown in Fig. 1, although we treat these categories uniformly under "smart meters" in our analysis.

Smart meters are often described in conjunction with the closely related term of a "smart grid." In a way, a smart meter is one component of a smart grid—the meter is an individual technical artifact, the grid the broader system that the meter contributes to and operates in. But the two are often conflated, and smart meters are frequently described as integral to smart grids (Erlinghagen and Markard, 2012). For example, Bugden et al. (2021: 2) state that "the core infrastructural component of a smart grid is the smart meter, which enables the flow of information upon which other services and innovations are built (e.g., access real-time energy use information and real-time pricing)." Strong (2019: 1345) adds that "smart meters are considered an enabling technology crucial to the development of smart grids that efficiently and reliably match supply and demand in electricity markets." Frickel et al. 2017 (694) concur when they write that "smart meters are one key component of the smart grid," and Milam and Venayagamoorthy (2014: 5) agree when they note that "smart meters are the face of smart grid technology for the public because they are the most customer-integrated aspect of the smart grid." For all of these reasons, we treated smart meters and smart grids as closely linked and reviewed both in the literature (in Section 3).

2.2. Building the dataset and limitations

With our three classes of smart meters and their critical importance to smart grids acknowledged, we then identified national or subnational smart meter programs. This included large-scale programs with diffusion underway or about to commence, but excluded pilots and trials (we wanted only the actual main rollout programs). We then proceeded to collect data globally on these programs from a collection of credible sources around the world, most often coming from the national programs themselves but in some cases relying on the peer-reviewed literature or the grey literature. As one example, The U.S. Energy Information Administration (EIA) provided smart meter data (by request) for programs operating in all 50 states with data from 2364 electric utility companies, electricity suppliers, and cooperatives (updated to 2019).

We moreover tracked total installations of smart electricity meters, meaning we catalogued not only residential or household smart meters but also those for commercial enterprises and industrial facilities (and in some cases when classified for transmission and distribution upgrades). For countries such as the UK (which uses a different way of categorizing smart meters), this means our smart meter coverage includes domestic and non-domestic smart meters as well as those from all suppliers (small and large).

Whenever conflicting data presented itself, we went with either the more recent evidence or the more credible source, i.e. one from an official source related to the smart meter program or the peer reviewed literature. In some situations, when building our arguments, we also relied on data external to our dataset, such as when plotting national GWh of electricity consumption, levels of load control, or shares of renewable electricity supply. Whenever this occurs, we duly note the external source of data, for transparency.

One limitation that deserves mentioning relates to tracking smart meter retirements. Although we were able to track annual smart meter installations in most countries for many points in time, we were unable to track *un*installations, as there was no available data on them. However, we also posit that such replacements do not significantly offset new installations. Even early programs, such as Italy, which began their rollout in the early 2000s, decided to upgrade older smart meters rather than replace them—implying that once smart meters are installed, they will generally be *enhanced* rather than "stop" being smart (Stagnaro, 2019). This nevertheless means we likely overestimate (slightly) the diffusion of smart meters as we are not capturing any retirements or replacements. Notably, a smart meter lifespan is typically 15 to 20 years, and most rollouts have taken place within the past decade.

Another limitation is language—we searched only for results in English which may means we may have missed data for some particular programs e.g. China, India, Russia, etc.

As Table 1 indicates, our completed dataset—drawn from the best available evidence within and across national smart meter reports, media reports, government datasets, and industry datasets—has captured smart meter diffusion across 102 national and subnational programs in 47 countries. Within this dataset, we catalogue the diffusion of an unprecedented 729,131,824 smart meters installed from 2007 to 2019 at a program cost of roughly $138.16 billion (in 2020US$, when adjusted for inflation and currency conversions). Our coverage includes the ten largest electricity markets in the world (China, United States, India, Russia, Japan, Canada, Germany, South Korea, Brazil, and France) and a list of programs that are targeting about 1.4 billion total smart meters, meaning that roughly 52% of the world's smart meters planned as of 2020 have so far been deployed. Most programs involve only residential meters, although a few—notably those in the United States as well as Mexico, South Korea, Thailand, and Russia—involved installations at commercial or industrial entities.

In terms of completeness of coverage, our tracking is about twice as large as the best existing publicly available dataset, from IRENA. IRENA (2019) reported in 2019 that they had tracked residential smart meter installations across about 25% of global households. Given that the world has about 1364 billion households, IRENA was tracking 340 million smart meters. Our coverage is more comprehensive and tracks more than 729 million smart meters.

For purposes of transparency, and in the hope that others will build on our work, we offer full data tables for all graphics and images used in the study in the Supplementary Online Material (SOM).

2.3. Data analysis techniques

To assess the robustness of our results, in many instances we conducted linear as well as polynomial regression analyses on our data to give readers an indication, through R^2 values, for how strong our trend lines are. For our linear regression analysis, we employed the "slope-intercept" form of $y = mx + b$. Given a set of data (x_i,y_i) with n data points, the slope, y-intercept and correlation coefficient, we calculated r by employing the following:

$$m = \frac{n\sum(xy) - \sum x \sum y}{n\sum(x^2) - \left(\sum x\right)^2}$$

$$b = \frac{\sum y - m\sum x}{n}$$

$$r = \frac{n\sum(xy) - \sum x \sum y}{\sqrt{\left[n\sum(x^2) - \left(\sum x\right)^2\right] - \left[n\sum(y^2) - \left(\sum y\right)^2\right]}}$$

In some situations, we calculated a polynomial or curvilinear trend line by modifying our linear analysis with the following equation: $y = b + c_1x + x_2x^2 + c_3x^3 + \ldots + c_6x^6$, where b and $c_1 \ldots c_6$ are constants.

We also conducted analysis of variance, or ANOVA, on some of our results. ANOVA is a strong statistical technique that is used to show the difference between two or more means or components through significance tests. It also shows us a way to make multiple comparisons of several populations means. We offer full data tables for both our regressions analysis and ANOVA in our SOM.

To determine significance within our regression and ANOVA results, as suggested by Field (2009) and Cohen (1988, 1994) we treat $r = 0.1$ ($r^2 = 0.01$) as the threshold for a "small effect," $r = 0.3$ ($r^2 = 0.09$) as our threshold for a "medium effect," and $r = 0.5$ ($r^2 = 0.25$) as the threshold for a large effect.

We have also utilized Pearson values (p-values) and t-tests as

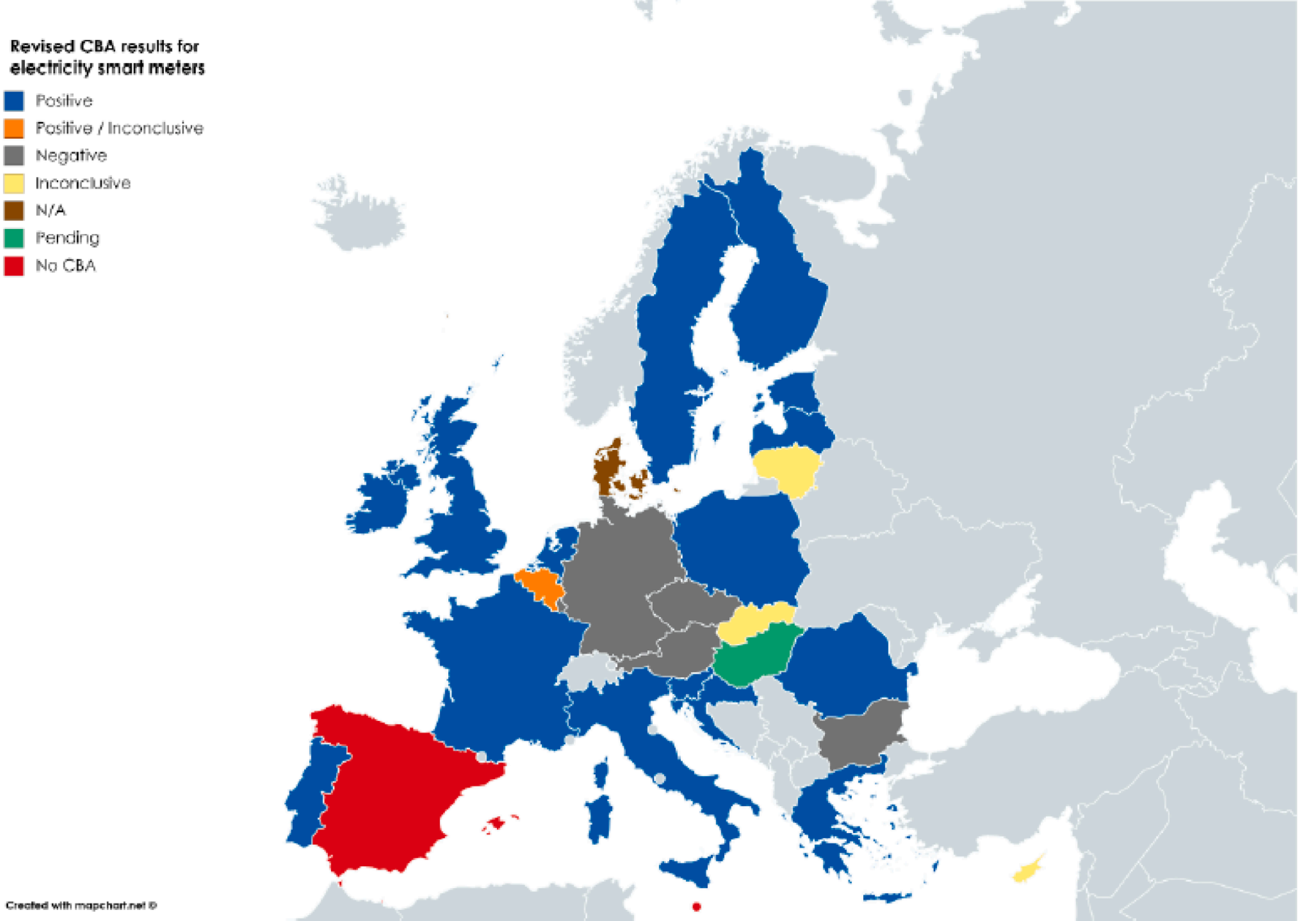


Fig. 2. Revised cost-benefit analysis (CBA) results for electricity smart meters when considering a large-scale rollout to at least 80% by 2020 in the European Union. *Source*: European Commission, 2019.

elucidated by Sheskin (1997) and Gardner and Altman (2000) to further contextualize our results.

In some cases, we present “box and whisker plots” as a way of visualizing more complex statistics. These draw from calculations of the 1st quartile (Q1), 2nd quartile (Q2 or median) and 3rd quartile (Q3), and then interpolate between the data points to depict a box and whisker plot.

To supplement some of our spatial analysis, we have generated global and national maps of diffusion using ArcGIS.

Lastly, to ensure the robustness of the statistical results, we did simulate our analysis with all countries but also by removing outliers that we felt could skew results (notably China and the United States, which accounted for the largest two programs of smart meter diffusion). We are pleased to confirm that removal of any single country from the dataset did not significantly change R squared values (they remained to within one to two percentage points) or the significance levels of any of our findings. This underscores the benefits of relying on a “big” multi-country dataset.

3. Literature review, analytical protocol and dimensions of analysis

In terms of an analytical protocol, we searched the academic and policy literature for studies published in the past 20 years (from roughly 2000 to 2020) on the topic of smart meters or smart grids. Based on an extensive review across the fields of energy studies but also innovation studies and sustainability transitions, business and management, psychology and behavior, political science and public policy, environmental studies, and geography, we decided to center our analysis of smart meter diffusion on five themes.

3.1. *Deployment and accelerated diffusion*

Our first dimension of deployment, in terms of degree and scale of adoption or installations, connects with emerging debates over how fast or slow transitions are or can be (Sovacool, 2016), as well as how much they may be accelerated or reconfigured to achieve “deep decarbonization” (Geels et al. 2017). The European Commission (2019) reports greatly divergent rates of smart meter adoption across its member states, with some, such as Belgium and Germany, having selective or minimal adoption, while others such as Estonia or Italy already seeing their first programs completed, and most other countries falling in the middle. Independent studies have also confirmed this trend (Bularca et al., 2019).

The literature on sustainability transitions discusses myriad factors that can facilitate accelerated diffusion or household energy transitions (Roberts and Geels, 2019a, 2019b; Sovacool et al., 2020a). External shocks such as oil embargoes or wars or gradual global trends such as increasing purchasing power can all generate periods of rapid uptake and diffusion of new technologies, such as gas boilers replacing oil boilers. New coalitions can come to support radical innovations (such as smart meters), including firms and civil society groups, that can then achieve economies of scale that witness declines in cost and improvements in performance. Incumbent regimes that may be hostile to smart meters may also see themselves destabilized by new energy or climate regulations (focusing on energy efficiency, or enhanced digitization), or further weakened if some incumbent actors defect to adopt the new technology.

3.2. Economics, costs and benefits

Our second dimension relates to the fairly nascent literature on the economics of smart meter programs (Zhang and Nuttall, 2011; Römer et al., 2012; Rixen and Weigand, 2014; Spodniak et al., 2014), which shows that there is significant variation across both the overall size of programs as well as their cost per smart meter and the nature (positive or negative) of their total cost-benefit-analyses. Strong (2019) adds that the economics of smart meter programs can be shaped by factors such as standards, patterns of innovation and experimentation, firm strategy, expectations of consumers, and regulatory and policy regimes. The costs of particular programs can thus diverge appreciably.

For instance, the European Commission (2015) noted across their member states that total program costs on a net-present value basis can range from a low of €254.1 million (for Hungary) to a high of €18.94 billion (for Germany, the estimated cost of their full national rollout). It also noted more recently (European Commission, 2019) that total CBA valuations of European programs varied greatly as well with some net-negative, others neutral, and yet others net-positive (see Fig. 2). Indeed, we come back to this point with updated data in Section 4.2.

3.3. Governance and management

Our third area is the governance of programs, including their management structure as well as whether smart meter programs are deemed acceptable and legitimate by stakeholders, including users. One key aspect here is polycentrism, the involvement of multiple actors at varying scales (Ostrom, 2010a, 2010b; Sovacool, 2011; Jordan et al., 2015, 2018; Sovacool and Van de Graaf, 2018) in smart meter programs. For instance, Nyangon (2020) writes about the value of polycentric actors in facilitating smart grid transitions, noting that other actors, especially cities, intergovernmental organizations, and private sector companies, can assist governments in implementing smart meter and smart grid plans. Goldthau (2014) hypothesizes that as (smart) energy infrastructure develops in a coevolutionary manner with socio-economic institutions, actors and social norms, polycentrism can allow for valuable contextualization, experimentation and innovation. Buchmann (2017) also suggests that in the realm of smart grid deployment, polycentric governance approaches can compete with each other to define the optimal degree of decentralization.

Here, issues of whether a program was driven by governments or (often incumbent) energy suppliers seems relevant (Giest, 2020), as well as whether it operated at a subnational or smaller regional level or a national level. Indeed, Zhou and Brown (2017) find that countries with strong governance networks for smart meters, including policy coordination to tackle barriers, are better positioned to promote adoption as well as broader community acceptance. In their review, Mah et al. (2017) also note that empirical evidence on the role of incumbent utilities in promoting smart meters is mixed. On the one hand, they find that some studies discuss how incumbent actors are essential to the effective implementation of energy transitions, as they can be “prime movers” who push innovation, especially in contexts such as the United Kingdom (dominated by seven big energy suppliers), France (dominated by Électricité de France), or the United States (where incumbent utilities often act as network operators or orchestrators over distributed resources such as smart meters). On the other hand, they note in Germany that incumbents were “laggards” at promoting low-carbon innovation and that change was more driven by bottom up actors such as “small challenger” institutions including cooperatives or new market entrants.

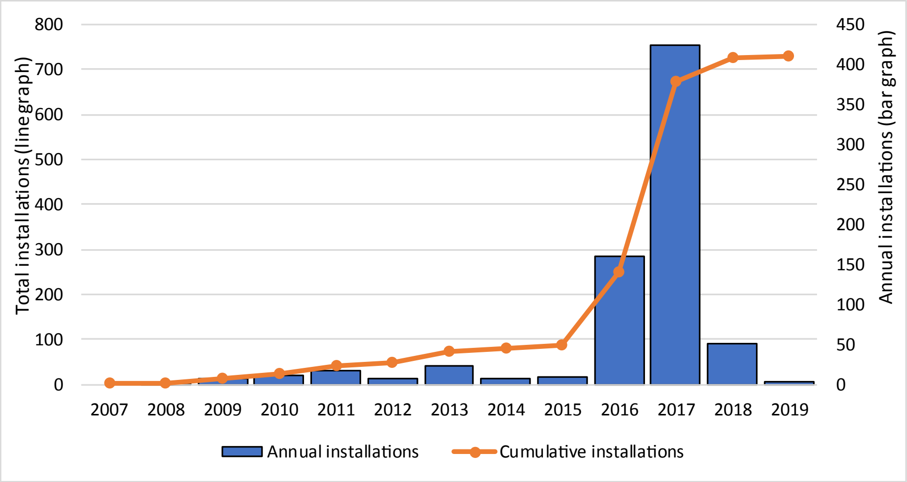
Additionally, the lack of governance, e.g. poorly managed issues of privacy, data, and customer segmentation, can stymie the success of smart meter programs (Silvast et al., 2018; Véliz and Grunewald, 2018) or even lead to the rejection or non-use of smart meters (Kahma and Matschoss, 2017; Hoenkamp et al., 2011). Governance issues can even create other complications over social acceptance or speed of transition, especially in contexts where the smart meter program is not necessarily being driven in a cohesive, coordinated manner, such as the UK. Indeed, Britton (2019) recently examined the smart meter program in the United Kingdom and noted that under the current national framework, city-scale actors are largely excluded from utilizing smart metering data unless they partner with a large incumbent company. Geels et al. (2021) similarly classify the UK smart meter program as having a technocratic style characterized by top-down specifications of technical standards and a supplier-led roll-out model that paid little attention to consumers or social issues. The UK program had complex smart meter specifications and IHD requirements, and an inefficient roll-out program by making energy companies responsible rather than DSOs who could have done roll-out on a street-by-street basis. They use the analogy of the UK program having the dynamics of a snow blowing machine, where the government plowed forward (acting as a show shovel) and pushing objections (snow) aside, until accumulating social acceptance problems piled up to block and halt it. This is a general problem identified within the environmental governance literature as “big brand sustainability,” where energy suppliers or corporate supply chain actors proclaim that they are making sweeping changes when in fact their contributions to environmental sustainability are limited (Dauvergne and Lister, 2012).

3.4. Energy and climate sustainability

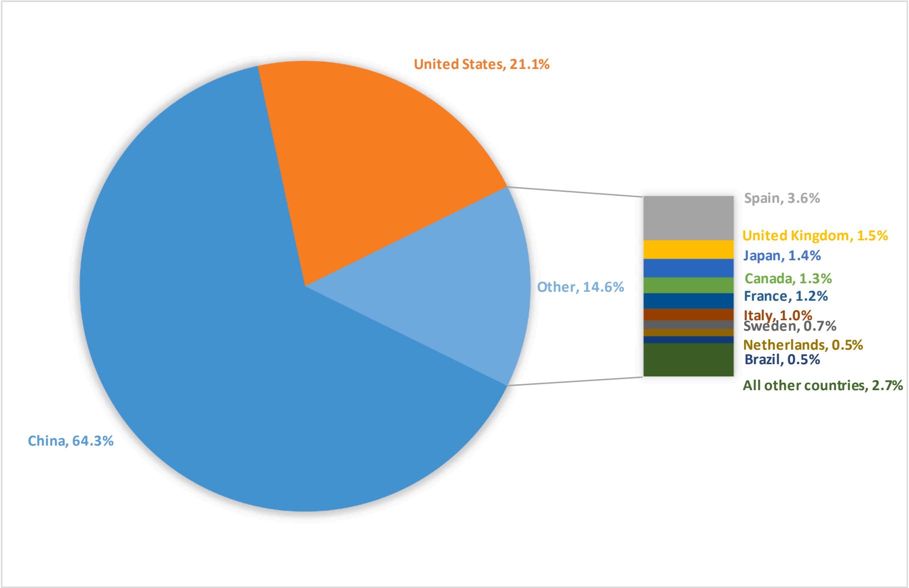
Our fourth area relates to debates about sustainability, or the extent to which smart meters lead to energy savings or reductions in energy demand and associated carbon emissions reductions. Smart meters can further enable decentralization of resources within the electricity sector and to some degree gas sectors, promote automatic control, and enhance the security and variability of energy transactions (Thomas et al., 2019)—all improving (in theory) the efficiency of the electricity system. One synthetic review of smart meter programs noted that while they *can* reduce energy consumption, they must overcome a host of serious impediments, including lack of user knowledge, learning, interest, and established practices, in order to do so (Mela et al., 2018). One meta-analysis of 70 empirical and modeling studies found that the feedback offered by devices such as smart meters would rarely save more than 20% of energy (admittedly a large amount) but more often fall in the interval of 4% to 11% in terms of reductions in household energy use (Zangheri et al., 2019). Another meta-analysis of 42 energy feedback studies was more circumspect, merely concluding that such programs had “significant variation” in their effects (Karlin et al., 2015).

However, other evidence suggests that the energy (and emissions) saving potential of smart meters may be meagre and negligible, and in some situations may even lead to increases in energy consumption or rebounds (as households learn how to better control energy consumption and may use this knowledge to match changes in preferences for new energy services) (Sovacool et al., 2017). Conversely, Lammers and Hoppe (2019) note how in the Netherlands, most stakeholders in smart grid projects (including consumer and community groups) take on only passive observer roles, failing to substantially change their behavior. Pallesen and Jacobsen (2018) also caution that when households do begin to engage via smart meters to prosume or provide distributed energy services, the act of balancing becomes more complex and smart infrastructure grows in scope to the point that it becomes challenging for grid operators to manage. Raimi and Carrico (2016) found, paradoxically, that the more information and education households received about smart meters, the more they began to express concerns over health, privacy, and cost. Bugden et al. (2021) similarly find that over time in New York, the social acceptance of smart meters and smart grids in the United States seems to *decline*, with people being less satisfied or willing to accept them the longer their rollout takes.

a. Cumulative and annual smart electricity meter installations across 102 programs (in millions)



b. Total installed smart meters by country (2007-2019)



c. Annual growth rates

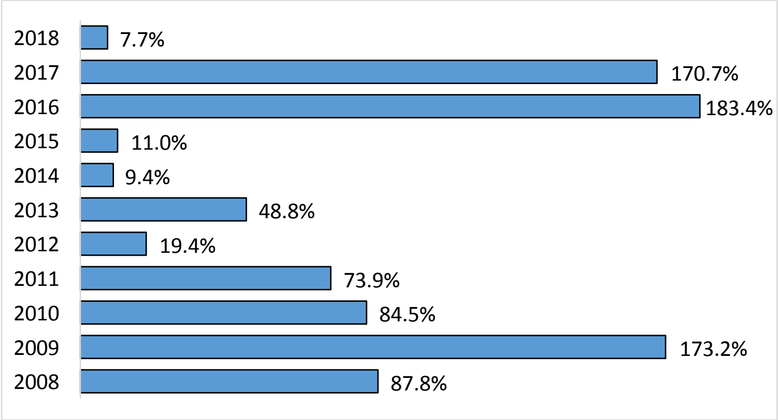


Fig. 3. Global smart meter installations by volume, growth, and geographic location. *Source*: Authors. * Darker color indicates higher rates of diffusion compared to other countries in the dataset, lightest blue constitutes countries with the lowest rates of diffusion, grey countries are those for which we had no data. The full data behind this table is offered in the Supplementary Material. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

*d. Diffusion by region, country, and state 2007-2019**

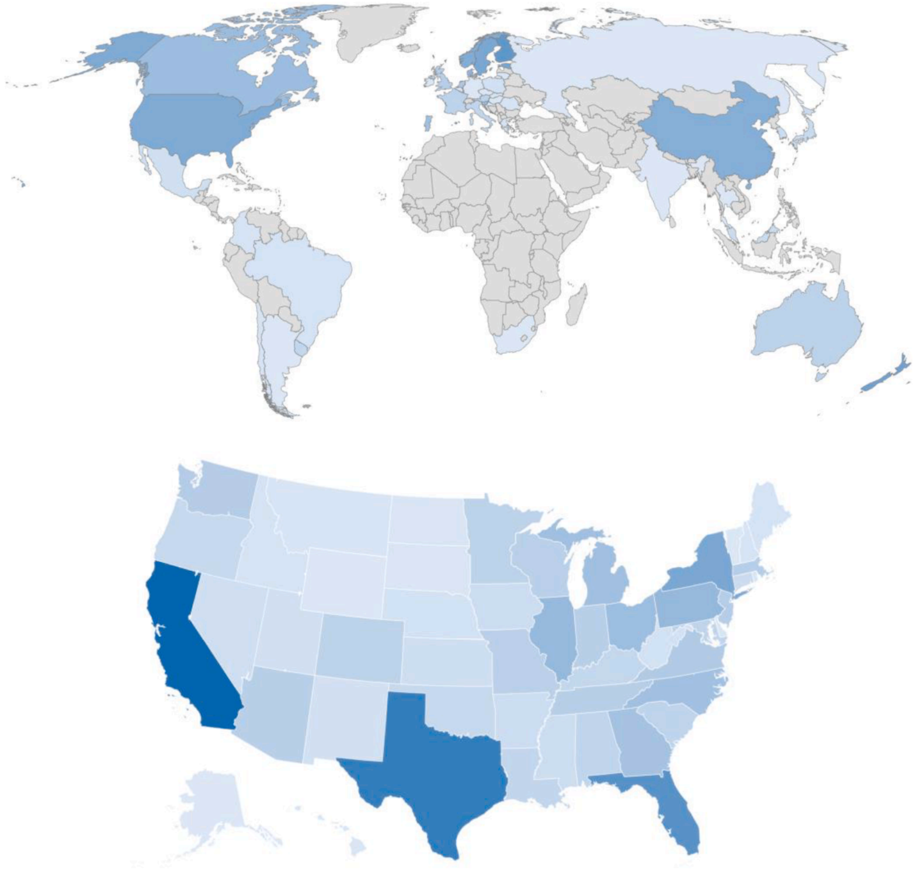


Fig. 3. (*continued*).

3.5. *Transformation and catalysing other transitions*

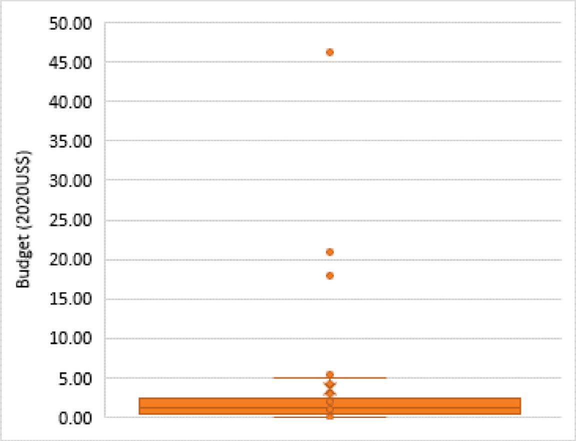
Our fifth area concerns what we have termed transformation, meant to include the degree to which smart meter diffusion is aligned with other low-carbon technologies or practices. Indeed, some of the emerging literature on behavioural economics, environmental psychology, and environmental sociology discusses how the adoption of one innovation, such as a smart meter, can catalyse increased interest in or likelihood of adopting another innovation, such as renewable energy. For example, Ryghaug and Toftaker (2014) noted that adopters of battery electric vehicles in Norway were more likely to consider adopting other low-carbon options such as household solar panels or eating less meat. This provoked them to label driving an electric vehicle a possibly “transformative practice.” Evidence from the United States also suggests that those adopting electric vehicles are more interested in purchasing solar panels for their homes, and vice versa (Delmas et al., 2017). Most relevantly, Sovacool et al. (2020b) found in a Living Laboratory that those using enhanced smart control and visualization over their heating were more likely to consider low-carbon household retrofits than non-adopters at a later stage. So, smart meter adoption may be coupled or connected with the uptake of renewable energy (especially solar PV) as well as energy efficiency/demand response, retrofits, electric vehicles, and household energy storage. Others discuss how smart meters are key to “intelligent energy networks” (Avancini et al., 2019) or even open up a route to decarbonizing transport or homes in their entirety by incorporating “vehicle-to-grid” and other low-carbon energy sources (Mwasilu et al., 2014).

Other literature mentions how smart meters can be a key component of enabling households and consumers to become prosumers, entities that not only consume energy, but also self-generate and possibly sell it. Multiple recent studies envision how smart meters may empower households, create more resilient local energy communities and networks (Lavrijssen and Carrillo Parra, 2017; Wilkinson et al., 2020; Parag and Sovacool, 2016), or contribute to the emergence of new business models for households, intermediaries and aggregators (Rodríguez-Molina et al., 2014; Brown et al., 2019). Brown et al. (2020) surmise that such smart energy business models need not be only offered by traditional energy or smart grid companies; they could also be designed and deployed by a range of market, municipal and community actors. Exceptionally, some literature even suggests that such acts of prosuming could lead to a new democratic and digital era, one where “prosumer capitalism” generates an economy driven by people rather than firms, with local interests at the heart of most transactions (Ritzer and Jurgenson, 2010). That said, other literature challenges the democratic credentials of smart prosuming, noting that it can alienate users, enable them to be more easily monitored and controlled (Comor, 2011), or commodify them via extracting data on their private energy use practices through dangerously predatory forms of “surveillance capitalism” that serve to exploit households (Zuboff, 2019).

4. Results and discussion

In this section, we present and discuss our core results on the five analytical dimensions derived from our literature review. To provide some context and depth to our sections, we also explore the smart meter dynamics of six selected countries from the dataset: China and the United States (stronger patterns of diffusion), Canada, Japan and the European Union (moderate patterns of diffusion), and India (weaker patterns of diffusion).

a. Smart meter program budgets (n=39), billions of dollars, the three most expensive programs are China, India, and the United Kingdom, the three least expensive NB Power, Malta, and Luxembourg



b. Smart meter unit costs (n=37), the three most expensive unit costs are Austria, Israel, and West Virginia, the three least expensive are Germany, Spain, and Belgium

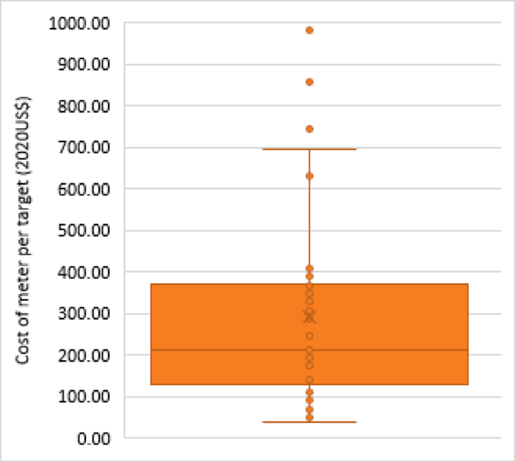


Fig. 4. Smart meter program budgets, costs, and benefits (in US$2020). *Source:* Authors. The orange and blue dots represent actual data points for program budgets or units costs, and the whisker lines the maximum and minimum values without outliers. The central box shows the interquartile range including the median (line in the middle of each central box) as well as the upper and lower quartiles (the remainder of the box). *Note:* Smart meter roll-out cost benefit analyses conducted in different countries are not always directly comparable. Cost-benefit analysis (CBA) results highly depend on project assumptions, for instance, discount rate, project life span, rollout scenarios, and how smart meters will be utilized by consumers and utilities. Energy saving and carbon reduction benefits, in particular, depend on project assumption of grid efficiency and electric market segment characteristics. Different rollout scenarios highly influence costs and benefits of rollout programs. For instance, the smart meter CBA report for Germany laid out multiple rollout scenarios, with different investment packages, benefits, charges to consumers, and timelines. Given the varying national contexts, rollout scenarios and CBA assumptions, the mere comparison of CBS results (i.e. savings and costs) of smart meter programs is prone to uncertainty. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

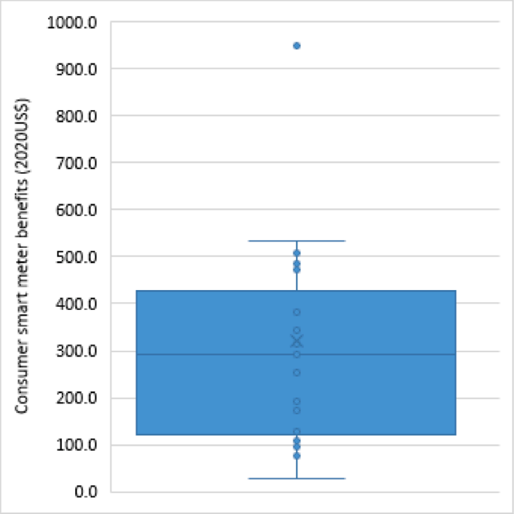
4.1. Deployment and accelerated diffusion

In terms of deployment, our data suggest a remarkable speed and uptake of smart meters over the past decade, which we measured as the absolute number of smart meters installed. This may make smart meters one of the great household electricity technology transitions of our time, growing by our calculations from less than 2.5 million smart meters in 2007 (albeit based on limited data points) to an estimated 729.13 million in 2019, a growth rate of a factor of 294 in only 13 years (See Fig. 3a). By our estimate, about half (53.43%) of all households in our sample have at least one smart meter.

The smart meter market is highly concentrated, however. As Fig. 3b indicates, the top two countries, United States and China, account for an overwhelming 85.4% of the global share in adoption. This also explains the large drop in new installations between 2017 and 2018, by which point the programs in the United States and China had largely achieved their targets. Europe has more modest numbers, despite having a larger population than the United States (about 330 million people reside there, compared to about 450 million in Europe) and a determined push across most EU member states. Meanwhile Canada has exhibited slower progress due to uneven provincial support for smart meters and Japan is still recovering from the Fukushima nuclear accident. Adoption in some countries with large populations is negligible so far, notably India (0.2%) as well as Russia (0.04%). See Data Table A1 in the SOM for more detail on these numbers.

Putting national diffusion rates aside, cumulative annual growth rates are nevertheless staggering, with triple digit growth in the years 2009, 2016, and 2017 (see Fig. 3c). Even though installations slowed for 2019, something that may also reflect lack of updated data, the smart meter market is still growing at a rate of 52.1 million meter installations per year. Panels D and E of Fig. 4 plots smart meter diffusion geographically. Clear leaders include China and the Nordic region, as well as parts of Central Europe along with New Zealand and the United States. When data is examined by each of the 50 states, California, Texas, and Florida have the greatest volumes.

As mentioned above, our dataset indicates that China and the United States are both global leaders in the diffusion of smart meters. China has made great efforts in using smart meters as a way of modernizing and substituting their traditionally energy-intensive and inefficient power grid; in the 12th Five-Year Plan in particular, it was stated that emphasis should be placed on the development of renewable energy and smart grids. A series of blackouts caused by severe storms, especially icy weather in 2008, saw the Chinese electricity grid encounter severe reliability problems across 13 provinces, the power supply of 170 cities cut off, and more than 36 *thousand* lines in need of immediate upgrading (Yu et al., 2012). These dysfunctional aspects of the grid created a strong *c. Range of reported smart meter program consumer benefits within formal programs (n=25)*



d. Cumulative expected smart meter consumer benefits in CBA estimates plotted by selected program (n=25)

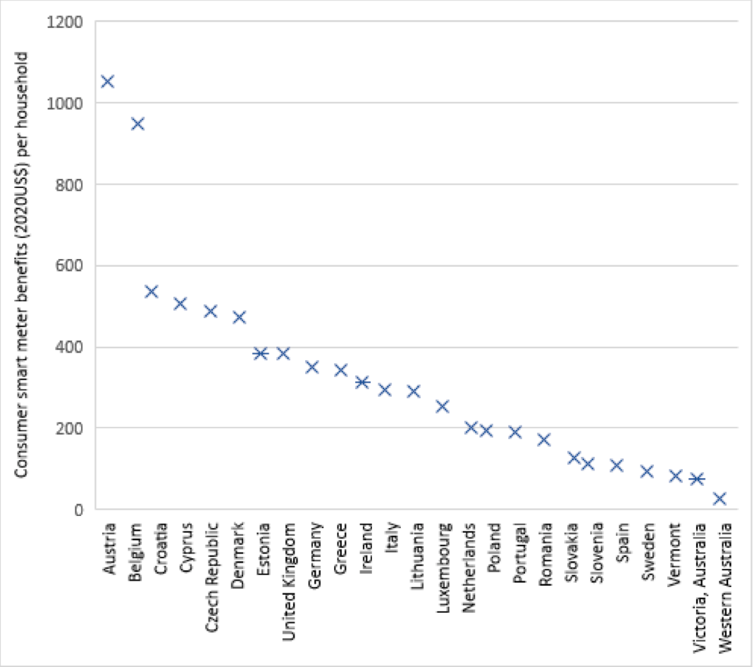


Fig. 4. (*continued*).

push for smart meters within the country.

In the United States, smart meters were similarly seen by state and national planners as a way to achieve essential grid updates, especially following the August 2003 blackout spreading from Ontario, Canada throughout the entire Eastern Seaboard of the United States, cutting off power from 45 million people in eight U.S. states. As a response, federal and state policy backed the adoption of smart meters and time-based electricity tariffs, with strong support from the Federal Energy Regulatory Commission (at the interstate level) as well as the Energy Infrastructure and Security Act of 2007 (the formal response to the 2003 blackout), the Emergency Economic Stabilization Act of 2008 and the American Recovery and Reinvestment Act of 2009 (Strong, 2019; Bugden and Stedman, 2019; Frickel et al., 2017). The Recovery Act in particular launched the Smart Grid Investment Grant program that disbursed over $2 billion in subsidies to 81 utilities leading to the installation of more than 16 million smart meters across the country at the start of the program (Strong, 2019). Smart meters lastly had the benefit of entering a national electricity market that had already promoted net metering, a sort of precursor to smart metering that positively affected adoption.

Canada, Japan, and parts of Europe have seen more moderate deployment of smart meters. In Canada, much like the United States, "the blackout affected Ontario significantly and raised concerns about the electricity system's reliability" and led to momentum to invest in smart meters and smart grids (Winfield and Weiler, 2018), although as we will see in Section 4.3, their approach to deployment was notably different than the United States, resulting in slower (comparative) diffusion. Japan, known for already having a modernized grid and $100 billion invested in grid updates and demand side management in the 1990s (U.S. Energy Information Administration, 2011), represented a natural home for smart meters but also a market that has been relatively stable or stagnant (depending on perspective). A great diversity of policy

Table 2

Depictions of shifting positive, negative, and neutral or unknown cost-benefit analyses for smart meter programs (using most recently available data).

Location	CBA positive	CBA negative	CBA unknown
Austria	2010	2010	N/A
Belgium	2017	2013	N/A
Cyprus	N/A	N/A	2014
Hungary	N/A	N/A	2018
Luxembourg	2013	2016	N/A
Norway	N/A	2007	2011
Portugal	2015	N/A	2012
New Zealand	N/A	N/A	2009
Connecticut	2011	2011	N/A
Victoria, Australia	2005	2011	N/A

architectures and fragmentation within and between member states of the European Union contributed to inconsistent diffusion rates there (European Commission, 2019). Some countries such as Spain, United Kingdom, and France have installation rates in the millions to tens of millions; whereas other countries such as Ireland, the Czech Republic and Belgium have rates close to zero.

India has been a comparative laggard, with several pilots and emerging projects signaling that near-future expansion is likely (Chawla et al., 2020). Even though the Electricity Act of 2003 and National Energy Policy of 2005 discussed national objectives of improving grid reliability and quality and protecting consumer interests (U.S. Energy Information Administration, 2011), far more effort has been invested in energy supply and attempts at expanding access to conventional forms of energy for cooking (Stephenson et al., 2021)—not smart meter diffusion, although some socially situated instances are evident (Kumar, 2019).

4.2. Economics, costs and benefits

Our data revealed a rich variance of total and unit costs for national and sub-national programs, which we explored at various angles.

For the 39 programs we had detailed budgets on (adjusted to US $2020 to enable like-for-like comparison), and not taking into account the different types of meters involved or local program cost differences including taxes, the three most expensive programs (for the entire rollout) were China ($46.2 billion), India ($21 billion) and United Kingdom ($17.8 billion), although we were not able to find aggregate numbers for the United States. Most programs, as Fig. 4 indicates (Panel A), were in the range of $3 to $5 billion. Most meters are also projected to cost between $150 and $380, inclusive of hardware, program costs, installation, and overheads, with some exceptions of expensive meters in Austria (more than $980) and Israel (more than $850) or cheaper meters expected in Germany ($36, based on future projections) or Spain ($51). Note that we are presenting results from these CBAs at face value, we are not normalizing or correcting for how such assessments may differ in their valuation processes, methodology, or issues such as national electricity prices or subsidies.

Panel C of Fig. 4 suggests that most programs will deliver $100 to $400 in cumulative consumer benefits, at least over their entire lifetimes and for the 25 smart meter programs we had data for. Panel D of Fig. 4 plots expected consumer benefits over the lifetime of the programs, with some as high as $1050 (for Austria), but others as thin and low as $28 (for Western Australia), and this is excluding negative CBAs. However, a few others gave large estimates of benefits conflated as a single figure, such as the UK suggesting £1.2 billion per year overall or one CBA of Germany at €1.6 billion in benefits over 20 years, still less than the costs. Some CBAs discussed a subsample of these benefits to energy suppliers, rather than consumers, e.g. California projecting a net benefit of $30.6 million over 10 years, or Connecticut estimating benefits between plus or minus $392 million over a 20 year period, or an average plus of $87 million. The state of New York disclosed network benefits of $1.15 billion over 10 years.

We were able to find cost-benefit analysis (CBA) data for 35 programs, although confusingly, in 10 national programs, CBAs changed over time from positive to negative, or were stated to be unknown (see Table 2). Some countries such as Germany or the United Kingdom also had multiple CBAs conducted, with varying results and assumptions. Going with the most recent CBA available, and removing the unknowns and contested CBAs where both positive and negative CBAs are given for the latest year of data available, 23 programs reported being CBA

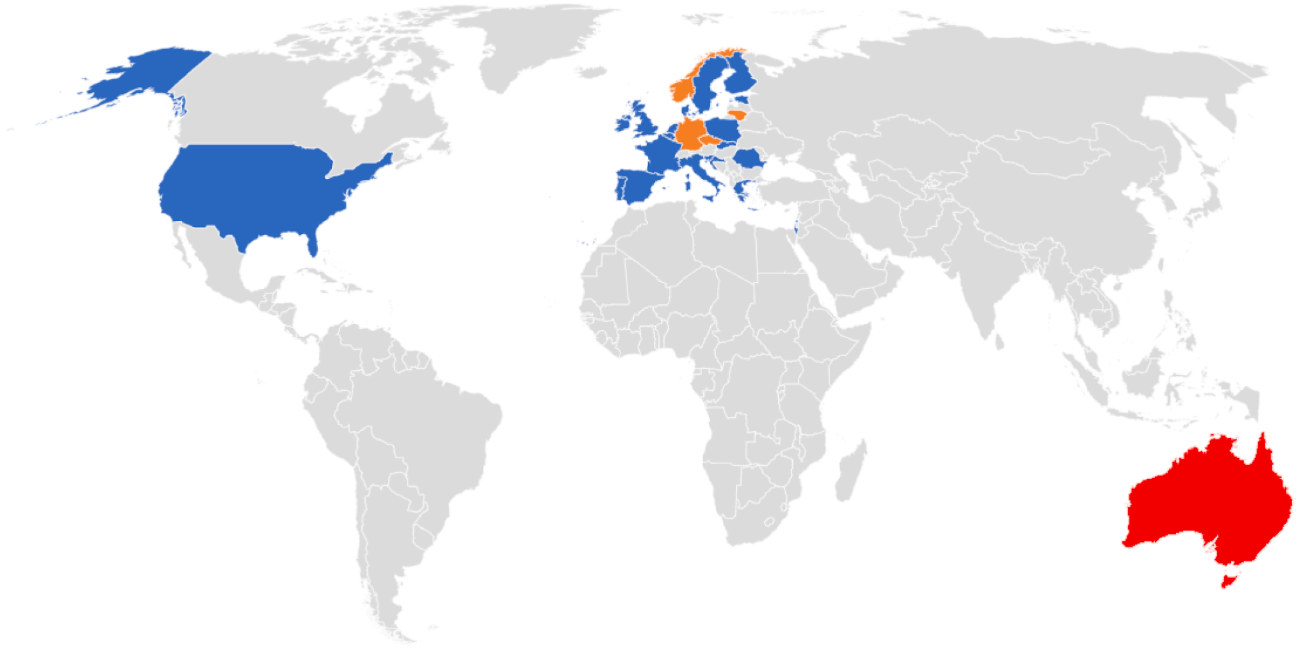


Fig. 5. A global depiction of cost-benefit positive (blue), negative (orange) or neutral/mixed (red) smart meter programs. *Source:* Authors. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

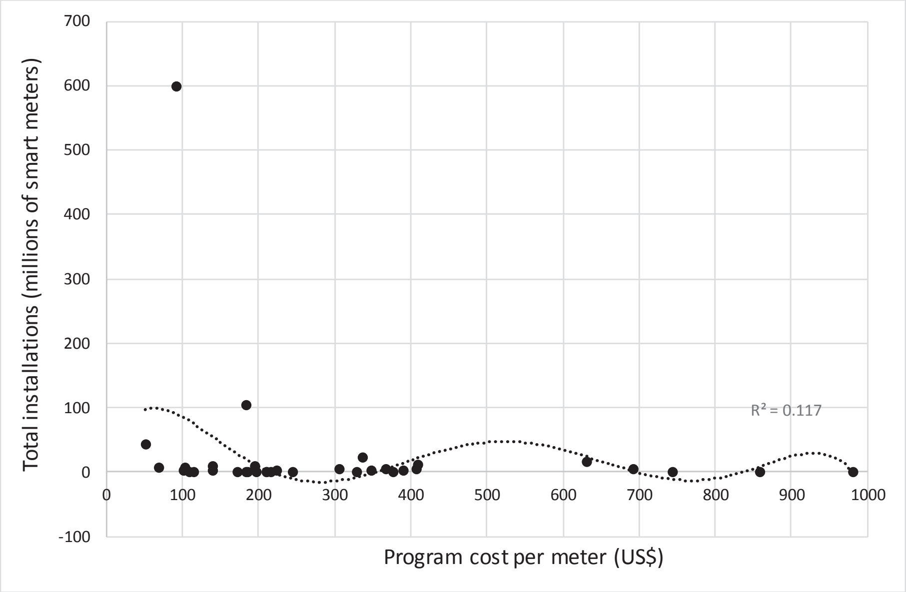


Fig. 6. Smart meter adoption and program cost (n = 34) Source: Authors. Note R^2 has been adjusted to account for polynomial variance.

positive (see Fig. 5), but 6 reported being CBA negative. Nevertheless, most CBA analyses are positive, and the implication is clear that smart meters have net positive CBA in far more countries than not.

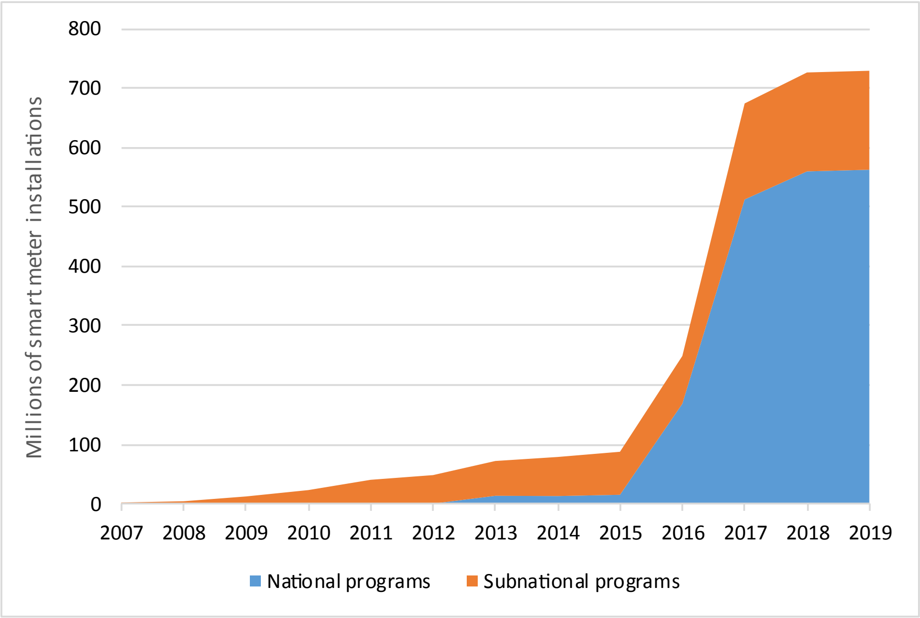
Interestingly, when one plots both adoption *and* cost, one might think that more rapid adoption might be more costly, but the data does not support this contention. Instead, it seems that a more rapid roll out is more efficient and better organized. For the 34 programs we had sufficient data for, removing those that had no installations or missing cost or diffusion data, there is no meaningful relationship and a small effect size ($P = 0.29$, $t = -1.07$, $R^2 = 0.117$) on the relationship between total installations or program cost (see Fig. 6 as well as Data Table A3). This trend is definitely impacted by one of the most significant programs (China, 469 million smart meters) also being relatively inexpensive (less than US$100 per installed meter), perhaps because the Chinese program did not include IHDs. Mah et al (2017) argue that limited features have not enabled effective dynamic pricing and web-based data visualization. Nonetheless, some of the cheaper programs (per unit) have the highest diffusion rates. Does this mean that some costs are “hidden” from the balance sheets? Or could it indicate that China, due to its involvement in manufacturing, has gained a significant advantage on cost for its smart meter rollout, and that the equipment has more limited functionality to reduce associated costs? These are important but understudied aspects.

As perhaps to be expected, the types of expected benefits to be achieved or secured by smart meters vary by national context. In China, the emphasis has been on grid modernization and thus benefits to grid operators, especially incumbents (see more on this in Section 4.3). China already had established comprehensive digital network coverage and erected an integrated power communication network service that were seen as complementary and interoperable with smart meters (Yu et al., 2012). In the United States, smart meter benefits have been centered on energy efficiency and enhanced grid management. This contrasts with Canada, where smart meters have been promoted more on environmental grounds, along with the European Union, where smart meters are often pitched as a key enabler of carbon reduction (European Union (2012); more on this in Section 4.4). In Japan, smart meters have been seen as a way to deliver benefits to industry and technology firms, with a strategy “focused on connectivity, energy efficiency, and the integration of renewable resources into the grid, as well as concerns regarding sustainability and reduction of carbon emissions” (U.S. Energy Information Administration, 2011: 44). Whereas in India, more emphasis has been on theft prevention and protecting energy suppliers (U.S. Energy Information Administration, 2011), a feature that may explain why diffusion there has been slower, given the lack of an emphasis on consumer benefits.

One of the key drivers of the cost and performance of smart meters has been policies and regulations that focus on cost effectiveness. These have undoubtedly made smart meters attractive investments for many critical stakeholders. Strong (2019) intuitively notes that utilities will embrace smart meters only if benefits exceed costs. Nevertheless, the costs of deploying them are not insignificant, as they involve hardware and software costs as well as installation, project management, adjustment, integration, and maintenance. To put this into perspective, the cost of the actual smart meters constitutes only about half of the cost of an entire AMI system at utility scale. Milam and Venayagamoorthy (2014) note how in the United States, the federal government ran a Smart Grid Investment Grant program that began in 2009, one that covered up to 50 percent of the costs of smart meter projects with a grant. This mobilized literally hundreds of utilities to embark on smart meter projects that could not otherwise afford them, and to implement them very quickly. And even when utilities had to bear the cost of implementing upgrades to their digital and communication networks, and advanced metering systems, these tended to pay for themselves quickly through cost savings associated with greater insight into outages, decreased outage response time, reduced meter tampering, faster resolution to theft of service, operational savings, and an increase in operational efficiency. We will return to discussing some of these additional benefits in Section 4.5.

4.3. *Governance and management*

We examined how smart meter programs were governed and managed and analysed if there was any possible connection between this and adoption speeds and cost dynamics. In terms of actors involved in rollouts, we had data linked to two dimensions: scale of implementation (national or subnational), and number of actors, notably energy suppliers, transmission operators, and distribution operators. For the first, we had data on the scale of a program for 101 programs (Argentina was missing), and we looked at diffusion trends across them in terms of national vs. subnational deployment. National programs bring volume, as visible in Panel A of Fig. 7, and account for most installations (77.2% for national compared to 22.8% for subnational). As Panel B of Fig. 7 reveals, for the 38 programs we had data on, national deployment tends *a. Smart meter diffusion by national or subnational scale of implantation (n=101)*



b. Smart meter costs per unit for national vs. subnational programs (n=38)

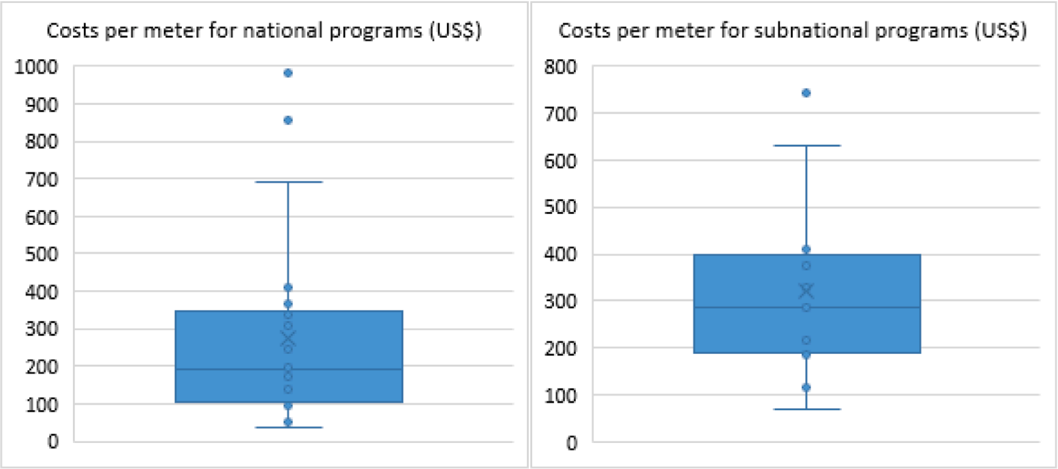


Fig. 7. Smart meter diffusion by scale and cost. *Source:* Authors.

to be cheaper, likely due to economies of scale, given that national level programs have an average cost of an installed meter at $252 (in 2020US$) compared to subnational programs that cost $321.

However, while they may be more expensive and prone to smaller total volumes, sub-national programs seem to have the highest rates or bursts of accelerated diffusion. When we break diffusion rates (number of installations) into very detailed % increases per year (see Data Table A4), there are some very rapid “bursts” (one year seeing huge increases). Although often moving from a small number of initial units, all of the top 20 fastest annual changes are *all* in subnational programs, led by Vermont (279387%, in 2011), Utah (248400%, in 2007), Rhode Island (200173%, in 2016), and Louisiana (179750%, in 2007). Interestingly, these rates are never sustained for more than a few years, and they almost always involve programs just starting up. This implies the most accelerated growth rates for installations are in the beginning when growing from smaller numbers, but that once you have higher numbers, such growth rates are difficult to sustain. As mentioned earlier, the smart meter roll out led by electric utilities in the U.S. were largely driven by a federal matching fund - the Smart Grid Investment Grant (SGIG) under the American Recovery and Reinvestment Act. This is probably why we see dramatic increases of smart meter adoption in subnational smart meter programs in the U.S. for only a short time period.

We lastly investigated the number of actors involved in smart meter programs, in this case calculated as the number of energy suppliers, utilities, transmission network operators, or distribution companies (see Fig. 8). We hypothesized that the greater the number of actors, the greater the possible “lag” in fast rates of adoption, given there is a greater chance for fragmentation, complexity, duplication, and miscommunication. Nevertheless, after removing countries where we could not establish the number of actors or those that had no installations yet, for the 40 countries or programs we could examine, we found almost no effect or significant relationship ($P = 0.60$, $t = -0.52$, $R^2 = 0.0071$) between the two. This suggests both centralized and bottom up multi-actor programs or electricity markets see almost the same rate of smart meter diffusion. Note that as a limitation here, we did not assess the *quality* or specific type of actor(s), or who the lead actor was, as these varied across many programs and in other cases were unidentifiable, or the role they played. Instead, in line with the thinking about polycentrism and the numbers of diverse institutions involved (see Section 3.3), we assessed only the *quantity* of actors.

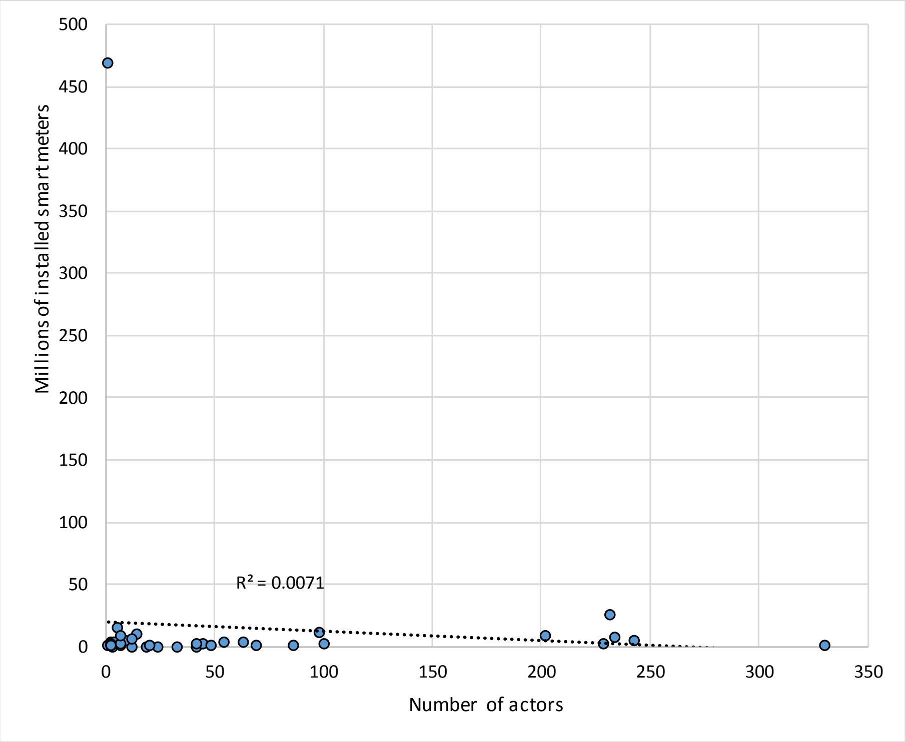


Fig. 8. Smart meter adoption and number of actors in the electricity market in 2019 (n = 40). *Source:* Authors.

As with our other Results, governance and management are strongly shaped by context-specific institutional factors. China, despite being a world leader now, was a relative latecomer to smart meters, benefiting (and learning) from experiences in Europe and North America. In essence, their strategy can be caricatured as one of waiting and watching, before China pushed its state owned utilities to implement an aggressive national program. The State Grid Corporation of China (SGCC) only announced its three-stage smart meter program in 2009 (Mah et al., 2017). Yet even as a latecomer, by 2010 they had "leap-frogged" to surpass the United States in total smart meter and grid expenditures, which exceeded $100 billion (Mah et al., 2017). China has also been able to harness an incumbent-led model of deployment, steered almost entirely by two key actors: the SGCC (which has 88% of the national power market) and China Southern Power Grid Company (another 17%). This incumbent-led model was seen to offer numerous advantages, given such incumbents had the technical expertise, financial resources, and external networks to successfully steer diffusion (Mah et al., 2017; Yu et al., 2012). The two incumbents also oversee power generation, transmission, distribution, and retailing, giving them control over the entire supply chain, as well as the ability to set technical standards, which they did finalize for smart meters in 2011. The incumbents used this authority to implement massive numbers of pilot projects subsidized by the state; from 2008 to 2010, for example, the SGCC alone sponsored 228 smart meter pilot projects covering 21 technological categories (Yu et al., 2012).

The United States also saw their smart meter transition receive large support and buy-in from incumbents, notably investor owned electric utilities, who viewed smart meters as an important way to manage demand, avoid costly grid updates, and implement time of use rates. Given these investor owned utilities were often much larger than cooperatives or municipal utilities, they (as in China) had the resources to steer and shape smart meter diffusion. Smart meters therefore became instrumental to utility portfolio planning and began to be implemented at scale in almost all states as a way to enhance automation of meter reading and billing, and improve the operational management of the distribution grid (Zhou and Matisoff, 2016). Furthermore, the United States was a strong creator and backer of emergent smart meter standards, introducing state of the art (and later globally adopted) standards for smart meter performance criteria (2008, 2009, and 2012), firmware upgradability (2009), and interoperability (2008 and 2012) (Strong, 2019). Intermediary actors such as the Federal Energy Regulatory Commission (a federal institution), the Electric Power Research Institute (an industry trade body), and the National Energy Technology Laboratory (one of the Department of Energy's national laboratories) put their additional support behind smart meter deployment. In addition, the individual states facilitated smart meter diffusion further through major changes to regulatory frameworks and legal codes—by 2011, for example, all 50 states had enacted a combined 247 changes to law and regulation to facilitate smart meter expansion (Frickel et al., 2017).

In contrast to the United States, municipally owned local distribution companies or national utilities such as SaskEnergy or Hydro Quebec (2017) primarily led smart meter efforts in Canada. Even though these initiatives were catalyzed by the same 2003 blackout that prompted American investment, the Canadian model did not utilize vertically integrated utilities (Winfield and Weiler, 2018). This perhaps slowed diffusion efforts comparatively given the lack of resources and reach these municipal utilities had. In the European Union, rather than come to an agreement or alignment about smart meters, incumbents appeared split and more strategically opposed. Erlinghagen and Markard (2012) note how in Europe, although in 2011 more than 800 actors were involved in smart grid projects (most of them related to smart meters), these tended to be split into information and communication technology firms (selling smart grid technology) and energy utilities (selling energy, electricity, or energy services). Rather than always cooperate, sometimes these two different groups of incumbents strategically opposed each other and sought to protect their own markets and domains of intellectual property. Japan executed a notably different deployment pattern of formal partnerships. The government via the Ministry of Economy, Trade, and Industry (METI) established the New Energy and Industrial Technology Development Organization (with important members of industry) to oversee smart grid development as well as the Japan Smart Community Alliance, a public private partnership intended

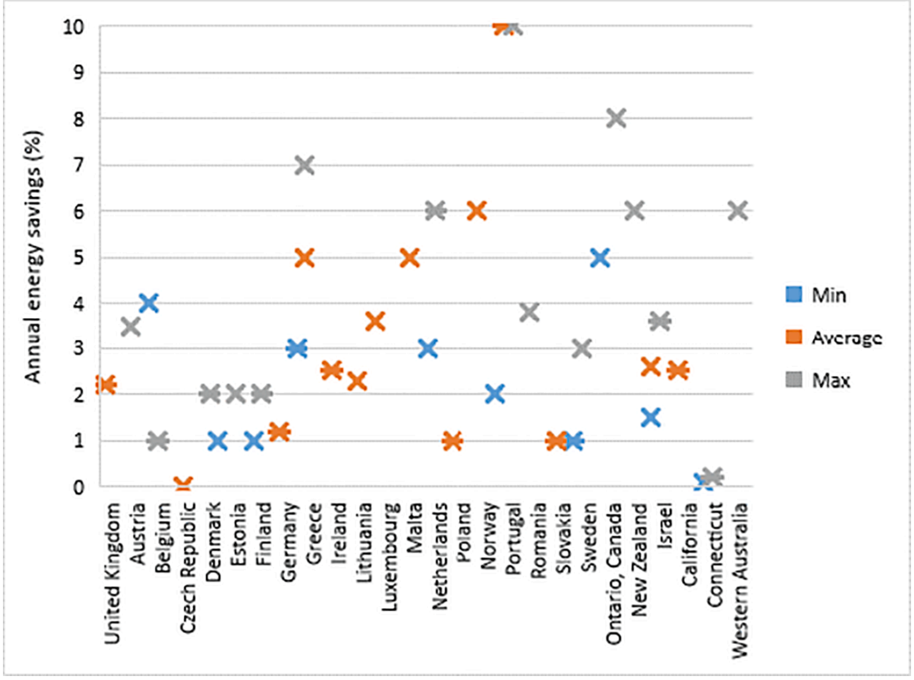


Fig. 9. Estimated *ex ante* energy savings (%) associated with smart meter programs 2008–2019 (n = 26). *Source:* Authors. *Note:* New Zealand and Western Australia estimates presume smart meters are coupled with demand response. Diagram depicts the expected average energy savings achieved over the lifetime of each smart meter program, even if in practice savings could increase or decrease over time. Many of the potential energy savings relating to smart meters require additional reforms (to electricity markets, settlement processes to enable real time pricing, etc.) and therefore many assessments tend to focus on more immediate awareness/behaviour changes in households. For more on the transformative effects of smart meters, see Section 4.5.

to spur smart meter standardization (U.S. Energy Information Administration, 2011). Its model thus was a mix or balance of state and corporate interests.

Lastly, India perhaps shows what happens when the inverse of an incumbent led model occurs. India pursued yet another path largely driven by the government via the Ministry of Power, the Central Power Research Institute, the Central Electric Authority, and the Power Finance Corporation (U.S. Energy Information Administration, 2011). It was these entities that created a Smart Grid Task Force (SGTF), but this Task Force remained almost entirely governmental. The India Smart Grid Forum, which involved utilities and other interested groups, was seen as largely subordinate to government efforts (Sinha et al., 2011). In 2016, the National Smart Grid Mission became operational, as a move to more coordinated smart grid governance.

4.4. Energy and climate sustainability

Both the literature on smart meters as well as many of the national CBAs of smart meter programs we examined stated high hopes (and ambitions) for their ability to cut greenhouse gas emissions or energy consumption.

However, we discovered that finding robust estimations of energy savings is a weak spot for the literature, and only *one* program discussed or quantified potential emissions reductions. We were able to find energy savings estimations for only a smaller subset of 26 programs (roughly a quarter), and of these, no rollout came with any sort of “rider” about an ex-post analysis. All of these CBAs came in advance of a rollout (*ex ante*), with only a few being updated during a rollout, none have been completed after a rollout (*ex post*), with sobering implications for determining whether any carbon savings or for that matter any consumer benefits were in fact delivered. For the CBAs we did examine, most did not give a range or sensitivity of estimates, only 10 programs gave minimal estimates and 14 studies maximum estimates (see Fig. 9). The largest expected savings are at a maximum in Greece (7%), Ontario (8%) and Portugal (10%), with a mean of 3.2% across the averages of the studies with a minimum of 0.1% .

Furthermore, the numbers provided for annual energy savings are much higher than independent *meta*-analyses in the peer reviewed literature. Meta-studies of energy feedback that take into account sample size and methodological inconsistencies of earlier studies report savings effects in the range of only 0–4% (McKerracher and Torriti, 2013; Buchanan et al., 2015). Sovacool et al. (2017) qualitatively reviewed European smart meter programs and pilots, and noted reported household energy reductions of 0.9% to 11% (for electricity and/or natural gas), but the bulk of these estimates were less than 5%.

We found even less evidence on the carbon savings associated with smart meter programs. Only *one* formal CBA found mentioned carbon, and that was the 2019 version for the UK (BEIS, 2019), which stated that “For electricity, reductions in energy use will mean the UK purchasing fewer (or selling more) allowances from the current EU ETS. We estimate a reduction in traded carbon emissions of 11.2 million tons, which accounts for a monetary benefit of approximately £320 m. For gas, the value of carbon savings from a reduction in gas consumption uses the non-traded carbon prices under the Government’s carbon valuation methodology. We estimate a reduction in non-traded carbon emissions of 23.2 million tons, which accounts for a monetary benefit of approximately £1.3bn.” This is clearly an area in need of more attention, data, and research.

Although China did not have a formal CBA for its smart meter program mentioning energy savings, evidence suggests the potential for more significant savings. Given very rapid growth in electricity demand and the nature of their grid, China offers perhaps some of the largest potential for capturing energy savings and cutting energy bills via interventions such as smart meters. In the decade preceding the launch of China’s smart meter program, for example, annual growth rates in electricity demand averaged 8.5 to 11% (Yu et al., 2012; Zhang et al., 2017). To put this into perspective, from 1980 to 2009 (the start of their program), annual electricity demand in China grew more than 12-fold, from 300 to 3660 TWh (Yuan et al., 2012). Such growth created opportunities or at least hopes to deploy smart meters to enable remote energy management applications of smart phones and personal computers to allow residents to access household energy consumption data “in a more efficient and comfortable manner” (Wang et al., 2020). Indeed, real-time empirical data in Shanghai has shown that smart meters with IHDs could lead to approximately a 9.1% reduction in monthly electricity consumption and about 11% reduction in monthly electricity bills (Zhang et al., 2019).

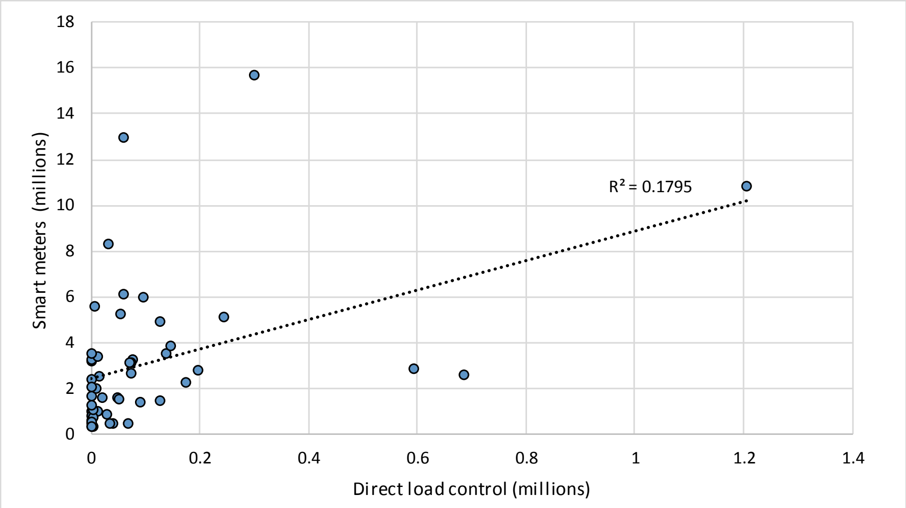
Such high energy (and consequent emissions) savings seem the

Table 3
Linkages between national smart meter programs and other innovations (N = 63).

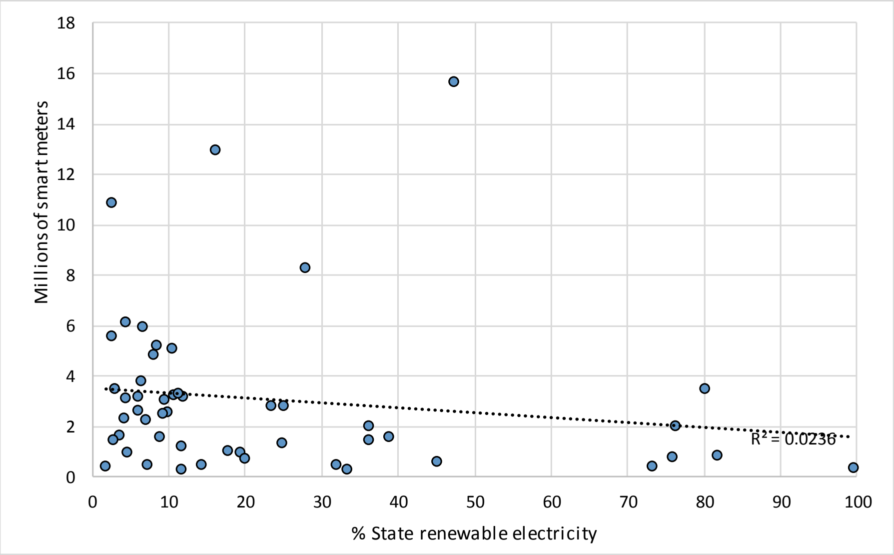
Location	Renewables	Prosuming	EVs	Community ownership	Theft prevention	IoT	Time of Use Pricing	Real-time/ hourly pricing	Critical peak pricing	Remote disconnection
United Kingdom	+	+	+	+	+	+	+	+		+
Austria	+	+	+	+	+	+	+	+		+
Belgium	+				+		+	+		
Croatia	+	+	+	+	+		+	+		+
Cyprus	+	+	+	+	+					
Czech Republic	+	+	+	+	+					
Denmark	+	+	+	+	+	+				
Estonia	+	+	+	+	+	+	+	+		+
Finland	+	+	+	+	+	+	+	+		+
France	+	+	+	+	+		+	+	+	+
Germany	+	+	+	+	+					
Greece	+	+	+	+	+	+	+	+		+
Hungary	+	+	+	+	+		+	+		
Ireland	+	+	+	+	+	+	+	+		+
Italy	+	+	+	+	+	+	+	+		+
Lithuania	+	+	+	+	+		+	+		+
Luxembourg	+	+	+	+	+	+	+	+		+
Malta	+	+	+	+	+					
Netherlands	+	+	+	+	+	+				
Poland	+	+	+	+	+	+	+	+		+
Norway	+	+	+			+	+	+		
Portugal	+	+	+			+	+			+
Romania	+				+	+	+	+		+
Slovakia	+				+		+	+		+
Slovenia	+	+	+		+	+		+		+
Spain	+	+	+		+	+	+	+		+
Sweden	+	+	+	+	+	+	+	+		+
Ontario, Canada	+	+	+			+	+	+	+	+
BC Hydro, Canada	+	+	+			+	+	+	+	+
NB Power, Canada	+	+	+			+	+	+	+	+
Nova Scotia Power, Canada	+	+	+			+	+	+	+	+
Quebec, Canada	+	+	+			+	+	+	+	+
SaskPower, Canada	+	+	+			+	+	+	+	+
Mexico	+		+		+	+	+	+	+	+
Chile	+		+		+	+	+	+	+	+
Colombia	+		+		+	+	+	+	+	+
Uruguay	+		+		+	+	+	+	+	+
Brazil	+				+	+	+	+	+	+
Argentina	+		+		+	+				
New Zealand	+	+	+			+	+	+	+	+
Singapore	+		+		+	+				
Malaysia	+		+		+	+				
Israel	+		+		+	+				
South Korea	+				+	+	+	+	+	+
China	+		+		+	+	+	+	+	+
Japan	+		+		+	+	+	+	+	+
India	+	+	+		+	+	+	+		
South Africa	+				+					
Thailand	+		+		+	+	+	+		+
Russia	+				+	+				
Arizona	+		+		+	+	+	+	+	+
California	+	+	+		+	+	+	+	+	+
Connecticut	+	+	+		+	+	+	+	+	+
Massachusetts	+	+	+		+	+	+	+	+	+
Maryland	+	+	+		+	+	+	+	+	+
New York	+	+	+		+	+	+	+	+	+
Pennsylvania	+	+	+		+	+				
South Carolina	+		+			+	+	+	+	+
South Dakota	+		+			+				
Vermont	+		+		+	+	+	+	+	+
West Virginia	+		+		+	+				
Victoria, Australia	+	+			+	+	+	+	+	+
Western Australia	+	+			+	+				
Totals	**63** **100.0%**	**40** **63.5%**	**54** **85.7%**	**20** **31.7%**	**52** **82.5%**	**52** **82.5%**	**46** **73.0%**	**46** **73.0%**	**25** **39.7%**	**42** **66.7%**

Source: Compiled by the Authors, with a + sign indicating that a particular innovation was mentioned explicitly in one of the primary sources for our dataset shown in Table 1.

a. Smart meter installations and direct load control in the United States (n=50)



b. Smart meter installations and renewable energy mix (including hydro) in the United States (n=50)



c. Smart meter installations and renewable energy mix (excluding hydro) in the United States (n=50)

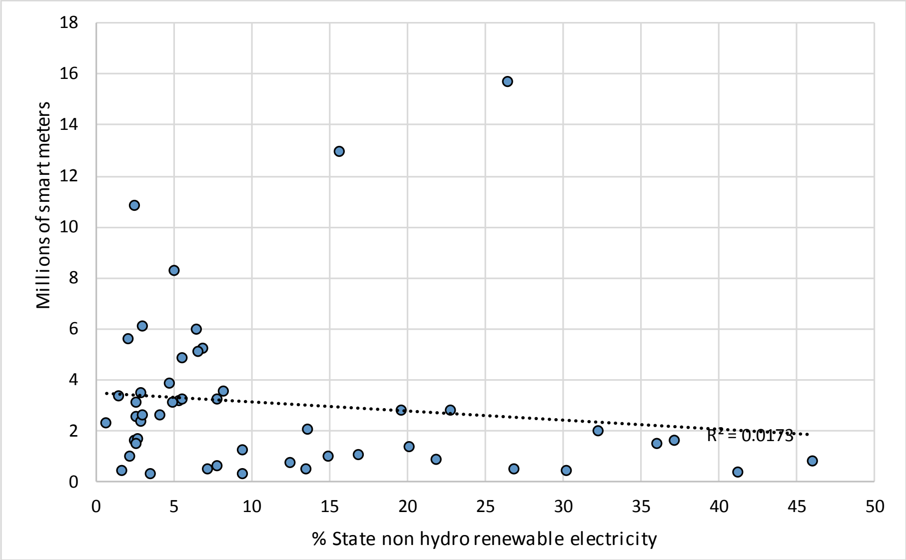


Fig. 10. Correlations between smart meters and load control, fossil fuel mix, and renewable electricity in 2019 *Source:* Authors. All smart meter data comes from our dataset. All electricity data and load control data have been redrawn from 2019 data provided to the authors by the U.S. Energy Information Administration. Renewable energy in some states may be driven by stringent renewable portfolio standards or other renewable energy policies, not necessarily by smart meter roll outs. Smart meter counts and carbon emissions/electricity generation are likely correlated with state population.

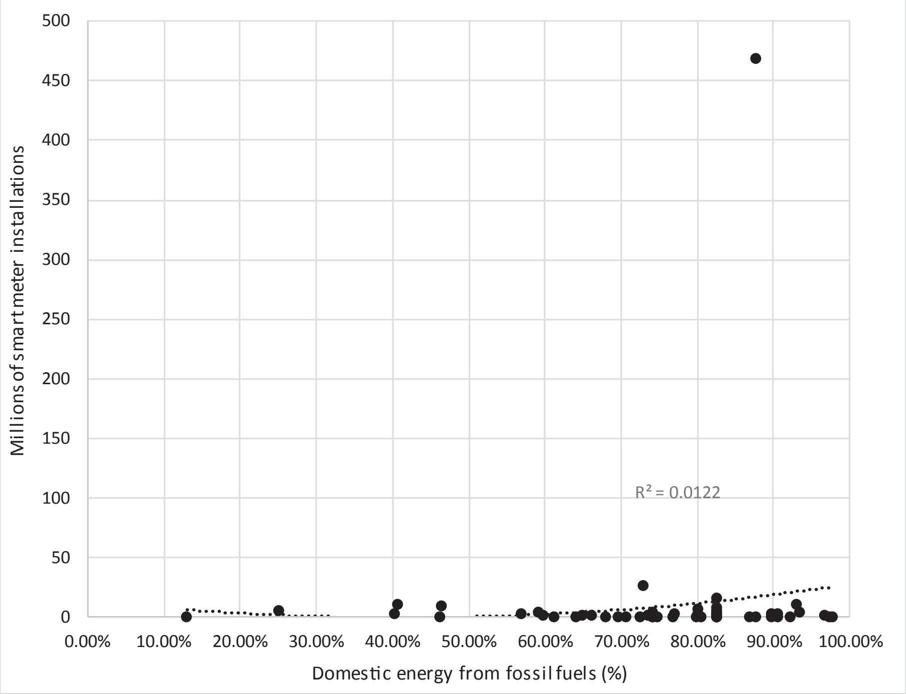


Fig. 11. Smart meter installations and fossil fuel mixes across global programs (n = 57). *Source:* All smart meter data comes from our dataset.

exception, not the rule, however. Agee et al. (2021) offer one explanation for why. Collecting longitudinal data from smart meters in the United States, they noted that over time people tend to engage less with (and perhaps care less for) their smart meters, especially those who are elderly, a rapidly growing part of the population. Bugden and Stedman (2019) reach similar findings and have found in their surveys in the United States that ratepayers are often unfamiliar with smart meters and their benefits, have ambivalent or negative attitudes toward them, and may outright oppose their use. Some of the literature in Section 3.4 also noted that the social acceptance of smart meters and grids *decreases* over time. All of these could explain why the energy and climate sustainability benefits of smart meters are not greater than they are.

4.5. Transformation and catalyzing other transitions

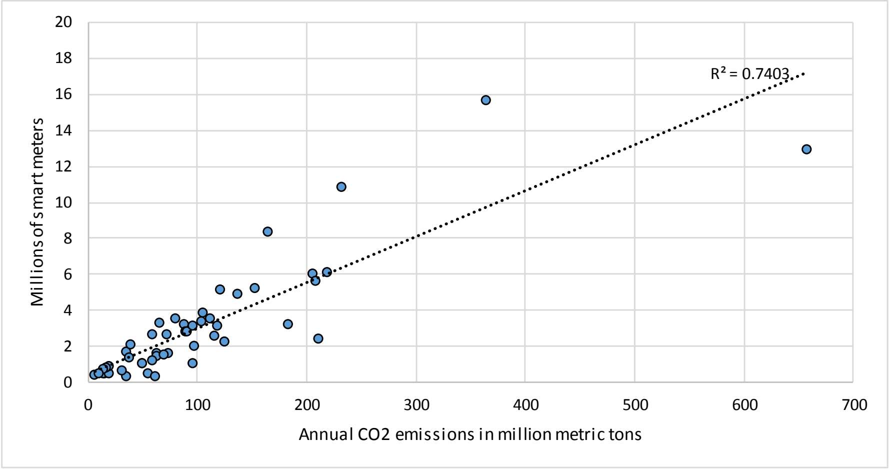
We lastly looked at transformation, or the degree to which smart meters were aligned with other low-carbon technologies or trends or innovations in pricing. This theme also connects with discussions of fossil fuel incumbency and disruption, namely whether smart meters are viewed as technologies complementary to existing firms and markets, or ones that threaten to compete with them.

As Table 3 highlights, for the 63 programs we were able to find data for, *all* of them claimed—in official project documents, or press releases or media reports—to be supportive of renewable energy, and a strong majority reported connections with prosuming (63.5%), electric vehicles (85.7%), theft prevention (82.5%), Internet of Things co-evolution (82.5%), time of use pricing or hourly pricing (73%), and remote disconnection (66.7%). About a third (31.7%) claimed associations with community energy, and 39.7% claimed associations with critical peak pricing. Many of these connect with the economic rationales behind promoting smart meters mentioned in Section 4.2.

However, although smart meter program materials and CBAs may mention these linkages, in practice they seem more difficult to validate. The only exception to this trend of coupling innovations with smart meters is direct load control (people giving control over appliances or household devices to a utility) . When examining a subset of our dataset on the United States (which featured data on both smart meters and load control for all 50 states), we can say with a high degree of confidence that smart meters enable or correlate strongly with load control, with a statistically significant (almost very significant) effect of a medium size ($P = 0.0021$, $t = 3.24$, $R^2 = 0.1795$) (see Panel A of Fig. 10, as well as Data Table A7).

Secondly, as also indicated in Figs. 10 and 11, smart meters appear to have a weak connection with fossil fuel regimes. Oddly, Panels B and C of Fig. 10 reveal that states with a higher share of renewable electricity in their overall mix have fewer smart meters, which contradicts the assumed positive correlation mentioned in much of the literature—with a small effect size—and this holds true for both renewables as a whole (including hydroelectricity) ($P = 0.29$, $t = -1.07$, $R^2 = 0.0236$, see Data Table A9) as well as non-hydro sources (such as wind and solar) ($P = 0.36$, $t = -0.91$, $R^2 = 0.0173$, see Data Table A10). Fig. 11 presents diffusion and fossil fuel mix data for 57 countries, and only shows a small relationship ($P = 0.48$, $t = 0.69$, $R^2 = 0.0122$) between the fossil fuel supply (as a % of total energy supply) and smart meter installation rates (see Data Table A8).

Thirdly, and finally, we see a surprising relationship between both carbon emitters and large electricity markets and smart meters. In both cases, the larger the proportion of total greenhouse gas emissions that come from an electricity sector, the more likely it is to install smart meters. Similarly, the larger the overall size of the annual electricity supply (GWh), the higher the proportion of smart meters that have been installed. Here, we find consistently strong and highly significant relationships. As Fig. 12 indicates, when annual carbon dioxide emissions are plotted along with the installation of smart meters in the United States, a large effect of very high significance is observed ($P = <0.00001$, $t = 11.7$, $R^2 = 0.7403$, see Data Table A11). This is likely shaped significantly by the fact that California and Texas have large populations, the largest number of smart meters installations in the country as well as the largest aggregate carbon dioxide emissions. We also find very strong correlations—for the United States as well as the entire dataset—between the size of an electricity market and smart meter diffusion, implying that places that use more electricity install more smart meters. In Figs. 12 and 13, we see a strong effect that is very statistically significant between total annual electricity (in GWh) and smart meter installations for the United States ($P = <0.00001$, $t = 11.7$, $R^2 = 0.7407$, see Data Table A12) as well as for 47 national countries *a. Smart meter installations and total carbon dioxide emissions in the 50 United States (n=50)*



b. Smart meter installations and size of the annual electricity market (in GWh) in the 50 United States (n=50)

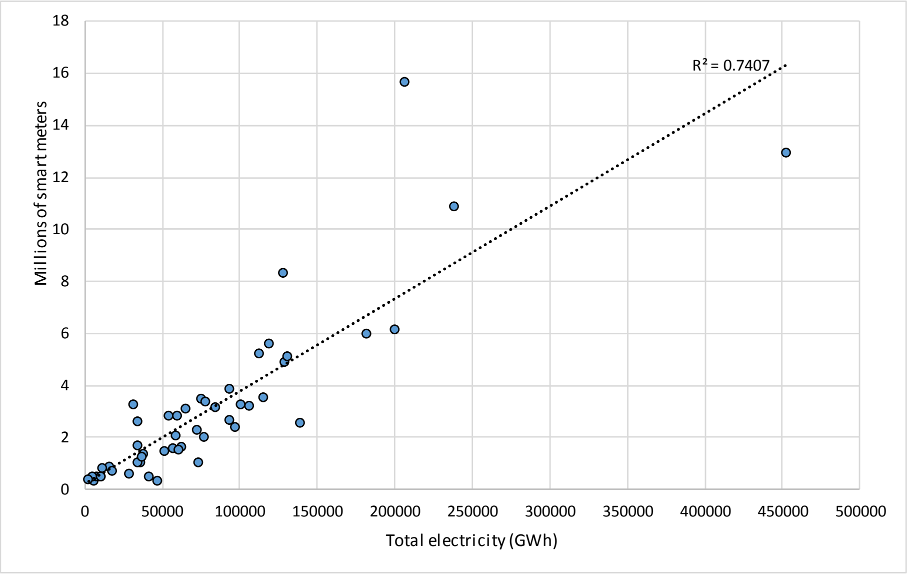


Fig. 12. Correlations between smart meters, carbon dioxide emissions, and electricity market size in 2019 (in GWh) in the United States. *Source:* All smart meter data comes from our dataset. Renewable electricity data comes from the United States Energy Information Administration's *Electric Power Monthly*, carbon dioxide emissions come from the CIA's *World Fact Book*.

which we had data on ($P = <0.00001$, $t = 19.1$, $R^2 = 0.8909$, see Data Table A13).

What may explain these trends? Population density, and how it correlates strongly with the size or number of electricity customers and households, clearly plays a role. It could be that smart meters are deployed in electricity markets with more greenhouse gas emissions precisely because it is hoped they can start to bring emissions down, though as we noted earlier inSection 3.4, we did not always find compelling evidence of a link between deployment and carbon emissions reductions. It could also perhaps be that smart meters are a useful tool at helping incumbent fossil fuelled, carbon intensive regimes—-primarily in large electricity markets—utilize smart meters in ways that benefit them, such as through remote disconnection (present in 43 programs, see Fig. 14), or innovations in hourly or time of use pricing (present in 46 programs, see Fig. 14). What is not apparent is whether smart meters are being used primarily for transmission or system upgrades, which would benefit energy firms and incumbent regimes directly. It is possible that these benefits accrue further down the line through enablement of smart grids on preferred terms for incumbents with dominant positions in electricity distribution sectors, but our dataset cannot provide insight into this future development. From the data we collected on smart meters in the United States, which disaggregate them by type, of the 154.07 million meters we tracked, 87.5% of them are for residences and households, only 11.9% are for commercial enterprises, and far fewer are for industrial facilities (0.5%) or transmission operators (0.002%).

Finally, our findings buttress an emerging body of evidence all suggesting that smart meters may not be as transformative as envisioned. Mallett et al. (2018) note that the mainstream media in the United States tends not to discuss the consumer empowerment elements of smart meters and grids, focusing instead on commercial opportunities for private sector actors. Meadowcroft et al. (2018) frame smart meters as a site of negotiation and contestation, rather than transformation, one where utility interests are paramount in influencing the perceptions and even valuation of smart grids. Meadowcroft et al. (2018: 1910) thus warn that "there is a vast gulf between the idealistic visions of an enhanced grid – that would allow electricity to do so much more for societies – and the practical experiences with smart meter deployment

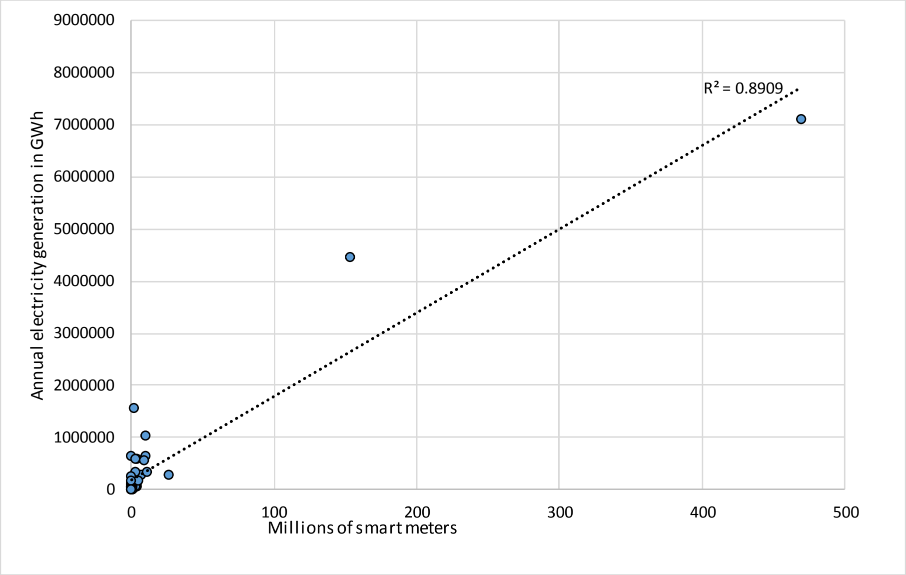


Fig. 13. Correlations between smart meters and electricity market size in 2019 (in GWh) globally. *Source:* All smart meter data comes from our dataset. Country electricity generation comes from the International Energy Agency.

Fig. 14. Number of smart meter programs with innovations beneficial to energy suppliers. *Source:* All smart meter data comes from our dataset.

Text Box 1: Future research questions derived from our analysis

1. In what ways are the drivers of smart grid transitions (at the system level) differentiated from the drivers of smart meter transitions (at the individual technology level), given that many studies conflate the two?
2. What are the *ex post* benefits of smart meters, especially those related to energy savings or carbon emissions, and how do these compare to ex-ante benefits in cost-benefit analyses (CBAs)?
3. What are the governance dynamics and techno-economic characteristics of the Chinese rollout, which constitutes a large portion of our installations but remains under-examined within the academic literature?
4. What qualitative actor types and forms of leadership are most strongly associated with successful smart meter adoption?
5. Why have more installations occurred under the subnational smart meter rollouts in the United States than the national level rollouts across the European Union?
6. What does the future hold in emerging markets with very different electricity regimes (such as those in Bangladesh, Ghana, India, South Africa, or Tanzania, to name a few)?
7. Will smart meters become more strongly aligned to other transformations such as electric vehicles, renewable electricity, Internet of Things, or smart homes, and which actors benefit?
8. How does the use of smart meters vary across the political economy of electricity distribution contexts, and what implications does this have for the nature, scale and pace of rollout?
9. What lessons can we learn from smart meter rollouts for future layered infrastructure in low-carbon energy transitions, in terms of user involvement, revenue sharing and accountability?

(the first public face of the smart grid) experienced by consumers in some areas." Smart meters thus become caught and constrained by their own competing "field of visions" (Frickel et al., 2017). Zhou and Matisoff (2016) lastly note that smart meters in the United States have been less about radical innovation and introducing new products, and more about preserving markets and industry, with "socioeconomic factors surprisingly unimportant" and pressures from energy consumer groups and environmental organizations seeming to exert very little influence over the system. These attributes may all serve to blunt the transformative potential of smart meters.

5. Conclusion

Smart meters have emerged from a new innovation over the past fifteen years into a technology that has diffused to more than *half* of global households in our sample. They have grown from a mere 23.5 million installations tracked in 2010 to more than 729 million installations tracked in 2019, including a strong presence in the ten largest electricity markets in the world. Based on bivariate as well as multivariate analysis of our dataset across 102 smart meter programs in 47 countries, we advance the following four conclusions.

First, despite the almost ubiquitous diffusion of smart meters around the world, reliable data on them is far from plentiful. Numerous weak spots in the literature became apparent, including not only the lack of a single harmonized dataset (we had to build our own), but also inconsistent data concerning CBAs (which were sometimes conflicting or which changed significantly year to year). Moreover, energy savings data was present in only a small number of programs (26), a striking conclusion given that smart meter programs are often implemented on the grounds that they will improve the efficiency of household energy consumption. Climate impacts and carbon savings are an extremely weak spot for the literature, being present in only *one* CBA for the United Kingdom. The statistical and data collection agencies involved in energy, including various national ministries but also the IEA and IRENA, ought to prioritize addressing these shortcomings. There is a distinct lack of ex-post assessments that include attention to aspects such as carbon savings and consumer benefits (even though countries, e.g. Italy, are already undertaking second-generation rollout). There is similarly little evidence of any sanctions for not delivering some of the promises indicated by CBAs as and when ex-post assessments are indeed implemented – users have in most cases paid (through increased bills) for an infrastructural intervention, but few measures guarantee that benefits will accrue to them. This leads to a number of compelling research questions posed in Text Box 1 that we are unable to answer, but believe are worth exploring.

Second, the 102 programs we tracked are targeting smart meter installations in roughly 1.4 billion households, but have already reached more than half of them (52% of households in our sample). The fact that more smart meters have been installed already than will be installed in the future based on current targets bodes well for transition dynamics. But it leads to an equally compelling problem: moving from installation to after sales service, maintenance, repair, care, and end of life. There will be hundreds of millions of smart meters (and their in-home displays) that may enter electronic waste and recycling schemes within the next decade, demanding concomitant improvements in smart meter waste management. And, given that roughly another 700 million meters are to be installed, there is still ample time to shape future deployment patterns in ways to make smart meters more recyclable or better designed for reuse or dismantling. This would be in line with global Green New Deal calls to ensure that such transitions create global public goods, as opposed to socio-spatially biased benefits with displaced negative externalities.

Third, the empirical governance dynamics of smart meter diffusion revealed in our analysis are compelling and perhaps surprising. National-scale programs account for a far larger number of installations than subnational ones, even when accounting for the United States, where state programs took the lead with support from the federal government, rather than a single federal program. National scale programs also install smart meters with a mean cost reduction of more than $100 per installed meter between the two scales of programs. However, the specific diffusion dynamics of particular smart meter programs, such as those in China, the United States, Canada, the European Union, Japan and India, are remarkably varied and context specific. Moreover, it is sub-national programs that have far more spurts of accelerated growth, although these often begin at a smaller scale with lower diffusion volumes. It may be that such smaller programs capitalize on the ability to place a single large order with one equipment manufacturing consortium. Notably, many countries with weaker economies lag in smart meter deployment; lessons learnt can help reduce their costs during rapid rollouts.

Fourth, the transformative effect of smart meters may be oversold. According to the agencies and ministries deploying them, smart meters are progressively linked to a host of other low-carbon innovations including renewable electricity, dynamic pricing, energy efficiency and the Internet of Things. In practice, our data confirms a statistically significant link between smart meter installations and direct load control. Nonetheless, countries with higher proportions of renewable electricity supply are less likely to have high diffusion of smart meters. Moreover, there are very statistically significant correlations between greenhouse gas emissions (as you increase total emissions, you see an increase in smart meter adoption within countries or subnational regions) as well as the size of electricity markets (as you increase the GWh of consumption, you increase the adoption of smart meters). Many policymakers or smart meter program advocates may think that deployment is a climate issue, but a closer look at our data reveals the correlation with renewables and carbon is complicated. While size is telling for the case of China, European countries exhibit considerable variation at similar sizes, as do states within the USA. The academic literature also confirms in some situations that the more smart meters are deployed, or the longer they are used, or the longer deployment takes, the more social acceptance can oddly decline.

This implies that greenhouse gas emitting regimes pursue smart meters, not the other way around, perhaps to lower their carbon footprint, and perhaps because they want to capture regime benefits such as the ability for theft prevention, more accurate billing, or remote disconnection. The incumbent regime-friendly nature of smart meters may very well explain why they have been so successful at achieving such mammoth transition speeds and volumes over the past few decades. Incumbents are motivated perhaps not primarily by climatic or environmental benefits, but by more pragmatic ones such as capturing economic benefits or enhancing supplier control. In some cases, smart meters may even be tools of exclusion, for disconnecting households that are unable to pay their electricity bills. Ultimately, smart electricity meters are a technology that is complementary, rather than cannibalistic, to existing electricity markets and their stakeholders. They interface between supply and demand, but do not otherwise disrupt the practices of dominant electricity suppliers, firms, or network operators.

CRediT authorship contribution statement

Benjamin K. Sovacool: Conceptualization, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing - original draft, Writing - review & editing. **Andrew Hook:** Data curation, Formal analysis, Investigation, Methodology, Resources, Software, Validation, Visualization, Writing - original draft, Writing - review & editing. **Siddharth Sareen:** Formal analysis, Investigation, Methodology, Resources, Software, Validation, Visualization, Writing - original draft, Writing - review & editing. **Frank W. Geels:** Formal analysis, Investigation, Methodology, Resources, Software, Validation, Visualization, Writing - original draft, Writing - review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

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