Energy Policy xx (xxxx) xxxx–xxxx

Contents lists available at ScienceDirect

Energy Policy

journal homepage: www.elsevier.com/locate/enpol

Comparing electricity transitions: A historical analysis of nuclear, wind and solar power in Germany and Japan

Aleh Cherp[a,b,*], Vadim Vinichenko[a], Jessica Jewell[c], Masahiro Suzuki[d], Miklós Antal[a,e]

[a] Department of Environmental Sciences and Policy, Central European University, Nádor u. 9, 1051, Budapest, Hungary
[b] International Institute for Industrial Environmental Economics at Lund University, Tegnérplatsen 4, 22100, Lund, Sweden
[c] Energy Program, International Institute for Applied Systems Analysis, Schlossplatz 1, Laxenburg, Austria
[d] Institute for Global Environmental Strategies, 2108-11 Kamiyamaguchi, Hayama, Kanagawa 240-0115, Japan
[e] Eötvös Loránd University, Institute of Empirical Studies, Department of Social Research Methodology, Pázmány Péter sétány 1, 1117 Budapest, Hungary

ARTICLE INFO

Keywords:
Germany
Japan
Renewable electricity
Nuclear power
Energy transitions

ABSTRACT

This paper contributes to understanding national variations in using low-carbon electricity sources by comparing the evolution of nuclear, wind and solar power in Germany and Japan. It develops and applies a framework for analyzing low-carbon electricity transitions based on interplay of techno-economic, political and socio-technical processes. We explain why in the 1970s–1980s, the energy paths of the two countries were remarkably similar, but since the 1990s Germany has become a leader in renewables while phasing out nuclear energy, whereas Japan has deployed less renewables while becoming a leader in nuclear power. We link these differences to the faster growth of electricity demand and energy insecurity in Japan, the easier diffusion of onshore wind power technology and the weakening of the nuclear power regime induced by stagnation and competition from coal and renewables in Germany. We show how these changes involve the interplay of five distinct mechanisms which may also play a role in other energy transitions.

1. Introduction

Though internationally comparative analyses of energy transitions remain rare (Geels et al., 2016), they are necessary for understanding variation in the use of low-carbon electricity across countries (Lipp, 2007; Schneider et al., 2011), which in turn is important for governing energy transitions required to mitigate climate change (GEA, 2012). Since contemporary energy transitions are driven by political goals, approaches for their analysis should come not only from economic and technology history (Fouquet, 2010; Kander et al., 2013) but also from political economy.

Political economy of energy dates back to the 1970s and 1980s when scholars sought to answer why nations responded differently to the oil shocks (Hughes and Lipscy, 2013; Keohane, 1984). In a seminal piece from that era, Ikenberry (1986) pointed out that in the 1960s-1980s Germany and Japan pursued a similar energy policy of ‘competitive accelerated adjustment’: they expanded nuclear power, restructured industries, and promoted efficiency to counteract insecurities of oil supplies. However, in the 1990s, their energy paths diverged. While Germany expanded wind and solar and is phasing out nuclear power, Japan deployed much smaller amounts of renewables but became a world leader in nuclear power.[1] The classic theories do not explain these diverging energy paths and should be revisited to better account for contemporary energy transitions (Hancock and Vivoda, 2014; Hughes and Lipscy, 2013).

The divergence of Germany's and Japan's energy paths is more than a theoretical problem. In recent years, there have been numerous calls on Japan (and other countries) to learn from Germany's energy policies (Hake et al., 2015; Huenteler et al., 2012; Lovins, 2014; Nature News, 2013). Yet, such calls only make sense if we understand the reasons for the original divergence. In this paper we compare and explain the difference in the use of nuclear, solar and wind power in Germany and Japan in order to contribute to a theory and policy of sustainable energy transitions.

The starting point for our analysis is the same as it was for Ikenberry: analyzing '*the way in which … problems were defined*

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* Corresponding author.
E-mail addresses: cherpa@ceu.edu (A. Cherp), vinichenko@gmail.com (V. Vinichenko), jewell@iiasa.ac.at (J. Jewell), masahiro.suzuki@mespom.eu (M. Suzuki), antalmi@gmail.com (M. Antal).

[1] In 2014, Germany produced more than 20% of its electricity from non-hydro renewables and was within the top five countries in terms of installed solar PV, wind and biomass-based capacity as well as investment in renewable power and fuels (REN21, 2015). In parallel, Germany plans to phase-out nuclear power by 2022; and has reduced the share of nuclear in its electricity mix from 28% in 2002 to 16% in 2012. In contrast, in 2010 Japan operated the third largest nuclear fleet in the world but produced less than 2% of its electricity from new renewables.

http://dx.doi.org/10.1016/j.enpol.2016.10.044
Received 24 November 2015; Received in revised form 3 May 2016; Accepted 30 October 2016

Please cite this article as: Cherp, A., Energy Policy (2016), http://dx.doi.org/10.1016/j.enpol.2016.10.044

and … the policy responses perceived as possible' (1986, 105). However, we do not assume that the two countries faced the same problems. Such an assumption was valid in the 1970s when the risk of oil embargoes and price volatility was *the* energy problem that all industrial countries tried to solve (Katzenstein, 1977). We show that since the 1980s the challenge of secure electricity supply has become increasingly different for Germany and Japan. We also show how the capacity of the two states to introduce (or discontinue) energy technologies was influenced by the dynamics of socio-technical regimes. Therefore, our analysis relies on three distinct fields of knowledge: political science, energy systems analysis, and socio-technical transition studies.

2. Existing theories and analytical framework

A comparative study of energy transition should start with justifying the case selection and the scope of analysis with respect to the technologies and time period covered. Though some existing studies (Hermwille, 2016; Huenteler et al., 2012; Strunz, 2014) focus only on post-Fukushima period when the German government declared *Energiewende* an official policy and Japan changed its nuclear plans, other literature (see Hake et al., 2015; Jacobsson and Lauber, 2006) points out that the changes in Germany can be traced back to the 1970s. We agree with the latter observation and thus compare transitions in both countries starting from 1970. However, such a long time period includes many entangled change processes presenting a methodological challenge.

To overcome this challenge, we use the 'comparable case – most similar system' study design (Przeworski and Teune, 1970) where the cases are different on a dependent variable and similar on as many explanatory variables as possible. Germany and Japan have advanced market economies, lack of domestic oil and gas reserves, and a similar history of post-war reconstruction. These overarching similarities make it easier to pinpoint differences that could explain variations in energy transitions. Further in line with this design, we compare the use of specific technologies – nuclear, wind and solar power[2] – between the two countries. This makes it possible to take the differences between *technologies* out of the equation and concentrate on the differences between *countries*.

2.1. Existing theories

While only a few papers (Feldhoff, 2014; Hermwille, 2016; Huenteler et al., 2012; Lovins, 2014) specifically compare Germany and Japan, more general literature offers many explanations of low-carbon energy transitions. A common starting point is that differences in transitions result from differences in national energy policies. For example, Lovins (2014) argues that Japan does not expand renewable electricity fast enough because '*its leaders* […] *worship old policies that retard wide use of* [renewable] *energy sources'* (see Huenteler et al. (2012) for a similar view). Such arguments lead Jacobsson and Lauber (2006, p. 257) to ask: "*Why do … some countries choose policies which apparently are superior in terms of inducing transformation whereas other countries choose policies which work less well?*". This question invokes others: what do countries seek to achieve with their energy policies? Are countries free to choose their energy policies? Do energy policies reflect common national or special interests? Do energy policies always work as intended and if not, why? The remainder of this sub-section explains how the existing literature addresses these questions.

2.1.1. Secure supply-demand balance and other state goals

An influential body of political science literature views *states*[3] as relatively autonomous actors that adopt policies in order to achieve their specific goals, such as internal order, external independence, or economic growth (Dryzek et al., 2002; Skocpol, 1979). One of the main energy policy goals is what Helm (2002) formulated as balancing demand with secure supply. Others pointed out that 'secure' often meant 'domestic' (Yergin, 1988). The history of state-backed nuclear power is a good illustration. For example, Nelson and Sprecher (2008) linked the use of nuclear power to lack of domestic coal reserves, and Fuhrmann (2012) and Gourley and Stulberg (2013) – to energy import dependence, while Jewell (2011) observed that periods of rapid electricity demand growth preceded the launch of national nuclear power programs.

Ikenberry (1986) described how both Germany and Japan sought to reduce their dependence on oil imports. More recently, governments of both countries used projections of demand growth and targets of energy self-sufficiency in formulating their energy strategies: Germany's 2010 *Energiekonzept* (Knaut et al., 2016) and Japan's 2010 Basic Energy Plan (BEP) (Duffield and Woodall, 2011). Germany, with its large coal reserves, has been less concerned about importing fuels for electricity generation. In contrast, Japan always connected energy self-sufficiency with national security (Atsumi, 2007), something that Calder (2008) called Japan's "energy angst". Suzuki (2014) and Price (1990) linked these energy security concerns to the fast development of nuclear power in Japan and Feldhoff (2014) further explained this development by the isolation of Japan's electric grid (in contrast to Germany which can trade electricity with its neighbors). These theories explain faster expansion of nuclear power in Japan in the 1990s, but not why nuclear power was growing similarly fast in both countries in the 1970s–1980s or why Germany initiated a nuclear phase-out in the early 2000s. More importantly, they do not explain why it was the coal-rich Germany[4] and not the coal-poor Japan that more actively developed domestic renewables?

States can, of course, act on concerns other than energy security. For example, Joas et al. (2016) identify 14 diverse goals of *Energiewende* supported by German political elites and dominated by climate change mitigation, a goal also frequently mentioned by other authors (Duffield and Woodall, 2011; IRENA, 2015a; Jacobsson and Lauber, 2006; Lauber and Mez, 2004). The climate imperative cannot explain the difference between Germany and Japan. Although climate-related arguments have been used in both countries to support nuclear power, renewables or both, there is no evidence that commitment to climate mitigation has been higher in either country[5] and, more importantly, climate concerns cannot explain the policy focus on either nuclear or renewables as both are low-carbon options. There are also no obvious reasons why other state goals (employment, economic growth, technology leadership etc.) would differ between Germany and Japan.

2.1.2. Vested interests

Energy policies may be shaped not only by autonomous goals of the state but also by special interests of particular social groups (Hall, 1993). For example, pro-nuclear interests may have promoted nuclear power and suppressed renewables in Japan (Huenteler et al., 2012; Kingston, 2013; Valentine and Sovacool, 2009). In contrast, a pro-

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[2] We exclude other low-carbon electricity sources because these either did not change much (hydro power), followed comparable trajectories in both countries (waste and biomass), or have not been significant (geothermal power) (Figure SM-1).

[3] In this paper we refer to 'the state' as state bureaucracy rather than 'a nation' (which includes all citizens).

[4] According to Laird and Stefes (2009), the difference in fossil fuel endowments cannot explain faster deployment of renewables in Germany compared to the US. Keller (2010) disagreed with this argument.

[5] According to Pew Research Center (2009, 2015), in 2009 65% of Japanese considered global warming as a very serious problem and 64% were prepared to protect the environment even if it slows growth and costs jobs, whereas in Germany the relevant numbers were 60% and 77%. In 2015, 42% of Japanese and 34% of Germans considered global climate change as a very serious threat.

renewables coalition supported wind and solar while pushing for the nuclear phase-out in Germany (Jacobsson and Lauber, 2006; Lauber and Jacobsson, 2016; Mez and Piening, 2002). This narrative cannot fully explain why the pro-nuclear interests suppressed wind, but not solar in Japan and why the pro-renewables coalition defeated nuclear but not coal in Germany. Moe (2011) answers the first question by identifying a 'solar (but not wind) lobby' in Japan. But if solar and wind had separate interests in Japan, what made them cooperate in Germany? Furthermore, whom did solar and wind compete against? Was there a monolithic 'conventional fossils-nuclear lobby' (Strunz, 2014) or did coal miners, gas importers, electric utilities, and manufacturers of nuclear equipment pursue somewhat separate interests? If such interests were aligned in the 1970s, and the 1980s, what made them diverge later? Have they influenced the state policies all the time or only in certain periods?

2.1.3. *Anti-nuclear sentiments and other ideas and social movements*

Many political scientists argue that a state's policies can be affected by ideas advocated by broad social movements and capable of shifting 'policy paradigms', i.e. fundamental patterns of how states define problems and search for solutions (Hall, 1993; Kern et al., 2014). From this angle, anti-nuclear sentiments could be the main driver of Germany's *Energiewende* (Hake et al., 2015; Mez and Piening, 2002; Schreurs, 2012). Such ideas clearly played a role in Germany, but cannot convincingly explain its difference with Japan where anti-nuclear sentiments have also been strong both pre- and post-Fukushima[6] (Valentine, 2010; Aldrich, 2012; Feldhoff, 2014). This lack of systematic comparison also relates to other public attitudes used to explain energy transitions, such as the 'environmentalist tradition' in Germany (Geels et al., 2016) and 'national prestige' in Japan (Valentine and Sovacool, 2009). More importantly, comparing the effects of public sentiments on energy transitions is methodologically difficult because the causality between public opinion, state-backed ideologies, and energy system change is difficult to establish (Laird and Stefes, 2009), as is the effectiveness of any public opposition in altering government or investment decisions.[7]

2.1.4. *State capacities and institutions*

The state's ability to achieve its goals may be constrained by material or institutional factors. For example, Jewell (2011) observed that civil nuclear power is primarily deployed in large, rich and politically-stable countries. Burke (2010) showed that more advanced energy technologies are used in countries with higher GDP per capita and lower resource endowments (the 'electricity ladder'). Csereklyei et al. (2016) show that per capita energy use 'converges' for countries with similar economic development, a long-term pattern that would hinder demand management policies.

Ikenberry (1986) argued that states choose their energy strategies depending on their patterns of industry-state interaction, what he called 'institutional capacity'. In his view, similar institutional capacities explained why Germany's and Japan's energy strategies were alike in the 1970s–1980s. Recently, Geels et al. (2016) used a similar institutional argument to explain the difference in energy transitions in Germany and the UK by the fact that the former is a 'coordinated market economy' and the latter – a 'liberal market economy' (Hall and Soskice, 2001). Other institutional explanations of *Energiewende* in Germany stress federalism, a multi-party political system and a strong civil society (Jacobsson and Lauber, 2006; Schreurs, 2012). Accounts of energy in Japan, in contrast, stress centralization, technocratic governance (Lovins, 2014; Moe, 2011; Valentine and Sovacool, 2009), and even a 'clientelist' state (Feldhoff, 2014), 'homogenous policy culture fixated on sub-optimal strategy', and a one-party reign controlling public discourse (Valentine, 2010, 6851).

Yet state capacities and institutions cannot fully explain the difference between Germany and Japan. Both are large, wealthy and politically stable countries with 'alliance capitalism' (Lauber and Mez, 2004; Shonfield, 1968) or 'coordinated market economy' (Hall and Soskice, 2001) featuring close state-industry interaction. If anything, this explains the similarities in the 1970s–1980s but there is no systematic account of whether there was a subsequent divergence and if so what was its exact role in energy transitions.

2.1.5. *States and socio-technical regimes*

To implement its energy goals, states must interact with other social actors (industry, banks, utilities, end users etc.). In particular, a state may choose to work with already established ('incumbent') actors or try to foster new ones ('newcomers').[8] Incumbents may have sufficient resources to help the state reach its goals, but they are also capable of strongly resisting needed change. This is because they are organized in *socio-technical regimes*, complex heterogeneous systems which include both technical artefacts and human actors, and are stable, resilient and capable of self-reproduction potentially leading to technological lock-in (Geels, 2014; Kemp, 1994).

As part of their self-reproduction, incumbent regimes may coopt state institutions and alter or reinterpret the state goals to their own advantage (i.e. act as vested interests). Geels (2014) describes such strategies of the coal and nuclear industry in the UK and Leung et al. (2014) show how the oil regime affects national energy policy in China through 'securitizing' energy supply chains. In Germany, the nuclear power regime exerted significant political influence in the 1970s-1980s (Mez, 2002) and the coal regime – in the 1950s-2000s (Frondel et al., 2007; Pahle, 2010; Storchmann, 2005). Several scholars (e.g. Kingston (2013) and DeWit and Kaneko (2011)) have described the so-called 'nuclear village' in Japan, which according to Hermwille (2016) "comprises of government, businesses and political institutions (particularly – the Liberal Democratic Party, LDP)".

The ability of a regime to either deliver on a state's goals or else reinterpret these goals to its own advantage depends not only on state capacities and motivations but also on resources and coordination of the regimes (Smith et al., 2005). Can these characteristics explain why the nuclear (but not the coal) regime collapsed in Germany (but not in Japan) during the 2000s, given that in the 1980s the nuclear regimes were similarly strong in both countries and the coal regime was stronger in Germany?

2.1.6. *States, innovation and technology diffusion*

In striving towards their energy goals states may seek to introduce new energy technologies which often means replacing or at least reconfiguring existing socio-technical regimes. Although potentially more effective, this strategy is also more risky. Innovations emerge and take initial hold in 'niches' protected from incumbents (Geels, 2002; Raven et al., 2015). The state can play a role in this process by nurturing protected niches through research, development and demonstration (RD & D) funding, and other strategies (Smith et al., 2005; Smith and Raven, 2012). However, adoption of new technologies does

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[6] Joas et al. (2016) point out that the last systematic study of energy-related values in Germany (Keeney et al., 1987) is almost 30 years old. The only *comparative* (and very general) study of public narratives by Hermwille (2016) relates to the post-Fukushima period when anti-nuclear sentiments were similarly strong in both countries and resulted in even more drastic adjustment of nuclear plans in Japan (see Section 3.2).

[7] In Germany, the peak of anti-nuclear protests was in the 1970s, when they stopped construction of an NPP in 1974 and fuel cycle facilities in the 1980s (Mez and Piening, 2002). But it was before the bulk of the NPPs was constructed. The extension of the lifetime of NPPs in 2010 triggered national demonstrations, but the opposition was "not overwhelming" (Schreurs, 2012, 35). In Japan, anti-nuclear protests prevented siting over one-half of its planned nuclear reactors (Aldrich, 2012). In a related observation, Pahle (2010) writes that "public protest proved little effective to hamper new coal plants [in Germany], which otherwise had broad political support" (p.3441)

[8] A detailed description of states' strategies to influence socio-technical regimes is provided by Smith et al. (2005) and Smith and Raven (2012).

not entirely depend on a particular state's efforts. Technologies usually emerge in 'core' countries from which they diffuse to 'periphery' nations (Grubler et al., 1999; Raven et al., 2015) depending on many non-policy factors (Breukers and Wolsink, 2007; Gossens et al., 2015).

Technology diffusion and innovation played a significant role in Germany and Japan. Both had some of the world's highest public energy RD & D spending and pioneering research and demonstration schemes. Both countries were early adopters of nuclear power from the US (Poneman, 1982) and Germany adopted wind power from Denmark in the 1990s (Heymann, 1998; Klaassen et al., 2005). Mizuno (2014) explains socio-technical obstacles facing wind power and Kurokawa and Ikki (2001) describe much more successful development of solar in Japan, the global frontrunner in solar power in the 1980s–2000s. Yet, it is less well-studied how and why these niche developments affected large-scale differences in the use of nuclear, wind and solar power. For example, why did wind power not take off in Japan and why did solar power develop faster in Germany in the 2000s when Japan was the world's technology leader?

2.1.7. *Regime shifts*

Energy transitions may involve complex processes known as 'regime shifts' when incumbent socio-technical regimes give space to newcomers emerging from previously protected niches. Regime shifts have been extensively analyzed, particularly within the multi-level perspective (MLP),[9] a prominent ontological framework connecting regime shifts to pressures from both niches and wider 'landscapes' (e.g. state policies) (Geels, 2002; Raven et al., 2015).

There are several accounts of regime shifts from conventional to renewable sources in Germany starting with Jacobsson and Lauber (2006). Strunz (2014) views post-Fukushima developments in Germany as a shift from the "conventional fossil-nuclear energy regime" to "a new RES-regime". Geels et al. (2016) compare transition pathways in Germany and the UK. In particular, they point to the role of Germany's strong manufacturing sector in its shift to renewables. However, the existing literature offers no systematic explanation of why such regime shifts did not occur in Japan which also has an impressive manufacturing sector that could have potentially benefited from producing wind turbines and other renewable energy equipment.

2.2. *Analytical framework, method and data*

Our analytical framework is constructed to elaborate and combine the insights from the literature described in the previous section with respect to electricity transitions in Germany and Japan (Fig. 1, Table 1).

First, we address the extent to which the state's energy strategies were driven by autonomous state goals (1) vs. vested interests (2). We are particularly interested in the states' goals related to secure supply-demand balance or energy security. We define energy security as 'low vulnerability of vital energy systems' (Cherp and Jewell, 2014). Our assumption is that both states considered their electricity generation and relevant international markets as 'vital energy systems'. Another assumption is that the states viewed vulnerabilities from three distinct perspectives (Cherp and Jewell, 2011): sovereignty (i.e. maximum national control over energy systems), robustness (i.e. low risks from such predictable threats as resource depletion, aging of infrastructure and demand growth), and resilience (i.e. the ability of vital energy systems to respond to disruptions). This approach makes our analysis more detailed and specific than in the previous literature. For example, instead of measuring primary energy import dependency we analyze self-sufficiency of sources used specifically for electricity generation and also consider growth of electricity demand, aging of infrastructure and developments in international energy markets.

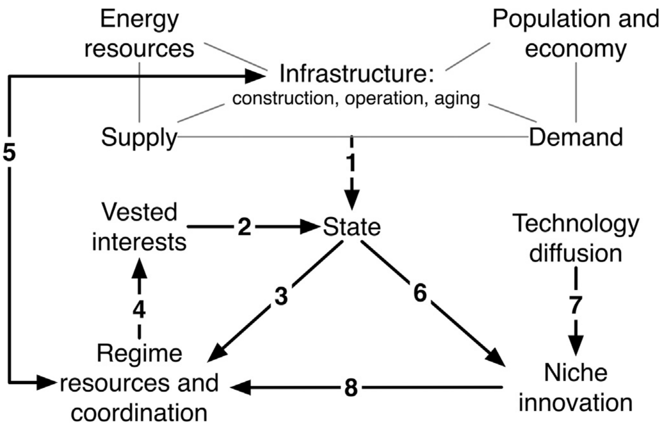

Fig. 1. Analytical framework: processes in the focus of the comparative analysis.*Notes*: 1 – state 'autonomously' reacting to threats to secure supply-demand balance; 2 – state responding to pressures from vested interests; 3 – state working with incumbents; 4 – socio-technical regimes seeking reproduction through vested political interests; 5 – socio-technical regimes interacting with energy infrastructure; 6 – states working with protected niches; 7 – diffusion of technological innovation; 8 – niche becoming a regime capable of self-reproduction and competition with other regimes.

Table 1
Existing theories, focus and limitations of the study.

Theories in existing literature	Comparative focus of this study	Out of scope of this study
States pursue their 'autonomous' goals, in particular secure supply-demand balance	Vulnerability of electricity supply in terms of self-sufficiency, aging of infrastructure, and demand growth	State goals other than energy security[a]
State policies are affected by vested interests and social movements	Connection of vested interests to socio-technical regimes, their comparative strengths, coalitions, and impact on policy choices	Effects of social movements and public opinion
States may pursue different strategies but are constrained by their material and institutional capacities	Strategies pursued by states, in particular working with incumbents and nurturing protected niches	Material and institutional capacities[b]
Socio-technical regimes are stable and capable of self-reproduction including through affecting state policies	Strength, resources and coordination of socio-technical regimes related to coal, nuclear, wind and solar power. Connection of socio-technical regimes to vested political interests	Discursive strategies of socio-technical regimes e.g. 'securitization'
Innovations emerge and take hold in protected niches. Innovations can also diffuse from abroad. Success in niche innovation/technology diffusion may overturn incumbent regimes	Niche innovation in low-carbon technologies. Diffusion of innovations from abroad. Evolution of niches into regimes capable of self-reproduction and competition with other regimes	Nuclear power niche innovations before 1970[c]

[a] Climate mitigation does not explain the choice between low-carbon options such as nuclear and renewables; public opinion about climate change is similar in both countries.

[b] Literature indicates similar material and institutional capacities of Germany and Japan.

[c] Except general facts.

We trace two types of state's strategies: working with incumbent regimes (3) and nurturing protected niches (6). With respect to

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[9] Socio-technical scholars also use 'resilience framework' (Strunz, 2014), Strategic Action Fields (Schmid et al., 2016) and other social theories explaining regime shifts in addition to or instead of the MLP.

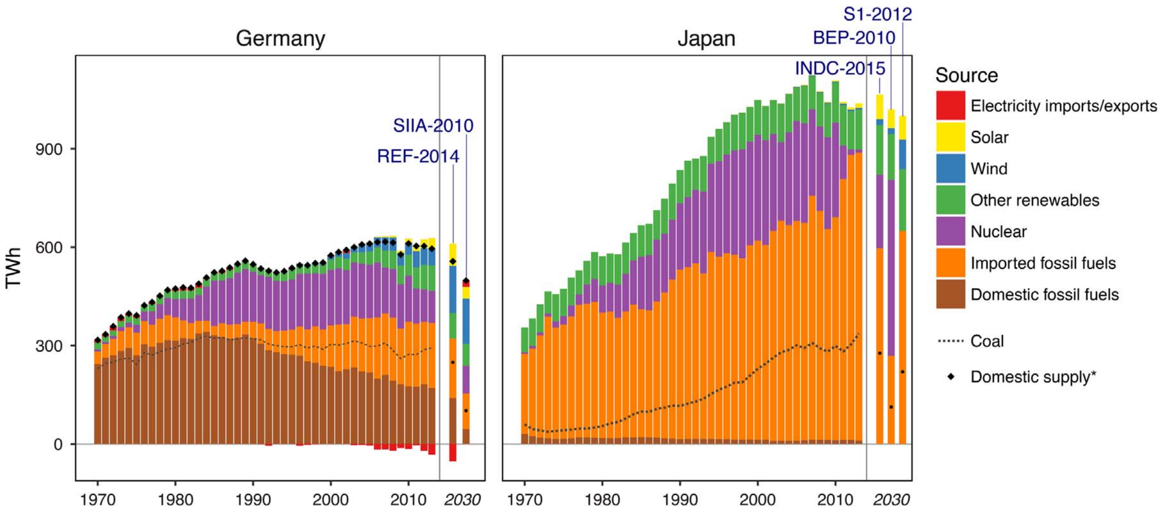

Fig. 2. Electricity mix in Germany and Japan, 1970–2013 and projections for 2030.*Notes:* The bars to the right of the vertical lines depict plans and scenarios for 2030. * – domestic supply = domestic production + net imports for Germany and strictly equals domestic production in Japan. *Sources:* 1970-2013 data: IEA (2015a). For Germany, Ref-2014 is the reference scenario from Schlesinger et al. (2014) based on the current policies and SIIA-2010 is the SIIA scenario from Schlesinger et al. (2010) which formed the basis for the Energy Concept 2010 (Bundesregierung, 2010). For Japan, S1-2012 is the post-Fukushima scenario from Japan's Ministry of the Environment (2012) and EXResearch Institute et al. (2011); BEP-2010 is based on the Basic Energy Plan (BEP) of 2010 (Duffield and Woodall, 2011; METI, 2010); INDC-2015 is derived from INDC of Japan (Government of Japan, 2015). Aggregation into categories of sources by the authors.

incumbent regimes, we focus on two further processes: (4) how socio-technical regimes seek self-reproduction through vested political interests, and (5) how their strengths are affected by the type of energy resources (domestic vs imported) as well as by construction, operation and aging of related technical infrastructure. Since coal has played a key role in electricity generation, we analyze the coal regime as well as nuclear and renewables regimes and related political interests.

With respect to protected niches, we analyze the impact of both state's strategies (6) and international technology diffusion (7). We are particularly interested in the process by which a niche becomes a fledging regime capable of self-reproduction (including through political influence) and competition with other regimes (8).

Our analytical framework does not cover all processes potentially important for energy transitions (Table 1). For example, we do not analyze climate commitments and state capacities both of which are similar in Germany and Japan, or the role of ideas and social movements, and institutional and social change which can accompany energy transitions. Our aim is to explain the observed difference with the limited set of mechanisms shown in Fig. 1, leaving space for other mechanisms to provide complementary or alternative explanations.

Our analytical framework is the foundation for exploring the two cases by 'structured focused comparison … [i.e.] using a set of … theoretical propositions to structure an empirical inquiry' (Levy, 2008, p. 2). We provide four parallel historical accounts for the evolution of electricity systems in general (Section 3.1) and of nuclear, wind and solar power specifically (Sections 3.2–3.4) starting from 1970 and including plans up to 2030. We use energy statistics from the IEA, IRENA and the IAEA, scholarly literature as well as government, corporate and media documents in English, German and Japanese as our data sources as documented in the Results section.

3. Results

3.1. Electricity supply, demand and overarching state strategies

Fig. 2 shows the evolution of electricity generation in Germany and Japan between 1970 and 2013 as well as plans and scenarios for 2030 (see also Table 2, Table SM-1). One obvious difference is the faster growth of **electricity demand** in Japan. In 1970, the two countries had similar electricity consumption (though per capita it was much lower in Japan), but by 2010, Japan used almost 80% more electricity than Germany. In the 1970s and the 1980s, electricity demand grew in both countries, but in the 1990s it stagnated in Germany while continuing to grow in Japan. What was the reason for faster consumption growth in Japan: difference in industrial structure, life styles, energy efficiency, or other factors?

To begin with, the growth of electricity consumption was almost entirely limited to the residential, commercial, and public services (RCP) sector; whereas non-RCP (transport, industry and agriculture) consumption has remained stable and similar between the two countries (Figure SM-2). The *total energy* consumption in the RCP sector per capita in Germany has been the highest among EU-G7 countries and relatively stable. In contrast, RCP energy consumption in Japan increased from the lowest among G7 countries in the 1970s to the levels of Italy, France and the UK in 2013, with electricity responsible for most of this growth (Figure SM-3). Thus, the higher electricity consumption in Japan was a consequence of (1) convergence of per capita total energy use (see Csereklyei et al. (2016)) and (2) preference to electricity in Japan and to other forms of energy (e.g. natural gas) in Germany (Fig. 3).

Electricity supply in both countries has been dominated by fossil fuels, but with an important difference: these were primarily domestic in Germany and almost entirely imported in Japan (Fig. 2). Therefore electricity self-sufficiency of the two countries has been dramatically different. In Germany, 75–90% of electricity was generated using domestic sources,[10] compared to 20–45% in Japan (Figure SM-4).

The main reason for Germany's high self-sufficiency has been the abundance of domestic coal. Germany has world's 7th largest coal reserves (US EIA, 2011), was the third largest coal producer until 1989 (IEA, 2015d), and remains by far the largest producer of lignite (WCA, 2014). Coal was crucial for Germany's post-war restoration and the welfare of several regions (Jungjohann and Morris, 2014). In the 1960s, the coal industry employed up to 600,000 people, in the early 2000s – close to 70,000 (Frondel et al., 2007; Storchmann, 2005). Since the late 1940s, the German government justified its support to domestic coal extraction and use by economic and energy security arguments (Frondel et al., 2007; Lubell, 1961). The main political voice for coal interests has been the SPD[11], a major political party. Since 1980, coal has

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[10] For the purposes of this paper we assign nuclear to domestic sources. More accurately, it is 'quasi-domestic' because not all elements of the fuel cycle (e.g. uranium mining and fuel reprocessing) are located within the country.

Table 2
Electricity production and trade in Germany and Japan in 2010 and 2030 (plans and projections), TWh.

Source	Germany			Japan				
	2010[a]	2030		2010[a]	2030			
		Reference[b]	SIIA 2010[c]		INDC[d]	BEP 2010[e]	S1-2012[f]	S2-2012[f]
Nuclear	141 (23%)	0	84 (17%)	288 (26%)	213–234 (20–22%)	537 (53%)	0	150 (15%)
Coal	274 (44%)	249 (41%)	102 (21%)	299 (27%)	277 (26%)	113 (11%)	232 (23%)	220 (22%)
Wind	38 (6%)	143 (23%)	137 (28%)	4 (0.4%)	18 (2%)	18 (2%)	90 (9%)	66 (7%)
Solar	12 (2%)	67 (11%)	36 (7%)	4 (0.4%)	75 (7%)	57 (6%)	72 (7%)	67 (7%)
Other RE	41 (7%)	59 (10%)	49 (10%)	39 (4%)	55 (5%)	32 (3%)	68 (7%)	57 (6%)
Hydro	20 (3%)	19 (3%)	26 (5%)	82 (7%)	96 (9%)	107 (10%)	120 (12%)	110 (11%)
Other fossils	99 (16%)	73 (12%)	52 (11%)	392 (35%)	320 (30%)	156 (15%)	418 (42%)	330 (33%)
Total production	**626**	**611**	**485**	**1109**	**1065**	**1020**	**1000**	**1000**
Net imports[*]	−15	−53	19	–	–	–	–	–
Total domestic supply	**611**	**558**	**504**	**1109**	**1065**	**1020**	**1000**	**1000**

Notes: Percentages indicate share in the domestic electricity production; negative values for net imports are exports of electricity;[*] – negative values indicate exports. See Table SM-1 in supplementary materials for additional data.
Sources: [a] IEA (2015a), [b] Schlesinger et al. (2014), [c] Scenario IIA from Schlesinger et al. (2010), [d] METI (2014a) and Government of Japan (2015), [e] Basic Energy Plan (BEP) 2010 from METI (2010), METI (2014b), [f] Japan's Ministry of Environment (2012), EX Research Institute et al. (2011), and Tsukamoto (2012)

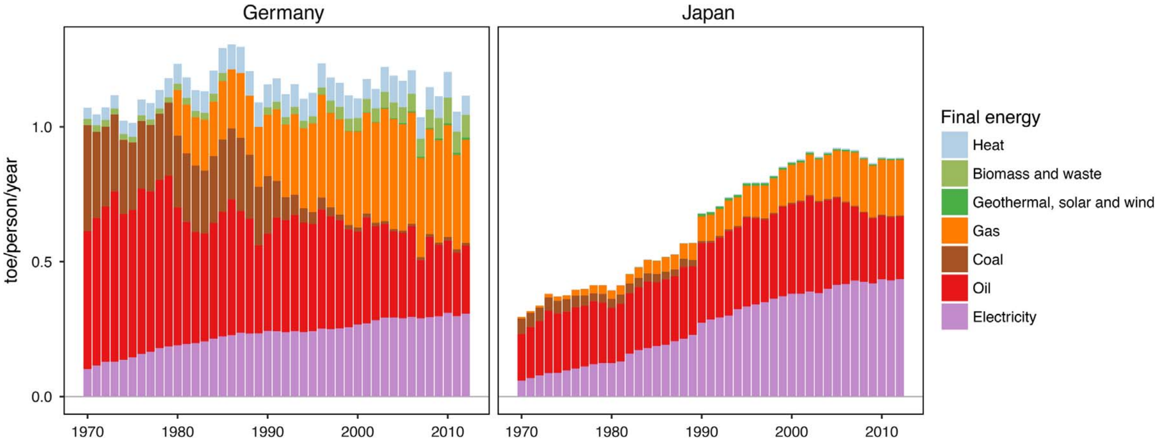

Fig. 3. Energy consumption per capita by final form of energy in the residential, commercial and public sector in Germany and Japan, 1970–2013.
Source: IEA (2015a), calculations by the authors.*Notes:*Germany has been using more residential energy per capita than Japan, but a higher proportion of this energy has been in the form of coal and subsequently natural gas as well as heat and biomass.

received over €150 bln in subsidies (Frondel et al., 2007), reaching over €7 bln/year in the mid-1990s (Ecofys, 2014; Küchler and Wronski, 2015; Storchmann, 2005).[12] In contrast in Japan, domestic coal was hardly used for electricity generation after 1970 and coal extraction had become negligible by 2000. Coal mining jobs declined from 122,820 in 1963 to 4,651 in 1990, 1,336 in 2000, and 600 in 2007 (Kunitomo, 2009, p. 5). By the 2000s, there were no mining unions or coal-dependent regions that would seek political support.

Other than the difference related to coal, energy policies of both countries were by and large similar in the 1970s and the 1980s and included industrial restructuring to reduce energy intensity (Ikenberry, 1986) as well as extensive RD & D spending on nuclear, fossil and 'alternative' energy as well as energy efficiency. The successful introduction of nuclear power was more important for Japan, where it significantly improved its otherwise low self-sufficiency ratio, than for Germany, where it had a small effect on its already relatively high self-sufficiency (Figure SM-4, Fig. 2).[13]

In the 1970s, West Germany started 'pipes for gas' deals with the USSR and in the 1980s natural gas deliveries increased substantially (Stern, 2005) as the oil prices went down. At that time, Germany's energy RD & D spending started to decline, a trend that continued until the early 2000s (Figure SM-5). In the 1990s, with continuously low prices and improved access to Eurasian hydrocarbons resulting from the end of the Cold War, energy security concerns decreased further and there was less justification for the hard coal subsidies though they will not be fully removed until 2018.

Japan's energy security concerns have been graver than Germany's not only because of the scarcity of domestic coal. Japan has an isolated and fragmented electricity grid[14] whereas Germany has a single grid

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(*footnote continued*)
[11] Sozialdemokratische Partei Deutschlands (Lauber and Jacobsson, 2016), Social Democratic Party.

[12] The coal subsidies were regulated by the so called *Jahrhundertvertrag* which assured that until 1995 a specified quantity of domestic hard coal was purchased for electricity generation at a price equal to the domestic extraction cost to be used in electricity generation (Welsch, 1998, p. 204). Since the mid-1990s this subsidy was reduced and the share of cheaper imported hard coal has been increasing. Hard coal mining is projected to end in 2018, but the use of both hard coal and lignite in electricity generation will likely continue almost undiminished until 2030 (Table 2, Fig. 4). The most recent attempt at curbing coal use through introducing a levy on the most polluting lignite power plants was aborted after backlash from the coal industry and unions (Vasagar, 2015).

[13] Nuclear power made up only about half of domestic electricity sources in Germany, most of the rest being coal with expandable production. In contrast, in Japan, nuclear power accounted for three-quarters of domestic sources, the rest being hydro-power, whose potential was almost fully tapped out (IEA, International Energy Agency, 2008, p. 122), Figure SM-4.

[14] Japan's national grid consists of 10 largely isolated grids, which operate on different frequencies in the East and the West (FEPC, 2013).

well-connected to the European electricity market[15] and in addition can rely on its neighbor countries for emergency gas supplies (European Commission, 2014). Secondly, starting from the 1990s Japan grew concerned with global and Asian energy markets, in part due to China's switch from being an oil exporter to the world's largest oil importer, along with its growing appetite for coal and natural gas imports.[16] Third, Japan's tragic experience of the Second World War associated with energy supply issues made a strong imprint on national energy policy priorities (Sagan, 1988; Suzuki, 2014). Nuclear power offered an alternative and allowed Japan to diversify away from these persistent energy security concerns.

Reflecting these concerns, Japan's energy-related RD & D spending consistently increased from the 1970s until the 2000s (Bointner, 2014). In 1980, Japan passed the pioneering *Alternative Energy Act* which supported solar and other 'alternative' energy through financial, technical, and regulatory measures. Prior to the adoption of the Act, Hamakawa (1979) argued that solar energy is needed to face the 'prospective future energy crisis' to which Japan is especially vulnerable due to its extremely high rate of demand growth (p. 444). Japan's other energy security policies included diversification of supply away from Middle Eastern oil (including to Australian coal and gas), acquisition of overseas energy assets, and 'energy diplomacy' in Asia (Atsumi, 2007; Toichi, 2003).

In 2010, both countries adopted comprehensive and somewhat similar energy plans for the next two decades. In Germany, the *Energiekonzept* aimed to reduce the use of coal by 2.7 times and increase non-hydro renewables by 2.4 times. In Japan, the 3rd Basic Energy Plan (BEP) proposed to reduce the use of fossils by 2.5 times and almost triple non-hydro renewables. Both plans also envisioned a larger role for nuclear power: in Germany, the *Energiekonzept* proposed extension of life-time of NPPs and in Japan the BEP proposed to double nuclear power output (Bundesregierung, 2010; Duffield and Woodall, 2011, Fig. 4, Fig. 5). The rationales for these plans cited both climate and energy security considerations. The Fukushima nuclear accident in 2011 changed both plans in a similar way: the targets for renewables were practically unchanged while nuclear plans were significantly downscaled: Germany essentially reversed to its nuclear phase-out schedule established in 2002[17] and Japan more or less cancelled its plans for new nuclear power plants construction (see Section 3.2 for detail). Naturally, this meant that the share of fossil fuels in the electricity mixed projected for 2030 has dramatically increased – Table 2, Fig. 4 (Cherp and Jewell, 2016; Knaut et al., 2016; Government of Japan, 2015; METI, 2014).

3.2. Nuclear power

The history of nuclear power in both Germany and Japan dates back to the 1960s when both states worked with the US (and in the case of Japan – UK) manufacturers and local industries and utilities to build their first commercial reactors (Poneman, 1982; Smith and Rose, 1987, 1989). Deployment of nuclear power required public RD & D spending, financial, and political support, which was hastened by the 1970s oil crises (Mez and Piening, 2002; Suzuki, 2014). This support was not without political opposition, especially after the Chernobyl accident in 1986 (Jacobsson and Lauber, 2006; Schreurs, 2012; Aldrich, 2012; Feldhoff, 2014; Valentine, 2010). This, however, did not have practical consequences for new reactor connections[18] whose output peaked in Germany in the 1990s contributing 29% of electricity supply and reaching 27% in Japan (Fig. 2, Fig. 5).

In the 1990s, Germany did not formally change its nuclear power policy, but did not connect any new NPPs to the grid[19] and continued reducing its public RD & D energy spending (a large part of which was for nuclear energy, Figure SM-5). Without new reactor builds, domestic nuclear equipment manufacturers sought contracts abroad and non-nuclear opportunities including in the nascent wind turbine industry. Siemens, which was involved in the construction of all German nuclear reactors, sold its reactor business to French Framatome in 2001[20] and in 2011 announced the end of its nuclear activities (BBC, 2011). In contrast, Japan built 15 new reactors and increased state support for nuclear power. In addition to large and stable RD & D funding, the Japanese government overpowered local resistance to nuclear power (Feldhoff, 2014) through increasing monetary support to siting NPPs from about ¥10 bln JPY/year in the mid-1970s to ¥120–180 bln/year in the 1990s-2000s, with the majority of the funds being allocated to host communities (Suzuki, 2014, see Table SM-2).

In the 2000s, nuclear power policies of the two countries further diverged as a result of decisions by the German 'red-green' coalition government of the SPD and the Greens (1998–2002). Though the Greens were in the Parliament since 1983, it was only during this period that they could achieve their ultimate political goal: the end to nuclear power (Jacobsson and Lauber, 2006; Schreurs, 2012). Why did the other coalition partner, the SPD, agree to support this goal? SPD had been traditionally linked to pro-coal interests and was represented by several pro-coal politicians in the red-green government (Lauber and Jacobsson, 2016; Lauber and Mez, 2004). The tension between the coal and nuclear agendas, competing for base-load power, started already in the 1970s[21], but it clearly intensified in the 1990s when SPD started supporting a nuclear phase-out (Lauber and Jacobsson, 2016). During that time stagnating demand and falling electricity prices did not allow for simultaneous expansion of coal and nuclear, especially if wind and solar were to grow as well. Moreover, nuclear power was cast as 'climate-friendly' (in comparison to coal), the *Jahrhundertvertrag*[22] expired in 1995 and cheap coal imports combined with international energy markets liberalization threatened the main trump cards of domestic coal: energy security and jobs (Welsch, 1998). By 2002, the Greens and the SPD negotiated a law (Atomgesetz, 2002) prohibiting construction of new NPPs and limiting the lifetime of existing reactors to 32 years on average.

This decision was a clear loss for electric utilities which owned NPPs (Mez and Piening, 2002), but barely damaged nuclear manufacturers who by that time had largely left the sector. And it was a huge win for coal. Not only did the output of coal-based electricity remain stable, but coal power industry also received the biggest investment

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[15] This also allows Germany to balance intermittent electricity from wind and solar by exporting or importing electricity, the possibility that does not exist in Japan (see Fig. 2 and Table 2).

[16] China also mimicked Japan's strategy of acquiring overseas fossil fuel assets (Leung et al., 2014) which sometimes put the two countries in direct competition with each other (Atsumi, 2007).

[17] However, as a whole the 2010 *Energiekonzept* was not updated and thus the 2010 GHG reduction target for 2030 is likely to be missed unless new policy measures are adopted. In the reference scenario where nuclear power is phased out by 2022, the output of solar and wind will be some 18% higher than in the 2010 Energy Concept, the output of natural gas some 50% higher, and the output of coal-fired power plants some 140% higher (Schlesinger et al., 2010,2014), (Fig. 4, Table 2)

[18] The German government successfully argued that the Chernobyl accident resulted from unsafe Soviet reactor design, which prompted the shut-down of five East German reactors of the same design during the unification, but did not affect the 'safe' West German plants (Schreurs, 2014). In Japan, the safety concerns following Chernobyl were counteracted by a similar narrative (Nakano, 2011).

[19] In 1989–1990 in the process of German reunification, five smaller nuclear reactors of Soviet RBMK design in Eastern Germany were disconnected. One of them operated only for three weeks in 1989 (IAEA, 2015; WNA, 2015a).

[20] Subsequently it established a joint venture between its "conventional island" business (i.e. hi-tech components of NPPs which are not part of the 'nuclear island' (fuel rods and reactors) and thus include pressurised vessels, turbines, safety systems etc.) and Framatome's successor AREVA to participate in a problematic construction of a reactor in Finland, then dissolved this partnership, to consider a deal with Russian Rosatom which was eventually cancelled as well.

[21] According to Mez and Piening (2002) the nuclear sector in the 1960s insisted on subsidies similar to coal, and electric utilities resisted surcharges on using domestic coal (Jacobsson and Lauber, 2006, p.265).

[22] See footnote 12.

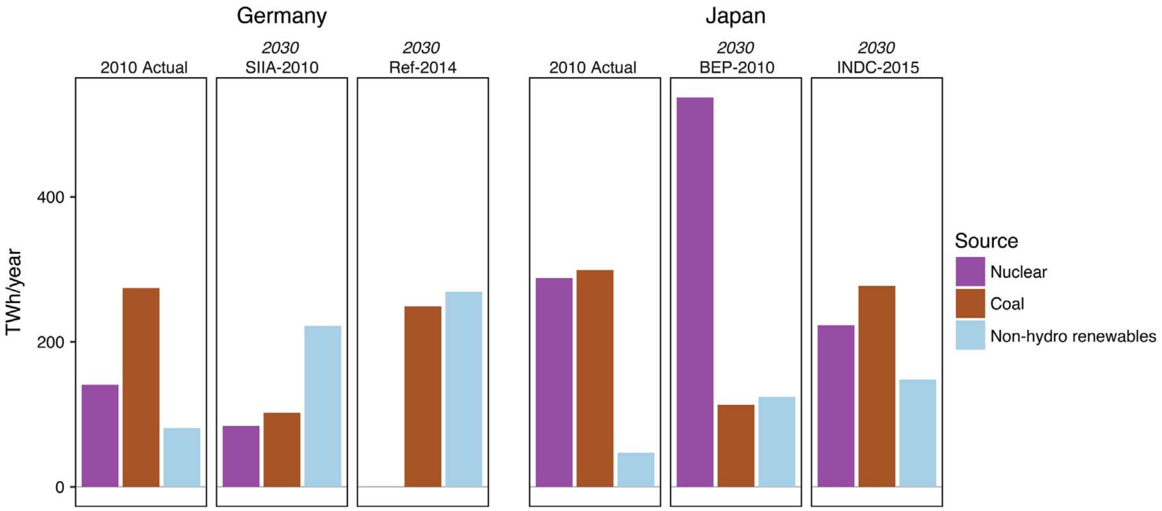

Fig. 4. Nuclear, coal and renewables (excluding hydro) in electricity production in Germany and Japan in 2010 and in plans for 2030.
Sources: IEA (2015a) for 2010; for Japan, BEP-2010 is based on Duffield and Woodall (2011); METI (2010); INDC-2015 is based on Government of Japan (2015). For Germany, Ref-2014 is the reference scenario from Schlesinger et al. (2014) based on the current policies and SIIA-2010 is the SIIA scenario from Schlesinger et al. (2010) which formed the basis for the Energy Concept 2010 (Bundesregierung, 2010).

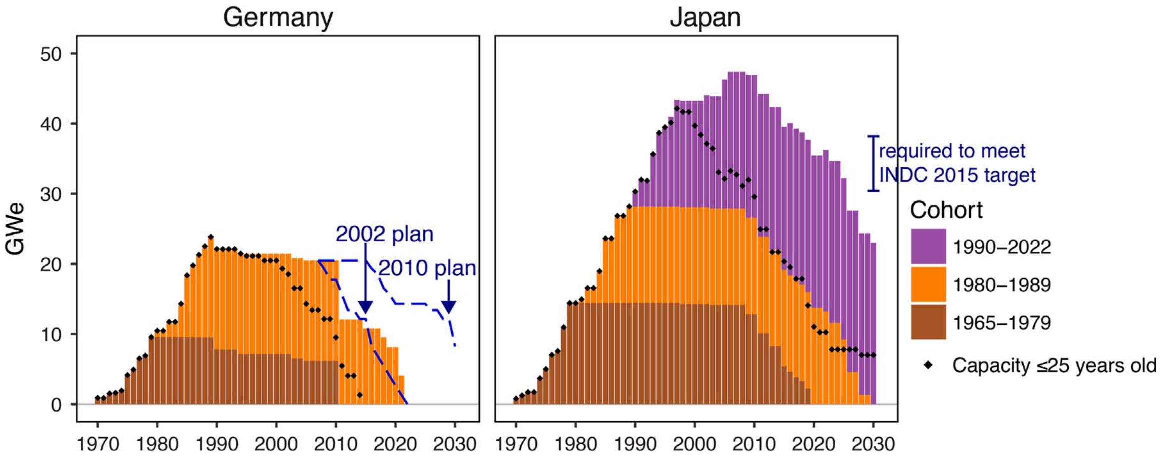

Fig. 5. Installed nuclear power capacity in Germany and Japan by cohort of nuclear power reactors and the capacity of reactors 25 years old and younger, 1970–2030.
Sources and notes: Reactors are assigned to a cohort depending on the year they enter commercial operation. Capacity for a given year accounts for all reactors in operation on the last day of the year including all reactors in temporary shutdowns, but not permanently retired reactors. The age of a reactor in a given year is calculated based on the year of connection to the grid and rounded up to the nearest year. IAEA (2015) is used for 1970–2015 data in both countries. For Germany: projections (bars) are based on WNA (2015a) referring to Atomgesetz (2011); 2002 plan shows own calculations based on 32 years of service according to Atomgesetz (2002); 2010 plan shows retirement according to Atomgesetz (2010). For Japan: projections for decommissioning are according to Takahashi (2015) and own calculations based on projected 40 years of service including finishing the construction of the reactors at Shimane-3 (1325 MWe, originally planned commissioning in 2016) and Ohma (1325 MWe, originally planned commissioning 2022) (scenario S2-2012 in Table 1); the vertical line shows the capacity bracket required to meet the INDC's (Government of Japan, 2015) target for 2030: the lower end corresponds to 20% share of nuclear power with the capacity factor of 80%; the upper boundary corresponds to 22% share of nuclear power with the capacity factor of 70%.

since post-war reconstruction (Lauber and Jacobsson, 2016, p. 159), amounting to almost 15% of the standing capacity and triggered by both projected capacity deficit due to the nuclear phase-out and by strong political support (Pahle, 2010). Between 1997 and 2003, coal subsidies, totaling around €35 bln, only decreased slightly (Storchmann, 2005, p. 1491). In 2003, a decision to continue support for mining until 2012 was made (Bosman, 2012, p. 8), and coal was exempted from the 'eco-tax' which was imposed on other fossil fuels (Lauber and Mez, 2004, p. 608). Furthermore, in negotiating SPD's support for renewables, the Greens agreed to higher taxes on natural gas which kept coal competitive (Bechberger, 2015, p. 33).

Tensions between coal and nuclear power in Germany continued through the late 2000s when a broad political coalition negotiated the *Energiekonzept* adopted in 2010 (Bundesregierung, 2010). It envisioned slashing the use of coal in electricity and extending the lifetime of seven NPPs by 8 years and of the remaining ten by 14 years (Table 1 and Fig. 4) (Atomgesetz, 2010). One year later, following the Fukushima accident in 2011, the government returned to the previously agreed phase-out timeline (Atomgesetz, 2011). Since 2003, Germany has stopped nine reactors with plans to decommission the remaining nine by 2022 .[23]

The developments were different in Japan. Its nuclear sector did not face political competition from strong coal or renewables interests; its powerful supporters included not only electric utilities but also equipment manufacturers; it commanded many more jobs than in Germany (Table SM-3); and it had the energy self-sufficiency argument

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[23] All decommissioned reactors have been or will be between 31 and 36 years old. The Krümmel reactor built in 1983 was stopped first in 2007 and then in 2009 for safety reasons (IAEA, 2015). Despite the drama of closing seven reactors in 2011 immediately following Fukushima, they all fit this age pattern and the shut-down schedule agreed in 2002 (Fig. 5).

firmly on its side. In the 2000s, Japan constructed five more reactors, though the share of nuclear power in its electricity declined to 26%[24] by 2010. It expanded its nuclear R & D spending to twice the size of all other OECD countries combined[25] and achieved the largest knowledge stock in nuclear power, at least 15 times larger than Germany's (Bointner, 2014). Toshiba, Mitsubishi Heavy Industries, and Hitachi have all acquired nuclear manufacturing capacities overseas.[26] Besides these industrial giants, Japan's $15 bln nuclear market involved about 10,000 companies, including more than 400 with dedicated nuclear technologies, and provided jobs to 80,000 people in 2010 (Mitsui Knowledge Industry, 2013). Japan's nuclear business has also been active globally: Japan helped build reactors in South Korea and has recently signed cooperation agreements with Turkey, U.A.E., Jordan, and Vietnam, among others (AIF, 2014; Jewell and Ates, 2015).[27]

Japan's New National Energy Strategy (METI, 2006b) and the 2010 BEP (METI, 2010) aimed to increase the role of nuclear power. The 2010 BEP cited climate concerns and energy security as the rationale that "the government itself will continue taking the lead in the further development of nuclear energy". It aimed to increase the share of nuclear power to 53% of total electricity production in 2030 by constructing 14 additional reactors (Duffield and Woodall, 2011, Fig. 4, Table 2). After the Fukushima nuclear accident, this plan was cancelled and several other scenarios for the future of nuclear power were proposed. The 2014 BEP (METI, 2014a) also communicated in Japan's INDC (Government of Japan, 2015) is for nuclear power to contribute 20–22% of electricity in 2030. This goal would require that either new reactors are constructed and/or some of the existing get their licenses extended beyond the statutory 40 years[28] (Fig. 5). In fact, as of October 2016, three rectors (Takahama-1, Takahama-2, and Mihama-3) have been approved by the Nuclear Regulation Authority of Japan to operate beyond this limit for additional 20 years (NRA, 2016).

3.3. Wind power

Similar to nuclear, wind power technology matured outside of both Germany and Japan. It was commercialized during the 1980s in Denmark (Quitzow et al., 2016), which remains a global leader in the technology (Bointner, 2014). Germany supported research into wind power in the 1970s and 80s, but it failed to produce a commercially viable design and abandoned the project (Heymann, 1998; Klaassen et al., 2005; Lauber and Mez, 2004). In 1990, Germany passed a Feed-in-law (StrEG) (Stromeinspeisungsgesetz, 1990) backed by the 'unlikely coalition' (Laird and Stefes, 2009) of the Greens, liberal-conservatives and the SPD. The StrEG was primarily intended to benefit small hydro-power plant owners by requiring utilities to buy electricity at 90% of retail prices, but unexpectedly led to an 'unimaginable' 100-fold increase in wind power in the 1990s (reaching about 1% of the total electricity generation by 1999) (Jacobsson and Lauber, 2006; Lauber and Jacobsson, 2016). This explosive growth of wind power in Germany in the 1990s was initially based on Danish technology (Heymann, 1998; Klaassen et al., 2005).[29]

Following this expansion, many German manufacturers, including Siemens, entered the market and by the early 2000s the German wind turbine industry had become the second largest in the world (Jacobsson and Lauber, 2006, p. 267; Siemens, 2015); the number of jobs in the wind industry was comparable to, if not larger than, in the stagnating nuclear power industry without any new manufacturing (Table SM-3). Germany established the world's second largest knowledge stock on wind energy after the U.S. (Bointner, 2014). Additionally, individual citizens and cooperatives invested extensively in wind energy installations.[30]

Thus, over the 1990s, wind power in Germany evolved from a protected niche to a fledging regime which started to compete with existing regimes and gained political influence. Political battles over the StrEG began in the second half of the 1990s, when the law was challenged in courts by electric utilities (Jacobsson and Lauber, 2006). These battles intensified as low electricity prices around 2000 made the position of all electricity actors, including the nascent wind manufacturing industry, more precarious (Lauber and Jacobsson, 2016, p.150). The pro-wind coalition allied with the 'red-green' government not only managed to defend support for wind, but also succeeded in replacing the StrEG with a much stronger law on renewable energy, EEG (EEG, 2000). The EEG established a guaranteed (for 20 years) feed-in-tariffs (FIT) for wind and solar PV (Jacobsson and Lauber, 2006). As a result, Germany installed 3.5 times more wind in the 2000s than in the 1990s (Fig. 6). The 2010 *Energiekonzept* envisioned that onshore and offshore wind output would increase 3.5 times and supply over 28% of electricity by 2030 (Table 2, Fig. 4). The 2014 EEG re-affirmed this commitment but set a ceiling on the maximum capacity of renewables (Lauber and Jacobsson, 2016).

In contrast to Germany, Japan did not support research in wind energy in the 1970s or 1980s (Mizuno, 2014; Moe, 2011). Technical conditions for wind in Japan are more challenging than in Germany or Denmark, where wind power first took off. Mizuno (2014) and Ushiyama (1999) document a lack of viable turbine designs suitable for Japan's strong turbulent winds, lighting strikes, and high seismicity. Lu et al. (2009) estimates the technical potential of onshore wind in Japan as about 6 times smaller than in Germany and IRENA (2012) and IEA (2015b) assess the cost of a wind farm in Japan as significantly larger than in other countries (see also Mizuno (2014, p.1011)). The areas with the largest onshore wind potential are far from Japan's electricity consumption centers and transmission and balancing is complicated due to the national grid fragmentation and island topography. Finally, it has been difficult to site wind turbines due to siting and construction rules made more stringent after a series of accidents (Mizuno, 2014).

Nevertheless in the 1990s, Japan introduced technical and fiscal measures, regulations and voluntary commitments supporting wind power (Mizuno, 2014), which were similar to Germany's[31] but did not result in similar developments. Danish Vestas installed their first commercial wind turbines in Japan in the mid-1990s but the market

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[24] This was due to the overall growth in electricity production and to the temporary shut-downs responding to accidents and safety concerns e.g. following the scandal at the Tokyo Electric Power Company (TEPCO) in 2002–2003 and suspension of several NPPs in 2007 after the Chuetsu Offshore Earthquake (Suzuki, 2014).

[25] This R & D is spearheaded by the Japan Atomic Energy Agency with its 4400 employees at ten facilities and an annual budget of $US 1.7 bln (WNA, 2015b).

[26] In 2006, Toshiba acquired Westinghouse, the world largest nuclear reactor manufacturer, which ironically built the first nuclear power plants in both Germany and Japan in the 1970s. In 2007, Hitachi formed a joint venture with General Electric, another world leader in reactor manufacturing (METI, 2006a). Mitsubishi Heavy Industries has closely cooperated with AREVA, a global leader in nuclear industry.

[27] Japan also viewed nuclear energy cooperation as a way to reduce energy-related tensions in Asia (Toichi, 2003).

[28] If all reactors are strictly decommissioned at 40 years, Japan will have less than 15% of electricity generated from nuclear power in 2030 (Scenario 2012-S2 in Table 1 based on (Takahashi, 2015)). One possible pathway of achieving the current government goals involves completing construction of two reactors which were under construction in 2011 (Ohma and Shimane-3) and extending the licenses of 9–12 the reactors beyond 40 years. Another possible alternative, not mentioned in the current policies, is constructing a few new reactors while strictly adhering to the retirement schedule. Other proposed policies include the 2012 post-Fukushima policy of completely phasing out nuclear power by 2030 (which would mean retiring NPPs constructed after 1990 at the average age of 33.6 years).

[29] Since the early 1990s, Vestas installed over 7000 turbines with a total capacity over 10GW in Germany, its second largest market after the US (Vestas Wind Systems AS, 2014).

[30] According to Morris and Pehnt (2015) about 46% of solar and wind installations in 2012 were owned by some 1.4 mln citizens and their cooperatives (including through indirect investment). Borchert (2015) estimates the number of direct and indirect owners at between 1 and 2 million in 2010.

[31] IThe rates in the voluntarycommitments at ca JPY 11.2/11 US cents per kWh were similar to the FIT rates used in Germany in the same period of ca DM 0.17/9.5 US cents per kWh (Table 1 in Lauber and Mez (2004) and Mizuno (2014) p. 1002)

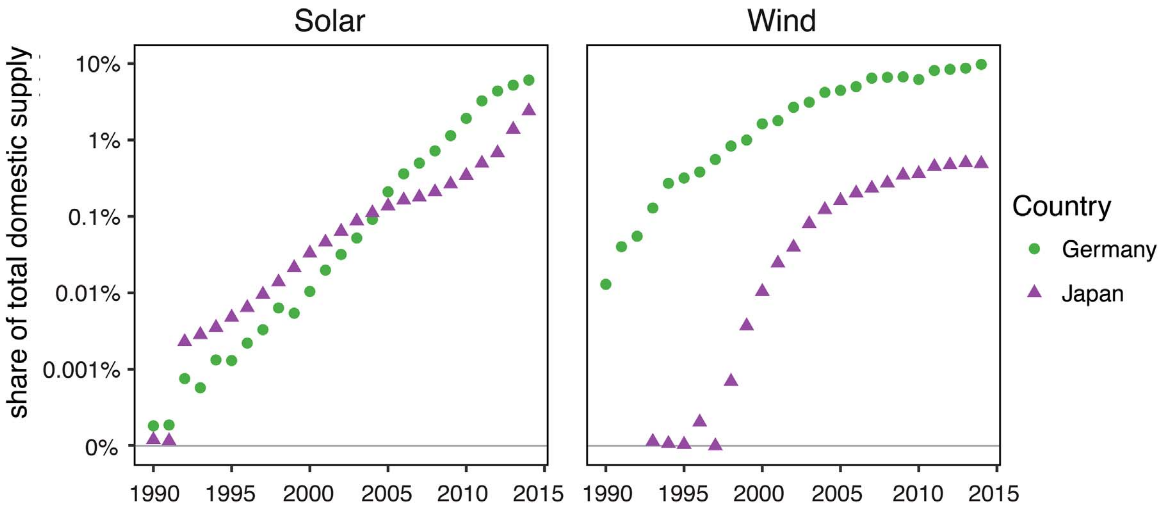

Fig. 6. Installed capacity of solar PV and wind power in Germany and Japan, 1990–2015.
Sources: IRENA (2015b) for 2014 and 2015; IEA (2015c) for all other data.

did not grow as it did in Germany, the US and elsewhere.[32] By 2001, foreign firms (German Siemens and Enercon, Dutch Lagerwey and Danish Vestas) had provided some 95% of wind turbines in Japan (Mizuno, 2014).[33] Without becoming a mature regime, the wind power sector did not have political influence to trigger a policy similar to Germany's EEG and it was not clear whether such a policy would give similar results in Japan. The gap in wind deployment between Japan and Germany has continued to grow (Fig. 6, Figure SM-7). Japan's planned wind power deployment for 2030 is 4.5 times larger than in 2010, but still less than half of Germany's capacity today (Table 2) .[34]

3.4. Solar power

Solar PV power technology was promoted in both countries since the 1970s through public RD & D funding (Figure SM-6), and pilot programs such as Germany's ‘Solar Roofs’ programs (Jacobsson and Lauber, 2006) and Japan's Sunshine program started in 1974 and expanded in 1980 with the *Alternative Energy Act* (Kimura and Suzuki, 2006; Kurokawa and Ikki, 2001). It was Japan rather than Germany that first became the global solar PV leader. In the 1990s, the Japanese electronics industry – in particular Sharp, Sanyo and Kyocera (Moe, 2010) – had the world's largest share of PV panels manufacturing and installations (IEA, 2014). During the 1990s, the use of solar PV was still at a low level, but increased in both countries with Japan installing 6–7 times larger capacity than Germany (Fig. 6). In a report prepared for the US Government by Lawrence Berkeley National Laboratory in the early 2000s Japan was named as the world leader in solar power policies, from which the US had much to learn (Wiser et al., 2002).

However, the 2000 EEG changed the situation by providing very high FITs for solar power in Germany. The rate of solar installations in Germany increased while in Japan it remained the same and in the mid-2000s Germany overtook Japan in both installations and manufacturing of solar PV panels (IEA, 2014). The 2010 *Energiekonzept* in Germany envisioned tripling of solar power output by 2030 and the BEP in Japan planned for an estimated 15–20 times increase in solar power in the same time period (Table 2, Fig. 4). After 2012, R & D for renewables in Japan increased (Figure SM6; Bointner, 2014) and the renewable support policies were strengthened. Subsequently the rate of solar PV installations increased in Japan and slowed in Germany so that the gap between the two countries has reduced and will most likely close in the near future[35] (Fig. 6, Fig. SM-7). According to the current (2014) plans, the output of solar power will be similar in both countries by 2030 (Table 2). Japan remains the global knowledge leader in this technology, followed by Germany and the US (Bointner, 2014, p. 739).

3.5. Summary

The evolution of nuclear, wind and solar power in Germany and Japan is summarized in Table 3 with the differences and similarities explained in the next section.

4. Discussion

This section describes five mechanisms, which can explain the observed differences and similarities in electricity transitions in Germany and Japan. The mechanisms are shown in Fig. 7, which is an expanded version of Fig. 1 from the analytical framework (Section 2.2) (see also Table 4).

4.1. A. States working with incumbents for secure supply-demand balance

Both states worked with incumbents to increase domestic supply, constrain demand, or otherwise reduce the vulnerability of energy systems. This mechanism explains Germany's continuous support for domestic coal, both countries’ efforts to reduce energy intensity[36] and their support for nuclear energy in the 1980s. It also explains why in the 1990s Japan, which faced rapidly rising demand and a worsening energy security outlook, continued to support nuclear energy much more intensely than Germany, which had stagnating demand and

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[32] The latest Vestas installation in Japan was in 2008 (Vestas Wind Systems AS, 2015).

[33] Japanese companies, Mitsubishi, Hitachi, and Japan Steel Works (JSW) started to play a role by 2010 and 2011 (Mizuno, 2014).

[34] Proponents of wind power have made more proposals for wind expansion which are more ambitious and more similar to German plans (JWPA, Japan Wind Power Association, 2014, 2015; Ministry of the Environment of the Government of Japan, 2012; Mitsui Research Institute, 2015).

[35] In 2015, Japan added 9–10GW and reached 33.3GW of solar PV capacity and Germany added 1–2GW and reached 39.6GW. By 2020 Germany is projected to have 50.5GW and Japan 59.3GW (IEA, 2015b, pp. 46, 59).

[36] Demand reduction strategy was hardly feasible in Japan in the 1990s when it faced convergence of per capita use of energy in the RCP sector with other G7 countries and would need to constrain residential consumption to a level much lower than in them (see Section 3.1) against the global trends (Csereklyei et al., 2016).

Table 3
Differences in the evolution of nuclear, wind and solar power in Germany and Japan in 1970s–2000s and its context.

		Period			
		1970s	1980s	1990s	2000s
Context					
Germany		Large domestic coal reserves			
			Wind takes off in Denmark	Optimistic energy security outlook	
		Demand growth and oil crises		Demand stagnation	Red-green coalition in power
Japan				Demand growth	
				Worsening energy security outlook	
Changes in use of nuclear, wind and solar power					
Nuclear power	Germany	Expansion		Stagnation	Phase-out
	Japan			Expansion	
Wind power	Germany	RD&D (abandoned at the end of 1980s)		Rapid uptake	Expansion
	Japan	-		Slow uptake	
Solar PV	Germany	RD&D		Uptake	Rapid expansion
	Japan				Expansion

Note: Shaded cells highlight the differences between the countries.

optimistic energy security outlook.[37] This fits Helm's (2002) observation that *“governments have always intervened for security-of-supply reasons, although their enthusiasm depends on the supply-demand balance”* (174). Demand growth and deployment of nuclear power correlated in the 1970s–2000s (Fig. 8)[38] in both countries. In particular, in the 1990s, Japan experienced a similar growth in electricity demand and connected the same number of new nuclear units to the grid as in the 1980s. At the same time, Germany experiencing a more optimistic energy security outlook reduced its energy RD & D spending and did not construct any new plants.

4.2. B. Regimes gaining and losing strengths from energy resources and infrastructure dynamics

The strengths of socio-technical regimes depended on energy resources and infrastructure which they exploited, constructed, and operated. Electricity regimes were stronger when they were (a) based on domestic rather than imported sources or (b) involved new construction rather than merely operation of existing infrastructure. Regimes based on domestic fuels more easily mobilize the ‘energy security’ argument to their advantage but also involve more actors and interests connected to fuel extraction (Table SM-3). This explains why the coal regime has been stronger and more influential in Germany than in Japan.

Expanding regimes, where many new facilities are installed, involve not only operators and owners but also equipment manufacturers, installers and the construction sector. When no new infrastructure is constructed, manufacturers may distance themselves from owners and operators. In the early 2000s, the nuclear regime in Japan was a large and growing industry with extensive supply chains and global leadership, promising employment and exports in addition to energy self-sufficiency (Table SM-3, Fig. SM-4). In Germany, the manufacturers were looking for opportunities elsewhere and it was primarily the utilities which fought to profit from already existing plants.[39] Naturally, it was easier to legislate nuclear phase-out in the latter case of a weak and fragmented regime.

In the same time period, the situation was the reverse for renewables. The wind regime in Germany was much stronger because it

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[37] Until the end of the 1990s the absolute majority of NPPs in both countries was under 25 years (Fig. 5). thus aging did not affect political decisions in this period although it started to matter in the 2000s.

[38] This analysis generates a hypothesis, of a broader correlation between electricity demand growth and nuclear expansion, which is in line with Fouquet's and Pearson's more general observation of demand growth usually accompanying past energy transitions (Fouquet and Pearson, 2012). This would expand Jewell's (2011) finding of a link between demand growth and the *start* of national nuclear power programs. It also echoes Fuhrmann's (2012) finding that countries are more likely to build nuclear power plants during times of high economic growth. However, Japan did not have fast economic growth during the 1990s even though it constructed new NPPs. Thus it is electricity demand growth rather than economic growth which may be of more significance for nuclear expansion.

[39] The split between the interests of utilities and manufacturers was not unique to Germany. Nakata (2002) noted that electric power utilities are ‘conservative about future investments in nuclear power stations in Japan’ (p. 364).

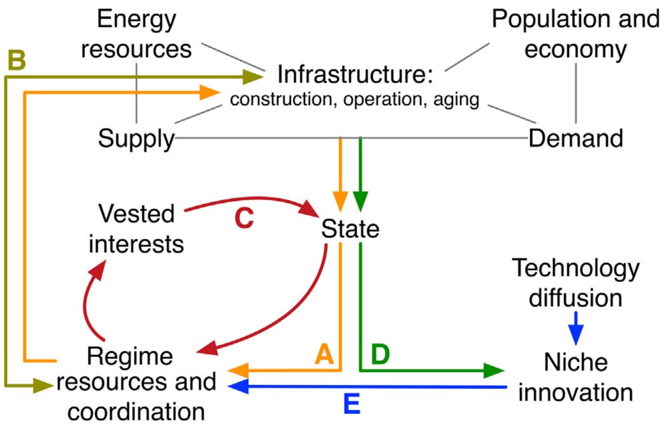

Fig. 7. Explanatory mechanisms for electricity transitions in Germany and Japan.*Notes*: Each mechanism is designated by a specific color and letter. A – states working with incumbents for secure supply-demand balance; B – regimes gaining/losing strengths from energy resources and infrastructure dynamics; C – regimes' self-reproduction through vested political interests; D – states nurturing niches as a parallel strategy; E – cross-border technology diffusion and niche innovation.

involved owners, manufacturers and installers of wind farms. Subsequently, the solar regime gained strength with the increased rate of manufacturing and installation and it recently weakened when manufacturing moved from Germany to Asia (Lauber and Jacobsson, 2016). The strength of a regime affects its ability to shape state policies in its own favor as described in the next sub-section.

4.3. C. Regimes self-reproducing through vested political interests

A state's 'autonomous' pursuit of its goals cannot explain why it was Germany and not Japan that boosted renewables and started nuclear phase-out in the early 2000s. Both developments occurred when demand growth in Germany was sluggish, the energy security outlook positive, and electricity prices were low. The energy politics under the 'red-green' government of that period was, however, far from tranquil because of the battle between several vested interests. The boost to renewables (the 2000 EEG) was strongly advocated by manufacturers and owners of renewable energy (at that time primarily wind) installations (Jacobsson and Lauber, 2006; Lauber and Mez, 2004) (Section 3.3), whose ranks swelled during the 1990s. This mechanism did not exist in Japan, because it did not have significant renewables industry in the early 2000s (Table SM-3).

The German nuclear phase-out occurred because the weakened and fragmented nuclear interests were defeated by competitors including a strong newcomer (wind) and a politically powerful incumbent (coal). These anti-nuclear interests acted through a political coalition of the pro-renewables Greens and pro-coal SPD in the red-green government. This could not have happened in Japan where a larger and more cohesive nuclear regime did not have economically and politically strong competitors. Moreover, the nuclear regime's political influence could also be an explanation (additional to security of supply considerations) for increasingly ambitious plans for its expansion under the 2000s (Kingston, 2013).

Our findings advance theories connecting political agendas to the interests of socio-technical regimes (Geels, 2014). We show that the politics of regime actors is aligned with the structure of their activities, and may not fit into common analytical and normative categories (high- vs. low-carbon, renewable vs. fossil, centralized vs. decentralized, incumbents vs. newcomers, conventional vs. alternative). For example, the concept of the 'conventional fossil-fuels nuclear regime' (Strunz, 2014) would not help our analysis. Although some electric utilities own both thermal and nuclear power stations, most actors in coal and nuclear technologies had distinctly different interests and political agendas. Although electric utilities often opposed renewables, companies such as Siemens and Mitsubishi had stakes in both nuclear and wind power.

Table 4
Explanatory mechanisms for transition processes in Germany and Japan.

Country and period	Transition processes	Mechanisms
	Nuclear power	
Germany and Japan 1970s	Fast uptake	D: state support to niche technology in response to oil crises and demand growth E: nuclear niche becomes a regime
Germany and Japan 1980s	Expansion	A: state working with incumbent in response to oil crises and demand growth
Japan 1990s-2000s	Expansion	A: state working with incumbent to ensure secure supply-demand balance in response to demand growth and worsening energy security outlook B: nuclear regime strengthened based on vigorous growth C: emergence of the 'nuclear village' further supporting pro-nuclear policies
Germany 1990s	Stagnation	A: declining interest in energy security due to low prices and optimistic outlook B: lack of new orders results in manufacturers' searching for opportunities elsewhere; nuclear regime weakened and fragmented
Germany 2000s	Nuclear phase-out	C: a coalition of pro-renewables and pro-coal interests defeats weakened and fragmented nuclear regime
	Wind power	
Germany 1970s-1980s Japan 1990s-2000s	Niche developments, negligible uptake	D: state supports niche technology in response to energy security concerns
Germany 1990s	Rapid uptake	E: wind power diffuses from Denmark. Wind niche becomes a fledging regime
Germany 2000s	Expansion	C: pro-wind interests advocate for strongly supportive FITs (EEG, 2000)
	Solar power	
Germany and Japan 1970s-1990s, Japan 2000s	Niche developments slow uptake	D: state supports niche technology in response to energy security concerns
Germany 2000s	Rapid uptake	C: pro-renewables/wind interests advocate for strongly supportive FIT (EEG, 2000) E: solar niche becomes a fledging regime

Note: For letters designating different mechanisms see Fig. 7.

The so-called 'renewables regimes' deserve an equally careful analysis. Solar and wind technologies have little in common in so far as the underlying research, technological development and manufacturing is concerned. This is why they did not support each other at the niche level (Moe, 2011). However, when deployed on a large scale they may benefit the same actors: property owners, cooperatives, municipalities, construction companies. This is, probably, why pro-wind interests and pro-solar interests were united in advocating for higher FITs in Germany.

4.4. D. States nurturing niches as a parallel strategy

In pursuing their goals, both states nurtured protected niches including nuclear power in the 1950s–1960s and renewables from

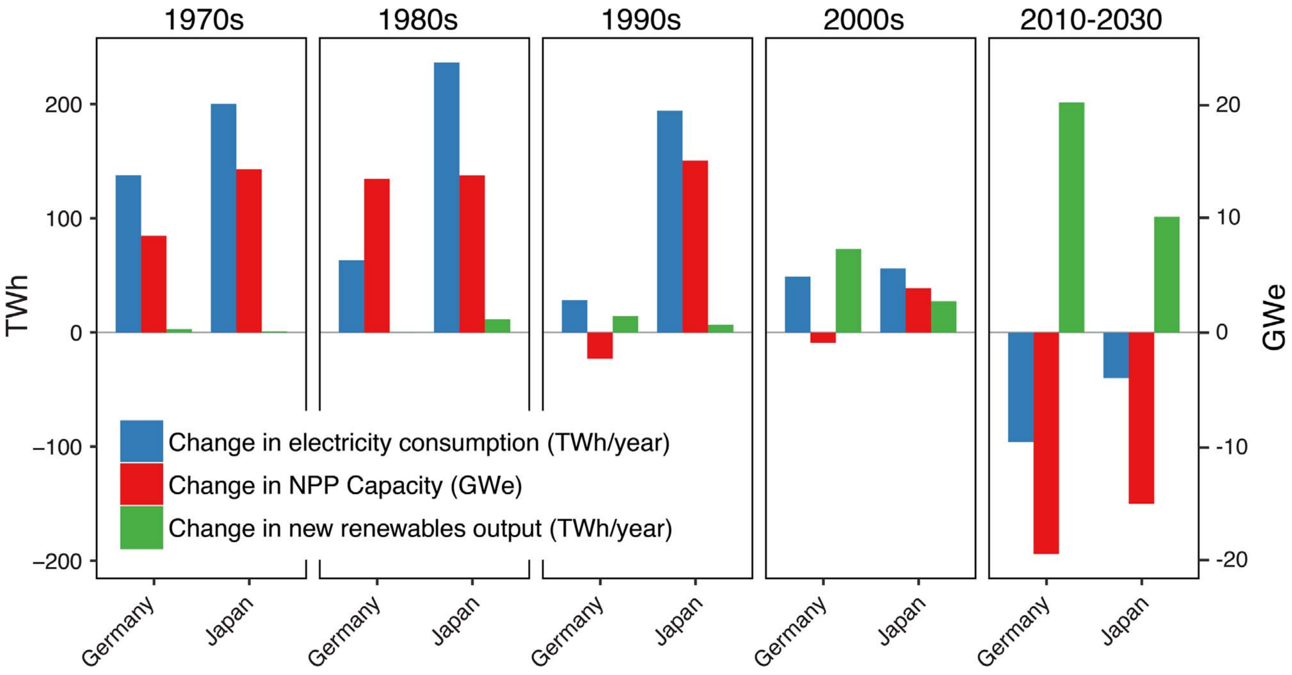

Fig. 8. Changes in annual electricity consumption, nuclear power capacity and non-hydro renewables output by decade, 1970–2010.
Sources and notes: For 1970–2030, the bars show the change in final electricity consumption and non-hydro renewables (IEA, 2015a) as well as the net change in the installed nuclear capacity (IAEA, 2015) in a given decade. For 2030, the bars show the same values calculated by the authors based on Schlesinger et al. (2014) Reference scenario for Germany and INDC (Government of Japan, 2015) for Japan. The chart illustrates the correlation between the growth in electricity construction and construction of new NPPs in 1970s-1990s and in the 2000s in Japan. The decline in nuclear capacity in Germany since the 2000s and in Japan after 2011 is partially compensated by an increase in non-hydro renewables.

the 1970s. Their efforts did not guarantee success. Japan's four-decade long pursuit of solar power through massive RD & D resulted in its technological leadership but only marginal installations until very recently. Other niche technologies included in the Sunshine program – hydrogen, coal-to-liquid, and geothermal (Kurokawa and Ikki, 2001) – yielded even less results. Germany eventually abandoned its attempts to commercialize its own wind power technologies in the 1970s-1980s and Japan failed in a similar effort in the 1990s-2000s.

Precisely because of high risks of failure, states nurtured niches in parallel, not instead of, working with incumbents. Even successful efforts would initially result in only modest payoffs in terms of improving secure supply-demand balance. For example, even if Japan had been as successful as Germany in promoting wind power in the 1990s it would have covered only about 5% of its demand increase over that decade (Fig. 8). This is why we observe mechanisms A and D unfolding in parallel in both countries. Starting from the 1970s, Germany nurtured solar and wind in parallel with providing massive coal subsidies. For several decades, Japan supported solar (and eventually wind) while putting the real emphasis on a surer option: incumbent nuclear power.[40]

4.5. E. Niches maturing into regimes

When a niche expands, it may become capable of self-reproduction and competition with other regimes. One example is the rapid expansion of nuclear power in both countries from a niche in the 1960s to a full-fledged regime in the 1970s. In both countries this expansion depended not only on state support but also on non-domestic (US and UK) actors. A similar, although less expected,[41] expansion of wind power occurred in Germany in the 1990s with technology diffusing from Denmark. The third niche-regime breakthrough involved solar PV in the 2000s, first in Germany and then in Japan.

The evolution of protected niches to formidable regimes has been extensively documented in the literature. There is, however, not enough reflection on the role of *non-domestic* actors such as US Westinghouse or Danish Vestas in these shifts. Proper analysis of such actors can contribute to the ‘techno-nationalism’ vs. ‘techno-globalism’ debate in the history of technology (Edgerton, 2006).

4.6. Summary

The explanatory mechanisms for the observed differences and similarities between Germany and Japan are summarized in Table 4 and further detailed in Tables SM-5 and SM-6.

5. Conclusions and policy implications

This paper explains why the use of nuclear, solar and wind power has been different in Germany and Japan. Responding to Lauber's and Jacobsson's challenge we propose a framework for analyzing energy transitions which is “more interdisciplinary than those currently deployed” (2016, p.161). In line with Turnheim's et al. (2015) concept of the multiplicity of analytical perspectives on transitions, we consider political, techno-economic and socio-technical explanations in their interaction.

We identify five mechanisms explaining different transition episodes in Germany and Japan (Fig. 7). We show how states’ quest for secure supply-demand balance shaped both countries’ strategies in the 1970s and the 1980s and affected their different commitment to nuclear power in the 1990s. This quest was pursued in two parallel

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[40] Nuclear power both strongly responded to state support and could provide rapid capacity increase in relatively short time periods (Table SM-4).

[41] Jacobsson and Lauber called it an ‘unimaginable’ (2006, p. 264) consequence of a ‘lukewarm’ (Lauber and Mez, 2004, p. 599) policy backed by an ‘unlikely’ (Lauber and Mez, 2006) broad coalition not specifically aimed at wind support. Lauber (2004), Jacobsson and Lauber (2006) and Laird and Stefes (2009) suggest that the German reunification distracted the electric utilities from lobbying against StrEG. This may

(*footnote continued*)
partially explain the difference with Japan in the early 1990s, but not in a longer-term and not in a wider geographic context.

strategies: (1) working with incumbent regimes and (2) nurturing protected niches. Under the first strategy, the states strengthened or weakened incumbent regimes, but could also become manipulated by these very regimes. Regimes based on domestic resources and on expanding infrastructure were politically stronger. That is why coal and wind were stronger in Germany and nuclear was stronger in Japan in the early 2000s, which explains the boost to renewables and the nuclear phase-out in Germany but not in Japan. Our analysis shows that political agendas of regimes depend on their material interests and may not correspond to common analytic and normative categories (such as low- or high-carbon).

The second strategy, working with niches, makes the state less vulnerable to the capture by vested interests but it does not guarantee success. In many cases niche energy technologies did not make it to the market. When they did, it often involved technology diffusion from other countries, such as nuclear from the US or wind from Denmark. Such diffusion was not predictable or linear: e.g. wind power could diffuse to Germany but not to Japan in the 1990s. In this case geographic proximity and similarity may be one plausible factor. Cross-border technology diffusion (or across-border regime expansion) needs further analysis in energy transition studies.

All in all, our analysis shows that transitions in Germany and Japan comprised distinct change processes, not necessarily abiding by the same logic. The identified 5 mechanisms are sufficiently generic to explain dozens of transition episodes in Germany and Japan but their importance vary from one episode to the other. This is in line with Geels et al. (2016) observation that energy transitions may follow different 'transition pathways' at different points in time. This does not mean that more general theories of energy transitions are impossible, but rather that such theories are unlikely to be useful if they claim to explain grand 'transformations' encompassing wide ranges of technologies, countries and periods of time. Instead, a good theory of contemporary energy transitions is likely to be an assembly of 'micro-logics' of its specific constituent elements combined with an understanding of the applicability of such logics to specific situations and their relationships to each other. The five mechanisms identified in our analysis are a good starting point for such explanations.

Our findings also have implications for Japan's and other countries' prospects of learning from Germany's policy experience. First, we show that the space for policy choice is often limited. For example, in the 1990s Japan did not have much other choice than to expand its nuclear energy in response to the electricity demand converging to the levels of other developed countries. It may be reasonable to assume that economies with nuclear programs and rapidly rising electricity demand may not be interested or prepared to copy Germany's nuclear phase-out policies.

Second, we show that in many other situations, policies targeting niches did not bring the expected results. For example, support for wind power in Germany in the 1970s–1980s and in Japan in the 1990s–2000s was not successful. On the other hand, a 'lukewarm' StrEG (1990) in Germany unexpectedly worked. This means learning should incorporate not only 'superior policy choices' but also failed policies as well as unintended outcomes.

Third, we show that some policy choices may have resulted in dubious compromises. For example, compromising with the coal industry to achieve the nuclear phase-out in Germany may not be a desirable solution for some countries or for the global climate, despite the fact that it resulted in a faster expansion of renewable electricity. Our analysis shows that it might be especially difficult to refuse compromise with a domestic fossil fuel sector, which means that countries with large fossil endowments would find it harder to decarbonize.

Finally, in our view the most problematic aspect of the common policy learning advice is that it is wrapped in a narrative of coherent and deliberate 'transformation-inducing' policies. Our study shows that while in hindsight it is possible to spin a narrative of policy coherence, in reality policies are more likely to be fragmented and emergent, responding to specific challenges rather than aiming to ‘induce transformations’. To be useful for policy comparison and learning, the grand narrative of energy transformations should be replaced by more detailed and cautious accounts of how certain combinations of economic factors, socio-technical conditions, and policy choices define change and continuity in energy systems.

Acknowledgements

The research reported in this paper was supported by Central European University's Intellectual Theme Initiative and the European Union’s Horizon 2020 research and innovation programme under grant agreement No 642147 (CD-LINKS). The authors would like to thank Elina Brutschin and participants of the International Sustainability Transitions 2015 conference in at the University of Sussex for providing useful comments on a draft of this paper.

Appendix A. Supplementary material

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.enpol.2016.10.044.

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