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Exploring sustainability transitions in the electricity sector with socio-technical pathways

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ABSTRACT

This paper analyses sustainability transitions in the electricity system, using recent theories on socio-technical pathways. The paper describes three possible transition pathways and indicates the implications for (grid) infrastructures. The 'transformation pathway' is characterised by a further hybridization of the infrastructure; in the 'reconfiguration pathway', internationalisation and scale increase in renewable generation lead to the emergence of a 'Supergrid'. The 'de-alignment and re-alignment pathway' is dominated by distributed generation and a focus on more local infrastructures. We suggest that this pathway, which involves a major restructuring of the electricity system, is less likely than the other two. The de-alignment and re-alignment pathway is therefore more dependent on external developments and/or strong policy interventions. All pathways, however, require major investments in infrastructure and innovative technologies.

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1. Introduction

The energy sector faces serious problems, e.g. oil dependency, reliability and climate change. Large jumps in environmental efficiency may be possible with sustainability transitions, i.e. shifts to new energy systems. Hence, policy makers and NGOs show increasing interest in energy transitions. The Dutch government, for instance, gave transitions a central place in its fourth National Environmental Policy Plan, as did the Ministry of Economic Affairs in its recent Energy Report [1,2].

Transitions do not come about easily, because existing systems are characterised by stability and lock-in. This applies in particular to infrastructural systems like the electricity system. The sunk investments in technologies (power plants, cables and lines, transformer stations etc.), skills, social networks and belief systems complicate a swift shift to completely new systems. However, a major transition has occurred in the electricity sector in the EU during the last two decades: changes in the institutional framework have resulted in a shift from a system dominated by engineers to a market-based system, ruled by managers. But despite an increasing interest in renewable energy technologies, the recent transition has not (yet) contributed substantially to the 'greening' of electricity systems [3].

Several visions have articulated what a sustainable electricity system could look like in the future. Most popular are visions or scenarios with a central role for small scale or Distributed Generation (DG) like PV systems, urban wind turbines or small biomass plants. A couple of articles in *The Economist* can serve as an illustration. In August 2000 this magazine published an article on: 'The dawn of Micro Power', promising a more sustainable, cheaper and more reliable system [4]. A couple of years later *The Economist* wrote: "More and bigger blackouts lie ahead, unless today's dumb electricity grid can be transformed into a smart, responsive and self-healing digital network—in short, an energy internet" [5]. However, in another provocative article published in 2007 a grandiose plan was presented to link electricity grids all over Europe. The proposed Supergrid would enable wind energy to become one of the major suppliers of electricity, or the 'Star of the show', as they put it [6]. The Global Energy Network Institute

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goes even one step further by trying to combine both visions: “Research shows that the premier global strategy is the interconnection of electric power networks between regions and continents into a global energy grid, with an emphasis on tapping abundant renewable energy resources—a world wide web of electricity” [7].

It is difficult to assess the quality and value of such visions and scenarios [8]. In our view, most of them suffer from one or more problems: a) they tend to be more about ‘end states’ than about dynamic pathways towards end states, b) they focus too much on technological fixes and pay too little attention to social dynamics and contexts, c) dealing with discontinuities and transitions remains difficult in the scenarios literature [9] partly because it lacks a good understanding of socio-technical transitions, d) if there is attention for dynamics of change, the scenario conceptualization tends to be either exogenous, which is related to the typical ‘scenario axes technique’ that varies two macro-variables in a 2×2 matrix [10] or mechanistic, due to exclusive emphasis on economic mechanisms (prices, investments, supply, and demand); while external contexts and economic mechanisms are important, most scenarios pay insufficient attention to *endogenous* dynamics, which relate to beliefs, decisions, struggles and interactions between various actors and social groups, e) most scenarios focus on particular aspects of transitions, often technological change (which tends to be conceptualized via learning curves and/or R&D investments), rather than on changes in broad socio-technical systems, which not only include technology and markets, but also infrastructure, cultural aspects, regulatory paradigms and consumer behaviour [11].

Because of these problems, we use a different approach to explore future transitions in electricity systems. We are inspired by and build on the socio-technical scenario approach [12,13], which uses the multi-level perspective (see below), as scientific theory to conceptualize transition dynamics, focuses on socio-technical systems, pays attention to co-evolution and the role of actors. Our contribution to this approach is the introduction of new theoretical ideas about transition pathways [14], which provides a stronger theoretical logic for our scenarios. A similar approach has been adopted by Foxon et al. for developing transition pathways for the UK [15]. With our contribution, we aim to address the following research questions: (1) how can we analyse sustainability transitions for the electricity sector, with a particular focus on electricity generation and infrastructure and (2) who are the main actors in different transition pathways? To answer these questions, we will not present full scenarios, but only give brief indications of the main characteristics of these scenarios, the pathways leading to these scenarios and some implications for infrastructure development and policy.

2. Multi-level perspective and transitions

Academics show increasing interest in the dynamics of transitions and system innovations [16,17] and governance aspects [18]. An important theory in this respect is the multi-level perspective [19], which understands transitions as the outcome of multi-dimensional interactions between radical niche-innovations, an incumbent regime, and an external landscape.

Transitions are about changes at the meso-level of *socio-technical regime*, which consists of three dimensions: a) material and technical elements; in the case of electricity systems, these include resources, grid infrastructure, generation plants, etc., b) network of actors and social groups; in the electricity regime important actors are utilities, the Ministry of Economic Affairs, large industrial users, and households; c) formal, normative and cognitive rules that guide the activities of actors (e.g. regulations, belief systems, guiding principles, search heuristics, behavioural norms). Existing socio-technical regimes are characterised by path dependence and lock-in, resulting from stabilising mechanisms, e.g. vested interests, ‘organizational capital’, sunk investments, stable beliefs [19].

Niches form the micro-level, the locus where novelties emerge. Small market niches or technological niches act as ‘incubation rooms’, shielding new technologies from mainstream market selection. Such protection is needed because new technologies initially have low price/performance ratio. Protection comes from small networks of actors who are willing to invest in the development of new technologies. The macro-level is the *socio-technical landscape*, which forms an exogenous environment that usually changes slowly and influences niches and regime dynamics. The relationship between the three levels is a nested hierarchy (Fig. 1). Pioneers

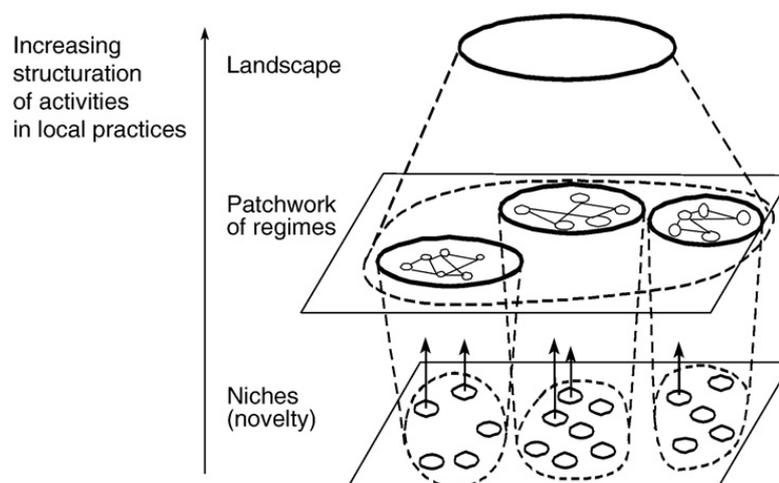


Fig. 1. Multiple levels as a nested hierarchy [18].

and innovators always work on novelties, but these usually remain restricted to niches (e.g. R&D projects or small market niches). New technologies have a hard time to break through, because the existing regime is stabilised and entrenched. Historical studies have shown that transitions only come about when developments at all three levels link up and reinforce each other.

Early multi-level studies suggested that radical innovations emerge in niches, break through and overthrow the existing regime. While this pattern does exist, it is less likely in systems with large infrastructures, where sunk investments and high entry barriers are important. To analyse electricity systems, we therefore use a more refined typology of transition pathways, which distinguishes four ideal-typical paths, based on different *kinds* and *timing* of multi-level interactions. The kinds of multi-level interactions refer to the nature of the relation between niche-innovations and landscape pressure with the regime (reinforcing or disruptive). Timing is in particular relevant in the case of landscape pressure on regimes. If this pressure occurs at a time when niche-innovations are not yet fully developed, the transition path will be different than when they are fully developed. These pathways, developed by Geels and Schot [15] are:

1) Transformation

This pathway is characterised by external pressure (from the landscape level or outsider social groups) and gradual adjustment and reorientation of existing regimes. Although external pressures create 'windows of opportunity' for wider change, niche-innovations are insufficiently developed to take advantage of them. Change is therefore primarily enacted by regime actors, who reorient existing development trajectories. Outside criticism from social movements and public opinion is important, because it creates pressure on regime actors, especially when they spill over towards stricter environmental policies and changes in consumer preferences. Although regime actors respond to these pressures, the changes in their search heuristics, guiding principles and R&D investments are modest. The result is a gradual change of direction in regime trajectories. New regimes thus grow out of old regimes through cumulative adjustments and reorientations. Radical innovations remain restricted to niches.

2) Reconfiguration

In this pathway, niche-innovations are more developed when regimes face problems and external landscape pressures. In response, the regime adopts certain niche-innovations into the system as add-ons or component substitutions, leading to a gradual reconfiguration of the basic architecture and changes in some guiding principles, beliefs and practices. In the reconfiguration pathway, the new regime also grows out of the old regime it differs from the transformation pathway in that the cumulative adoption of new components changes the basic architecture of the regime substantially. The main interaction is between regime actors and niche actors, who develop and supply the new components and technologies.

3) Technological substitution

In this pathway, landscape pressures produce problems and tensions in regimes, which create 'windows of opportunity' for niche-innovations. Niche-innovations can use these windows, when they have stabilised and gathered momentum. Diffusion of these new technologies usually takes the form of 'niche-accumulation', with innovations entering increasingly bigger markets, eventually replacing the existing regime. In this pathway newcomers (niche actors) compete with incumbent regime actors.

4) De-alignment and re-alignment

Major landscape changes lead to huge problems in the regime. The regime experiences major internal problems, collapses, erodes and de-aligns. Regime actors lose faith in the future of the system. The destabilisation of the regime creates uncertainty about dimensions on which to optimise innovation efforts. The sustained period of uncertainty is characterised by the co-existence of *multiple* niche-innovations and widespread experimentation. Eventually one option becomes dominant, leading to a major restructuring of the system (new actors, guiding principles, beliefs and practices).

Geels and Schot stress that these pathways are non-deterministic ideal types, which are influenced by social processes [15]. Empirical cases may therefore have elements of more than one pathway. Moreover, over an extended period of time, a sequence of transition pathways can occur. This sequence starts usually with a transformation phase, when regime actors only perceive moderate pressure. Gradually increasing pressure can result in more disruptive changes leading to a phase of reconfiguration and de-alignment/re-alignment.

We will now apply this conceptual framework to the electricity system (see also [3]). We distinguish and discuss only three different transition pathways. The technological substitution pathway is less likely for infrastructural regimes, as we do not foresee the complete replacement of the electricity system. In all pathways the need for 'greening' the system is acknowledged and substantial gains in environmental efficiency can be achieved, despite a large increase in demand. For each pathway we give an indication of the main dynamics and consequences for the electrical infrastructure. The technical details are based on a study by Meeuwsen on future electricity networks. Meeuwsen has studied the consequences of a transition to a (more) sustainable system of electricity supply. The focus of this study was on The Netherlands, although cross-border interactions have been included, as the Dutch grid has several links to the European high voltage network. Meeuwsen assumes that demand will increase with 100% in 2050; 50% will be provided by renewable sources. He uses three diverging scenarios, developed on the basis of the same pathway typology as presented here and estimates the different mixes of generation technologies and electricity flows in the transport and distribution networks [20].

3. Transition pathways in electricity systems

The current electricity regime experiences several landscape pressures: neo-liberal ideologies (privatization, deregulation, and liberalization) and the creation of a single European market led to major institutional changes in the energy sector in the 1990s

(although there are still large differences between the various member states). Moreover, rapid economic growth in China, India and other emerging economies is putting pressure on the availability of resources and has led to a large increase in the prices of fossil fuels. Although the economic crisis that started in 2008 has reversed this trend, the general expectation is that prices will become much more volatile and will rise again on the longer term [21]. Concerns over the impact of climate change, resource depletion and supply security (Russia and Middle East) also create uncertainty over the long term feasibility of our current system of energy supply.

These developments have caused several tensions in the electricity regime. The 1990s saw the rapid rise of local cogeneration of heat and power (CHP) by large industrial firms. In some countries (such as the Netherlands), CHP now produces more than 50% of electricity, *de facto* leading to a hybrid central–decentral system [3]. The electricity infrastructure has to adapt to the resulting two way flows in the system. In the old central power station model electricity flowed from the power station to the users, but local generation of electricity can lead to flows in the other direction. The liberalization of energy markets and the construction of high voltage connections have increased international electricity flows. This presents potential problems for the stability of the system as the share of fluctuating energy sources, in particular large off shore wind parks, has increased substantially [20,22]. Moreover, the introduction of a market mechanism in the electricity system has made balancing demand and supply and planning of capacity much more complicated.

Actors like utilities, producers, network operators and regulators are grappling to come to terms with the new institutional configuration introduced in the 1990s in Europe. The utilities have become more short term, cost competition oriented, but at the same time public pressure to 'green' the production is increasing [18]. Network operators are not allowed to have any spare generation capacity, as was often the case when they were still part of the public utilities. So, regime actors have to deal with these problems and pressures. Both regime actors and policy makers believe that the introduction of so-called smart grids will solve most of the networks problems, but as the few examples in the introduction demonstrated, opinions on the direction of change differ greatly. Using the pathway typology we will briefly explore three different pathways for the electricity system. Landscape pressures have resulted in several policy efforts to increase the share of renewables.

3.1. Transformation: further towards hybrid grids

In this pathway, the existing regime actors adjust to the outside pressure and the internal regime tensions by modifying the direction of development. In particular, they respond to increasing criticisms and pressures from outsiders, such as environmental pressure groups and social movements, who demand a significant greening of the generation of electricity and reduction of the emission of greenhouse gases. Although there are many and frequent interactions between those pressure groups and regime players, the latter remain outsiders and most of the regime actors will survive. However some changes can occur in the social network as some regime actors disappear through mergers or take-overs, while others redefine their roles and strategy and a few new actors emerge on the scene like energy service companies (ESCOs) [23]. Because changes in the search heuristics, guiding principles and R&D investments of the regime actors remain modest, electricity systems, actor networks and rules are a continuation of the current hybrid situation (with some changes). The utilities focus on constructing large-scale offshore wind farms and large-scale biomass gasification and combustion plants, but coal or multi-fuel fired plants (co-combustion of biomass) in combination with Carbon Capture and Storage (CCS) and nuclear power plants remain important. All options fit well within the existing system, although some adaptations are needed, e.g. the construction of a CO₂ transport infrastructure and new high voltage cables connecting the off shore wind farms to the main land grid.

The main dynamism is an economic one: the market mechanism, introduced in the 1990s, remains the dominant organising principle. National and European policies focus on market-based instruments, e.g. the expansion of the carbon emission trading system in Europe. Cost-effectiveness is the most important criterion in the scenario. The share of small scale (renewable) energy technologies, like PV panels, urban wind turbines, small scale biomass plants and micro-cogeneration, increases, but remains confined to specific niches, in particular in the built environment. These niche-innovations do not disrupt the basic architecture of the regime, but stimulate reorientation in a more sustainable direction.

In this scenario, the generation capacity in 2050 consists of a few large-scale generation units as well as a large number of small units nearby consumers, producing a hybrid system. The average size of the production units decreases slightly and balancing and load management take place at the national level. The utilisation degree of the generation capacity will decrease significantly because of low load factors of distributed generation plants. The utilisation time of wind turbines and PV systems, but also micro CHP is rather low. The electricity infrastructure is characterised by increasingly bidirectional flows at both the transmission and the distribution level. Dominant issues will be the need for sufficient network capacity and system balancing facilities. The balancing difficulties are mainly caused by offshore wind farms. Except for balancing via generation, also strong demand management will be needed, e.g. through smart meters and other electronic components [20].

3.2. Reconfiguration: towards a Supergrid

In this transition pathway the regime faces major external landscape pressures, in particular security of supply issues because of global competition for resources and markets and geopolitical instability in regions with major reserves of fossil fuels. These developments and the impacts of climate change induce more cooperation on the European level. In response to the challenges, EU integration and policies becomes more dominant. The regime actors also increasingly become international players, leading to the domination of the European market by a few very large companies; several smaller niche players emerge to develop and provide

new technologies, components and services. Also network management and control will increasingly take place at the international level by new institutions. There emerges a strong collaboration between regime actors and outsiders [23]. The main dynamism here is a political one. The shift to the international level requires several institutional changes, but the operation of the electricity system will be mainly driven by techno-economic considerations.

The adoption of a set of niche-innovations in the system leads to a gradual reconfiguration of the basic architecture of the system. In this case, an up scaling of the system takes place: management and control of the system shifts to European load control and dispatch centres. The new guiding principles, beliefs and practices are a partial return to the more top-down control and management philosophy that was dominant before the introduction of market mechanisms. This is reinforced by the large-scale increase in the renewable energy technologies. Very large wind farms offshore, very large solar power plants (both PV and Concentrated Solar Power) in southern Europe and in the Sahara are being linked to hydropower stations in Scandinavia and the Alps. Part of the base load is still provided by large coal fired power plants (with CCS).

The integration of these large-scale renewable power plants requires a strengthening of the transmission grid, followed by the gradual emergence of a European Supergrid. At the same time such a powerful grid, partially consisting of High Voltage Direct Current (HVDC) lines, enables the further development of a more sustainable and more self-supporting electricity system. In this situation wind power transforms from a nuisance for network operators (because of threats for system stability) to one of the pillars of a more sustainable system [6].

In this pathway the system in 2050 is characterised by very large-scale generation units, which are in general located far from consumption centres. Despite the fluctuating nature of some of resources (in particular wind) the overall power production is well predictable and controllable. Balancing via generation and some demand management will suffice for stable alignment of demand and supply in the system. The main infrastructural issue is to create sufficient network capacity [20].

3.3. De-alignment and re-alignment: towards distributed generation

In this pathway regime actors are not capable of dealing with extreme landscape pressures on the electricity sector. These pressures might come from very high oil prices (e.g. accelerated Peak Oil, war in the Middle East) or gas scarcity (e.g. Russia cutting of gas supplies because of escalating international tensions). The regime actors lose faith in the usual solutions, leading to a period of uncertainty about the direction of the system and experimentation with multiple niche-innovations and more local or regional based systems. These local/regional systems use renewable resources and efficient technologies, e.g. onshore wind, PV panels, small scale biomass power plants, and micro-cogeneration. Production takes place near to the consumers.

These experiments start in specific niches like new urban areas and gradually spread to other applications. The experiments are supported by new networks of actors. These 'new entrants' can include local utilities and companies, consumer co-operations, housing associations and municipalities, who gradually take the place of the old incumbents, leading to the emergence of a new regime. The guiding principle is a strong preference for (predominantly) local or regional generation and balancing [23]. The main dynamism here is a cultural one, with an emphasis on regionalism, community based organizations and autarky.

This pathway leads to a major restructuring of the electricity system. The system in 2050 could be dominated by a set of loosely coupled regional and local grids (micro grids). If necessary, these micro grids can operate in island operation, but exchange of electricity with other systems increases reliability and enables cost optimisation. Therefore, completely isolated and autonomous operated networks are not probable. A few large-scale generation units provide backup capacity and can supply large consumers, e.g. heavy industry; they also will help in balancing supply and demand. In this situation, the utilisation degree of the composite system is quite low. This means that there has to be a lot of redundant capacity in the system. Poor predictability and controllability and bidirectional flows in the distribution grids make balancing demand and supply the main issue, but power (voltage) quality also can be a problem. Storage facilities will be essential to warrant balancing in the local and regional systems. Also, the development and application of ICT for monitoring and control, power electronics and the use of more flexible components in the system will be essential for a smooth operation of the system. In this pathway the operation of very large numbers of generators, storage facilities and controllable loads make a shift from the traditional central control philosophy to a new distributed control paradigm paramount. It will become necessary to split the large balancing problem into smaller parts as well as to optimise the operation of individual distribution networks (Fig. 2) [20]. Making the grid 'smarter' is important in all pathways, but especially so in a shift towards distributed generation.

4. Discussion of pathways

Each of the three pathways responds to the pressures on the current electricity regime and the resulting tensions, but they differ in the problems they prioritise, the social dynamics and the role of niches. In the *Transformation* pathway, regime actors keep control over the system. Reorientation occurs through the greening of centralised production (co firing of biomass, CCS) and the adoption of large-scale renewable options (e.g. wind parks). These options fit reasonably well within the system, although some adaptations and changes will accompany their integration. The dynamic is predominantly *economic*: producers operate mainly under a market regime; prices and costs play a crucial role in the competition; cost-effectiveness is a major criterion when evaluating radically alternative options. Policy interventions and regulations can mitigate a lack of competitiveness, but many options remain niche applications because they are perceived as too expensive.

In the *Reconfiguration* pathway, the (geopolitical and energy security) pressures on the regime are perceived as major threats, in response to which regime actors join forces to create a more sustainable European system (Supergrid). Coordination and

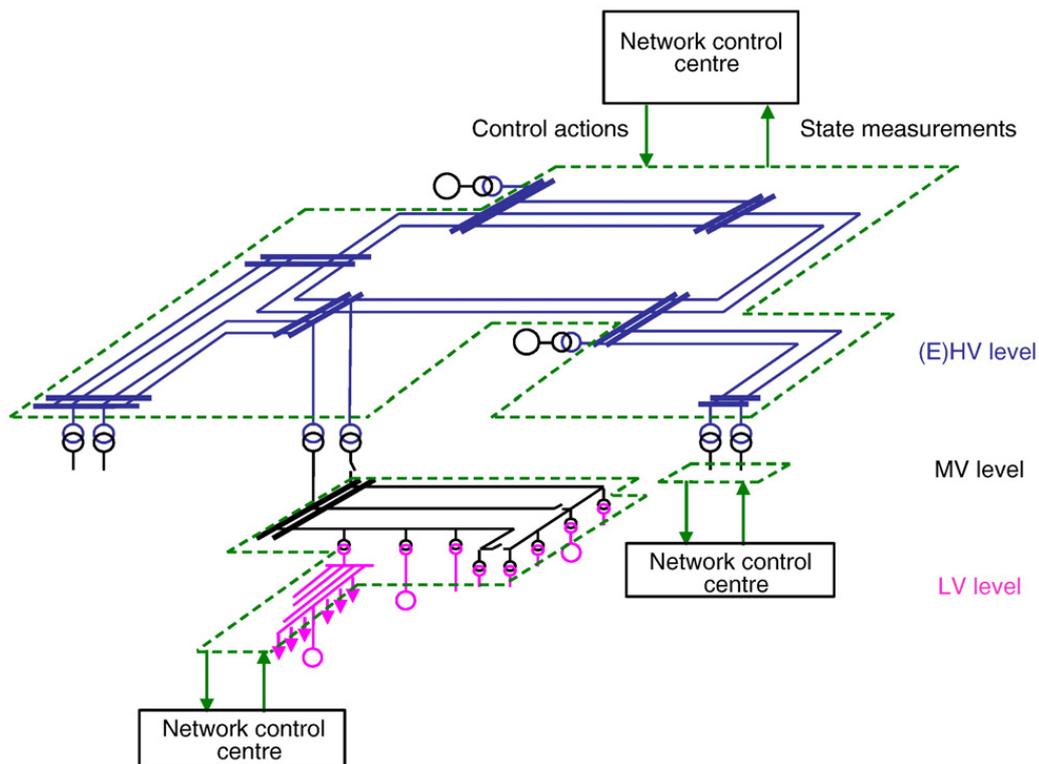


Fig. 2. Multiple agent network control at different voltage levels.
Source: [20], 59.

guidance at the European level play a major role in this scenario. In a way, this is a return to the dominant development pattern before the 1980s, although there are major changes in the generation part of the system. *Political* dynamics are important drivers. Some large-scale renewable energy technologies have been integrated in the Supergrid, while small scale alternatives are marginalised.

Finally, in the *De-alignment and re-alignment* pathway, regime actors lose faith in the 'normal' solutions and the regime crumbles under severe landscape developments. New system configurations gradually emerge around local or regional power plants, linked together in new networks, e.g. *micro grids*. These configurations are (partly) carried by new actors, who also introduce a new set of rules. *Cultural* dynamics (regionalism, autarky) are important. Because of major changes in social networks, regime rules and infrastructure, this pathway entails the most radical shift.

Which of the pathways is the most likely? In fact, elements of all three pathways can be distinguished in the current regime. The Transformation pathway remains closest to the current situation, but proposals for large distance high voltage lines (including HVDC) are regularly articulated and some of those plans are already being implemented, e.g. the link from the Netherlands to Norway and to the UK. Also, expectations about the potential of wind offshore are very high. Large-scale implementation of wind farms on the North Sea will inevitably lead to the expansion of the high voltage grid. At the same time distributed generation is being promoted and stimulated by national and European policies. Germany is a world leader on PV, both in production and implementation [24]. Gas utilities in the Netherlands are pushing micro-cogeneration systems [25]. Also, R&D of new grid configurations are taking place, supported by national and EU R&D grants [26]. Because all three pathways are technologically feasible, future sustainability transitions are mainly determined by economic, institutional and cultural dynamics. However, we suggest that the de-alignment and re-alignment pathway is less likely than the other two pathways, which stay to closer vested interests and are more in line with ongoing dynamics. The de-alignment and re-alignment pathway is therefore more dependent on external developments and/or strong policy interventions.

Investments and infrastructure innovations are needed in all pathways, not only for the Supergrid and hybrid system, but also for the decentralized scenario (micro grids). Contrary to the common belief (and promise) that distributed generation will reduce the need for transmission and distribution infrastructure, micro grids also require expansions and improvements of the central infrastructure, e.g. to provide backups and balancing supply and demand [27]. However, a shift towards distributed generation will require more emphasis on local distribution grids. These will acquire the characteristics of HV grids, requiring a paradigmatic change of operation principles. Also, new innovative components and technologies are needed [22]. Infrastructure thus remains crucially important in all transition pathways.

All the scenarios assume that electricity networks remain necessary in the future. Completely different configurations are feasible, e.g. it is possible to construct a hydrogen economy with local electricity generation, but this does not seem very likely because electricity networks provide a high degree of reliability and reduce the need for spare generation capacity. Also, the embedded nature of the current infrastructure creates a high degree of path dependency. At the other extreme completely different

electricity systems could be technologically feasible, e.g. an energy internet where everyone can plug into the energy internet, but this analogy with the existing internet is even less likely to occur. This highly technological vision seems to be inspired by ideological motives. This is very obvious in the work of Jeremy Rifkin, as the title of his influential book suggests “The hydrogen economy; the creation of the worldwide energy web and the redistribution of power on Earth” [28]. Although most publications on hydrogen quote Rifkin's book, very few refer to the political part of his vision. Such technological determinist visions, which believe in the power of new energy systems to radically change society, tend to neglect the economic, political, social and cultural dynamics in the energy regime, which in our view ultimately determine the shape of our future energy system.

5. Policy relevance and concluding remarks

To discuss policy relevance, we build on Hall's [29] distinction of three policy levels: a) the precise setting of policy instruments (e.g. strictness of regulations, height of taxes), b) the kinds of policy instruments (e.g. market based, regulatory, network/learning instruments), c) the overall goals that guide policies in particular fields and the associated belief systems (what he calls policy paradigm). Our scenarios and socio-technical approach are particular relevant with regard to Hall's highest level, providing a tool that enhances the reflexivity of policy goals and strategies [29].

In terms of policy goals, our scenarios imply different goal hierarchies. The hierarchy in the ‘transformation scenario’ is: 1) cheap (cost efficiency), 2) reliability, 3) environmental issues. Market-based instruments are likely to dominate. The hierarchy in the ‘reconfiguration scenario’, where energy security is more important, is: 1) reliability, 2) environmental issues, 3) cheap (cost efficiency). Regulatory instruments, planning and stronger government involvement will be more important, besides market-based approaches. In the ‘de-alignment and re-alignment scenario’, the hierarchy is: 1) local control and reduced external dependence (which is a new goal compared to the other scenarios), 2) reliability, 3) environmental issues, 4) cheap (cost efficiency). Policy instruments that stimulate network building and learning will be more important in this scenario (public participation, experimentation, interactive scenario exercises). The hierarchy in the first scenario is closest to goal set that dominated electricity systems in the last two decades [3], and therefore requires least change. Alternative transition pathways, articulated in the other two scenarios, are thus likely to involve changes in policy paradigms. Political changes like the election of Barack Obama in the US in 2008 and increasing evidence of the impact of climate change could facilitate such shifts to other policy paradigm. Also erosion of the neo-liberal ideology, which dominated politics during the last two decades, may contribute to such shifts. The financial crisis of 2008–2009 has damaged the credibility of this ideology to some extent and made ideas around stronger government interventions and regulation more acceptable. But it remains to be seen if this really leads to a shift in policy paradigm.

In terms of policy strategies, the scenarios also point to different emphasis in the two-pronged strategy that is suggested by multi-level perspective [30]: 1) increase the pressure on the existing regime e.g. with financial and regulatory instruments (e.g. carbon tax, emissions trading, emission norms, performance standards), 2) stimulate the emergence and development of radical innovations in niches. The ‘transformation pathway’, which is about reorientation of existing trajectories, places more emphasis on regime pressure than on stimulating niches. The ‘reconfiguration pathway’ has a more balanced approach: on the one hand, niche-innovations are stimulated, e.g. through dedicated large-scale renewable projects; on the other hand, regime actors are stimulated to incorporate these niches and align different national networks in a European Supergrid. The ‘de-alignment and re-alignment’ pathway, which assumes that regimes fall apart because of external landscape pressures, focuses primarily on policies that stimulate niche-innovations and nurture the emergence of a new system.

Based on these considerations we conclude that the transition theory and the pathway typology presented here provide tools for systematic exploration of possible transition pathways, policy goals and policy strategies. Although these tools cannot *predict* the precise development of future electricity systems, they can enhance the analytical depth and reflexivity in policy making, especially by explicating the dynamics of transitions and by opening up the (often hidden) choices at the third policy (paradigm) level of general goals and strategies.

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