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Sociotechnical scenarios as a new policy tool to explore system innovations: Co-evolution of technology and society in The Netherland's electricity domain

SUMMARY

System innovations are long-term transitions from one sociotechnical system to another. They involve not only changes in technology, but also changes in user practices, regulation, industrial networks, infrastructure, and culture. Current scenario methods are not entirely suited to explore possible system innovations. They lack attention to the co-evolution of technology and society, and to insights from innovation studies and sociology of technology. Hence, we propose a new tool: sociotechnical scenarios. We illustrate the tool with two scenarios in the electricity domain, sketching transition paths to more sustainable systems. We also derive strategic policy recommendations from the two scenarios.

KEY WORDS

co-evolution; sociotechnical scenarios; methodology; system innovation; electricity; strategic policy making

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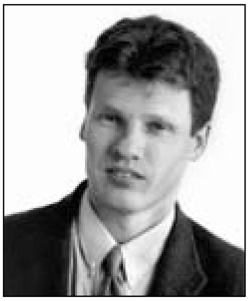

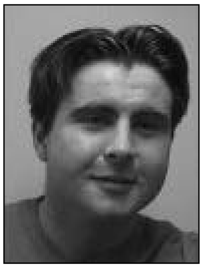

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1. INTRODUCTION

Modern societies face huge challenges related to existing sociotechnical systems which are difficult to tackle without fundamental change. One example is the transport system, which faces structural problems like congestion, atmospheric pollution (NO_x and particulates), and CO_2-emissions. And the energy system suffers from high CO_2 emissions and fuel supply uncertainties. Such problems are deeply rooted in societal structures and institutions.

In transport systems and energy systems there are promising new technologies with better environmental performance. But many of these new technologies are not (yet) taken up. This is partly related to economic reasons, but also to social, cultural, infrastructural and regulative reasons. Existing systems seem to be 'locked in' at multiple dimensions. Hence, recent articles have widened the analytical focus from artefacts to socio-technical systems (e.g. Unruh, 2000; Jacobsson and Johnson, 2000; Berkhout, 2002). Socio-technical systems consist of a cluster of elements, including technology, regulation, user practices and markets, cultural meaning, infrastructure, maintenance networks, and supply networks. Figure 1 gives an example for the system of electricity provision and use.

Sociotechnical systems are stable, because the elements are aligned and woven together. Yet, to solve structural problems in society, we need transitions in sociotechnical systems. Such system innovations not only involve technological changes, but also changes in user practices, policy and regulation, infrastructure, social networks, and culture.

Policy makers, NGOs, large firms and others show substantial interest in system innovations. The Stockholm Environment Institute, for instance, published a book on the *Great Transition* (Raskin et al. 2002). The American National Research Council (1999) and the Dutch Research Council NWO have made transitions part of their research portfolio. And the Dutch government gave transitions a central place in their fourth National Environmental Policy Plan (VROM, 2001). They think that system innovations promise large improvements in environmental efficiency (Figure 2).

But transitions are complex, uncertain and involve multiple social groups. Hence, decision makers struggle the question on how they can know and influence possible directions of such transitions. Scenarios or forecasting exercises are often used to guide strategic decision-making. But we will argue in section 3 that existing scenario methods are not entirely suited to explore system innovation. They are often based on too simple assumptions about the

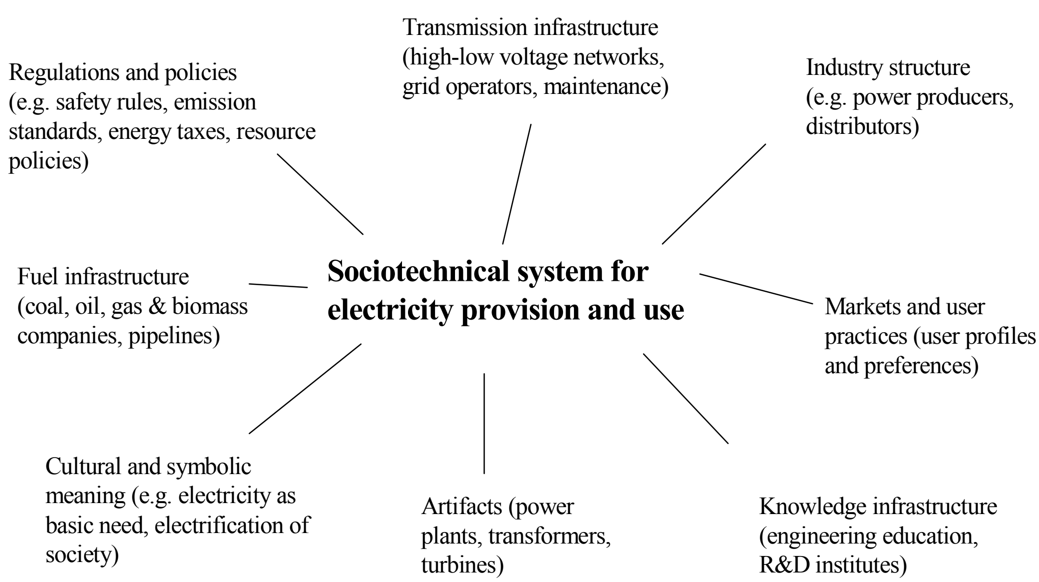

FIGURE 1: Sociotechnical system for electricity provision and use

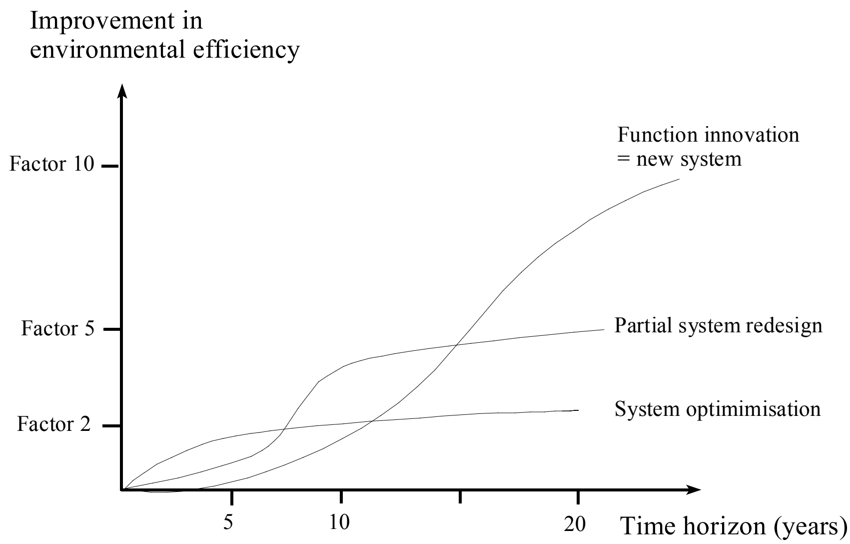

FIGURE 2: System optimisation versus system innovation (Weterings et al, 1997)

dynamics of technological change, and ignore the co-evolution of technology and society. Therefore, we propose a new scenario tool, sociotechnical scenarios (STSc), tailored to explore transitions and system innovations (section 4). This new tool does not replace existing scenario methods, but can complement them. A strength of the method is that it builds explicitly on a scientific transition theory, described in section 2. We illustrate the tool in section 5 with two sociotechnical scenarios for the development towards a more sustainable electricity system. Section 6 derives some strategic policy suggestions from the scenarios. The paper ends with conclusions about the added value of STSc.

2. TRANSITION THEORY

To understand technological transitions we use a multi-level perspective that builds on insights from innovation studies and sociology of technology. Sociology of technology emphasises the interrelatedness between technical and social change and the interaction between social groups (e.g. Bijker et al, 1987; Bijker and Law, 1992). At the heart of the transition theory are three 'levels' and the interactions between them. We will only briefly outline the multi-level framework, because it has been described more elaborately elsewhere (Kemp et al, 1998, 2001; Geels 2002a,c). The meso-level is formed by *socio-technical regimes*. Socio-technical systems are actively created and maintained by several social groups (Figure 3). Their activities reproduce the elements and linkages in sociotechnical systems and are coordinated and aligned to each other. This is represented with the concept of socio-technical regimes, which refers to the cognitive, normative and formal rules that guide activities of social groups. By providing orientation and co-ordination to the activities of relevant actor groups, sociotechnical regimes account for the 'dynamic stability' of ST-systems. This means that innovation still occurs but is of an incremental nature, leading to 'technical trajectories' and path dependencies.

The micro-level is formed by technological niches, the locus for radical innovations ('variation'). As their performance is initially low, they emerge in 'protected spaces', which shield them from mainstream market selection. Niches thus act as 'incubation rooms' for radical novelties. Niches are important, because

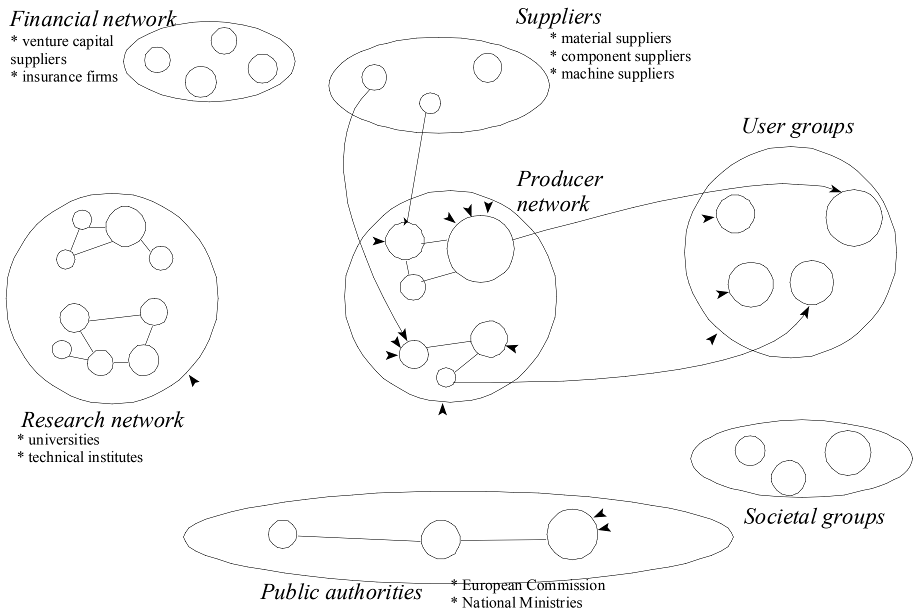

FIGURE 3: Social groups which (re)produce ST-systems (Geels, 2002a: 1260)

they provide locations for learning processes about the technology, user preferences, regulations, infrastructure, symbolic meaning etc. Niches also provide space to build the social networks that support innovations. These internal niche processes have been described under the heading of strategic niche management (Kemp et al, 1998, 2001).

The macro-level is formed by the *socio-technical landscape* which refers to aspects of the wider exogenous environment (e.g. globalisation, environmental problems, cultural changes). The metaphor 'landscape' is used because of the literal connotation of relative 'hardness' and to include the material aspect of society, e.g. the material and spatial arrangements of cities, factories, highways, and electricity infrastructures. The landscape forms 'gradients' for action; they are beyond the direct influence of actors.

The relation between the three concepts can be understood as a nested hierarchy or multi-level perspective. Regimes are embedded within landscapes and niches within regimes. Transitions and system innovations come about through the interplay between dynamics at multiple levels and in several phases (see also Rotmans et al., 2001). In the first phase, novelties emerge in niches in the context of existing regimes and landscapes with their specific problems, rules and capabilities. New technologies often face a 'mismatch' with the established economic, social and/or political dimensions (Freeman and Perez, 1988). Hence, novelties remain stuck in niches. In niches, actors improvise, engage in experiments to work out the best design and find out what users want. In the second phase the novelty is used in small market niches, which provide resources for technical specialisation. Engineers gradually develop new rules, and the new technology gradually improves, as a result of learning processes. The third phase is characterised by a breakthrough of the new technology, wide diffusion and competition with the established regime. On the one hand, there are internal drivers for breakthrough. For instance, actors with interests may push for further expansion of the technology. Or price/performance dimensions gradually improve. On the other hand, breakthrough depends on external circumstances, i.e. 'ongoing processes' at the levels of regime and landscape, which create a 'window of opportunity' (see Figure 4). There may be changes at the landscape level, which put pressure on the regime. There may be internal technical problems in the regime, which cannot be met with the available technology. There may be negative externalities, which are problematised by 'outsiders', e.g. societal pressure groups (e.g. Greenpeace), outside scientific professionals, or outside firms (Van de Poel, 2000). Or there may be tensions within the existing regime, because of changing user preferences or stricter regulations. The key point of the multi-level perspective is that system innovations occur as the outcome of linkages between developments at multiple levels. As the new technology enters mainstream markets it enters a competitive relationship with the established regime.

In the fourth phase the new technology replaces the old regime, which is accompanied by changes on wider dimensions of the socio-technical regime. The new regime may eventually influence wider landscape developments.

This generic multi-level perspective can be further refined in terms of transition routes. Geels (2002c) distinguished two routes: (1) technical substitution and (2) broad transformation. In the *substitution route*, socio-technical regimes are relatively stable until the breakthrough of new technologies. The wide diffusion into mainstream markets triggers wider changes, and may cause established producers to fail (Schumpeter's 'gales of destruction'). On the level of regimes, this route can be described with punctuations between relatively stable socio-technical configurations. It is called 'substitution' because the user substi-

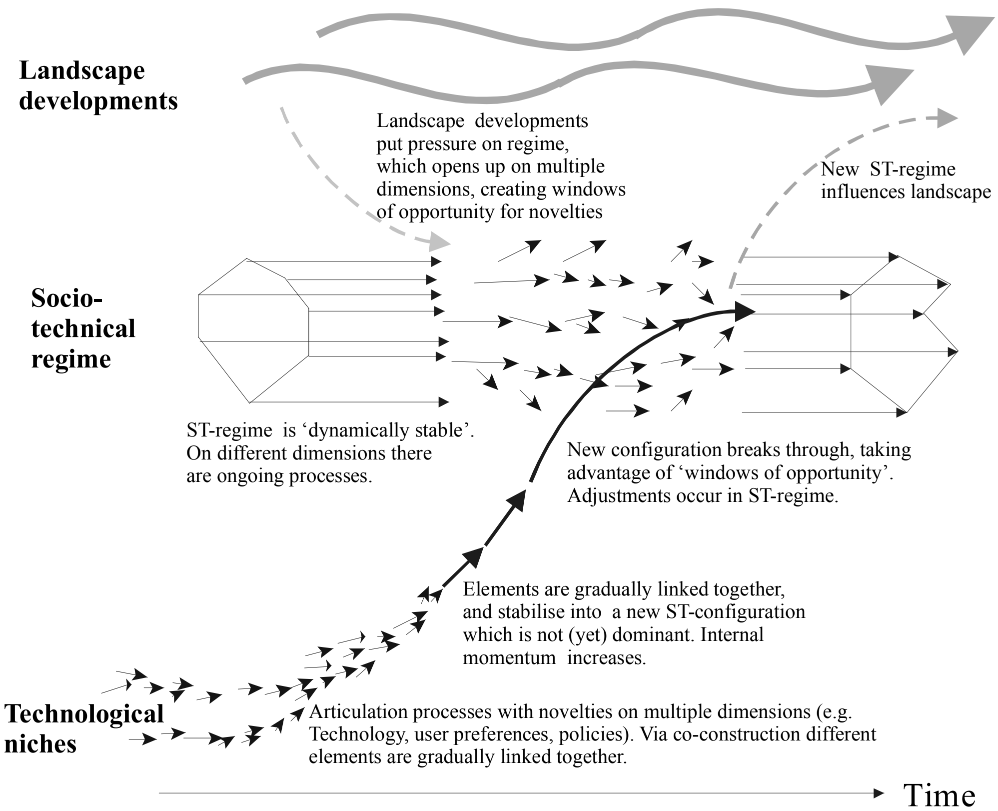

FIGURE 4: A dynamic multi-level perspective on system innovations (Geels, 2002c)

tutes one technology for another with relatively little change in meaning and behaviour. In the *transformation route*, much more is at stake than a technical substitution. There may also be changes in user behaviour, cultural change, policy changes, infrastructural change, etc. The loosening up of the existing regime may create windows of opportunity for multiple novelties and stimulate actors to experiment with many technical options. Often, these novelties do not break through individually but first merge with each other or with parts of the regime. The typical pattern in broad transformation is that the regime (usually under pressure) first *opens up* and creates room for a wide variety of niches. One or more of these may then start to grow at the expense of the existing regime until they become the new dominant regime. Then the regime tends to *close in* again, reducing the room for niches.

Below these general longer-term patterns some shorter-term mechanisms can be distinguished. One example is the *sailing ship effect*, which means that the existing regime defends itself against upcoming niches via technical improvements (after sailing ships which added more sail and masts to counter the threat of steamships). Another example is the mechanism of niche-accumulation. A new technology diffuses via successive domains of application and market niches. A third mechanism is hybridisation: the merger of two technical options to create something new (e.g. the merger of the gas turbine and the steam turbine into combined cycles (Islas, 1997). A fourth mechanism is that new technologies may induce (initially small) groups of users to change their behaviour and develop new user practices. Such new user patterns emerge through 'learning by using' (Von Hippel, 1988).

3. Strengths and Weaknesses in Existing Scenario Methods

There are several scenario methods and projects for the long-term exploration of fundamental and systemic change processes (30–50 years). Table 1 gives an overview of existing scenario methods illustrated by exemplar scenario projects, selected out of a larger evaluation of around twenty scenario projects. A short characterization is provided in terms of the type of scenario and the nature of the method. In the third column, we evaluate how the scenarios score on characteristics of system innovations (strengths and weaknesses).

From this overview we conclude that none of scenario projects and methods encompass all characteristics of system innovations, although most score well on some of them. One basic deficiency is the lack of a clear conceptual framework regarding the way transitions occur. Technological change is often conceptualised in a simple way, e.g. as determining force or as aggregate learning curve. There is a lack of attention for actors, their decisions, interactions and learning processes, and the way these shape twisting transition paths. The pathways in most scenarios seem to be determined mainly by external factors. But, of course, choices by actors in regimes and niches are also important for future trajectories, bifurcations etc. Macro-, meso- and micro-levels should all be included.

These conclusions do not mean that existing scenario methods are irrelevant. They may fulfil useful functions to explore *aspects* of transitions. But to encompass the entire complexity of system innovations, there is a need for a new tool.

4. Sociotechnical Scenarios and Guidelines for Their Construction

Scenarios are usually constructed following a sequence of steps (Table 2).

Our focal issue are system innovations, in this paper regarding the electricity domain. We make our contribution mainly to step 2 and 4, in the sense that we use an explicit theoretical

TABLE 1: OVERVIEW OF SCENARIO METHODS AND EXEMPLAR PROJECTS

Scenario project description	Method	Strengths (+) / weaknesses (–)
Forecasting		
IPPC (2000): Global greenhouse gas emission scenarios up to 2100	Combination of four basic narratives ('storylines') and more detailed modelling and quantification (forecasting)	(+) Aggregate attention for co-evolution; focus on uptake of radical technologies (–) Learning processes anticipated but not explained; limited attention for actor strategies
Foresight		
Shell (2001): Scenarios of societal change and impact on business and energy development (2020 and 2050)	Descriptive scenarios complemented by quantification of some main factors (demographics, incomes, energy demand, fuel and technology mix) used to support long-term business strategies.	(+) Focus on social and technological driving forces; taking into account discontinuous change; multi-actor and multi-level processes (–) Limited interaction between societal and technological change; Anticipation but no specification of learning processes; Macro-orientation and lack of actor interactions at lower levels
Backcasting		
SusHouse (Vergragt, 2000): Scenarios for sustainable household functions (food, shelter, clothing) by 2050 in several European countries	Creativity workshop with stakeholders to produce ideas on how to bring about factor 20 sustainability improvement for the functions; followed by construction of design oriented sociotechnical scenarios; and by an environmental, economic and consumer acceptability assessment	(+) Develops alternative fulfillment of functions based on technological and social change; strong focus on consumers as important actors (–) Limited insight in how co-evolutionary paths towards alternative future takes place; anticipates learning but does not specify how this may lead to uptake of radical practices
Technological roadmapping		
EPRI (1999): Electricity technology roadmap to 2050 for the US	In a process with around 100 stakeholders (mainly technically oriented) a vision is developed regarding the long term potential for electricity as a clean, flexible and growth enabling technology, accompantie by a R&D agenda to realise the vision	(+) Starts from premise of importance of institutional processes for technological change; takes into account long term technological change featuring hybridisations, cross-cutting technologies etc. (–) Very limited co-evolution through strong bias on technological change; lacks focus on interaction processes and explanation of learning
Breakthrough methods		
Noori et al (1999): Method for assessing breakthrough potential of new product or service, application for electric vehicle	An umbrella approach that assesses future goals, needs, desires, and product development direction, and works backward to the present to determine what steps must be completed to reach that state	(+) Takes into account importance of changing user preferences, cultural factors for uptake of breakthrough technologies (–) Limited explanation how learning processes occur; restricted focus on innovator and consumer as actors

TABLE 2: METHODOLOGICAL STEPS IN SCENARIO BUILDING

Step 1	Identify focal issue or decision
Step 2	Make an empirical analysis of aspects and processes which directly and indirectly influence the focal issue
Step 3	Rank aspects and processes by importance and uncertainty
Step 4	Select scenario logics (skeleton): give different scores to those aspects and processes which are most uncertain and have most effect
Step 5	Flesh out and write the scenarios
Step 6	Derive implications for initial decision

approach for the empirical analysis of the electricity system and the writing of the scenarios. Because co-evolution of technology and society are at the heart of the approach, we call the new tool sociotechnical scenarios (STSc). Using the multi-level perspective, we analyse the main variables in the electricity regime, promising niches and possible landscape developments, and indicate how important and uncertain they are. We also use the multi-level perspective to think and write about possible future transition paths. The perspective helps us identify plausible transition paths. Patterns and mechanisms can be used to include more fine-grained sociotechnical dynamics (Geels, 2002b).

In this paper we have no space to elaborate all methodological steps (see Elzen et al, 2002). We suffice with presenting the bare skeleton of two scenarios, by summarising the main characteristics. These characteristics are then translated into plausible dynamic transition paths. Table 3 shows that the main differences are not so much the consequence of different technologies being used, but follow from alternative actor strategies and choices. In the first scenario, traditional power producers are the dominant actor, utilising gasification technology on a large-scale through processes of hybridisation. Developments in the US provide an important stepping-stone for the niche through its focus on coal gasification. In the second scenario, energy distribution companies are a crucial actor, working together with gas utilities, which seek opportunities to increase their market share by the development of micro combined heat-and-power production (CHP) in coalition with other actors. Table 3 provides an overview of some of the main characteristics, drivers, networks and differences and similarities of the two scenarios.

5. TOWARDS A SUSTAINABLE ELECTRICITY SYSTEM: ILLUSTRATION OF TWO TRANSITION PATHS

This section describes two sociotechnical scenarios, illustrating two different transition paths towards a sustainable electricity regime. These paths follow the contrasting routes described in section 2 (technical substitution and wider transformation). In the first scenario renewable sources are gradually integrated into the existing regime; in the second scenario a broader transformation of the regime takes place towards distributed generation. Both stories build upon the static backbone, provided by table 3. The stories are written in the past tense as histories of the future.

1990–2000: THE ELECTRICITY REGIME OPENING UP

For more than a half century the electricity regime was rather stable, as a closed and stable network of actors had been able to control both the direction and speed of change in electricity generation, transmission and distribution, based on steady growth of electricity consumption (see for example Hughes, 1983; Hirsh, 1999; Unruh, 2000). In the last dec-

TABLE 3: CHARACTERISATION OF THE TWO SCENARIOS AND TRANSITION PATHS

	Large scale integration of renewables	Towards distributed generation
Initial niches	• Biomass co-combustion in coal-fired power plants • Offshore wind power farms • Coal/Biomass gasification; based on international niche proliferation • Fossil generation with CO_2 separation, storage.	• Combined heat and power production with small scale electricity generation technologies • Local power generation because of overburdened grid • ICT demand for reliable power • New housing districts with low energy impact
Main differences	Large scale power plants at international level, based on biomass gasification, wind power, photovoltaics and hydrogen facilities; international electricity highway; international coordination of electricity flows	Dominance of local based networks with electricity generation units dimensioned to local demand; high voltage grid serves as back up; integration of number of energy technologies/sources such as pv, wind, biomass, fuel cells, turbines
Main similarities	Gas and hydrogen important bridging resources, fuel cells important energy technology also in hybrid combination	Gas and hydrogen important bridging resources, fuel cells important energy technology also in hybrid combination
Drivers		
– *Landscape*	Liberalisation, EU integration, Climate change	Liberalisation, ICT, Sustainability/climate change
– *Regime*	Increasing international character of regime, uptake of renewables by regime	Battle between electricity producers, multi-utilities and gas companies; changing position of consumer
– *Niches*	Hybridisation of niches with regime; niches adapt to dominant design of central station electricity	First niches because of differentiation in regime; niches slowly built new power system design of distributed generation
Barriers	Mismatch of renewables with regime, problems of integration into existing regime	Design, regulation, routines based on central station electricity regime, not on local generation with local grid
Dominant networks	Networks with traditional electricity producers, distributors and government actors; oil and chemical sector becomes part of electricity regime	Networks of energy distributors, engineering firms, construction companies, housing associations and municipalities
Policy	Strengthening of international grid, EU policies, support for green electricity, and labelling of electricity flows	Local energy policy, stimulation of alternative infrastructures, integration of energy in built environment

ades, however, the electricity regime opened up. Its social network became unstable as national government aimed to exercise more control, and industrial and societal actors challenged guiding principles of the regime (Joskow, 1998; Hirsh, 1999; Patterson, 1999). The regime was long able to deal with increasing external demands such as efficiency and environmental emissions without fundamentally changing the sociotechnical configuration. The process of liberalisation, however, led to increasing tension within the social network of regime actors. For example in the Netherlands, new coalitions were formed between electricity distributors and industrial actors for decentral cogeneration of heat and power at the expense of central electricity generation. The over capacity that followed was a sign of the loss of control by regime actors (Arentsen et al, 2000). The anticipation of further liberalisation and the increasing importance of the climate problem led also to new actor coalitions that developed and marketed the novel concept of green electricity (e.g. energy distribution companies and environmental NGOs). With the emergence of new markets, exchanges and actors old social networks vanished and new networks emerged. The landscape developments of liberalisation, climate change and information technology increasingly penetrated the electricity regime and uncertainty over the future direction and speed of developments in electricity generation and use became high (e.g. van Hilten et al, 2000).

Scenario 1: Large scale integration of renewables in the electricity regime

2000–2010: Liberalisation creates tension in the regime

Five landscape trends were driving further change in the electricity regime with liberalisation as the most pervasive one. In combination with European integration, climate change, ICT and the new economy, and security threats it led to a totally different setting in which the electricity regime was operating.

Several patterns of change were visible in the electricity regime. Established power producers engaged in international price competition in order to realise full utilisation of their power plants and to satisfy customers' demand for low prices. A sharp increase in international trade in electricity was the consequence. To guarantee a European free market the EU intensified its role in harmonising the processes of liberalisation of national electricity sectors and in safeguarding sufficient capacity for crossborder electricity transport. The more volatile market conditions also demanded more flexible power plants that could produce efficiently at different loads and had short start up times. This reinforced the shift towards gas within the fossil fuel mix because of the higher flexibility and efficiency of the gas turbine relative to the more capital intensive and rigid coal-fired and nuclear power plants (see also Shell, 2001). Large oil and gas companies such as Shell were also able the enter the electricity generation market by investing in combined cycle gas turbines that produced electricity and heat fuelled by their own gas supply. This gave them an edge over other power companies with gas-fired power plants that had to cope with volatile market conditions for gas.

The emancipation of the previous mostly passive electricity users led to various changing user preferences. The penetration of ICT and the new economy, for example, led on the one hand to higher quality and reliability demands while on the other hand it facilitated e-commerce in the electricity system. Also, industrial users settled one contract for the combined purchase of heat and power or different contracts for base-load and peak-load electricity delivery. Households with commitment to sustainability were keen on a green profile of electricity. Especially energy distributors and new entrants were developing innovative products and services that could meet the changing user preferences.

Alternative strategies were enabled by available niche technologies that better suited new user preferences. In the Netherlands the concept of green electricity provided momentum for investments in especially wind and biomass. Constraints for wind energy on land (regulatory, societal) led to increased expectations and investments in off-shore wind farms where these constraints were less complex to deal with. The biomass niche and its constituency expanded as it hooked up with the regime. To improve their carbon profile and to reduce Dutch political pressure, coal power producers adopted strategies of co-firing coal fired power plants with biomass. Political support for this strategy was given through the exemption of the regulatory energy tax for the biomass-fired part of electricity generation.

2010–2025: Regime increasingly adopted climate friendly energy technologies

Climate change concern became a more significant driver of regime change as carbon emissions were priced through policies of emission trading and carbon taxes. Pilot projects in emission trading in the Netherlands, UK, and Denmark served as examples for the design of a European trading scheme. The European Union also reinforced its role in international electricity trade to secure to reliability of the emerging European electricity system. ICT technologies became more pervasive throughout the electricity system as it enabled online energy resources and electricity markets and fine-tuning of power plant utilisation.

In the electricity regime coal power plants started to reach the end of their life-time and new investments occurred in energy technologies that suited power and environmental demands better. The strategy of co-firing with biomass reached its limit as the rising share of biomass in the fuel mix led to high capital costs to clean exhaust gases. Coal gasification, which enabled better emission control, increased in several coal dependent countries. Especially the USA was a frontrunner, with R&D in coal gasification boosted after the September 2001 terrorist attacks intensified the strategy towards resource independence. In Europe, with stronger climate pressure, the higher efficiencies that could be reached with coal gasification in combined cycles were accompanied by strategies to reduce the carbon content. This involved projects with carbon removal and sequestration and co-gasification with biomass.

While co-combustion and co-gasification stimulated early demand for biomass, later biomass gasification technology became more prominent. Regulations regarding emissions of CO_2, NO_x and other substances became based on the performance of the integrated gasification combined cycles, making further installation of traditional coal-fired power plants difficult. Moreover, biomass gasification became more attractive as costs of carbon removal were becoming a heavier burden for coal power plants.

In the Netherlands the number of households purchasing green electricity steadily grew from 10% in 2000 to 30% in 2015. Its price level remained competitive as cost reduction of biomass and wind energy offset the reduction of tax benefits. The introduction of the regulatory energy tax for industries, later replaced by the carbon tax, increased the number of companies using green electricity. This also provided momentum for industries to invest in and buy renewable energy. Green electricity from foreign sources grew as Dutch growth of renewable energy was insufficient. This gap closed as more wind farms and integrated gasification combined cycle power plants were constructed to replace power plants from the 1980s.

A relatively new niche development involved hydrogen production from gas, with hydrogen mixed in the gas network and CO_2 removed and either used in horticulture or sequestrated. Also conversion from gas to hydrogen and carbon black was initiated in demonstration projects, with the carbon reused in the tire industry, as it was thus able to improve its carbon profile. Hydrogen was also used for first mobile applications of hydrogen fuel cells. Another niche for hydrogen powered fuel cells concerned data processing stations that needed very reliable power that could be served by fuel cells that additionally are quiet, clean without the need for a strong grid. The growth potential of these niche market led power equipment sector to further develop and market the combined fuel cell and microturbine that with its very high electric efficiency and low emissions was very attractive in several fast growing niche markets such as back-up systems and ICT concentrated demand. The system was especially suited for power supply to areas where power demand was high and heat demand low.

2025–2050: Regime shift to international renewable electricity generation

The process of European unification continued and political power increasingly shifted to the European level. Authority over high voltage grids shifted from the national to the European level and the reliability of electricity supply was guaranteed through European law, rules and agreements.

At the regime level in the Netherlands, coal was only utilised in a gasification plant in the Rijnmond area, with the CO_2 re-used in other processes, such as in horticulture. In Europe the number of coal power plants was dropping because of the costs of CO_2 removal and the difficulty, also due to societal opposition, of finding proper locations for carbon sequestration. With a significant price on carbon emissions, investments in integrated gasification combined cycles started to outrun those in combined cycle gas turbines as they combined high efficiency with an ability to deploy various feedstocks and produce multiple products. Coalitions between energy companies and agricultural and chemical companies emerged to bundle expertise regarding biomass utilisation, electricity marketing and chemical production and marketing. Hydrogen, as one of its products, was utilised increasingly for mobile applications. Global use of biomass as an electricity generation source increased rapidly and spurred trade in various waste and biomass products. Several developing countries shifted part of their commodity production towards biomass crops that guaranteed better income than traditional crops. ICT played a role in facilitating on-line exchanges of electricity and of resources for electricity generation such as biomass, hydrogen.

After production of several thousand units of hybrid microturbine/fuel cell systems lowered their costs, power equipment producers started to produce larger scale units in the megawatt range because the enabled them to reduce costs even further and to tap other than niche markets. The systems began to compete effectively with combined cycle gas turbines especially for peak and medium loads. While initially the hybrid fuel cell/gas turbine systems were powered by hydrogen through gas reforming, they increasingly used direct hydrogen.

One source for hydrogen were offshore wind farms that produced hydrogen from surplus electricity at low demand periods. Combined production of power and hydrogen gained momentum as it solved both the problems of discontinuity and storage. Utilisation of ICT also enabled better anticipation of discontinuous resources such as photovoltaic and wind power, and thus enabled better overall control of the international electricity regime. Expectations regarding large-scale solar power increased as further strengthening of the grid, long distance transport at higher voltage, and improvement of cable and conduction technologies, led to reduction of transport losses and made transport at longer distances possible. Solar hydrogen systems were developed in Southern regions (Europe and Africa) as they served local hydrogen need and produced power for the international grid. In 2050, then, electricity demand in the Netherlands was met half by national power production with several highly efficient combined cycles based on inputs of gas, biomass and coal (with CO_2 removal) and offshore wind-hydrogen systems, leading to a halving of CO_2 emissions compared to the 1990 level. The other half was met by import of electricity based on combined cycles, offshore wind farms, solar hydrogen systems and hydropower.

Scenario 2: Towards distributed generation

2000–2010: Diverging actor strategies in the electricity regime

Changing user preferences facilitated by liberalisation induced increasing divergence in strategies of mainly international operating electricity producers and more national focussed energy distribution companies. *Producers* supplied cheap base load electricity by full utilisation of their large-scale power plants based on coal, oil, gas or nuclear energy. *Distributors* were more focussed on customers with smaller electricity demand, such as households and small firms. They were attracting customers mainly by highlighting the specificity of their product and service. Distributors aimed to further expand market niches such as industrial combined heat and power production, in collaboration with industrial actors, and they further explored technological niches such as micropower in coalition with gas utilities and electric equipment producers. *Gas utilities* were involved to expand the market of gas relative to central produced electricity. Several *industries* were involved because they needed electricity in combination with high quality heat that could be provided by microturbines. Projects with micropower for several households were supported by coalitions involved in the development of energy-efficient housing districts. The Dutch world-wide fund for nature (WWF) had developed a set of design criteria that were used in several housing projects by project developers, construction companies and municipalities. They explored the potential of further improving energy efficiency in houses by installing these micropower systems. Potential buyers were not scared away by the relatively small additional costs also because of the continuing housing scarcity, while some leading edge buyers were specifically attracted by the green profile of the houses.

The projects induced further experiments with local generation systems because several problems were encountered. Distributors had to solve problems of increasing two-way electricity flows in the local low voltage networks as these networks were designed to carry flows from central production units to users. The projects did not discern between the different heat and power demand profiles of users, leading to surplus heat production that needed to be stored. Power equipment producers began to work on designs for micropower systems with different heat-power ratios, while distributors in collaboration with producers of domestic appliances began to focus on smart appliances that could be switched on and off at the most feasible periods. As growth of electricity demand was rather concentrated, such as in areas with many ICT companies, the capacity of the grid was insufficient to serve this power demand. This led to collaboration of ICT companies and energy distributors to develop local systems that were able to serve high electricity demand and a high level of reliability.

2010–2025: Decentral combined heat and power production and micropower gained momentum

Climate change gained priority as the Netherlands had been unable to realise the Kyoto targets and Dutch government aimed to intensify its climate policy. The policy to exempt combined heat and power production partly from the regulatory energy tax became into operation, while the regulatory energy tax was now also applicable for large energy users. In the electricity regime central producers were faced with increasingly obsolete power plants that needed replacement. The relative share of central power generation continued to fall as various energy technologies provided opportunities to produce power efficiently locally.

At the niche level, leading edge companies followed examples in the USA and installed fuel cell stacks to secure their electricity supply. Several users needed more reliable power delivery for on-line financial transactions, exchanges and ICT operations. These companies installed local power back up that could handle short black outs. Also electricity contracts were settled between ICT, financial companies and energy companies that combined high reliability with high liability, and energy companies installed reliable local capacity with fuel cells for these companies.

Microturbines became more widespread as the coalition of energy distributors and gas utilities spread the application of combined heat and power systems to smaller companies, neighbourhoods and households. In several projects users were involved in the design phase of these houses to improve the balance between individual demand and the micropower system installed. Smart electrical equipment was used to improve utilisation. Leading edge users were able to effectively reduce their energy costs. This led to more users wanting to be involved in the early stage of the housing project. The high energy efficiency of these houses also led to sharpened energy performance standards in energy and housing policy. After installation companies gained experience with the design and installation of micropower in new housing districts they became convinced of its potential to replace conventional heating systems in existing houses. Users became increasingly accustomed to the use of micropower as it slowly became available in companies that provided household equipment. Marketing campaigns convinced customers of the economic and environmental benefits.

The rise of micropower for neighbourhoods and of more reliable local power supply led energy distributors to focus on the design and management of local electricity networks. In these market niches the role of energy distributors shifted towards managing local electricity flows. Until then, development of photovoltaics and wind power had been relatively independent of the development towards micropower. This started to change, as further progress was necessary to tackle the climate problem. Energy distributors played a central role in the emergence of local systems with combined use of fuel cells, photovoltaics in urban areas and wind plus photovoltaics in rural areas. WWF now aimed for housing districts that were emission free and with used renewable sources for hydrogen production. The fuel cells in the cars that used hydrogen both served as a source for mobile power and for stationary power in the districts. Especially Greenpeace had been involved in getting these cars to the market in collaboration with car companies. The systems made balanced use of renewable energy production from photovoltaics, wind and biomass, and use hydrogen as an important intermediary resource. Photovoltaics and wind could either produce electricity for the households, or, in periods that power demand was low, hydrogen through electrolysis for the fuel cell.

2025–2050: Regime transformation towards distributed generation

Gas was still exploited as a resource for the production of hydrogen but its share in power generation was falling. Alternative options for the production of hydrogen steadily increased their share, such as hydrogen from biomass sources, wind energy and solar energy. Investments in power generation virtually all took place in flexible power systems that offered power close to the customers and were based on sources varying from wind and sun, to biomass and hydrogen. The systems were designed for specific local or regional demand for electricity, with connections to specific industrial users, commercial users and neighbourhoods. Also micropower systems continued to take a significant share of the power market. Investment in central capacity was absent in this period, although some larger power plants were built related to specific electricity and heat demand of industrial users.

In 2050, around 25% of electricity generation capacity was handled by relatively autonomous distributed generation systems. This emerged through the connection of previously independent small scale power generating technologies in local systems, facilitated by on-line monitoring and power management. Newly built neighbourhoods became self supportive for power generation while existing neighbourhoods increased their share of local produced power. This was stimulated by new legislation that prohibited the construction housing areas that drew external power. Standards were developed to increase the share of local produced power in existing houses. Apart from wind and photovoltaic power, also locally produced biomass was becoming part of a local cycle of power and hydrogen production. Another 50 % of electricity generation was provided by decentral systems with a connection to the central grid. Around 25% was provided by central power plants that were not connected to specific users. Overall this resulted in a halving of CO_2 emissions compared to the 1990 level.

6. The value of STSc for transition policy in the electricity domain

We can use the two scenarios to evaluate current policies, and come up with strategic recommendations. Ongoing dynamics in the current electricity system offer starting points for two diverging transition paths, which are both plausible. It would be wise to develop policies, which are robust in the sense that they hold strength and relevance in both scenarios. Based on the two scenarios we draw two main policy recommendations to support a transition to a sustainable electricity system.

1) Avoid lock-in to existing design; support the built up of alternative infrastructures

A significant part of current government efforts is focussed on the path of large-scale renewable energy development, especially large-scale wind energy and the development of biomass applications. While the first scenario shows the promise of this path, a sole focus on large-scale integration has the risk of locking out other promising routes. This is unwise because there is much uncertainty whether large-scale integration will succeed. Factors that contribute to uncertainty are the shaky path of European convergence, problems of spatial integration and societal opposition, and the difficulty to integrate the various technologies into a reliable system. It is therefore sensible to invest also in other promising routes, such as distributed generation. It would be a fail-safe strategy to invest more effort in exploring other routes, rather than betting on one horse. The scenarios show that most of the promising niches do not easily adapt to the central station electricity model and have other kinds of systems and infrastructure requirements. Hence, there is a need to build up experience with alternative infrastructures, such as those for biomass, hydrogen, and local microgrids. Real-life experiments are a good way to do this, also enabling further refinement of future visions on the basis of concrete learning experiences.

2) Exploit linkage potential of niche technologies and resources

Current policies focus too much on *individual* technologies, and do not look at interesting *combinations* of technologies. This strategy is risky, because individual technologies may be unable to break out, because of specific constraints (such as wind, photovoltaic power and its intermittent character). The scenarios give insight in the potential of certain technologies and resources to act as *stepping-stones* or *linkages* in the changeover from fossil fuel based technologies to renewable sources. Fuel cells, for instance, are flexible in terms of energy resources (gas, hydrogen, (m)ethanol), and can play a role in energy storage. They can have value as a complementary technology for gas turbines, photovoltaic power, wind power, as well as biomass. Another example is the importance of gas as an energy source that can bridge the development from traditional technologies to emerging niche technologies and can create linkages between alternative designs. Combined heat-and-power production and its micro forms can pave the way for experiments with fuel cells. Gasification technology can provide a stepping-stone for further integration of the biomass niche into the regime. Moreover after initial use of gas as a power resource it has the potential in a subsequent step to shift towards production of hydrogen. In sum, the scenarios point to interesting linkages *between* niches.

7. Conclusion

In comparison to other scenario methods, the STSc tool has two strong features:

1. The tool is based on a scientific theory on transitions. The patterns and mechanisms used in the tool provide an insight in why certain linkages and developments occur. This renders better clues for policy intervention than more deterministic methods.
2. The tool not only pays attention to *future end states* but also to transition *paths*. This does not take the form of simple diffusion paths. The paper showed that the tool can lead to scenarios in which a transition emerges, not as a *deus ex machina* but as the result of plausible linkages, actor strategies, learning processes and social interactions.

The primary aim of this article is to show the promise of sociotechnical scenarios as a reflexive tool for transition policy. It can be used as a strategic framework to make explicit political considerations, thus contributing to reflexive decision-making (Geels, 2002b). We have shown how STSc can help design more robust transition oriented policies, which hold in multiple futures. The approach can also help select promising niches that can form the seeds for a transition and thus are good options for experimentation in the near term. In particular STSc tool is well-suited to explore how *combinations* of niches may open up different pathways. Transition policy should not just look at individual technologies, but also at processes of hybridisation and linkages between technologies and specific user preferences.

The STSc tool is not an automaton that provides a detailed prescription of instruments. We characterize STSc as a ‘tool’ rather than as a ‘method’. The use of a tool requires skills on the part of the user, while a method refers to a sequence of steps that automatically lead to the end result. STSc is a tool, because it requires at least two kinds of skills: empirical knowledge of the relevant domain and theoretical sensitivity regarding the co-evolution of technology and society. Maybe this hampers the transfer of the tool to others. But mindful use of the tool may also lead to more interesting outcomes.

As a weakness, the method in its present shape is that it is not well suited to compute the effects of (combinations of) policy instruments. For instance, it does not render suggestions for the exact level of eco-tax, adoption subsidies etc. Other methods may be better suited for that (e.g. computer models). This means that sociotechnical scenarios do not replace other methods, but provide an additional tool to the arsenal of future exploration.

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