Distributed power-supply systems in the built environment

Co-evolution of institutes and technology for different transition paths

Albert Faber*

* Netherlands Environmental Assessment Agency (PBL), PO Box 303, 3720 AH Bilthoven, The Netherlands.
T + 31 (0)30 2743683. E albert.faber@pbl.nl

Keywords: distributed energy systems, co-evolution, sustainability transition.

Abstract

Distributed power generation in the built environment

Sustainable local power generation technologies and technologies with a high domestic electricity demand are generally expected to develop in the future. Sustainable distributed power-supply systems are a realistic option to ensure a sustainable, affordable and secure energy supply, but systemic, technical and institutional adaptations are required for their further development and incorporation in local electricity networks. This paper explores the coherence between technical and institutional design in three models for the develoment of distributed power networks. *Company Control* is a model where regular energy companies retain a high level of control, which requires institutional changes with respect to network management. *Community Microgrid* is a bottom-up model controlled by local stakeholders, which requires fundamental modifications in the property relationships, market structure and regulation context. *Plug & Play* is a hybrid model that allows electricity-producing consumers to be partially or completely independent from the conventional power-supply system. This model pre-suppposes the existence of a grid that suits the requirements to add on distributed technologies, which requires the co-development of a new institutional layout. In all these cases, a radical decentralisation of the power-supply system requires a signficant institutional modification, specifically in regulatory context, and probably also for utilising market mechanisms.

1 Introduction: distributed power generation as a transition process

For a large part of the twentieth century, power supply in the Netherlands and other European countries was subjected to an apparently autonomous expansion and scaling-up. This was prompted by advantages of scale, interaction with other energy systems and by changes in societal context, as a result of further European integration, market processes and increasing concerns about the environment (Verbong, 2000). However, large-scale technical systems always include residual elements, which function as barriers to further development (Hughes, 1987). Residual elements in the strongly supply-driven public energy sector are a lack of flexibility to address environmental problems, to respond to increasing market processes, and to meet specific wishes of customers. Since the end of the 1980s, the power-supply system in the Netherlands and in many other western European countries, gradually changed from a public utility system to a complex and deregulated market with supervising bodies, introducing competition as a means of increasing efficiency, to promote client orientation and to enhance freedom of choice.

In this market context, strategic management for a reliable, affordable and sustainable power supply has fundamentally changed. The present-day power grid is not only the substrate for the distribution of energy to consumers, but also for trade between contracting parties, which demonstrate greater fluctuations in the transmission and distribution of energy through the grid. Moreover, grid managers have no formal influence on the development of power plants anymore, due to the separation of ownership of production units and grids. This has resulted in a gap between the technical configuration of the energy system and its institutional embedding, a discrepancy leading to frictions in the functioning of the energy sector: from an institutional perspective the electricity value chain seems to evolve towards unbundling and specialisation, whereas technology is based on integrated system planning (Künneke, 2008). A second significant development with respect to power grids is the increasing importance of sustainable and distributed energy production. Energy production based on wind or sun is difficult to moderate and can fluctuate strongly under different weather conditions, which reinforces the problem of maintaining grid stability. These difficulties will further require the set up of additional production capacity or other supplies (specifically storage), to provide a constant and sufficient supply of energy, at all times (Meeuwsen, 2007). Third: the current Dutch power grid is approximately fifty years old and is, therefore, reaching the end of its technical lifespan (Department of Economic Affairs, 2008). Estimates concerning the term of this depreciation vary somewhat, but large-scale investments in the not too distant future are certainly needed for an upgrade of the grid to guarantee a properly functioning infrastructure in the future (European Academies Science Advisory Council, 2009).

These developments drive the development of alternative perspectives for the power supply in various western countries, including the Netherlands. The development of *distributed energy systems* provides a strategic opportunity to deal with the above challenges, by incorporating a large share of sustainable energy technologies into the energy system, while maintaining security of supply. Moreover, it allows the integration of electricity and heat supply systems at the local level, which could help to optimise overall system efficiency. Distributed power-supply systems involve the use of innovative technologies, organisational concepts and management philosophies. With respect to *power supply*, consumers become co-producers of electricity, which can shift management of grid balance to a local or regional level. These transformations are at least partially shaped by the technological possibilities for management and monitoring of energy and information flows.

A great challenge for incorporating large shares of small-scale sustainable power production in the local grid lies in the magnitude of and difficulty with the moderation of fluctuations in energy production from sustainable energy production technologies, for example, on days with variable wind or cloudiness. The strain on the grid increases with production surpluses or shortages, which can severely disrupt power quality and, consequentially, the operation of electric devices (Meeuwsen, 2007). Arguably even more important, the shifting positions of consumers and producers in local power systems change the social and institutional context of energy production (Faber and Ros, 2009). The role and functioning of grid management will fundamentally change, due to renewed ownership relations, integration of various electricity flows, interconnection of energy and information, shifting of economic motives, renewal of stakeholder positions, and behavioural changes.

A wide-spread adoption of small-scale sustainable energy production is therefore difficult without a radically different organisation of power supply. Since large-scale technical systems often strongly determine their own evolution, their development is known to have some determinism based on choices made in the past (Hughes, 1987). This requires a so-called transitional process, that is to say, a radical system innovation moderated by policy. Transition policy has become accepted practice in the Netherlands since the early years of this century (Department of Public Housing Spatial Planning and the Environment, 2001), and specifically on the nexus between energy and environment this policy field is now well established (see for an interesting assessment on this policy field Smith and Kern, 2009). In the Netherlands, the future of power supply has been elaborated in three scenarios (Department of Economic Affairs, 2008). While two scenarios focus on centralised power production, a third scenario sketches smart grids as the foundation for a future energy infrastructure. Preconditions for such a development would be an active innovation policy with a focus on new, small-scale energy technologies, in coherence with policies that enhance flexibility and intelligence of energy infrastructures. The ambitions, ideas and activities are in accordance with the European Strategic Energy Technology (SET) Plan (European Commission, 2007). This plan concentrates on six themes, including the development of 'intelligent power grids'. The European Commission aims to bring cohesion to research and development at European level.

This paper takes the proposition that the evolution of large-scale technological systems requires that technological developments take place in coherence with their institutional and social embedding. I recognise that a gap between technological systems and institutional setting may exist for a while, but it is always well in flux as it drives a dynamic process of re-settling to a more coherent system. This paper explores the required institutional changes in co-evolution for three distributed power supply scenarios, assessing the main barriers and opportunities for their developments in the future.

2 What is a distributed power system?

Distributed power systems are primarily characterized by the local level of power production. The level of power production can be at households, but, for example, wind turbines powering entire neighbourhoods are also considered to be distributed power producers. Often, distributed power production involves (semi-)sustainable and relatively small-scale energy technologies such as (urban) windturbines, various types of photovoltaic solar cells or micro-cogeneration (CHP: co-heat and power). Small-scale sustainable energy technologies are usually difficult to moderate and they have relatively large fluctuations in power production, which is not generally levelled off by production peaks elsewhere (so-called 'peak shaving').

Power produced at the local level may be used at the local level, but not necessarily so. Excess power production may be fed back to the higher level power grid, while shortages may be taken in. Excess power may also be temporarily stored in batteries or be converted to another energy carrier and be stored in thermal buffer systems. With respect to battery systems still some technical and economic issues remain to be solved before full-scale application becomes feasible, but this option may well prove to be an interesting business case or a sheer necessity from the grid manager's point-of-view. Another option for local system balancing is by manipulating demand, for instance by affecting load patterns for charging vehicle battteries.

Moderate input of local power production can be incorporated relatively easy in the local grid without endangering grid balance, but larger production levels require information to be able to manipulate production, demand or storage and to deploy a regulation strategy for grid balancing. Essential to these grid management mechanisms is the coupling of energy flows with information flows, which requires at least development of so-called smart meters in households. The design and layout of the local network in relation to the role and position of the grid manager gives rise to various regulation strategies for balancing the local power network.

Consumers who manage production technologies can become co-producers of energy, which could result in major changes occurring in the market mechanisms for energy. Moreover, development of micro-CHP, electric heat pumps and various storage systems involves an increased integration of different energy systems, in particular those of power and heat. In addition, many scenarios and forecasts show a significant increase in power demand for households, which relates to further use of electric household appliances, but possibly also to the large scale application of electric vehicles, which could significantly strain local power systems (Faber and Ros, 2009). This increase in domestic power demand could co-evolve with the deployment of local power supply systems, thus bringing power production and consumption closer to each other within the system.

Jointly, these features pose considerable challenges: new and diverse technologies for generating power; new ownership arrangements; alternative technological and organisational systems for grid management (including energy storage); alternative guarantees with regard to quality and security of power supply, including new corresponding legal agreements and behavioural changes, all playing a part in the development and utilisation of a distributed power-supply system.

3 Three models for distributed power-supply systems

Although there are several common characteristics for distributed power-supply systems, there are also a number of features that define some differences. Diverging institutional arrangements within a distributed power-supply systems render various configurations and roles of stakeholders, which opens perspectives to define three models for the outline of distributed energy systems (Sauter and Watson, 2007; Watson *et al.*, 2006):

- *Company Control* is a model in which distributed energy technologies are introduced on the market by energy companies through marketing and (lease) contracts. These companies then retain control over the application of distributed energy production by remote coordination, in line with the concept of the virtual power plant. In this model, the consumer is fairly passive and, in fact, primarily serves as an available location for the placement of the technology.
- *Community Microgrid* is a model in which different small-scale power production technologies, owned by households or local shareholders, are interlinked to create a local grid that is owned and controlled by the community. Optimisation takes place at local grid level, not necessarily connected to a central grid. In this scenario, the consumer acts as a booster for the development of the distributed grid, which guarantees a high degree of involvement for local energy production, independent of energy companies. The (financial) motivation can lie in the shares that consumers have in the locally established and community-owned energy company. This scenario is remarkably similar to the development of power grids at the end of the nineteenth century and the early twentieth century.
- *Plug & Play* is a model that allows electricity-producing consumers to be partially or completely independent from the conventional power-supply system. In this model, the consumers own and finance the energy technologies. Consumers respond to price mechanisms through which they maximise their production and corresponding profits. They will assume the role of energy producer and possibly change energy consumption patterns. In this model, ‘early adopters’ are needed to kick-start the spreading of the new technologies.

The models differ from each other in the way technologies are dispersed in the market, property relationships, parties taking initiative, role distribution with its corresponding institutional layout, degree of acceptance, system optimisation levels with corresponding environmental effect, and, finally, the ability to be geared to the central energy system. Essentially, all models present equal future visions in terms of economic and environmental preference, although we will see that there are various obstacles in the pathways to realisation.

4 Analytical framework: co-evolution of institutions and technological development

4.1 Technological development

The dynamics of technological development can be described at various levels, ranging from an overarching technological paradigm to daily operational practices. For the purpose of this analysis, we delineate four levels for analysis of technological development (Künneke, 2008):

1. The *technological paradigm* involves principles of natural science, materials and values, that determine the broad direction of development and general application of technologies in society. Changes in paradigm are rare and generally involve very fundamental social transformations.
2. *Technological trajectory* refers to ‘the pattern of normal problem solving activity […] on the ground of a technological paradigm (Dosi, 1982: p. 152). It involves first-order economizing, i.e. the development of coherent and efficient technological systems (Künneke, 2008).

3. *Technological routines* involve behavioural similarities in the search for innovative solutions. It involves second-order optimization, i.e. the optimization of individual technical components.
4. Such routines govern short-run behaviour that may be referred to as *operating characteristics*. These are guided by heuristic rules-of-thumb for process management. They involve day to day operation and management, embedded in routines, trajectories and paradigms.

The four levels for technological development can be expected to be arranged according to a certain logic and consistency. However, as certain technical restrictions at lower levels become obvious, challenges arise for trajectories or paradigms at a higher level. If certain technical restrictions at a lower level become too stringent, this might be an important stimulus to challenge the existing trajectory or even paradigm (Künneke, 2008).

4.2 Institutions

As with technological development, a similar multilevel perspective can be elaborated with respect to institutions. Building on work by Williamson (1998), further adapted by Künneke (2008), we distinguish again four levels, based on the main purpose and the frequency of change of institutions.

1. *Values* and *traditions* within a society define the functioning of social systems, determine customs and the formation of all lower level institutions. The frequency of change is typically in the order of decades to centuries.
2. The *institutional environment* is distinguished by legal arrangements, formal regulations and bureaucratic structures. The typical frequency of change is in the order of decades.
3. *Governance structures* and *informal rules of play* are concerned with 'the play of the game' within the formal arrangements of the upper level. It associates transaction costs, negotiations, monitoring, etc., serving the objective of collective institutional structures such as firms, groups, universities, etc. The typical frequency of change is in the order of years.
4. *Daily workfloor decisions* are concerned with day to day resource allocation processes. This level essentially serves the individual objectives of the actor. The frequency of change is continuous and essentially refers to adaptation of marginal conditions.

This framework is illustrative rather than a strict analytical reality. Differentiating criteria are not always very clear and may be obscure at times. Furthermore, the interrelation between the levels is not always obvious and may include various feedback mechanisms (Künneke, 2008). For now, we leave these comments as a critical aside, but it clearly requires more attention in future work.

4.3 Co-evolution of institutions and technology at multiple levels

For a fundamental transformation of the power-supply system, the technological configuration and the institutional context must change in tandem. This is a co-evolutionary process in which the technical and institutional practices are geared to each other in a coherent system. This balance can be analysed at different system levels for both the institutional and the technological domain (Kemp *et al.*, 2007; Künneke, 2008). Künneke (2008) distinguishes four analytical levels for both domains, and compares the development at each level, for the Dutch power-supply system (see Table 1). In all of these levels, the terms landscape, regime, and routine or actual practice, are identified in line with the multi-level approach generally used in transition theories (Geels, 2002; Kemp *et al.*, 1998; Loorbach, 2007; Rotmans *et al.*, 2001; Rotmans *et al.*, 2000, among many others).

Table 1 Institutional and technological layout at different system levels

Level	Institutional layout	Technological layout
1	Social context with values, traditions and social systems	Technological paradigms
2	Institutional environment with formal regulation	Technological courses of action
3	Governance structures and (informal) rules of play	Technological routines
4	Daily decisions on the work floor	Technical management and operational matters

Source: Künneke (2008)

The more encompassing levels are very resilient to change, whereas dynamics in the underlying levels become increasingly more volatile. In both systems, (resistance to) change relates to the presence of earlier development costs, learning curves, coordination effects, and expectations with regard to adaptive possibilities. The institutional and technological layouts can be examined at all four levels, to see if they develop cohesively. With regard to liberalisation of the energy market, Künneke (2008) proposes that a development takes place within the institutional framework at the legislative level, with modifications of technological processes still strongly bound to the preceding system of large-scale and centralised coordination (lock-in). The co-evolutionary perspective provides two modification options: technical modifications towards a more market-oriented coordination, or institutional adjustment to the technological lock-in.

The analytical framework can be used to specify institutional or technological salients in the development paths for a distributed power-supply system. Generally, the technological layout of a distributed energy system changes at all analytical levels, compared to the present energy system:

- The technological paradigm fundamentally changes into a distributed infrastructure that is based on sustainable techniques.
- Within technological processes, different degrees of decentralisation can be imagined, with different types and degrees of linkage between energy generation techniques.
- Technological routines expand because of the prospects of demand management and the application of storage technologies.
- Technical management becomes increasingly more dependent on situational factors, such as sun and wind, and on optimisation through other competing or collaborating parties.

The question now is whether the institutional layout can effectively adjust to these developments.

5 Co-evolution of institutions and technologies in distributed energy systems

5.1 Multi-level assessment of institutional barriers and opportunties

In this section, I provide some brief and still very preliminary thoughts on the institutional and technological alignment at the four levels indicated in section 4.3. Much more elaboration needs to be done, but this shows a direction for analysis that could be fruitful for understanding institutional/technological mismatches.

LEVEL 1: Values, standards and traditions

For the acceptance of distributed energy generation by citizens, *attitude* plays an important role (Sauter and Watson, 2007). A positive fundamental attitude any stakeholder involved in the distributed energy system strongly depends on their *knowledge* and their *value* about this system. For a new sector such as this, a broad knowledge base is anything but general; and so far, the parties involved only play to a niche in the power-supply market. The visibility of distributed energy technologies, such as solar panels on roofs, the promotion of grant legislation and of technology producers, the increasing awareness of problems in the dominant technical system, and the media attention for these issues, can all play an important role in the development of a broad knowledge base and a positive attitude towards distributed energy systems (Genus, 2008; Sauter and Watson, 2007; Sine *et al.*, 2005).

Moral considerations, following from personal or social value sets, are often a core motivation for the early development of viable business models with regard to distributed power-supply systems (Genus, 2008). Front runners in the development of a new system, therefore, can choose to deviate from the regulations if (moral or economic) benefits outweigh sanctions or costs (Van den Hoed, 2004). Specifically for community-based microgrids, citizens will need to be positively inclined to bottom-up initiatives in the first place, enhanced by a feeling for public values and commons. The issue of values and moral considerations as an underlying driver for a direction of technological development has been recognized in the *worldviews* underlying various scenario-studies, specifically the IPCC scenarios on climate change (IPCC, 2000).

LEVEL 2: Governance structures and rules of play

Infrastructural investments

While power production plants in the Netherlands have become private enterprises in the last decade or two, ownership and control of, and investments in power grids largely remain a public service. However, there are also reasons for private parties to contribute (other than the more fundamental values discussed above): the power grid is the link between supply and demand and the grid accommodates the exchange of larger volumes between commercial parties in the liberalising energy market, which means a properly functioning grid is essential to their operations. Nonetheless, overall infrastructural investments from the privatised energy sector have diminished significantly since the wave of privatisation in the late 1990s (IEA, 2003). Therefore, it remains questionable whether the current market regime is able to effectively anticipate public values that are relevant in the long run, and along with that, if it is able to effectuate this anticipation with the appropriate investment decisions.

The legal and institutional context stabilises the existing system through, for example, standardisation of the energy system management, by limiting the possibilities for distributed return of energy to the grid, or through support for specific production techniques. Such an institutional stabilisation could lead to a lock-in if its regulations restrict the transformation to another type of system (Genus, 2008). The challenges of full-scale maintenance, new construction of infrastructure, and investments in system innovation may therefore well require a re-examination of public and private interaction (WRR, 2008).

Regulation strategies

An important institutional issue relates to the regulation strategies and coordination mechanisms of grid management. In a centralised grid, operational management is organised top-down. In a distributed grid, local coordination at low-voltage level is needed. Overall, there are three conceivable regulating strategies in a distributed power-supply system: management, coordination and cooperation (*Figure 1*).

- *Control* of a distributed power-supply system means that it is organised top-down or by a regulating authority within the system. The grid manager retains the control over the application of distributed production units, including the units which are situated at domestic residences. Balancing supply and demand between individual units can, for example, be coordinated based on energy-price scenarios and consumption patterns (Negenborn, 2007). The concept of the virtual power plant is often referred to, in which distributed production units function as remotely controlled modules for balancing the entire energy production (Overdiep, 2005; Scheepers *et al.*, 2007).
- *Coordination* within a distributed energy system places more emphasis on the mutual balance between individual stakeholders and/or energy production units. This balance can be achieved through mutual and equitable interaction, comparable with 'peer-to-peer' interactions on the Internet. In actual practice, this can mean that distributed energy production is applied in response to a local demand elsewhere in the system (Technology Review, 2009). A great advantage of such a system is that it no longer holds any critical elements for its functioning (Duan, 2008).
- *Cooperation* between the system elements occurs by brokering the balance between electricity-demanding stakeholders and energy-producing modules on a more aggregate level. This mechanism introduces a marketplace of units in which supply and demand are balanced on the basis of price, such that equilibrium is found and imbalance is avoided (Powermatcher, 2008). This market mechanism can be converted into an automated operation, and optimisation of the system is relatively simple and efficient in such a setting.

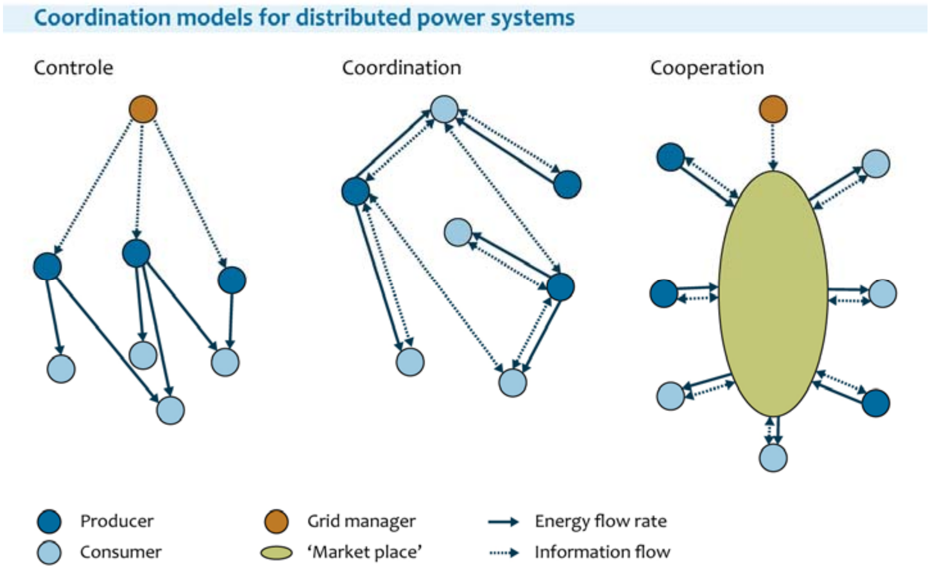

Figure 1 Coordination models for balance in a distributed energy system

An important distinction between the regulating strategies is the level of control, i.e. the level at which the grid authority functions to balance the grid. Balancing the grid on a higher scale usually allows the use of longer timescales and higher aggregated models, whereas more detailed models and shorter timescales are required for regulation at lower levels. A local regulating strategy will often be based on the coordination of a partial grid in which the balance between the various partial grids is a crucial element for higher grid balancing (Negenborn, 2007).

LEVEL 3: Formal regulations and routines

For the domestic installation of an energy generator, many often refer to the complex legal and administrative activities and obligations involved (Elzenga *et al.*, 2006). Moreover, there is debate about double energy taxation for the gross or net calculation of energy production, which makes the institutional embedding of micro-cogeneration difficult. The system of *checks and balances*, safeguarded by infrastructural reorganisation and adaptation to new requirements, was developed under the old regime, whereas most of its motivations under the current regime focus on expanding efficiency (WRR, 2008). A significant institutional barrier to the development of distributed power production relates to difficulties with feeding locally produced power into the system. These difficulties may arise from too low or absent feed-in tarriffs, or from systemic priority given to large institutional producers. However, the development of alternative technologies can also be stimulated *within* the institutional context, especially if legislation were to provide certainty of reduced operational risks in the sector, for example, through subsidies or tax benefits (Sine *et al.*, 2005).

The shift from being a passive energy consumer to becoming an active energy co-provider can be a very significant driver for changes in people's *behaviour* and daily routines. On the one hand, this may contribute to consumer energy awareness, but on the other hand, it can create a substantial barrier for the development of distributed energy technologies, as it often bears some relation to fundamental personal and social values at Level 1. Indicative test surveys subscribe the hypothesis that consumers tend to to value the reliability of the current energy system, while the desire for self-reliance does not tend to play a great role with consumers who already are utilising distributed energy technologies (SEO Economic Research, 2008).

LEVEL 4: Management considerations

Necessary institutional adaptations in a distributed energy system are often insufficiently recognised at grid management level, specifically with regard to shifting property relationships and associated responsibilities. Grid management is generally motivated by considerations of economic efficiency witin the current regulation framework, which in the present framework provides little incentive to invest in fundamentally different energy systems.

The degree to which households are prepared to make direct investments in energy technologies, generally, depends on the estimated time to recover the costs. However, it should be noted that consumers seldom turn to rational calculations for making this decision; instead, they make rough estimates based on limited information (Faber *et al.*, 2008). The fact that the purchase price must often be paid directly, while savings only become visible over the course of years, does play a part in people's general percenption of the costs of installing energy technologies at home (Sauter and Watson, 2007).

5.2 Evaluation: co-evolutionary assessment of three distributed energy models

In the *Company Control* model, the energy companies retain the possibility to coordinate distributed technologies that are set up in domestic residences, essentially creating a virtual power plant. The consumer takes a rather passive position in this model. At the institutional levels 3 and 4, managing coordination by the power companies can change substantially, because system monitoring and allocation of the applied technologies become much more complex, requiring some fundamental institutional adaptations. This does not necessarily have to lead to many modifications in daily household routines. Changes in institutional levels 1 and 2 remain restricted, since this model would still involve a central coordination, retaining existing property relationships, market structure and regulating framework. However, a value-set that more easily accepts top-down solutions will be a key condition to accept a *Company Control* outline.

In the *Plug & Play* model, distributed energy production technologies are owned, financed and maintained by consumers at the household level. In this model, consumers take on the role of co-producers of electricity, in coordination with, but not top-down controlled by, the conventional power system. This means that a new formal institutional layout will be needed, which incorporates rules or mechanisms to determine the decentralised application of technologies, and to align local production with demand patterns. Several options are available here: top-down demand management, local application of storage technologies (which could prove to be an interesting business case), or real-time price mechanisms to either boost or halt domestic power production. From the consumer's perspective, *Plug & Play* is acceptable from various value points, although the required underlying infrastructure requires considerable investments. Whether these infrastructural investments are public or private depends on the underlying worldview, articulating either market forces or public responsibilities.

In the *Community Microgrid* model, small-scale production technologies at the local level are interlinked in a ‘community-owned microgrid’. A local grid does not necessarily have to be connected to a central grid, although in practice it makes sense to use the central grid as a backup for temporary shortages or production surplusses. Another balancing option is to install substantial generation and storage capacity. This scenario involves a fundamental re-orientation in the technological paradigm, which in turn requires far-reaching institutional modifications. In its most extreme elaboration, there is no more linkage with a centrally managed power grid, essentially creating an autocratic power system. At times, the institutional layout at level 3 changes intensely through fundamental modifications in the property relationships, market structure and regulation context. In this scenario, the role of the energy companies as providers of electricity may well be over, although the companies may be able to transform this role into one of supplying power-generation technologies and providing technical service. Along with this, the municipality can develop a local energy company, possibly in consultation or partial ownership with an existing energy company. This model also requires fundamental institutional modifications in company operations. This scenario depicts the consumer as booster for the development of the distributed grid, which guarantees a high degree of involvement with local energy production. At the institutional level, this means a change from the role of consumer to co-producer in local power generation, following from a conditional shared value-set including a localised search area for solutions. The new role of consumers as co-providers of energy requires a completely overhauled societal framework of the energy infrastructure (Sauter and Watson, 2007).

In all these cases, a radical decentralisation of the power-supply system requires a significant institutional modification, specifically in regulatory context, and probably also for organising the proper utilisation of market mechanisms. Depending on the specific model, the roles of both energy companies and consumers will transform to varying degrees. These transformations are specifically related to the manner in which the management of the energy system is organised, which to a certain extent stipulates application and adoption of the available technologies.

6 Conclusions

An important motivation for the development of distributed energy systems relates to the idea that the current dominant system is faced with persistent and system-inherent challenges on all fundamental energy policy issues: affordability, reliability and environment (Department of Economic Affairs, 2008). In addition, the current energy system is approaching the end of its lifespan, which necessitates the replacement or upgrade of significant portions of the national power grid. These motivations leave room for different solutions, one of which involves a decentralisation of the power-supply system. With a distributed energy system, a large share of the power is produced locally. The development of a distributed system involves two-way traffic of power, which requires a linkage of electricity and information flow rates that is often referred to as ‘smart grid’.

Presently, most of the distribution grids still have enough capacity to include some share of distributed power supply, but with increasing shares the balancing of supply and demand may become more difficult, because the power supplied from sustainable sources often fluctuates strongly and is difficult to predict. System management may therefore become difficult and alternative institutional configurations will be needed for the organisation of a distributed power system and the allocation of management responsibilities. However, for a fundamental transformation of the energy system, the technological configuration and the institutional context must change in tandem. This is a co-evolutionary process in which technical and institutional practices are geared to each other in a coherent system. Such a balance can be analysed on different system levels, for both institutional and technological development (Künneke, 2008).

In this paper I explored three development scenarios (Watson and Sauter, 2007): *Community Microgrid* is a bottom-up, community-based model of interacting production units, *Company Control* is a top-down controlled system of aggregating locally placed power production units, and *Plub & Play* is a model where a well-developed infrastructure is managed in such a way that individual small-scale power producers can easily plug into the system. There are various gaps and alignments between the technological and insititutional systems at different levels of aggegration. Specifically, issues of system management and control, power feedback, alignment of energy and information and the distribution of responsibilities for the aggregate system are crucial to address for development of a distributed power system, but each issue requires different solutions for different development models.

Generally, it is advisable that grid managers and market parties make agreements and organise timely solutions, because of the increasingly more important role of information exchange and the prospect of two-way traffic. Such agreements and solutions need not only take into account the present technological outline of the power system, but also be resilient to various future outlines of distributed power systems.

Acknowledgements

This work follows from a report by the Netherlands Environmental Assessment Agency, co-authored with Jan Ros (Faber and Ros, 2009). Jim Caulfield provided a translation of my first draft, which must have been a very confusing job, considering the lack of cohesion featuring that version. Fortunately, Annemieke Righart provided excellent editing and further translations, greatly improving the style and structure of this paper. Geert Verbong and Floortje Alkemade provided some excellent comments and suggestions for improvements on an earlier draft, which will also help to further the underlying paper to a more definitive version in the future.

References

Department of Economic Affairs (2008) Energierapport 2008 (in Dutch), Department of Economic Affairs, The Hague.

Department of Public Housing Spatial Planning and the Environment (2001) *Een wereld en een wil, werken aan duurzaamheid - Nationaal Milieubeleidsplan 4 (in Dutch)*. Department of Public Housing Spatial Planning and the Environment, The Hague.

Dosi, G. (1982) Technological paradigms and technological trajectories. *Research Policy* 11, 147-162.

Duan, R. (2008) Agent coordination for supply and demand match in microgrid with auction mechanism. In: *Building Networks for a Brighter Future, 1st International Conference on Infrastructure Systems*, Rotterdam.

Elzenga, H.E., J.A. Montfoort and J.P.M. Ros (2006) Micro-warmtekracht en de virtuele centrale: Evaluatie van transities op basis van systeemopties. 500083003, MNP, Bilthoven.

European Academies Science Advisory Council (2009) Transforming Europe's Electricity Supply – An Infrastructure Strategy for a Reliable, Renewable and Secure Power System. EASAC policy report 11, EASAC, London.

European Commission (2007) A European strategic energy technology plan (SET Plan) - Towards a low carbon future. COM (2007) 723 final, European Commission, Brussels.

Faber, A. and J.P.M. Ros (2009) Decentrale elektriciteitsvoorziening in de gebouwde omgeving. Evaluatie van transities op basis van systeemopties. 5500083011, PBL, Bilthoven.

Faber, A., M. Valente, P. Janssen and K. Frenken (2008) Domestic micro-cogeneration in the Netherlands: an agent-based demand model for technology diffusion, DIME working paper (in review).

Geels, F. (2002) Technological transitions as evolutionary reconfiguration processes: a multi-level perspective and a case-study. *Research Policy* 31, 1257-1274.

Genus, A. (2008) Changing the rules? Regimes, niches and the transition to microgeneration. In: *DIME International Conference "Innovation, sustainability and policy"*, Bordeaux (Frankrijk).

Hughes, T.P. (1987) The evolution of large technological systems. In: *The social construction of technological systems* (eds W.E. Bijker, T.P. Hughes and T. Pinch), pp. 51-82. MIT Press, Cambridge (MA).

IEA (2003) *World Energy Investment Outlook*. IEA, Paris.

Kemp, R., J. Schot and R. Hoogma (1998) Regime shifts to sustainability through processes of niche formation: the approach of strategic niche management. *Technology Analysis & Strategic Niche Management* 10 (2), 175-195.

Kemp, R., D. Loorbach and J. Rotmans (2007) Transition management as a model for managing processes of co-evolution towards sustainable development. *International Journal of Sustainable Development & World Ecology* 14, 78-91.

Künneke, R.W. (2008) Institutional reform and technological practice: the case of electricity. *Industrial and Corporate Change* 17 (2), 233-265.

Loorbach, D. (2007) Transition Management. New mode of governance for sustainable development, Erasmus Universiteit, Rotterdam.

Meeuwsen, J.J. (2007) Electricity networks of the future. Various roads to a sustainable energy system, Eindhoven University of Technology, Eindhoven.

Negenborn, R. (2007) Multi-agent model predictive control with applications to power networks, TU Delft, Delft.

Overdiep, H. (2005) Thuiscentrale opvolger van de HR-combiketel? Micro-wkk als onderdeel van de Virtuele Elektriciteitscentrale. *Arena* 2, 25-28.

Powermatcher (2008) Zie website: http://www.powermatcher.net/

Rotmans, J., R. Kemp and M. van Asselt (2001) More evolution than revolution, transition mamagement in public policy. *Foresight* 3 (1), 1-17.

Rotmans, J., R. Kemp, M. van Asselt, F. Geels, G. Verbong and K. Molendijk (2000) Transities en transitiemanagement, de casus van een emissiearme energievoorziening., ICIS/ MERIT, Maastricht.

Sauter, R. and J. Watson (2007) Strategies for the deployment of micro-generation: implications for social acceptance. *Energy Policy* 35, 2770-2779.

Scheepers, M.J.J., A.J. Seebregts, C.B. Hanschke and F.J.D. Nieuwenhout (2007) Invloed van innovatieve technologie op de toekomstige elektriciteitsinfrastructuur. ECN-E--07-068, ECN, Petten.

SEO Economic Research (2008) Zelfvoorzienendheid in elektriciteit (in Dutch). 2008-53, SEO, Amsterdam.

Sine, W.D., H.A. Haveman and P.S. Tolbert (2005) Risky Business? Entrepreneurship in the new independent-power sector. *Adminstrative Science Quarterly* 50, 200-232.

Smith, A. and F. Kern (2009) The transition storyline in Dutch environmental policy. *Environmental Politics* 18 (1), 78-98.

Technology Review (2009) Managing energy with Swarm logic, Technology Review.

Van den Hoed, R. (2004) Driving fuel cell vehicles. How established industries react to radical technologies, TU Delft, Delft.

Verbong, G.P.J. (2000) Grote technische systemen in de energievoorziening. In: *Techniek in Nederland in de twintigste eeuw II: delfstoffen, chemie, energie* (ed J. Schot), pp. 113-123. Stichting Historie der Techniek/Walburg Pers, Zutphen.

Watson, J., R. Sauter, B. Bahaj, P.A. James, L. Myers and R. Wing (2006) Unlocking the Power House: policy and system change for domestic micro-generation in the UK, SPRU (University of Sussex), Brighton (UK).

Williamson, O.E. (1998) Transaction cost economics: how it works, where it is headed. *De Economist* 146, 23-58.

WRR (2008) Sturen op infrastructuren, een investeringsopdracht, Wetenschappelijke Raad voor het Regeringsbeleid, Den Haag.