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Addressing Uncertainties in the Design & Operation of Residential Distributed Energy Resources: Case study of a Micro-CHP System

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Distributed Energy Resources (DER) comprises three main concepts: distributed generation of electricity and heat, energy storage and responsive loads. Residential DER technologies are sub-systems that utilize varying types of resources to generate, store and manage electrical and/or thermal energy at the site where it is needed (households). At present, several new and hybrid generation technologies are being developed or advancing commercialization stage, e.g. Stirling and fuel cell Micro Combined Heat and Power technology (Micro-CHP). Furthermore, novel ICT systems facilitate a shift to smart power systems and active distribution network management. Also, regulatory and market changes pertaining to the utility industries have brought in different dimensions and a myriad of uncertainties to the design and operation of DER.
In this paper, the various forms of uncertainties (technical, economic and institutional/regulatory) that could besiege domestic DER system design and their application in the electricity system have been identified and classified. The focus thereby is on residential, Micro-CHP systems. As a step forward, we have proposed flexibility steps to handle these uncertainties at both the design, planning and operational phases of these DERs.

Keywords: Distributed Energy Resources, Micro-CHP, Power System Economics, Uncertainty.

1. Introduction

Distributed Energy Resources (DERs) technologies are systems or units that utilize varying types of resources to generate, store and manage electrical and/or thermal energy at the site where it is needed (households). DERs comprise three main concepts:

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distributed power generation (DG), energy (electricity) storage and responsive loads (demand-side management). In this paper we focus on residential (= micro) DERs. Micro Combined Heat and Power technology (Micro-CHP) is a promising option. Prime mover technologies in Micro-CHPs could be internal combustion engines, micro turbines, Stirling engines or fuel cells. Next to conventional hot water storage, several forms of distributed electricity storage technologies are also being researched and developed (Lysen, Van Egmond et al.). Furthermore, novel ICT systems facilitate intelligent control of DERs and load management schemes to actively incorporate end users in the electricity markets. A good overview of demand-side management arrangements is presented in (Hirst and Kirby 2001). With the integration and application of DERs, the electricity infrastructure will enable smarter power systems and more active and intelligent network management. Households thereby become so-called ‘prosumers’ and value webs are formed. However, in the design and application of residential DERs there are still many uncertainties. What retail market designs can benefit from DERs? How should contractual arrangements between DER operators and owners be devised? How to design suitable generators and generator controllers to meet economic and environmental objectives? For DER to withstand the test of time, the various uncertainties that might plague them during their entire lifespan ought to be identified and accommodated during their design, planning and operations.
In this paper we identify and explicate the economic, technical and regulatory uncertainties pertaining to the design and operation of residential DERs. We narrow the scope and consider only Micro-CHP DG systems. With this analysis we hope to provide designers and operators of DER systems and DER controllers with insight on the uncertainties they face in their design and operational activities and how to handle them efficiently. In section 2, the technical, economic and institutional uncertainties that could affect the design and operational robustness of the DER systems are identified. The identified uncertainties are mapped into various flexibility initiatives that could reduce the impacts of these uncertainties in section 3 while some conclusions and recommendations are drawn in section 4.

2. Identification of Design and Operational Uncertainties

In this section the various uncertainties (economic, technical and institutional/regulatory) that could besiege DER systems and their application in the domestic electricity system are identified and classified. In most design cases, an integrated approach where not only the technical constraints or uncertainties are taken into consideration, but also the economic and institutional constraints are considered, are still lacking. We conjecture that the first step towards designing for flexibility is the identification and consideration of uncertainties in an integrated form: all the constraints and uncertainties that could manifest themselves either during the design phase of the system or during its operational and other life cycle phases.

Economic Uncertainties

Market developments, which are usually very difficult to predict, affects to a high degree the success or failure of any new technology. Therefore we pay particular attention to the market uncertainties and the ways ahead. We first conceptualise the technical, market and economic interactions in an electricity infrastructure with residential DERs. Then we discuss the advantages of the aggregated utilization of DERs and we end with a summary of the main economic uncertainties in DER systems design, operation and control.

Electricity Infrastructure with Residential Energy Resources

The work presented in (Houwing, Heijnen et al. 2006) broadly discusses the socio-technical impacts of DER introduction on critical actors in the electricity infrastructure. Here we explain these impacts in more detail. The electricity infrastructure with a substantial share of DERs is shown in Figure 1 below. Electricity from large generators reaches the loads via the transmission and distribution networks (a-b-c). Distributed generators in households produce directly for loads (d) and surplus electricity flows into the distribution networks (e) and possibly into the transmission network (f). The transmission network manager guards against congestion, maintains reliability of transmission services and provides ancillary services for transport. These tasks are done by the distribution network manager for the distribution network. The system operator (SO) maintains system stability and manages the energy balance within a control zone. A second task is to provide (or contract) sufficient black-start power. The transmission network manager and the SO together form the transmission system operator (TSO). The TSO works together with the distribution system operator (DSO) in fulfilling its tasks.

In the economic subsystem the thick arrows designate electricity sales. Large producers can sell electricity directly to the market (1). Distributed generators/storages/loads (i.e. DER households) could sell electricity directly to the market (2), but as market participation costs are relatively high, this will not be the case in practice, however. DERs can deliver power directly to residential consumers (5). This could also be other households than the household owning the DER, thus creating an internal market amongst households. Furthermore, DER households can trade power with/through an aggregating body (‘aggregator’) who subsequently trades on different market types for clusters of DER households (bilateral/OTC, power exchange, balancing, ancillary services, etc.) (6, 3). Large consumers and aggregators can obtain electricity from the market (4, 3). Household consumers can obtain electricity indirectly from aggregators (7). Ancillary services are all services necessary for the operation of a transmission or distribution system. Large producers, TSOs and DSOs are currently responsible for these services. DERs, however, could provide ancillary services as well, possibly via ancillary services markets in the future (Van Werven and Scheepers 2005). The DSO (possibly in cooperation with the supplier) could function as aggregator in these trades on ancillary services markets.

Other important actors relating to the system of Figure 1 are metering companies and energy service companies (ESCOs). The metering company has full access to data but has no authority to set DER parameters (StratixConsulting 2006). An ESCO provides added value services with the metering data, which have been received after authorisation by household customers. Authorised parties for setting DER parameters are in principle only energy suppliers and DSOs. The DSO further owns and operates the required ICT infrastructure and necessary power electronic equipment. It is expected that suppliers will fulfil the role as metering entity once intelligent meters are widely used (StratixConsulting 2006).

All actors operating in the electricity infrastructure will be confronted with changing circumstances due to DER introduction and application. The technical and economic subsystems are linked by information flowing in both directions (information on prices and tariffs, electricity flows, capacity restrictions, dispatch instructions, etc.).

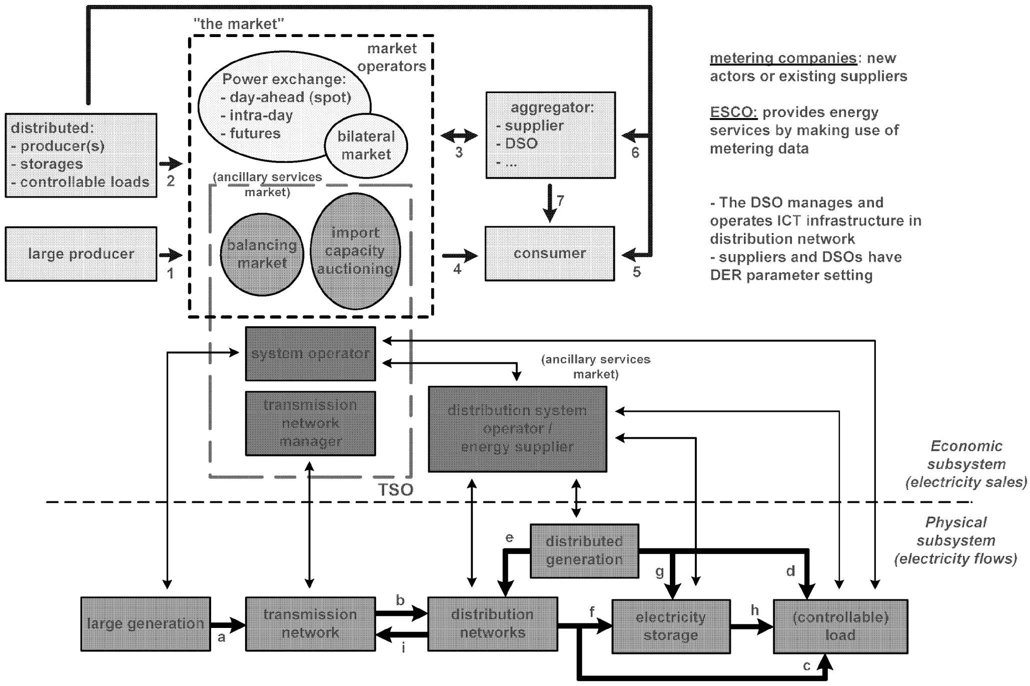

Figure 1: Socio-technical system of the electricity infrastructure with the application of DERs.

Enhancement of DER value through aggregation

Through aggregation of DER attributes, DER value can be enhanced. DER attributes may encompass products and/or services or relevant information for network management. The aggregating activity might encompass, for example, the collection of DER parameters and market information, the submission of residential bids and offers to market players and the making of optimision decisions on electricity trading to maximise the benefits for households and the aggregator.

The aggregation process can be conducted by electricity suppliers, generating companies (producers), DSOs or other independent aggregators as ESCOs or housing corporations. Aggregators can be program responsible parties themselves (for being able to trade on electricity markets), or they can fall under a separate program responsible party. The aggregator either deals directly on behalf of his DER clients or through a large intermediary with direct access to relevant markets.

Summary on economic uncertainties

As described, the electricity infrastructure becomes a more complex system due to the introduction and application of DERs and the necessary ICT infrastructure. The operational activities and economic decision-making of almost all actors is influenced and resulting economic impacts are uncertain. Here we will not go into detail regarding the complex build-up of the revenues and costs of all actors. Costs for actors include, for example, feed-back revenues for DER households and balancing costs for energy suppliers. For DSOs, costs include network reinforcement costs needed to mitigate technical problems associated with integrating DG into distribution networks. On the other hand, distribution losses are decreased and DG releases network capacity which can be used to accommodate future loads (Cao, Pudjianto et al. 2006).

We would like to note explicitly, however, that there is quite a big blank spot in literature on investment and operational costs of the necessary ICT infrastructure and systems to facilitate effective DER integration (e.g. intelligent meters, intelligent controllers, in house domotics, communication lines). Some indications can be found (see (Zoka, Sugimoto et al. 2006) and (Hawkes and Leach 2006)), but publicly accessible studies and data are scarce. Therefore, it is difficult to arrive at generic cost figures for smart power system components. Other uncertainties are the investment and operational costs of Micro-CHP and electricity storage systems.

For the government there are also important uncertain impacts of DER application. Main impacts are expected CO_2 emission levels of residential energy use, VAT and energy taxes and feed-in premium costs (a feed-in premium is a form of subsidy on electricity produced from renewable sources.

Technical Uncertainties

In (Peças Lopes, Hatziargyriou et al. 2006) a good overview of important technical challenges of increased penetration of DG is given. Main challenges are voltage rise effects, power quality aspects, protection and stability issues and lack of planned infrastructure upgrade (lack of structural flexibility of the existing energy-boiler systems). Positive network effects are decreased energy losses and investment deferral. Active network management can significantly mitigate negative network impacts of DER application and can increase the amount of DG to be connected to the existing network (discussed further in section 3). Besides the challenges in (Peças Lopes, Hatziargyriou et al. 2006) (that can be seen as challenges for the broader concept of DERs, besides just DG), we identify additional technical challenges and uncertainties for DER systems. Examples are lack of operational experiences due to the novelty of the technologies, uncertainties in the system being a multi-input acceptor, thermal and electric efficiencies and overhaul times of Micro-CHP systems, technical developments on fuel cell components, component lifetimes, volumes and capacities of energy storages and allowable number of start-stops per year for Stirling engines. Further the intelligence of DER controllers and metering equipmement that could enter the market is uncertain.

Institutional Uncertainties

The institutional uncertainties concern all aspects of the social, political, regulatory and legal uncertainties that may affect DERs. In the absence of a clear policy and associated regulatory instruments on the treatment of DG, it is very unlikely that this type of generation is going to thrive. The reasons for this are partly historical and related to the way distribution networks have been developed and operated as passive networks. In order to foster the required changes, there is a clear need to develop and articulate appropriate policies that support the integration of DG into distribution networks (Peças Lopes, Hatziargyriou et al. 2006).

Below we state the main institutional uncertainties regarding DER design and operation:

- CO_2 emission policy; emission policy determines the economic attractiveness of fuel efficient Micro-CHP systems;

- The subsidy scheme in place for promoting electricity generated by Micro-CHP systems;
- Regulation on DG connection charges (deep, shallow) and the design of use of system (UoS) charges (network tariffs) pertaining to DER operation;
- Uncertainties in actors behaviour;
- Uncertainties in the individual and general public perception of the technology;
- Uncertainties in granting the households, the right to produce electricity to be fed back into the grid.

3. Flexibility Strategies

The ability of the different DER technologies to adapt to different economic, technical and institutional uncertainties is an important criterion for its sustainable survival. In this section we establish a flexibility framework to handle these uncertainties at both the design, planning and operational phases of the DERs. The greater part of the strategy for handling these uncertainties consist in focussing on robust and flexible options to be embedded in the design of such DER technologies that will allow them survive or even flourish in a wide range of future uncertainties. To this effect we have had an implict mapping of the identified uncertianties into flexibility foms.

Multi-feed acceptor (Fuel Flexibility)

Up till now, Micro-CHP systems have mainly relied on natural gas. Although other fossil fuels, and to a limited extent renewable energy carriers can be used in most DER technologies, there is no single unit that have been designed to act as a multi-input acceptor which can accept (when desired) as feedstock, any of the energy carriers for onward conversion to heat and electricity. In the longer run, the design and operation of micro CHP with the multi-feed acceptance characteristic will render the technology more amenable to input feed switches and hence for more viability of the system.

Operational flexibility

Although, due to the modular nature and the small system size Micro-CHPs allow not only for flexible and immediate installation and thus better adaptation to unforeseen future developments in the electricity sector but also for relatively easier operation. However, this is true for stand-alone Micro-CHPs; it is envisaged that in the near future, the Virtual Power Plant (VPP) arrangement where larger number of Micro-CHP systems including heat storage, are connected through an intelligent ICT-network, and operated as if it were a power plant, if implemented, would introduce some elements of system complexity and hence some operational complexity. Therefore, in designing the VPP, operational flexibility and easiness should be considered.

Institutional flexibility

Generally, new technologies do not develop without the interactions and influences of varying actors and factors. An electricity infrastructure with DERs is a socio-technical system which is likely to be shaped by the actions and interactions of various technical and societal actors. To determine the likelihood of these influences and actions from actors, affecting the system, we propose a multi-actor modelling and analysis strategy from where the conflicts of interest and actions could be obtained and analysed prior to the roll out of the technology. Such analysis will reveal the robustness of the DER technology to in withstanding the actions and influences of the varying actors and their individual strategies. With respect to the public perception, debates, individuals and general opinions could be pooled and analysed before any technology mass introduction. This is because, perceptions and attitudes still matter when it comes to the introduction of new energy options. How would such influence the introduction of Micro-CHP concepts? On a localised and short time scale, it may not pose any problem but on global and long term, there may be problems associated with the introduction and use of hydrogen in fuel cell based Micro-CHP if that option technically becomes feasible. Also on the issue of bio-based Micro-CHP, the current debate options leading to competition with food production, nature and biodiversity is an issue to be critically looked into if the DER options are to be robust.

Retrofitional Flexibility

Currently, the Stirling engine, is the dominant technology during this experimental and market introduction phase, however, in the near future the introduction of and/or switching to other technologies (most of them being currently researched upon) may be imperative. Such switching will definitely depend on among other things, operational cost and technical adaptation easiness. Such switching will definitely come with problems and uncertainties which should be considered early in the design. According to (Van Soest, Bartholomeus et al. 2006), switching to different technologies will also lead to a different heat/electricity ratio, which is quite high (about 5-9) for the Stirling engine and much lower fuel cells (1–2, depending on the fuel cell type), gas engines taking an in-between position with 3 as a typical heat/electricity ratio. Also in the near future some “add on” technologies such as more sophisticated add-on control technology and more hybridized (fuel cell + convential boiler)systems to the existing form of Micro-CHPs may be imminent. Are the current states of technology amenable to such “add on”? The retrofitional flexibility of the system and local situations will determine to a large extent, the ability of the system to allow these “add on”.

Input flexibility

The major uncertainty that usually confronts technical and institutional designers is the uncertainty in the key variables used in the modelling of the system. In this regard, any optimization incorporating sensitivity analysis can help the designer understand the effects of such uncertainty and make good design decisions despite the source and class of such input uncertainties. Examples of such key variables in the design of Micro-CHP could be system efficiencies, the prices of imported and exported electricity, gas prices, residential electricity and heat demand, etc. Other inputs that may be uncertain are the lifetime of the system and investment and maintenance costs. During the design, these substantial input uncertainties can be circumvented through sensitivity analysis. This will place the designer on a better footing in determining the overall effect these variations will have on the behaviour, feasibility, and economics of the system configuration; the robustness of a such system configuration; and how the optimal system configuration changes across the range of uncertainty, for example, how the prices for natural gas (±30%) or status-quo-electricity (±20%) will affects the overall economy of a Micro-CHP operation project. Such information can help technical and institutional designers to establish the bounds of a confidence interval or to prioritize efforts to reduce uncertainty through the revelation of how different system configurations perform over a wide range of possible scenarios.

Conclusions and Future work

In the design and application of residential DERs there are still many uncertainties to be resolved. However, the fist step towards such uncertainty resolution is the comprehensive identification of these myraids of uncertainties. Therefore, the major contributions of this work is the identification of broader and integrated uncertainty classes than is usual in the domain and the exposition of some of the flexibility types worthy of consideration during the design of these DERs. This, the authors believe, will not only lead to the development of more robust and integrated design and operation of the residential DERs but will lead to a significant reduction in technical , societal and commercial risks. The current research efforts are geared towards the building and implementation of a sensitivity analysis model as well as the modeling of the various actors of the system.

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