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Towards a regulatory framework for microgrids—The Singapore experience

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ABSTRACT

Microgrids are increasingly put forward as key concepts of future energy supply complementing the conventional centralised energy system. This paper describes operational and regulatory microgrid challenges and makes suggestions regarding how to overcome them. Motivated by its unique liberalisation process, state guided growth processes and technology focused economic and sustainable growth ambitions, Singapore is put forward as a case study. An analysis of its legislative framework identified that advanced legislation is already in place regarding the distribution of locally generated cooling. However, a regulatory framework for full energy integrated modern microgrids is still in its infancy. Global lessons learned from the Singapore experience are therefore mainly with regard to utility based microgrids as they might facilitate the set-up of regulatory frameworks and standardisation. Additionally, grid connection codes and standards are needed to ensure safe microgrid operation. Furthermore, microgrids still need a legally defined identity. Here, global best practices are likely to lead the way.

1. Introduction

Energy is a key driver of industrialised societies. Consequently, in order to deliver energy to the consumer, the supply system is required to have high standards with respect to design, operation, safety and cost. The growing global population coupled with the growing global energy demand and climate change issues challenge the current standards and requirements of the energy supply system (Banerjee & Islam, 2011; Blumsack & Fernandez, 2012; International Energy Agency, 2012; Marks, Heims, & Fiebig, 2010). Moreover, the finiteness of conventional energy resources such as oil, coal and gas introduces additional restrictions on the development of the energy supply system (Banerjee & Islam, 2011; International Energy Agency, 2012). As a result, energy supply is an area of extensive research, which focuses on the challenge to achieve secure, safe and sustainable energy for the growing global population at an affordable price (Blumsack & Fernandez, 2012). The development of new technologies, such as centralised renewable energy plants, storage, small-scale decentralised generation units, microgrids and smart grids, is expected to play a major role in a momentous transformation of the conventional energy supply system to a future energy system (Alanne & Saari, 2006; Driesen & Belmans, 2006). Especially decentralised energy generation in the form of small-scale, locally controlled distributed generation (DG) units coupled in a single entity, a microgrid, is of increasing interest to accommodate for the new multidimensional needs of society (Blumsack & Fernandez, 2012).

At the time of writing, research regarding microgrids has mainly been focused on technical and economic aspects. Technical research is concerned with the effects of decentralised generation on the conventional electricity network through amongst others bi-directional electricity flows related to grid safety and islanding. Logenthiran, Srinivasan, and Wong (2008) and Mirsaeidi, Mat Said, Mustafa, Habibuddin, and Ghaffari (2014) for example, respectively carried out research regarding power flow calculations and reviewed the development of innovative protection systems to accommodate for microgrid operation. Economic research is especially concerned with cost benefit analyses, cost optimal design modelling and game-theoretic internal market operation models (Marnay et al., 2007; Mehleri, Sarimveis, Markatos, & Papageorgiou, 2012; Saad, Han, Poor, & Basar, 2012; Weber, Marechal, & Favrat, 2007). Even though such research is advancing the technological and economic barriers, the regulatory framework for microgrids is still lagging behind (Blumsack & Fernandez, 2012). Marnay, Asano, Papathanassiou, and Strbac (2008), Marnay, Zhou, Qu, and Romankiewicz (2012) and Romankiewicz, Qu, Marnay, and Zhou (2013) presented studies of global microgrids together with policy recommendations and existing regulations to enable microgrids. A detailed analysis of the appropriateness of an existing national regulatory framework is however not yet presented to date. The

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aim of this paper is to analyse the existing regulatory framework in Singapore regarding several identified microgrid challenges.[1] First, the position of microgrids within the energy system is presented. Second, operational and regulatory microgrid challenges are discussed with future lessons for Singapore based on the interaction between technology and regulation as well as policy recommendations to overcome such barriers in the future. Finally, global lessons are drawn from the Singaporean experience.

2. Microgrids and their place in the future energy system

2.1. The microgrid concept

Today, the microgrid concept has no unique definition since modern microgrids are not standardised in design but tailored to a specific location and to local requirements (Lasseter, 2002; Marnay et al., 2012). The modern microgrid concept, however, is not new when looking at the evolution of the energy supply system to what is today known as the *conventional* centralised energy system since it relates back to the initial development stages of the electrification in industrialised nations (Asmus, 2011; Van Hende & Wouters, 2014). The first 'electricity grids' emerged in the 19th century within countries that were marked through the industrial revolution such as the United States, Western Europe, Chile and Australia (Asmus, 2011; Van Hende & Wouters, 2014). These first grids were decentral isolated direct current based 'micro' grids that were privately owned and operated and served a local consumer base. The local 'micro'grids, based in major load centres, made way for an alternate current long distance interconnected transmission and distribution network at the end of the 19th century when the electricity demand and levels of industrialisation and urbanisation started to grow rapidly (Van Hende & Wouters, 2014). This up scaling of the network led to the centralisation of power plants at the peripheries of load centres. The latter evolution was coupled with a change in electricity regulation from local to State control and centrally controlled monopolies with enlarging central power plants owned and operated by utilities (Asmus, 2011; Van Hende & Wouters, 2014). The energy crisis in the 1970s led to an increase in fossil fuel prices. To counteract the finiteness and dependency on conventional fossil fuels such as coal, oil and gas and the dependency on imported primary energy resources as well as to increase energy security by diversifying the generation portfolio, independent power producers and large-scale renewables, such as wind farms, emerged (Asmus, 2011; Marnay et al., 2008; Romankiewicz et al., 2013; Van Hende & Wouters, 2014). These new technologies were however still set up within the conventional centralised network topology. The 1980s marked the global start of liberalisation of the electricity markets with the introduction of competition forming what is known today as the *conventional* centralised energy system which is still mainly based on fossil fuels (see Section 2.2). Within this liberalisation process two trends created favourable conditions for decentral generation to regain attention (Van Hende & Wouters, 2014). First, the conventional electricity supply structure is under pressure due to amongst others the growing global population coupled with an increasing energy demand and climate issues (Banerjee & Islam, 2011; International Energy Agency, 2012; Marks et al., 2010). Second, full retail contestability of consumers in liberalised electricity markets introduced increased consumer awareness in terms of energy efficient appliances and emissions (Blumsack & Fernandez, 2012). These trends form a catalyst for a change in philosophy regarding the future energy supply structure (Alanne & Saari, 2006; Blumsack & Fernandez, 2012; Driesen & Belmans, 2006; International Energy Agency, 2012; Marks et al., 2010; Marnay et al., 2007, 2008, 2012). Local energy generation and supply close to or at the premises of end-consumers would help to accommodate these trends since local generation can exploit the locally available (renewable) energy resources and can better balance local supply and demand whilst increasing energy supply efficiency (Blumsack & Fernandez, 2012; Marnay et al., 2012). Modern microgrids are here often put forward as key components that balance local supply and demand whilst potentially coupled with the central grid for increased flexibility and reliability (Blumsack & Fernandez, 2012; Marnay et al., 2012).

The modern microgrid concept gained increasing interest in the United States as a possible solution and prevention of black outs after the rolling black outs of 2001 (EPRI, 2011; Van Hende & Wouters, 2014). The Consortium for Electric Reliability Technology Solutions (CERTS) formulated a first definition of a modern microgrid in 1998 (Lasseter, 2002). Also, the European Union showed to be an initiator of microgrid research and developments through its 'More Microgrid' projects starting in the late 1990s (European Union, 2014; Marnay et al., 2012). Modern microgrids are defined on the basis of general characteristics since they are not standardised in design, but tailored to a specific location and local requirements (Lasseter, 2002; Marnay et al., 2012; Romankiewicz et al., 2013). A modern microgrid is a locally controlled entity technically defined through three main requirements; (1) comprising both locally controlled (small-scale) generation units (sources), energy loads (sinks), and possible energy storage units, (2) a potential interconnection with the central electricity grid, either on-grid or islanded, and (3) typically implemented at the low voltage distribution level (Lasseter, 2002; Marks et al., 2010; Marnay et al., 2012; NYSERDA, 2010; Romankiewicz et al., 2013). Microgrids often have a single point of common coupling with the grid and thus present themselves as single entities to the grid (Marnay et al., 2008, 2012). The introduction of decentral generation in the form of small-scale generation units and microgrids, however, introduces grid connection challenges in terms of bi-directional electricity flows, grid protection, islanding procedures, voltage stability and grid safety (Ackermann, Andersson, & Söder, 2001; Blumsack & Fernandez, 2012; Pepermans, Driesen, Haeseldonckx, Belmans, & D'haeseleer, 2005).

The modern microgrid concept is thus not new in that it consists of local balancing of energy supply and demand. The modern microgrid, however, is not solely a local provider of electricity but is also a smart and flexible energy supply system providing electricity as well as other services such as heating and cooling to its consumers making use of intelligent communication technology, storage and renewables (Blumsack & Fernandez, 2012; Lasseter, 2002; Marnay et al., 2008). Furthermore, it often complements a connection with the central grid increasing the reliability of its consumers through islanding capabilities (Lasseter, 2002). Microgrids optimise the local supply and demand of energy through small-scale generation units ranging in size from several kW to several MW in installed capacity (Kwee & Quah, 2010; Marnay et al., 2012; Pepermans et al., 2005). These units, key components of a microgrid environment, can be both dispatchable, such as micro combined heat and power (CHP) units, and intermittent, i.e. generation units based on natural resources such as solar and wind (Kwee & Quah, 2010; Marnay et al., 2012; Pepermans et al., 2005). Small-scale generation units are often referred to as DG units and are located close to or at the premises of end-consumers in the grid (Ackermann et al., 2001; Pepermans et al., 2005). The potential of waste heat recovery from local electricity generation for heating and cooling purposes is also an important benefit of microgrids (Lasseter, 2002; Marnay et al., 2008). Note that *thermal* energy supply refers in the

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[1] This paper uses legal sources but does not employ traditional legal methods. Instead, it departs from an engineering perspective to make regulatory recommendations. The author welcomes feedback and suggestions on the method and presented arguments.

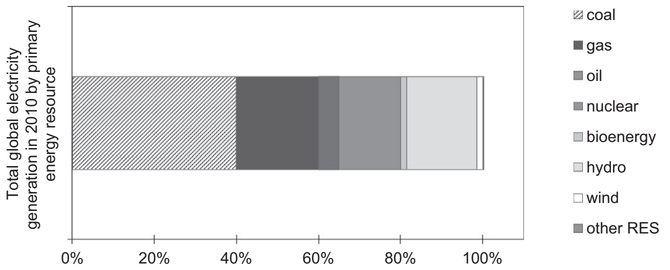

Fig. 1. The distribution of primary energy resources used for the total global electricity generation in 2010, adapted from International Energy Agency (2012). RES, renewable energy resource; PV, photovoltaic units.

context of this paper to both the supply of heating and cooling, which can be achieved through diverse primary energy resources and generation units.

2.2. The importance of microgrids in the transition towards a future energy system

Energy supply to buildings comprises both electrical and thermal energy supply where thermal energy supply alludes to the provision of both heating and cooling. Electrical energy supply conventionally involves a centralised vertical supply structure where electricity is generated in large centralised power plants and transferred to consumers through the transmission and distribution networks as explained in Section 1. Thermal energy demand comprises both heating and cooling supply and is conventionally addressed by self-generation through for example a central heating system or an air-conditioning system fuelled by inter alia natural gas or electricity (Marnay et al., 2012). The conventional central energy system is today still primarily based on centralised generation using fossil fuels as energy sources such as coal, oil and gas (International Energy Agency, 2012). Around the world, primary resources used for electricity generation vary depending on available conventional and renewable energy resources and technologies. In 2010 the total global electric energy generated was 21,410 TWh (International Energy Agency, 2012). About 65% of this was generated by fossil fuel plants driven by coal, gas and oil (International Energy Agency, 2012). Fig. 1 shows the share of primary resources used for the total global electricity generated in 2010.

The conventional energy supply structure, however, is under pressure (Ackermann et al., 2001; International Energy Agency, 2012; Marks et al., 2010; Pepermans et al., 2005). In response, climate change policy, such as the Kyoto Protocol, already encouraged new low emitting and efficient energy generation technologies to emerge on a large scale (United Nations, 1998). As of late, this initiated a gradual shift towards the introduction of large-scale renewables such as wind and solar parks as well as to decentral renewable energy generation such as rooftop photovoltaic units (PV) and small-scale wind turbines, located in buildings and houses as stated in Section 1 (Blumsack & Fernandez, 2012; International Energy Agency, 2012; Van Hende & Wouters, 2014). Increasing energy efficiency, decreasing emissions while balancing local supply and demand will impose new challenges on the system where decentral energy systems are expected to play an important role to both accommodate for the new needs of society – such as security of supply, peak load shaving and greenhouse gas reduction – as well as to complement the conventional system in a smart interconnected network (Ackermann et al., 2001; Blumsack & Fernandez, 2012; Jäger-Waldau, Szabó, Scarlat, & Monforti-Ferrario, 2011; Marks et al., 2010; Marnay et al., 2012; Pepermans et al., 2005). Future energy systems are therefore expected to comprise a greater utilisation of microgrids (Marks et al., 2010).

Globally, modern microgrids are starting to take up increasing interest. Most currently existing microgrids are off-grid systems, part of the electrification of rural towns in developing countries, high reliability systems or trial-systems (Lidula & Rajapakse, 2011; Marnay et al., 2012; Navigant Research, 2012; Wolsink, 2012). However, grid-tied commercial microgrids with the option for islanding with seamless transition still experience challenges regarding protection systems, fault ride-through, reconnection, safety as well as electricity regulations (Lasseter, 2002; Wolsink, 2012). In 2012, the global microgrid capacity was estimated at approximately 3200 MW (Navigant Research, 2012). Here North America leads the way in microgrid research and test trials, having approximately 65% of the global capacity. Europe and Asia Pacific are starting to catch up with respectively 12% and 9% of the global installed capacity (Navigant Research, 2012). The Asian region is also catching up, and in particular Singapore, being a prosperous and technology-focussed country, is benefiting from the globally established knowledge.

A major challenge for the widespread adoption of microgrids, however, is the lack of standardisation and regulations regarding the operation on and off-grid as well as both the energy and monetary transfers between the microgrid and the central grid and between the different microgrid participants (Ackermann et al., 2001; Akorede, Hizam, & Pouresmaeil, 2010; Van Hende & Wouters, 2014). The procedure for the introduction of microgrids within the conventional energy system is an area of extensive debate. Previous research identified that this process can only take place if governments take up a key role for the roll out of the future grid, focussing on the degree of market liberalisation, ownership models, structural operation and design as well as connection issues with the infrastructure at large (Van Hende & Wouters, 2014). Regarding interconnection, grid codes and standards are already being formulated around the globe. The Institute of Electrical and Electronic Engineers IEEE Std.1547.4-2011, Guide for Design, Operation, and Integration of Distributed Resource Island Systems with Electric Power Systems, is treated as a fundamental technical standard to play a key role for microgrid interconnection standardisation with intended islanding purposes, including voltage stability standards as well as grid safety precautions (Lidula & Rajapakse, 2011). Some countries already have regulation in place to enable the adoption of microgrids. In the United States, for example, regulatory frameworks for microgrids are the topic of extensive debate. Several states are identifying barriers for microgrids in their current legislation (e.g. state MN (Burr et al., 2013)). In the European Union (EU), the Electricity Directive requires Member States to define an implementation plan and timetable for the roll-out of smart metering systems, which is a first step in the right direction for microgrid regulation (SmartGrids European Technology Platform, 2013). Other countries, like Sweden, already have legislation in place for the sharing of locally generated heat under the form of a District Heating Act (District Heating Act of Sweden, 2012). Similarly to Sweden, Singapore already has legislation in place for the sharing of locally generated cooling under the District Cooling Act (District Cooling Act of Singapore, 2002). The presented regulatory developments may serve as regulatory models for microgrid regulation elsewhere.

2.3. Singapore as an example

Singapore is a state country with over 5 million inhabitants and a high economic standard and growth illustrated by a GDP of $59,813 per capita (Koh, Than, Wang, & Tseng, 2012). Renewable primary energy resources such as wind, hydro, geothermal and others such as wave energy are not readily available in Singapore to use for electricity generation due to its warm and wet tropical rainforest climate and lowland geographical location (Institute for Veterinary Public Health, 2011; Koh et al., 2012). Singapore is land scarce and disadvantaged with regard to alternative energy resources (Energy Market Authority, 2010e; Koh et al., 2012). It thus relies heavily for almost all of its electricity generation on imported fossil fuels such as oil, coal and gas (Koh et al., 2012). The steep increase of fossil fuel prices in the global market has introduced challenges with respect to the economic competitiveness and growth of Singapore since the country has a high rate of foreign investment and import of goods (Koh et al., 2012). To facilitate its growing economy in a sustainable way, Singapore has taken several measures such as energy efficiency targets and the ratification of the Kyoto protocol in 2006 (United Nations, 1998). The green strategies and initiatives of Singapore for the next two decades are formulated in the Sustainable Singapore Blueprint published by the Ministerial Committee on Sustainable Development (Sustainable Singapore, 2013). As part of its National Energy Policy Report, energy efficiency, diversification, renewables and research and development are put forward as important factors to sustain the continuous growth in Singapore (Ministry of Trade and Industry Singapore, 2007; Yeo & Hin, 2010). The Singapore Initiatives in New Energy Technologies (SINERGY) is a fundamental part of its National Energy Policy and includes a centre that focusses on research, development and testing of microgrids and other future technologies (Ministry of Trade and Industry Singapore, 2007). The Jurong Island microgrid in Singapore serves as a test-bed for new renewable energy technologies as part of SINERGY (Ministry of Trade and Industry Singapore, 2007). Microgrid and DG test-beds are also being created by the Singapore Agency for Science, Technology, and Research (A*STAR) as well as by the Energy Market Authority of Singapore, who established a microgrid on the Singaporean island of Pulau Ubin (A STAR Institute, 2011; Energy Market Authority, 2010a; Fan, Rimali, Tang, & Nayar, 2012).

Singapore is an ideal example for microgrid deployment from a regulatory perspective for several reasons. First, Singapore has moved to a partially unbundled and liberalised electricity market without full retail contestability, which facilitates energy supply without competition (Chang & Tay, 2006; Chang, 2007; Energy Market Authority, 2009, 2010d).[2] This creates an environment where the energy market is well regulated and transparent which makes an attractive climate for businesses and foreign investment (Koh et al., 2012). Second, Singapore already has advanced regulations in place for the local distribution of cooling, namely through the District Cooling Act (District Cooling Act of Singapore, 2002). Third, Singapore defined microgrids as *critical elements in its energy strategy* (Marks et al., 2010). Compared to the rest of the world, and especially North America, Singapore can however still learn from other countries with respect to their technology development. Hence, international cooperation is a key part of its energy policy framework (Ministry of Trade and Industry Singapore, 2007). Last, an observation of the country shows that most inhabitants live in high-rise buildings or in rural areas (Lee & Rajagopalan, 2008; Sustainable Singapore, 2013). The urban structure leaves limited choice for the inhabitants regarding their preferred type of energy use since this choice falls back on the respective landlords, which in turn falls back on the utility service providers and the general energy regulatory framework of the country (Koh et al., 2012; Lee & Rajagopalan, 2008). Although Singapore is partially liberalised in theory, in practice, the size of the country moderates this liberalisation process (Koh et al., 2012). Furthermore, the government has a clear vision in favour of economic growth of the country rather than prefacing individual consumer choice, which directs the energy climate (Koh et al., 2012; Sustainable Singapore, 2013). The small geographical size of Singapore, the well regulated and transparent regulatory framework, the openness of its economic market and the supportive political structure to (foreign) investment and businesses, makes that new developments can efficiently and readily take place. This could play in favour of the fast, aligned and coherent roll out of new technological developments such as microgrids if directed through governmental initiatives.

3. Materials and methodology

3.1. Methodology

This paper analyses the existing regulatory framework in Singapore for identified microgrid challenges. First, several operational and regulatory challenges of microgrids are identified and the governing regulatory framework for energy supply in Singapore is presented. The current regulatory framework in Singapore is subsequently analysed to find enablers and barriers for microgrid operation, which leads to lessons for a microgrid regulatory framework in Singapore, as well as globally.

The analysis in this paper is performed for residential microgrids. Two configurations are under research, either (1) a *neighbourhood consisting of several households* or (2) a *residential apartment building*. Either configuration has one point of common coupling with the central grid. Furthermore, to satisfy its electricity demand, each dwelling has the option to install DG units.[3] In addition, households in a neighbourhood setting can interchange locally generated electricity and cooling amongst each other. In case of the apartment, the generation units installed in the building can supply electricity and cooling to all the households within the building. Moreover, the microgrid as a whole can exchange locally generated electricity with the central grid. The cooling demand is established in the neighbourhood setting through a central pipeline system where households can share their locally generated cold water from micro combined heat, power and cooling (CHPC) systems.[4] The cooling demand in an apartment building is established centrally through medium sized CHPC systems and a cooling network throughout the building.[5] Two types of microgrids are thus under research, either a *microgrid in its purest form*, which refers to a residential neighbourhood setting where all households can install generation units and share energy, or a *utility owned microgrid*, which refers to centrally owned DG units and pipeline networks where the individual consumers are served under contract. The operation and local balancing of supply and demand in either microgrid is managed by a smart microgrid central control system.

The technologies focussed on in this paper are rooftop PV units, CHP units coupled with absorption chillers (AC) and cooling pipelines governing the considered building or neighbourhood. Microgrids in Singapore are most likely to consist of CHP units of which the generated electricity can either be locally used or exported to the central grid and the waste heat can be used in a district cooling system using an AC. Rooftop PV units gain increasing interest due to the favourable climate in Singapore with an average solar irradiation of 4.56 kWh/m^2/day (SYNENERGY, 2014). Table 1 summarises the characteristics of the considered technologies.

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[2] Unbundling of the electricity market refers to the structural and legal separation of the four market activities: generation, transmission, distribution and retail. Liberalisation in this context refers to the introduction of competition in all layers of the energy system (Van Hende & Wouters, 2014). Full retail contestability is considered as the ideal for liberalised and unbundled electricity markets and refers to the free choice of retailer for every end-consumer.

[3] *Dwelling* refers to either a single household in a neighbourhood setting or an apartment building as a whole.

[4] *Micro* refers to DG units with an installed capacity below 10 kW.

[5] *Medium* refers to DG units with an installed capacity between 10 kW and 1 MW.

Table 1
Characteristics of the considered distributed generation technologies for a residential microgrid based in Singapore.

Technology	Photovoltaic unit (PV) (Mehleri et al., 2012; Ren, Gao, & Ruan, 2009)	Combined heat and power unit (CHP) (De Paepe, D'Herdt, & Mertens, 2006; Mehleri et al., 2012)	Absorption chiller (AC) (Lozano, Ramos, & Serra, 2010)	Pipelines (Söderman, 2007)
Features	- Rooftop panels	- Stirling or gas turbine	- Hot water fired single effect	- Temperature difference between feed and return water 10 °C
	- Polycrystalline	- Natural gas fuelled	- Installed in dwellings with CHP	
	- Fixed tilted	- Installed in dwellings	- CHP waste heat utilisation	
	- Electricity supply to dwelling and microgrid	- Waste heat utilisation for cooling purposes	- Electricity for operation (0.2 kW electricity per tonne of refrigeration)	
		- Waste heat demand driven		
Efficiency/coefficient of performance (COP)	- 12% electrical efficiency	- Electrical efficiency 25%	- COP: 0.7 kW cooling per kW heating	- 0.1% loss per metre pipe
	- 0.15 rated capacity (kWp/m^2)	- Heat to electricity ratio: 3 kW heat per kW electricity		
Size range	1–50 kW	1 kW–1 MW	2 kW–1 MW	–

3.2. *Current regulatory framework for energy supply in Singapore*

Energy regulations govern both the electric and thermal (cooling and heating) energy supply. The principle legislation governing the *electricity sector* and the National Electricity Market in Singapore is the Electricity Act, which allocates inter alia the responsibilities of the different governing bodies (The Singapore Electricity Act, 2002), and the Energy Market Authority of Singapore Act, which governs the powers of the Energy Market Authority and wholesale market operation (The Energy Market Authority of Singapore, 2002). Recently, developments in the field of embedded generation are being made through policies and decision papers (The Frontier Economics Network, 2006a,b; Energy Market Authority, 2006a,b). Singapore relies heavily on international investment to drive and develop its economy (Chang and Tay, 2006; Chang, 2007; Energy Market Authority, 2010d; The Frontier Economics Network, 2006a). Foreign industries often make use of embedded generation, which is defined as energy generation for internal purposes on-site and on the same premises, owned by the same party (The Frontier Economics Network, 2006b). Currently, new embedded generation units have to register with the Energy Market Authority under the Electricity Act if they have a generating capacity above 1 MW (Energy Market Authority, 2006a,b, 2008a). Under the new regulations, these embedded generation units are also not allowed to export electricity to the central grid, unless registered with the Energy Market Authority as market participants (Energy Market Authority, 2008a). Although embedded generation units differ from DG units in installed capacity and regulations (DG units typically range from several kW (micro) up to 1 MW (Lasseter, 2002)), the local generation and supply of energy show some similarities.

Regarding *thermal energy supply*, cooling is needed throughout the year due to the tropical climate in Singapore (Institute for Veterinary Public Health, 2011). Most dwellings use air-conditionings to meet their cooling demands (Lee & Rajagopalan, 2008). A district cooling project aiding to increase energy efficiency, is being implemented in selected service areas (Chang & Tay, 2006). District cooling can be adopted in urban areas and comprises the central generation of chilled water in a service area. This chilled water is then distributed through a pipeline network to consumers (Energy Market Authority, 2010b). This cooling service is established under the District Cooling Act of Singapore (District Cooling Act of Singapore, 2002). According to the District Cooling Act, a district cooling service is defined under Section 2 as '[. . .] the sale of coolant for space cooling in a service area by a licensee operating a central plant capable of supplying coolant via pipe to more than one building in the service area' (District Cooling Act of Singapore, 2002). A centrally owned service, which can be seen in case of an apartment building, might facilitate the infrastructure, regulations and the local market operation compared to a spread out pure microgrid set-up.

3.3. *Identified operational and regulatory challenges of microgrids*

Five operational and regulatory challenges of microgrids, identified through literature, are put forward in this paper; (1) an apt legal design for microgrids, (2) liberalisation and competition requirements, (3) sharing of energy and ownership, (4) the interconnection with larger infrastructure, including grid safety and islanding procedures, and lastly, (5) the integration of renewable energy generation units (Ackermann et al., 2001; Marks et al., 2010; Pepermans et al., 2005; Romankiewicz et al., 2013). Note that the list of presented challenges is by no means exhaustive. It puts forward an illustrative example analysis of selected common microgrid challenges. The aforementioned Singaporean regulatory framework is subsequently analysed for the barriers and potential to accommodate for the presented challenges.

4. Microgrids in Singapore: overcoming operational and regulatory challenges

4.1. *An apt legal design for microgrids*

Currently, no technical or legal definition of a microgrid can be found in the Singaporean energy regulations (The Singapore Electricity Act, 2002). Moreover, microgrids are tailor-made in design (Lasseter, 2002; Marnay et al., 2008, 2012). The only global consistency in defining microgrids involves several principles as defined in Section 2. A microgrid could, however, be defined inspired by the definition of embedded generation, Section 2 of the District Cooling Act, and the technical definitions given in Section 2 of this paper (District Cooling Act of Singapore, 2002; Marnay et al., 2012; NYSERDA, 2010; Romankiewicz et al., 2013; The Frontier Economics Network, 2006b). For now, a small neighbourhood or building microgrid is most likely treated as a combination of both a utility energy service, such as a district cooling service, with a total on-site CHP and PV generation capacity below 1 MW, which allows DG units and the over-coupling microgrid to export electricity to the grid without registering with the Energy Market Authority (Energy Market Authority, 2006b).

4.2. Liberalisation and competition requirements

Singapore has been reforming the structure of its electricity market from a fully vertically integrated, government owned, electricity supply structure to an unbundled and deregulated electricity supply structure governed by the National Electricity Market of Singapore (Chang and Tay, 2006; Chang, 2007; Energy Market Authority, 2010d). This liberalisation process was introduced in several phases driven by the rapid economic growth and the increasing population combined with the quest for an efficient supply of competitively priced electricity to remain attractive to foreign investors (Chang & Tay, 2006; Chang, 2007; Energy Market Authority, 2010d). Other industrialised nations, such as Australia and most European jurisdictions (driven by the EU liberalisation packages such as the Third Energy package (Van Hende, 2011), have also chosen to liberalise their electricity markets, and for Singapore these processes showed a promising tool to decrease electricity prices due to competitive market operation and to increase grid efficiency (Chang & Tay, 2006; Chang, 2007; Energy Market Authority, 2010d). Liberalisation is the first phase of transformation of the energy supply structure (Blumsack & Fernandez, 2012). The incorporation of climate and renewable energy measures will introduce a next transition phase where microgrids could play a central role (Blumsack & Fernandez, 2012; Marnay et al., 2008).

The liberalisation process in Singapore is to date not completed, but has already resulted in the unbundling of generation, transmission, distribution and retail (Chang & Tay, 2006; Chang, 2007; Energy Market Authority, 2010d). Generation is fully competitive, while the transmission and distribution networks are maintained as a natural monopoly (Chang & Tay, 2006; Chang, 2007; Energy Market Authority, 2009, 2010d). The retail side is being reformed in several stages. Here the distinction is made between contestable and non-contestable consumers (Energy Market Authority, 2010c). Contestable consumers have full retail contestability, whereas non-contestable consumers are supplied through the Market Support Services Licensee, which provides a fair and equitable electricity price (Chang & Tay, 2006). Currently, residential consumers and other small consumers are considered non-contestable consumers (Energy Market Authority, 2010c). Full retail contestability is thus not yet achieved (Hogan et al, 2012). The analysis in this paper is done for residential households in Singapore. Hence it is assumed that this neighbourhood solely consists of non-contestable consumers. Although the electricity market in Singapore is moving towards a fully competitive and liberalised system, the government has a strong vision for the state's energy developments (Chang & Tay, 2006; Chang, 2007; Energy Market Authority, 2010d; Koh et al., 2012; Ministry of Trade and Industry Singapore, 2007; Sustainable Singapore, 2013; Yeo & Hin, 2010). The roll out of new technologies, such as energy efficient CHP generation units, PV units as well as district cooling services could benefit from this since the government can create a clear and transparent regulatory climate with a clear microgrid vision that welcomes foreign investment and businesses.

Under Section 3 (3)(g)(i) of the Electricity Act, the authority of the Electricity Market Authority is defined as promoting and safeguarding competition and fair and efficient market conduct or, in the absence of a competitive market, preventing the misuse of the monopoly position or market power (The Singapore Electricity Act, 2002). Since there is no full retail contestability in the Singaporean retail market yet there are thus opportunities for exemptions from the competition requirement under Section 52 of the Electricity Act (The Singapore Electricity Act, 2002). Under Section 3 (3)(g)(i) of the Electricity Act, non-competitive energy supply – like in a microgrid environment – is permitted as long as this is done without exploitation of the local monopoly and market power (The Singapore Electricity Act, 2002). The tariffs set for non-contestable consumers, served under monopoly retail, are regulated under Section 22 of the Electricity Act and are to be set with undue preference regarding the location of the consumers and with undue discrimination regarding consumers in the same area (The Singapore Electricity Act, 2002). A similar pricing definition can be found under Section 19 of the District Cooling Act (District Cooling Act of Singapore, 2002). Furthermore, Codes of Practice such as the Code of Conduct for Retail Electricity Licensees and the Market Support Service Code refer to maintaining fair energy pricing also for non-contestable consumers (Energy Market Authority, 2004, 2012a). Section 7 of the District Cooling Act states that, unless exempt, '[. . .] the occupier of every premise within a service area requiring air-conditioning *shall use* the district cooling services provided by a licensee if such services are available within the service area' (District Cooling Act of Singapore, 2002). Local dominations of energy supply are thus supported and the local licensee is ensured of consumers. This is similar to what happens within a residential microgrid environment, especially in utility operated apartment microgrids. The District Cooling Act thus forms a first basis for locally generated and managed energy supply, which complies with the exemption on the competition requirement.

4.3. Sharing of energy and ownership

Similarly to the previous characteristics, no explicit definition of ownership of units and sharing of energy within a microgrid is accommodated for under the Electricity Act. Nevertheless, ownership is defined on several occasions regarding the regulations on both district cooling and embedded generation. Two types of ownership are distinguished: first, the ownership of generation and supply facilities such as the PV units, CHP units, ACs and cooling pipelines, and second, the ownership of the locally generated energy and the internal microgrid market.

First, with regard to the ownership of generation and supply facilities, both the District Cooling Act and the Decision papers on embedded generation provide certain relevant definitions. In the situation of District Cooling facilities, a licensee is defined under Section 2 of the District Cooling Act in relation to any service area, as 'a person who is authorised by a licence to carry out all or any of the functions of providing district cooling services to the service area' (District Cooling Act of Singapore, 2002). The consumers still own their land and their houses as stated under Section 28 of the District Cooling Act (District Cooling Act of Singapore, 2002). This private ownership definition combined with public/state/utility ownership of the cooling distribution system will have an impact on the implementation of infrastructure necessary to establish the cooling network. Concerning embedded generation units, the revised rules of the Energy Market Authority state that the embedded generation unit, the load facilities of that unit and the land on which the unit is built should be majority owned by the same company (Energy Market Authority, 2008a). The company is additionally not allowed to export electricity to the grid unless it applies for a license for the embedded generation unit to be a commercial generation unit that participates in the wholesale electricity market (Energy Market Authority, 2008a).

Second, regarding the operation of the internal market and ownership of locally generated energy, no precedent can be found within Singapore's legislation. Models regarding ownership and service with respect to microgrids have, however, been proposed in literature. NYSERDA (2010) refers to several models developed by King (2006) that categorise microgrids regarding their ownership and business practices. Microgrids in their purest form are referred to as local cooperative neighbourhoods. Practically, in case of a residential microgrid in its purest form this implies that the ownership of the equipment, such as pipelines, CHPC systems and PV systems – which are not necessarily installed in each household – should be decided upon by the cooperating households. This introduces issues with regard to who owns and maintains those units that serve the whole neighbourhood but are not necessarily installed in all households. If a utility owned microgrid is installed, the utility will install a medium scale CHPC system as well as a district cooling network and might require each house to install a certain rooftop PV capacity. The utility can then serve the connected households under contract. When looking at a single apartment, the microgrid system is inherently utility owned. One medium size CHPC system can be installed which provides cooling and electricity to the different apartments in the building. Also a larger capacity of rooftop PV units can be installed on the roof of the building to supply the consumers.

The Singaporean legislation accommodates for a precedent of a microgrid environment that is supplied and managed by a single licensee in a certain service area, this is, a utility owned and operated microgrid, through the District Cooling Act. The consumers within that service area, however, must accept the energy supply from that licensee unless exempt (Section 7 of the District Cooling Act (District Cooling Act of Singapore, 2002)).

4.4. *Interconnection with larger infrastructure*

With respect to the connection of a microgrid with larger infrastructure, several challenges are introduced. First, *licensing requirements* are researched, second, *grid access* options combined with grid safety issues, third, *islanding* authorisation, and fourth, the responsibility to provide for additional *energy infrastructure* required for microgrid operation and the sharing of locally generated energy.

First, in the decision papers regarding embedded generation, the licensing requirements of on-site generation units are stated (Energy Market Authority, 2006b). Microgrids are made up of DG units that are typically several kW in electrical capacity in a residential setting and are thus exempt from registering with the electricity market (Costa, Matos, & Peças Lopes, 2008; Energy Market Authority, 2006b). Additionally, Section 6 of the Electricity Act states that a license or an exemption is needed to engage in electricity activities. Microgrids therefore need to make sure they are in accordance with the licensing requirements as they not only import and export electricity but also engage in the generation of electricity and potentially retail. Schemes are already provided for the installation of both rooftop PV units with grid export capabilities under the Handbook for Solar Photovoltaic Systems of Singapore as well as embedded generation units (Energy Market Authority, 2011a). Here, non-contestable consumers do not need to apply for a generation license nor register with the Energy Market Commission as market participants to export electricity in exchange for compensation (Energy Market Authority, 2011a). This is in contrast with the procedure for embedded generation units since they are obliged to register with the Electricity Market Authority (Energy Market Authority, 2006b). A special treatment lies in the operation of a so-called Master-sub metering scheme, which can be found in inter alia private condominiums and commercial buildings (Energy Market Authority, 2011a). A residential apartment building configured as microgrid falls under this category. Under this metering scheme, the total facility has a single point of common coupling and the electricity that each sub-unit attempts to export to the central grid may be used up by the common services or by other sub-units within the facility (Energy Market Authority, 2011a). The drawback under this scheme is, however, that sub-units cannot rely on compensation for exported electricity, since the actual amount of exported energy per sub-unit is untraceable (Energy Market Authority, 2011a).

Second, with regard to grid access, the Energy Market Authority provides non-discriminatory access to the grid as stated under Section 3 (3)(g) of the Electricity Act (Energy Market Authority, 2009; The Singapore Electricity Act, 2002). Electricity generating units thus have the right to access the transmission infrastructure. Furthermore, the open access principle (as opposed to firm access) is adopted for network planning in Singapore (Energy Market Authority, 2011b). This principle states that the transmission licensee has no obligation to reinforce the network, whether to mitigate transmission constraints beyond the connecting substation or otherwise (Energy Market Authority, 2011b). This implies that there is no guarantee for the transmission network to be constraint free or for the generation units to fully utilise the transmission infrastructure (Energy Market Authority, 2011b). Microgrids should thus be able to legally connect to the grid without discrimination if the open access principle is extended to the distribution network. The export of energy to the grid, however, is subjected to congestion management. Additionally, internal microgrid operation as well as the connection of a microgrid to the central grid introduces bi-directional electricity flows that require grid reinforcement since the central grid does not foresee bottom-up supply of electricity introduced by decentral generation at the distribution level (Ackermann et al., 2001; Lasseter, 2002; Pepermans et al., 2005). The operation of conventional protection systems in the distribution grid has to be adapted in order to isolate faults in the network in two directions to maintain safe operation. Furthermore, the installation of renewables such as rooftop PV units can affect the voltage stability in the network, which can also compromise grid safety (Ackermann et al., 2001; Pepermans et al., 2005). The connection of DG units as well as microgrids to the central grid thus has to be in accordance with the technical standards such as the Transmission Code and the Metering Code (Energy Market Authority, 2008b, 2013).

Third, authorised islanding is a major advantageous characteristic of microgrids as it increases reliability of the consumers and allows a microgrid to disconnect from the central grid when required and work autonomously (Costa et al., 2008; Lasseter, 2002; Marnay et al., 2012). The problem with islanding is that after the microgrid is isolated from the central grid due to a fault in the latter, the microgrid by itself has to operate under safe conditions after a short ride through period (Costa et al., 2008; Lasseter, 2002; Marnay et al., 2012). Since voltage stability issues, safety of operation due to bi-directional power flows and the small size of the network challenge safe operation, islanding is often prohibited under network regulations (Katiraei, Iravani, & Lehn, 2005). Anti-islanding requirements for generation units are, however, not explicitly mentioned in the Electricity Act. Several sections of the Act, amongst others Section 3 (3)(e), Section 39 (1), Section 94 (3) and Section 103 (m)(iii) refer to safe operation of the DG units (The Singapore Electricity Act, 2002). The Transmission Code has standards in Appendix C, Section 4 (e), regarding protective devices and mentions islanding in one paragraph as 'being an option to supply a load' (Energy Market Authority, 2008b). It therefore appears that islanding is not prohibited under Singaporean regulations.

Last, energy integration of a residential neighbourhood with microgrid configuration needs additional infrastructure that might cross publicly and privately owned land. Under Section 28 of the District Cooling Act, regulations are already formulated regarding the inspection, maintenance, repair, removal and alteration of cooling pipelines that run through privately and publicly owned land (District Cooling Act of Singapore, 2002). The Electricity Act addresses electrical supply infrastructure amendments over state lands by an electrical or a supply installation licensee under Section 69 (1), Section 71 (b) and Section 71 (c) (The Singapore Electricity Act, 2002). Additionally, the Singapore Public Utility Act has provisions regarding the electrical and water supply infrastructure under Section 24A (9), Section 32 (2) and Section 38 (2) (Public Utilities Act of Singapore, 2002). Noteworthy is that exemptions to the provisions under Part IX Section 71 (b) and Section 71 (c) of the Electricity Act might be granted by the Energy Market Authority for any electrical or supply installation used exclusively for *domestic* purposes or other installations where it is considered desirable (The Singapore Electricity Act, 2002). This latter section appears to leave room for the implementation of residential, this is, domestic, generation units regarding licensing and any other provisions under Part IX of the Electricity Act.

4.5. *Integration of renewable energy generation units*

As explained, future energy systems would not only allow for centralised renewable energy generators, such as wind farms, to be connected to the grid, but would also integrate renewable DG units. Microgrids are able to exploit locally available energy resources and can thus facilitate the incorporation of widespread locally controlled renewable energy sources in the system (Ackermann et al., 2001; Blumsack & Fernandez, 2012; Pepermans et al., 2005).

Solar and biofuels are the most favourable renewable energy resources to aid Singapore in its sustainable economic growth (Energy Market Authority, 2010e; Koh et al., 2012). Singapore has limited PV units installed due to their cost and the prevalence of apartment buildings (Ministry of the Environment, 2009). The installed capacity of PV units is however increasing. Singapore has currently no feed-in tariff in place but a compensation for electricity exported to the grid by residential PV units (Energy Market Authority, 2012b). Non-contestable consumers applying for the latter are compensated for exported electricity through a credit adjustment of their monthly electricity bill (Energy Market Authority, 2011a). Under the Master-sub scheme, no compensation is given to the sub-units, since part of their exported energy is used to supply auxiliary common services of the facility, which cannot be quantified through the single metre (Energy Market Authority, 2011a). Singapore thus still has growth potential regarding the implementation of renewable DG units and metering, especially in the residential sector. This growth could be achieved in a residential microgrid environment.

4.6. *Overcoming challenges in the future*

Singapore has with its District Cooling Act and decision papers on embedded generation already advanced legislation in place that can serve as a starting point to accommodate for residential microgrids employing rooftop PV as well as district cooling services. However, based on the identified challenges, some recommendations can be made to increase microgrid deployment in Singapore.

First of all a *legal definition* of a microgrid should be outlined in order to construct a supporting regulatory framework. Since microgrids have characteristics of both energy consumers and producers, an appropriate operational structure of a microgrid should be spelled out to clarify their place in the market. This can inter alia be a utility owned and operated microgrid or a cooperative microgrid and can either be from a consumer or producer perspective. Since most of the Singaporean population lives in apartment buildings, centrally managed utility based microgrids are most likely to be rolled out due to the ease of standardisation and the set-up of the regulatory framework.

Second, the Electricity Act provides exemptions from the *competition* requirement that characterises liberalised energy markets, for example under the District Cooling Act. Even more so, the District Cooling Act encourages local energy provision dominances. Microgrids are not fully competitive but allocate generation units optimally and share the locally generated energy. They might thus be able to be established under Singaporean law since non-competitive retail is inherently not prohibited, and sometimes even encouraged. In a utility based apartment microgrid, the principles governing the District Cooling Act can be readily extended to include an electricity provision service from a central CHPC system and rooftop PV installed in the building.

Third, the *sharing* of the locally generated energy and the *ownership* of the generation units, however, still needs to be accommodated for. Though, Singapore has with its District Cooling Act already a legislative framework in place for utility operated and serviced neighbourhoods regarding coolant supply. This is a first step towards the local generation and operation of both cooling and electricity supply within a service area or neighbourhood. It provides an example for a utility owned and operated microgrid which can be adopted in apartment based microgrids. Microgrids in their purest form are, however, more complex in terms of private ownership, licensing and contractual agreements.

Fourth, regarding the interconnection of microgrids with the larger infrastructure, there are no specific licensing requirements with the Energy Market Authority for residential microgrids. Furthermore, microgrids could be able to legally connect to the central grid infrastructure without discrimination if the open access principle is extended to the distribution level. This removes connection barriers for DG units, provided they follow the codes and technical standards in their connection procedure to ensure safe operation in an environment with bi-directional electricity flows. Nevertheless, for a microgrid to be able to rely on support mechanisms, more elaborate metering schemes and compensation mechanisms should be put into place, especially to identify the share of individual households within a residential microgrid. Furthermore, the Singaporean Electricity Act and Transmission code have no explicit anti-islanding provision. This might additionally facilitate the implementation of residential microgrids. Here, however, safe operation while transitioning to and operating in island mode should be ensured.

Fifth, *renewable energy* DG units are not common yet in Singapore due to its climatic and geographical conditions. Sun, however, is abundant. Hence, rooftop PV units are emerging in the residential sector. A stronger supporting framework with feed-in tariffs or tax reductions and an adequate metering scheme for all consumers could aid to the widespread implementation of these units as well as other highly efficient micro and medium cogeneration units, diversifying its generation portfolio and reducing its dependency on imported fossil fuels.

Despite the interest in microgrid test facilities in Singapore, several operational and regulatory issues still need to be addressed in order for microgrids to be established on a large scale. The main barriers in Singapore are identified as being (1) support and advanced metering schemes for DG units as key components of the microgrid, (2) ownership and internal market models for cooperative microgrid neighbourhoods, and (3) codes for safe operation especially in island mode.

5. Lessons learned

Although it can be argued that Singapore is not yet a leading nation with respect to microgrids from a technological point of view, due to its unique legal framework, governmental initiative and transparent regulatory climate, it could unarguably inspire other countries. Microgrids have specific characteristics and face operational and regulatory challenges, of which several were discussed in this paper. From the analysis of these challenges in

Singapore, some lessons can be formulated for other countries wanting to deploy microgrids in their (future) energy systems.

First of all, it is essential for countries to identify their *building structures and available renewable energy resources* to develop the most suitable legal microgrid definition within their legislation. A microgrid can be defined as a consumer or producer of energy and its operation can be organised in for example a utility or a cooperative neighbourhood depending on where the existing regulation provides an apt playing field (King, 2006). The choice of legal identity is of major importance as this will determine the required regulatory changes. The chosen approach, however, must be carefully selected since it determines who is responsible for operating the microgrid and interconnecting it with the central grid. This in its turn has consequences regarding access to the grid and competition requirements. Utility owned and managed microgrids that serve their consumer base under contract and manage micro or medium DG units are expected to be most attractive in terms of standardisation, organisation and regulation. The Singaporean District Cooling Act can here be put forward as an example of a utility owned energy provision service.

Second, many countries are evolving towards liberalised electricity markets and *competition requirements* are one of the keystones of their energy market policy (Van Hende, 2011). Often, liberalisation of the energy market is coupled with a free choice for all end-consumers regarding their retailer. This has consequences for utility owned microgrids since it could be argued that consumers within this service area have no choice of retailer. Consequently, microgrids may need an exemption from certain competition requirements that characterise liberalised electricity markets.

Third, the analysis in this paper showed that Singapore has, despite its *liberalisation* process, still a strong governmental vision in terms of its energy system. This is combined with a transparent and well-regulated market that encourages (foreign) investment and businesses. The roll out of new technologies such as microgrids and location specific DG technologies can be established readily and efficiently with a clear governmental direction and guidance. Jurisdictions around the globe can learn from this in that they should identify and formulate a clear vision for microgrids and DG units and increase transparency of the regulatory climate governing the energy system to attract investment.

Fourth, to be able to connect a microgrid to the energy infrastructure at large, standards and codes regarding grid connection have to be taken into account. These might not allow generation units to be connected at the distribution level or might disadvantage their connection (Costa et al., 2008; Marnay et al., 2008, 2012). A microgrid connection with the central grid could namely introduce technical issues that need additional investments to ensure safe grid operation especially when looking at islanding as an option for microgrid and DG operation (Alanne & Saari, 2006; Katiraei et al., 2005; Marks et al., 2010; Romankiewicz et al., 2013). Furthermore, regulations regarding islanding have to be evaluated (Romankiewicz et al., 2013). Often, centralised electricity networks and their operators require for any generation unit in the distribution grid to switch off in case of a fault on the higher level in the centra grid (Katiraei et al., 2005). Anti-islanding requirements can therefore form a barrier to microgrid implementation with intentional islanding purposes (Costa et al., 2008; Katiraei et al., 2005; Ropp et al., 2006). Although there are currently no regulations directly prohibiting the connection to the central grid and the islanding of microgrids within Singaporean regulations, Singapore could consider to adopt additional grid codes to ensure the safe operation of the network under bi-directional flow conditions (Katiraei et al., 2005). The potential of jeopardising safe grid operation is namely identified as one of the main barriers for the wide spread introduction of microgrids and DG units within the central grid (Katiraei et al., 2005; Ropp et al., 2006). Countries around the world already have grid connection codes and national standards for decentral generation units that Singapore can take notice of. These connection standards and codes are related to, amongst others, maximum installed capacity of generation units at different voltage levels, power factor and grid protection requirements due to bi-directional electricity flows as well as voltage stability and frequency requirements and islanding procedures to ensure safe grid operation (Ackermann et al., 2001; Katiraei et al., 2005; Pepermans et al., 2005; Ropp et al., 2006). In the United States for example, several states have DG interconnection guides and procedures characterised by the IEEE 1547 standards (Lidula & Rajapakse, 2011). National Grid (2011) for example, gives the procedures for the connection of DG units in the New York area. Within Europe, the United Kingdom has several standardised connection requirements and codes for DG units developed by the Office of Gas and Electricity Markets (Ofgem, 2014), this is, the ER G83/1 standard, and by the Energy Networks Association (Energy Networks Association, 2014), the ER G59/1 standard. Towards the future, the European Commission is setting priorities for the ACER and ENTSO-E to develop network codes that will eventually apply directly across Europe in the same way as EU regulations (SmartGrids European Technology Platform, 2013; Van Hende, 2011; European Standards, 2013).[6]

Fifth, since future energy systems emphasise *renewable energy* as part of the generation mix, they should be looked at in conjunction with microgrids. State specific regulations might include restrictions on installed capacity of renewable energy generation units or other DG units, as well as support policies that promote the implementation of small-scale generation units such as feed-in tariffs or a credit system (Menanteau, Finon, & Lamy, 2003). Having a support scheme in place causes the implementation of microgrids to be economically attractive due to the potential to create an income (Marnay et al., 2008). An additional requirement is an adequate metering system to allow for support schemes to take action, especially in microgrids where the individual participants as well as the microgrid as a whole have to be monitored. Restrictions on consumer data collection and consumer privacy, however, might disadvantage this (Kim & Kinoshita, 2010; Lasseter, 2002).

Even though global lessons can be a useful exercise, at least for operational or policy trends, microgrids are part of the national energy supply, which is mainly regulated at a national level. Hence, a regulatory framework is likely to be established either through private contracts between microgrid participants or through a central utility serving a consumer base under contract. Since microgrids are tailored to specific regional climatic conditions as well as political environment, chosen energy resources and regulations are too and will therefore not necessarily be transferrable amongst countries. Some general lessons can however be drawn:

- A central utility owned and operated residential microgrid might facilitate the regulatory process and standardisation. The District Cooling Act of Singapore can here be put forward as an example.
- National standards and codes for grid connection of DG units and small microgrids are already in place in some countries with liberalised electricity markets A revision of these standards, however, is desirable to ensure microgrid operation.

Further research could compare operational microgrids to assess the geographical and political reasons, enablers and barriers

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[6] ACER, Agency for the Cooperation of Energy Regulators, ENTSO-E, European Network of Transmission System Operators for Electricity. See for instance: European Distribution System Operators for Smart Grids (http://www.edsoforsmartgrids.eu/wp-content/uploads/EDSO-response-to-network-codes-priorities-for-2015-and-beyond.pdf).

to identify optimal conditions for microgrid deployment. Furthermore, the question whether or not it is realistic to set up a microgrid in its purest form instead of focussing on utility owned microgrids should be explored in more detail since the latter might facilitate the regulation, standardisation and unification process.

6. Conclusions

The increasing interest in and recognition of microgrids as key concepts for future energy supply has already initiated extensive engineering and economic research. Regulatory frameworks for microgrids, however, are still in their infancy and will be the next challenge to enable microgrids to globally emerge on a large scale. The appropriateness of the current Singaporean regulatory framework for microgrid operation was analysed as a case study for identified operational and regulatory microgrid challenges. Although it can be argued that Singapore is not yet a leading jurisdiction for technical microgrid development, it was chosen as a case study due to its unique legal framework and liberalisation process as well as its transparent and business friendly regulatory climate.

Analysis of Singaporean energy regulations determined that it already has advanced legislation in place regarding the distribution of locally generated cooling that can serve as a basis for a regulatory framework for residential microgrids in Singapore under the District Cooling Act. Although Singapore has a potential regarding decentral generation, the cost and limitedness of support mechanisms and metering schemes hinders widespread adoption. Moreover, competition and islanding are not prohibited under the Electricity Act and Codes of Practice, which leaves the door open for microgrids if additional standards and grid connection codes are developed to ensure safe operation under bi-directional electricity flow conditions. The main barriers for microgrid operation in Singapore are identified as being (1) support mechanisms and advanced metering schemes for DG units, (2) ownership and internal market models, and (3) codes for safe operation especially in island mode.

Microgrids are part of the national energy supply. Some general lessons can however be made from the Singapore experience. A central utility owned and operated residential microgrid might facilitate the regulatory process and standardisation. The District Cooling Act of Singapore can here be put forward as an example. Microgrids furthermore still need a legally defined identity to standardise and generalise its operational procedures as well as grid connection codes and procedures to ensure safe operation. Here, countries can learn from each other in setting up standards and regulations for microgrids from a technical perspective through the adoption of global best practices.

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