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The Role of Microgrids Within Future Regional Electricity Markets

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Executive Summary

As electricity markets across the globe are being partially or fully liberalized and are opening their markets to competition, electricity trading across those borders has caused a trend for these markets to become regionally integrated. While electricity markets are being regionalized, policy concerns on reliability and security of supply as well as flexibility and sustainability of the electrical grid are increasing. Enter microgrids, which have the ability to operate on- or off-grid and can offer the flexibility that future smart systems require. This paper argues that moving towards more microgrid integration does not necessarily need to be a contradiction to the trend of regionalization, but rather can happen simultaneously and even reinforcing this current trend of liberalization.

Accordingly, this paper describes how microgrids fit into our current energy system and into our future smarter energy system. After having described what microgrids are and what role they play, the two above discussed trends will be described at macro- and micro-level and their intrinsic connection will be discussed. The focus lies on trends in the European Union (EU) and East Asia (including Singapore) and the main argument states that East Asia will likely develop in the same direction as the EU. Namely, several lessons can be drawn from the EU experience:

- Deregulation naturally leads to more competition, which leads to interconnectors between regions that have diverse energy portfolios and, as a result, regional integration. An early example is the Nordic electricity market with the Nord Pool.
- Mature national electricity markets tend to respond quicker to deregulation requirements and hence accelerate regional integration. This is also the case for the Nordic electricity market.

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- Opening up the market to retail competition is not sufficient to achieve interconnection, but rather a full liberalization is motivating the creation of regional electricity markets. This is because without institutional structures and strict rules for unbundling, anti-competitive behaviour continues to exist.
- Within these future regional energy markets, renewable energy and storage will be key components that can be secured by (smart) microgrids, which can function on- or off-grid and can guarantee system security, reliability and sustainability.

After describing a few trends at macro- and micro-level some concrete microgrid examples are researched and divided by whether they occur in partially liberalized electricity markets or fully liberalized electricity markets:

- The microgrids discussed in this paper within *partially liberalized* electricity markets based in East Asia are the Sendai microgrid in Japan, the Xianmen University microgrid in China and the Pulau Ubin microgrid in Singapore.
- The microgrids discussed in this paper within *fully liberalized* electricity markets in the EU are the Kythnos island microgrid in Greece, the Mannheim Wallstadt microgrid in Germany and the Bornholm island multi-microgrid in Denmark.

Several lessons can be drawn from the above analysis:

- In the EU, microgrid development is focussed on highly integrated systems that look at all aspects of micro and smart grid operation. The Bornholm island, which is the microgrid test bed in Denmark, can be taken as a key example of a multi-microgrid integrated into a smart-grid and participating in the central electricity system and market, i.e. an example of a future smart electricity and energy integrated system. The advanced status of this microgrid is ascribed in this paper to the maturity of the electricity market in Scandinavia at an early stage and the swift move towards an interconnected Nord Pool. The Kythnos island is a microgrid that in the future could be part of such an interconnected multi-microgrid in a smart environment. The Mannheim Wallstadt microgrid, then, serves as an example that includes the socio-economic impact of smart grids.
- In East Asia it became obvious that all the microgrid test-beds are developed within a partially liberalized market, where vertical separation is not completely achieved. This setting leads to more directed microgrid demonstration sites that form a concrete example for other areas in the region. The Sendai microgrid, for example attempts to present a structure which supplies several power quality levels and increases flexibility, reliability and security of supply through islanding optionality. The Xianmen University microgrid aims to be an example for smart building management at university sites in the region through microgrid operation, and, lastly the Pulau Ubin microgrid serves as an example for rural sustainable electrification.

It is the recommendation of this research that governments pay more attention to the importance of microgrid connections to the distribution network and the central energy system and market as a whole and allow for the integration of the microgrid concept into the policy and legal framework by focussing on the four identified dimensions/drivers that are crucial for microgrid development and characterization:

- *Market Liberalization*: For microgrids to operate to their fullest extent, the recommendation made is for countries to liberalize their electricity markets fully as this will allow for the needed interconnection capacity and competition for new market entrants necessary to deliver a different electricity portfolio that will allow different sources to penetrate the market, such as wind and solar photovoltaic units, which would ideally work within microgrids.
- *Ownership:* Most current microgrids are still privately owned and operated. For microgrids to operate to their fullest extent and to be interconnected into smart multi-microgrid networks in the long term with participation in the central energy system and market, utility and commercial ownership and operation of the network should be established.
- *Structure*: Microgrid sites should be initially developed as single microgrid configurations with one point of common coupling with the central grid. This should be done in a standardized manner to allow for microgrids and later smart multi-microgrids to operate to their fullest extent. Microgrids can in this way be interconnected and implemented in a ‘plug-and-play’ manner speeding up the interconnection and scalability of the network at the bottom-up level, allowing for a broader customer portfolio where different customer needs and awareness can be accommodated for.
- *Connection*: Microgrids can be used for two main applications. First of all for the sustainable electrification of rural off-grid areas, and, secondly for fully regionally interconnected (smart) electricity networks. The latter will provide a pathway to the highly interconnected regional electricity market with active participation both at the top-down level as well as from the bottom-up level.

I. Introduction

At a macro-level, electricity markets across the globe are being deregulated from centrally controlled national markets to liberalized markets where producers compete within an open market structure. As a result of such competition, electricity trading across borders is becoming increasingly attractive, with the formation of electricity interconnections resulting in the creation of regional electricity markets where surplus energy generated through a variety of energy sources is traded when economically viable to do so.

This trend suggests a move from local or national electricity market regulation towards regional electricity market regulation and ultimately potentially global market regulation, provided interconnection capacity would increase. At the same time, however, a discussion is taking place at the micro level on why microgrids would be inevitable within our future smart energy system. While regional electricity markets bring challenges in terms of interconnection capacity, storage, congestion management and inter-transmission system operator (TSO) mechanisms, microgrids require a different response to those challenges since they have a different technical set-up.

The aim of this paper is to formulate policy drivers for the introduction of microgrids in the future smart electricity system. The approach used, is based on both electrical technical analysis and policy recommendations but does however not consider the impact on the electricity market from an economic perspective. When talking about micro- and macro-structures, the paper is not referring to economic structures but energy system structures, where macro-level stands for the electricity system as a whole including generation, distribution and transmission at a regional level, whereas micro-level stands for microgrids at a smaller scale. Future research could therefore analyse the impact on both the electricity market operation and the pricing in the future market from the policy drivers identified in this paper as the authors acknowledge that supply security is not only defined by guaranteeing a continuous supply but also at an affordable price.

This paper first explains what role microgrids play in our current electricity market and energy system and what role they could have in the future, which exposes the technical characteristics of microgrids. This paper then examines regional electricity markets and verifies the current trend of those markets moving to increased interconnection and regional market regulation. This paper also looks at and discusses concrete examples of microgrids within these regional markets and exposes some technical, market and regulatory features that can be identified from integrating these microgrids within increasing regionalized markets at macro-level. Finally, this paper discusses some lessons learned for the future role of microgrids within regional electricity markets.

II. Microgrids – what are they and how do they fit in?

1. Microgrids and their place in the current energy system

Multiple definitions of microgrids exist in literature, largely depending on time and available technologies.[2] The place of microgrids in the current energy system can be best explained by a brief overview of their evolution throughout history. This is because even though the microgrid is today revived, its concept is not new and dates back to the initial development stage of current electricity grids.

Early electricity grids emerged in the 19th century, which focussed on distributed energy generation. It was Thomas Edison who by 1886 had installed 58 direct current (DC) and about 500 isolated lighting plants in the United States, Chile and Australia.[3] Later in the 19th century, DC-based 'micro'grids were replaced by an alternate current (AC) long-distance interconnected transmission network.[4] Such 'micro'grids mark the start towards a future interconnected regional grid via an AC transmission network. Electric energy is no longer provided by local generation but by central generation plants that were becoming larger in scale and moved away from the cities. At the same time, the industry was faced with a change in regulation from local regulation to state control.

In the 20th century, privately owned, isolated grid networks established by competitive utilities had to give way to a centrally controlled monopoly, where centralized power plants were owned by utilities and a trend towards larger generation facilities began to accelerate. In the 1970s the energy crisis hit and the fossil fuel prices began to rise. Independent power producers emerged, building generation facilities relying on alternative energy such as wind and solar power that were still integrated and developed within the conventional radial distribution network topology.[5] In the 1980s electricity markets across the globe started to move away from the centrally owned monopolies towards liberalizing the electricity markets and re-introducing competition, allowing new producers to penetrate the market.

Within this liberalization, some current trends are starting to create favourable conditions for decentral operation. Two major trends can here be distinguished. First, the current conventional centralized and liberalized energy supply structure is under

[2] See for instance J. ROMANKIEWICZ, M. QU, C. MARNAY, N. ZHOU, 'International Microgrid Assessment: Governance, Incentives and Experience', Ernest Orlando Lawrence Berkeley National Laboratory, March 2013, LBNL-6159E; A. D. HAWKES, M. A. LEACH, 'Modelling high level system design and unit commitment for a microgrid', *Applied Energy,* vol. 86, no 7-8, July-August 2009, 1253-1256.

[3] P. ASMUS, 'Why microgrids are inevitable and why smart utilities should plan accordingly', *Business Energy,* 1 September 2011.

[4] See for their comparison J. J. JUSTO, F. MWASILU, J. LEE, J-W. JUNG, 'AC-microgrids versus DC-microgrids with distributed energy resources: A review', *Renewable and Sustainable Energy Reviews,* vol. 24, August 2013, 387-405.

[5] P. ASMUS, 'Why microgrids are inevitable and why smart utilities should plan accordingly', *Business Energy,* 1 September 2011.

pressure due to inter alia the growing global population coupled with an increasing energy demand and climate issues.[6] Second, full retail contestability of the end-consumers in liberalized markets combined with increasing consumer awareness of energy efficiency and emissions, leads to new multidimensional demands of society that have to be accommodated for.[7] These multidimensional demands refer to inter alia security of supply, energy supply reliability, flexibility of the energy supply and sustainability.[8] The previous trends introduced by the increasing involvement and awareness from participants in the liberalized market therefore form a trigger for a change in philosophy regarding the future energy supply structure. The idea of energy produced close to or at the premises of end-consumers, would help to address these demands and challenges since local generation can optimally make use of locally available (renewable) energy resources and can better balance and control local supply and demand.[9] Here microgrids are often put forward as key components of future energy supply since they combine local demand and local energy generation with local control and communication technologies to inter alia increase energy efficiency and decrease emissions.

It can be argued that the current modern microgrid concept has first been formulated in the United States as a possible solution and prevention of rolling blackouts in response to the 2001 rolling blackouts in California.[10] After these 2001 blackouts, the beliefs in distributed generation units to increase grid and supply reliability as well as local supply control were increasing.[11] The CERTS[12] microgrid concept was first formulated in 1998 as '*a cluster of micro-generators and storage with the ability to separate and isolate itself from the utility seamlessly with little or no disruption to the loads*'.[13] The EU in its turn was the initiator of microgrid development through extensive research and development efforts since 1998, led by the National University of Athens in Greece. The 'More Microgrids' program stipulated the EU initiatives and under the 5th, 6th and 7th framework programs, each time more

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[6] P. MARKS, J.HEIMS, B. FIEBIG, 'Microgrids: Intelligence and Autonomy Tear Down Hurdles for Next-Gen Systems', *ESI Bulletin*, vol. 3, no 1, 2010, 3-5; B. BANERJEE, S.M. ISLAM, 'Reliability Based optimum Location of Distributed Generation', *International Journal of Electrical Power & Energy Systems*, vol. 33, no(8), October 2011, 470-1477; INTERNATIONAL ENERGY AGENCY, 'World Energy Outlook 2012', *IEA/ OECD*, Paris.

[7] S. BLUMSACK, A. FERNANDEZ, 'Ready or not, here comes the smart grid!', *Energy*, vol. 37, no. 1, January 2012, 61-68.

[8] S. BLUMSACK, A. FERNANDEZ, 'Ready or not, here comes the smart grid!', *Energy*, vol. 37, no. 1, January 2012, 61-68; C. MARNAY, N. ZHOU, M. QU, J. ROMANKIEWICZ, 'International Microgrid Assessment: Governance, Incentives and Experience', Ernest Orlando Lawrence Berkeley National Laboratory, June 2012, LBNL-5914E.

[9] S. BLUMSACK, A. FERNANDEZ, 'Ready or not, here comes the smart grid!', *Energy*, vol. 37, no. 1, January 2012, 61-68 C. MARNAY, N. ZHOU, M. QU, J. ROMANKIEWICZ, 'International Microgrid Assessment: Governance, Incentives and Experience', Ernest Orlando Lawrence Berkeley National Laboratory, June 2012, LBNL-5914E;

[10] EPRI, 'Investigation of the Technical and Economic Feasibility of Micro-Grid-Based Power Systems', Palo Alto, CA: 2001. 1003973.

[11] EPRI, 'Investigation of the Technical and Economic Feasibility of Micro-Grid-Based Power Systems', Palo Alto, CA: 2001. 1003973.

[12] CERTS: Consortium for Electric Reliability Technology Solutions

[13] R.H. LASSETER, 'Control of Distributed Resources', *Bulk Power System Dynamics and Control IV - Restructuring*, August 24-28 1998, Santorini, Greece.

detailed and advanced research and microgrid demonstrations have been established in the area of microgrids and smart grids.[14]

A current wider definition of a microgrid is any localized cluster of facilities whose electrical sources, sinks and possibly storage, function simultaneously from the conventional centralized grid, or macrogrid.[15] Such definition implies two common basic requirements. First of all, a microgrid contains both sources and sinks under local control and secondly, a microgrid is able to function in connection with the central grid as well as in electrical island (i.e. islanding).[16] Microgrids balance the thermal and electrical energy supply and demand at a local scale through local control. The local energy supply is provided through small scale generation units which are key components in a microgrid environment. Those distributed generation units can be both dispatchable units and intermittent units depending on the usage of primary energy resource. Distributed generation units are located close to or at the premises of end-consumers in the distribution network and exploit as much as possible the locally available renewable energy resources.[17] Since microgrids are optimised for local implementation, their design is not standardised but tailored to specific locations and local requirements. Their definition is thus solely based on general characteristics.[18]

Microgrids and distributed generation units are typically implemented at the low voltage level in the radial distribution network, which is part of the conventional centralized energy system. Microgrids often have a single point of common coupling with the distribution network and as such present themselves as single entities to the

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[14] C. MARNAY, N. ZHOU, M. QU, J. ROMANKIEWICZ, 'International Microgrid Assessment: Governance, Incentives and Experience', Ernest Orlando Lawrence Berkeley National Laboratory, June 2012, LBNL-5914E; European Union, 'More Microgrids', http://www.microgrids.eu/default.php (last consulted 20 March 2014).

[15] J. ROMANKIEWICZ, M. QU, C. MARNAY, N. ZHOU, 'International Microgrid Assessment: Governance, Incentives and Experience', Ernest Orlando Lawrence Berkeley National Laboratory, March 2013, LBNL-6159E;

[16] J. ROMANKIEWICZ, M. QU, C. MARNAY, N. ZHOU, M. QU, 'Lessons from international experience for China's microgrid demonstration program', *Energy Policy,* vol. 67, 2014, 198-208.

[17] H.H. KWEE, M. QUAH, 'Microgrids: Delivering Energy Services beyond Electricity', *ESI Bulletin*, vol. 3, no 1, 2010, 6-7; G. PEPERMANS, J. DRIESEN, D. HAESELDONCKX, R. BELMANS, W. D'HAESELEER, 'Distributed generation: definition, benefits and issues', *Energy Policy*, vol. 33, no 6, April 2005, 787-798; T. ACKERMANN, G. ANDERSSON, L. SÖDER, 'Distributed generation: a definition', *Electric Power Systems Research*, vol. 57, no 3, April 2001, 195-204; C. MARNAY, H. ASANO, S. PAPATHANASSIOU, G. STRBAC, 'Policymaking for microgrids', *IEEE Power & Energy Magazine*, vol. 6, no 3, May-June 2008, 66-77; C. MARNAY, N. ZHOU, M. QU, J. ROMANKIEWICZ, 'International Microgrid Assessment: Governance, Incentives and Experience', Ernest Orlando Lawrence Berkeley National Laboratory, June 2012, LBNL-5914E.

[18] C. MARNAY, N. ZHOU, M. QU, J. ROMANKIEWICZ, 'International Microgrid Assessment: Governance, Incentives and Experience', Ernest Orlando Lawrence Berkeley National Laboratory, June 2012, LBNL-5914E; P. MARKS, J.HEIMS, B. FIEBIG, 'Microgrids: Intelligence and Autonomy Tear Down Hurdles for Next-Gen Systems', *ESI Bulletin*, vol. 3, no 1, 2010, 3-5; J. ROMANKIEWICZ, M. QU, C. MARNAY, N. ZHOU, 'International Microgrid Assessment: Governance, Incentives and Experience', Ernest Orlando Lawrence Berkeley National Laboratory, March 2013, LBNL-6159E; NEW YORK STATE ENERGY RESEARCH AND DEVELOPMENT AUTHORITY (NYSERDA), 'Microgrids: An Assessment of the Value, Opportunities and Barriers to Deployment in New York State', Final Report 10-35, 2010, NYSERDA 10675.

grid.[19] These decentral units, however, need to take into account challenges of introducing generation at a system level that does not foresee the injection of energy. The central distribution network thus needs to accommodate for effects of bi-directional power flow initiated by decentral generation units in terms of power quality, voltage stability and grid safety and protection.

Our current energy system is still primarily based on a centralized energy generation structure that mainly employs conventional energy resources such as coal and gas as primary energy resources for power generation. Lately, a gradual shift is being made towards the integration of new central energy generation technologies based on unconventional and renewable energy sources, such as nuclear energy and wind respectively. This shift is initiated through regional and global renewable and emission targets such as the Kyoto Protocol. The process of increasing the energy generation process efficiency and decreasing emissions while allowing local balancing and control of supply and demand will pose additional challenges.[20] Here, decentral energy generation and demand will aid to implement these new needs of society. Microgrids will play an important role to accommodate for these needs whilst complementing the conventional centralized energy system in a so-called 'smart' future energy system.

2. *Microgrids and their potential role in the future energy system*

The main difference between today's energy system and our future energy system in essence is that our future energy system will be *smarter.* One future vision is that of achieving the implementation of a so-called 'smart grid' in the transition of the future energy system. A smart grid interconnects central generation plants and multiple microgrids in a totally controlled and communicating network that can participate in the central energy system and market. It can be defined as an energy network that can cost efficiently integrate, balance and control the behaviour and actions of all the users and suppliers connected to it, those would include generators, consumers and so called 'prosumers' (i.e. where end-consumers are also producers) to maintain an economically efficient, sustainable power system with low losses and high levels of quality, security of supply and safety.[21] In essence the latter refers to the grid's capability to handle more complexity than today. Such complexity involves new forms of energy, such as unconventional and renewable energy sources, but also involves other elements. Such elements include innovative products and services designed together with intelligent monitoring, control, communication and self-heating technologies, in order to for instance better facilitate connection and

[19] C. MARNAY, H. ASANO, S. PAPATHANASSIOU, G. STRBAC, 'Policymaking for microgrids', *IEEE Power & Energy Magazine*, vol. 6, no 3, May-June 2008, 66-77.
[20] A. JÄGER-WALDAU, M. SZABÓ, N. SCARLAT, F. MONFORTI-FERRARIO, 'Renewable Electricity in Europe', *Renewable and Sustainable Energy Reviews,* vol. 15, no. 8, October 2011, 3706-3707.
[21] European Commission, *Smart grids: from innovation to deployment,* COM (2011) 202 final, Brussels, 12 April 2011.

operation of generators of all sizes and technologies, have consumers playing a part in optimizing the operation of the system and so forth.[22]

Microgrids fit into this description as key components of and first step towards this future smart grid vision. The reason for this is that microgrids can be adapted and adjusted to what is economically accountable and environmentally desirable to the location and jurisdiction at hand as long as it is implemented in accordance with regulatory guidelines to for instance guaranteed power quality and reliability requirements and fault isolation procedures. There are a few reasons why microgrids would ideally complement the conventional central energy system.

First of all, as explained in the definition of a microgrid (*supra* II.1), a microgrid can potentially isolate itself from the distribution system (i.e. islanding) when a fault occurs in the latter.[23] Often, any generation unit at the distribution level is required to switch off in case of a fault in the centralized grid under grid codes.[24] The benefit of microgrids is that they can, if authorized to do so, continue their local energy generation and supply after a fault in the centralized grid. In the latter case, the microgrid operates autonomously from the central grid after a short ride through period of isolating the fault on the central level, instead of experiencing a power outage due to isolation of a fault in the central grid. A power outage of a radial distribution network branch would in this case namely occur in conventional grid operation. Microgrids can therefore contribute to security of supply of end-consumers and on a more technical level to the increased reliability and flexibility of the energy system.

Second, due to its locally controlled feature, a microgrid can present itself to the macrogrid as a single controlled entity. As a consequence, it can deliver complex macrogrid services such as black start capacity and active and reactive power control while integrating more diverse energy generation units such as renewable energy generators. This aids to increasing not only the security of supply of the energy system as a whole through diversification and increasing sustainability, but also, to increasing flexibility and reliability of the energy system.

Third, microgrids are tailored in design and operation to local requirements and available (renewable) energy resources, whether in a grid-interconnected or in an off-grid implementation. This means that microgrids can be tailored to a specific situation as they are locally controlled and can also guarantee power quality and reliability at such scale. Moreover, microgrids are able to provide various levels of

[22] European Commission, *Smart grids: from innovation to deployment,* COM (2011) 202 final, Brussels, 12 April 2011.

[23] J. ROMANKIEWICZ, M. QU, C. MARNAY, N. ZHOU, 'International Microgrid Assessment: Governance, Incentives and Experience', Ernest Orlando Lawrence Berkeley National Laboratory, March 2013, LBNL-6159E.

[24] See standard IEEE P1547; F. KATIRAEI, M.R. IRAVANI, P.W. LEHN, 'Micro-grid autonomous operation during and subsequent to islanding process', IEEE Transactions on Power Delivery, vol. 20, no 1, 2005, 248-257.

power quality depending on customer needs, therefore increasing reliability and flexibility of the energy system as a whole.

III. Trends of macro- vs. micro-level in regional electricity markets of the European Union and East Asia

1. Macro-level: Market liberalization, interconnection and regionalization

Though traditionally, electricity markets operated at a national centralized level, liberalization of these markets has introduced new market entrants and has made trading across borders increasingly attractive. With the introduction of market-oriented mechanisms, national electricity markets progressively matured and opened their borders to a broader degree of competition.[25] As a consequence, electricity markets are slowly integrating into regional markets across the globe. The effect of liberalization and increased interconnection has not only led to an increased competition, but a new reality of regional electricity markets can produce benefits of its own. To start with, it has been argued that such an integrated electricity market at the regional level can improve efficiency and security of supply, reduce the cost of production and thereby accelerate a decrease in electricity prices.[26] Moreover, due to increased competition, integrated electricity markets at regional level could increase standards and be an effective way to reduce carbon emissions too.[27]

Such arguments have led to various measures being implemented across nations to promote such market integration, though the progress of those measures has varied amongst the major markets across the globe. The large markets include the United States and the EU, though there have been relatively successful examples of small economies such as Chile, New Zealand and Singapore.[28] The countries that will be discussed here are China, Japan and Singapore (though not traditionally part of East Asia, often discussed together as being part of East Asia as a regional economy) for the East Asian region and Greece, Germany and Denmark for the EU.[29] These countries share three commonalities. First of all, they all have well developed

[25] J. A. AGUADO, V. H. QUINTANA, M. MADRIGAL, W. D. ROSEHART, 'Coordinated Spot Market for Congestion Management of Inter-Regional Electricity Markets, *IEEE Transactions on Power Systems,* vol. 19, no. 1, February 2014, 180.

[26] Y. WU, 'Electricity market integration: global trends and implications for the EAS region', in Y. WU, X. SHI and F. KIMURA (eds.), *Energy market integration in East Asia: Theories, electricity sector and subsidies,* ERIA Research Project Report 2011-17, Jakarta, 59-81.

[27] See also Y. ZHAI, 'Energy sector integration for low carbon development in greater Mekong sub-region: towards a model of south-south cooperation', *World Energy Congress*, 9.

[28] Y. WU, 'Electricity market integration: global trends and implications for the EAS region', in Y. WU, X. SHI and F. KIMURA (eds.), *Energy market integration in East Asia: Theories, electricity sector and subsidies,* ERIA Research Project Report 2011-17, Jakarta, 63.

[29] See in relation to the development of Northeast Asia, B. CUMINGS, 'The origin and development of the Northeast Asian political economy: industrial sectors, product cycles and political consequences', http://bev.berkeley.edu/ipe/readings/The%20origins%20and%20development%20of%20the%20Northeast%20Asian%20political%20economy%20-%20industrial%20sectors,%20product%20cycles,%20and%20political%20consequences.pdf (last consultation 31 March 2014).

national electricity markets, which make interconnections with neighbouring nations possible. Secondly, they all have started a liberalization process of their electricity market. The reforms in some EU countries (such as Spain and the Netherlands) and in East Asia (such as Japan) have however not all been classic textbook examples of liberalization, due to the fact that they initially have only been partly liberalized or continued with the basic form of regulated vertically integrated monopolies.[30] Finally, all of them have started up microgrid trials, which will be investigated further (*infra* IV).

i) The EU

In the EU, energy services have traditionally not been open to competition as incumbent companies had exclusive rights to provide certain services. From the late 1980s onwards, the European Commission initiated a liberalization process, whereby the Member States were encouraged to open up their markets and abandon the energy monopolies.[31] In the early reform process, the EU only focussed on opening the market for retail customers by introducing retail competition rather than comprehensive reforms. The EU's internal energy market is designed to allow free movement of services, persons and goods (i.e. including electricity) across EU Member States and to achieve a market with competitive, secure and sustainable energy. It however became apparent that market opening alone would not suffice to achieve retail competition without appropriate wholesale market and network pricing institutions.[32] The European Commission has to this end gradually introduced legislative packages to achieve a liberalized internal energy market with the first liberalization directives for electricity adopted in 1996.[33] The first electricity directive was aimed at removing national monopolies, stimulating cross-border trade by introducing third-party access and protection against discrimination by vertically integrated utilities.[34] The second liberalization package reinforced the liberalization process by forcing Member States to open their markets by imposing regulated third-party access and establishing rules regarding ownership unbundling and national

[30] P. L. JOSKOW, 'Lessons learned from electricity market liberalization', *The Energy Journal,* 2008, special issue, 19.

[31] W. GELDHOF, F. VANDENDRIESSCHE, 'Chapter 1: European Electricity and Gas Market Liberalization. Background, Status, Developments', in B. DELVAUX, M. HUNT, K. TALUS (eds.), *EU energy law and policy issues,* ELRF Collection*,* 1st edition, Rixensart, Euroconfidentiel, 2008, 33.

[32] P. L. JOSKOW, 'Lessons learned from electricity market liberalization', *The Energy Journal,* 2008, special issue, 20.

[33] The last package was the Third Energy Package of the European Commission, including gas and electricity proposals introducing several measures to increase competition within the EU, http://ec.europa.eu/energy/gas_electricity/legislation/third_legislative_package_en.htm (last consultation 4 March 2014).

[34] Directive 96/92/EC of the European Parliament and of the Council of 19 December 1996 concerning common rules for the internal market in electricity, *OJ* 30 January 1997, L27/20; K. VAN HENDE, 'Internal and external policy and legal challenges in the EU in achieving a sustainable, competitive, and secure internal energy market and the integration of electricity from renewable energy sources into the energy system', *Nordic Environmental Law Journal,* vol. 2, 2011, 65.

regulatory bodies.[35] This however still proved insufficient in several Member States to achieve a fully competitive internal electricity market. Denmark, Germany and Greece for instance all struggled to achieve fully competitive markets even though they had started implementing the requirements of both packages.

The Nordic market started in 1991 with Norway, Sweden, Finland and Denmark. The wholesale market is integrated into the Nordic power exchange (i.e. the Nord Pool).[36] Despite Denmark's late start of deregulation compared to its Nordic neighbours, the Jutland and Fyn region have seen major restructuration in supply and production in anticipation of the formal liberalization agenda.[37] The liberalization of the Danish electricity market commenced in the late 1990s and has since been open to competition, although it remained highly concentrated as the market was dominated by a single state-owned entity and the TSO remained under ownership of the Danish state, while the supply and distribution companies had been legally unbundled.[38]

The electricity market in Germany was fully liberalized in 1998 by the Energy Industry Act, prior to which a defined supply area was typically served by a single supplier.[39] Even though several market players were present in Germany's electricity market, it was still not considered competitive due to a high degree of vertical and horizontal integration and domination of a few companies.[40] Most of the electricity network operators were however unbundled by 2007.

Greece has been making slow progress in its efforts to liberalize the electricity market and has only been liberalizing its electricity market since 1999. The degree of competition is low due to a dominance of the incumbent Greek utility.[41] The Greek TSO is, however, legally unbundled from the incumbent. Part of the problem is that the Greek state has a dual reform agenda as it tries to liberalize the market whilst

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[35] Directive 2003/54/EC of the European Parliament and of the Council of 26 June 2003 concerning common rules for the internal market in electricity and repealing Directive 96/92/EC, *OJ* 15 July 2003, L176/37; Regulation (EC) No 1228/2003 of the European Parliament and of the Council of 26 June 2003 on conditions for access to the network of cross-border exchanges in electricity, *OJ* 15 July 2003, L176/1; U. SCHOLZ AND S. PURPS, 'The application of EC Competition Law in the Energy Sector', *Journal of European Competition Law & Practice,* , vol. 1, no. 1, 2010, 37-38.

[36] IEA and OECD, *Lessons from liberalized electricity markets,* 2005, http://www.iea.org/publications/freepublications/publication/LessonsNet.pdf (last consulation 28 March 2013).

[37] J. M. GLACHANT, D. FINON, *Competition in European electricity markets: a cross-country comparison,* London, Edward Elgar, 2003, 157.

[38] European Commission, *Denmark internal market factsheet,* http://ec.europa.eu/energy/energy_policy/doc/factsheets/market/market_dk_en.pdf (last consultation 28 March 2014).

[39] Germany Trade and Invest, *Germany's energy concept,* www.gtai.de (last consulation 28 March 2014).

[40] European Commission, *Germany internal market factsheet,* http://ec.europa.eu/energy/energy_policy/doc/factsheets/market/market_de_en.pdf (last consultation 29 March 2014).

[41] European Commission, *Greece Internal Market Factsheet*, http://ec.europa.eu/energy/energy_policy/doc/factsheets/market/market_el_en.pdf (last consultation 29 March 2014).

retaining ownership of the previous monopoly provider.[42] However, competition is expected to increase through the integration of the Greek market into the regional South East Europe market.[43]

The implementation of the third package into these Member States is expected to accelerate their final reform processes as not only more strict measures have been introduced for unbundling, but also new institutional structures have been introduced by the Agency for the Cooperation of Energy Regulators (ACER) and the European Network for Transmission System Operators for Electricity (ENTSO-E) looking over the shoulders of the national regulatory authorities and TSOs. With the third liberalization package, the EU aims to prevent discriminatory access to networks and stimulate investment in energy infrastructure.[44] It includes rules on effective unbundling of electricity networks and offers TSOs a choice between three models for effective unbundling whereby a system of independent system operators and transmission entities is introduced.[45]

ii) East Asia

Within Asia, prior to electricity reform from approximately 1950 until 1990, the electricity provision in the Asian developing countries was an activity dominated by the state.[46] Since then however, especially East Asia has remarkably grown its economy with a dramatically increasing energy and electricity consumption as a consequence of its industrialization. While traditionally not classified under East Asia, Singapore is often discussed together with East Asian countries due to its classification as a newly industrialized economy, such as Hong Kong, South Korea and Taiwan and is part of the East Asia Summit. This is important as the energy market integration initiatives are supported by East Asian Summit member countries.[47]

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[42] N. DANIAS, J. K. SWALES, P. MCGREGOR, 'The Greek electricity market reforms: political and regulatory considerations', *Energy Policy,* vol. 62, November 2013, 1040-1047.

[43] European Commission, *Greece Internal Market Factsheet*, http://ec.europa.eu/energy/energy_policy/doc/factsheets/market/market_el_en.pdf (last consultation 29 March 2014).

[44] Directive 2009/72/EC of the European Parliament and of the Council of 13 July 2009 concerning common rules for the internal market in electricity and repealing Directive 2003/54/EC, *OJ* 14 August 2009, L 211/55; Regulation (EC) No 713/2009 of 13 July 2009 establishing an Agency for the Cooperation of Energy Regulators, *OJ* 14 August 2009, L 211/1; Regulation (EC) No 714/2009 of the European Parliament and of the Council of 13 July 2009 on conditions for access to the network for cross-border exchanges in electricity and repealing Regulation (EC) No 1228/2003, *OJ* 14 August 2009, L 211/15.

[45] K. VAN HENDE, 'Internal and external policy and legal challenges in the EU in achieving a sustainable, competitive, and secure internal energy market and the integration of electricity from renewable energy sources into the energy system', *Nordic Environmental Law Journal,* vol. 2, 2011, 66; P. L. JOSKOW, 'Lessons learned from electricity market liberalization', *The Energy Journal,* 2008, special issue, 19.

[46] J. H. WILLIAMS, N. K. DUBASH, 'Asian electricity reform in historical perspective', *Pacific Affairs,* vol. 77, no. 3, fall 2004, 411-436.

[47] Y. WU, X. SHI, 'The electricity sector leads energy market integration in East Asia: introduction', chapter 1 in *Energy market integration in East Asia: theories, electricity sector and subsidies,* ERIA Research Project Report 2011-17, Jakarta, 1-10.

Singapore is a state country with a thriving economy.[48] International investment is key to its growing economic standard. Singapore is, due to its lack of locally available energy resources, highly dependent on imported fossil fuels for its growing energy demand. To facilitate this growth in economy and energy demand, competitively priced energy is of major importance to attract foreign investment. Driven by an entrepreneurial industry, which aims for efficient and competitively priced electricity, Singapore has thus since 1995 been opening up its power system activities to facilitate liberalization and consequently privatization.[49] Singapore started its liberalization process with a first phase of reform in 1995 with the privatization of the electricity arm of the previously government owned Public Utilities Board. A second phase of reform established the Singapore Electricity Pool. Singapore has currently moved to a partially unbundled and liberalized electricity market without full retail contestability, which facilitates energy supply without competition.[50] The need for energy diversification and sustainability drive the developments in clean and efficient energy generation in Singapore.[51] Although, Singapore has unfavourable climatic conditions and as such cannot rely on most renewable energy technologies, solar photovoltaic units are gaining increasing interest as well as high energy efficient technologies such as distributed generation units mainly under the form of embedded generation units and district cooling systems. Singapore formulated its green strategies and initiatives for the next two decades in the Sustainable Singapore Blueprint published by the Inter-Ministerial Committee on Sustainable Development.[52] The development of intermittent sources of energy combined with widespread distributed generation units has currently led to the Singapore Initiative on New Energy Technologies (SINERGY) Centre, which has, amongst others, the task of developing microgrid test-beds in Singapore.[53]

China continues to have a growing economy with an increasing energy consumption. It however starts to recognize resource depletion and has embarked upon replacing a portion of its coal, gas and oil consumption with alternative energy sources such as solar photovoltaics, wind, solar thermal, wave movement, geothermal and biofuels

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[48] L. H. Koh, Y. K. Than, P. Wang, K. J. Tseng, 'Renewable energy integration into smart grids: problems and solutions-Singapore experience', *IEEE Power and Energy Society General Meeting - California*, 2012. *PESGM'12*, vol., no., 22-26 July 2012, 1–7.

[49] L. H. Koh, Y. K. Than, P. Wang, K. J. Tseng, 'Renewable energy integration into smart grids: problems and solutions-Singapore experience', *IEEE Power and Energy Society General Meeting - California*, 2012. *PESGM'12*, vol., no., 22-26 July 2012, 1–7.

[50] Energy Market Authority, (2009) 'Introduction to the National Electricity Market of Singapore', http://www.ema.gov.sg/media/files/books/intro_to_nems/Introduction%20to%20the%20NEMS_Jul%2009.pdf (last consulted 15 September 2013); Y. Chang, T.H. Tay, 'Efficiency and deregulation of the electricity market in Singapore', *Energy Policy*, vol. 34, no 16, November 2006, 2498-2508.

[51] C. Yeo, C. K. Hin, 'Energy Efficiency in Singapore's Industrial Sector', *ESI Bulletin*, vol. 3, no 1, June 2010, 2-3.

[52] Inter-Ministerial Committee on sustainable development, 'About the Sustainable Blueprint', http://app.mewr.gov.sg/web/contents/ContentsSSS2.aspx?ContId=1293 (last consulted 5 September 2013).

[53] Ministry of Trade and Industry Singapore, 'National Energy Policy Report - Energy for Growth', http://www.mti.gov.sg/ResearchRoom/Pages/National%20Energy%20Policy%20Report.aspx (last consulted 11 November 2013).

from non-food plants.[54] The Chinese electricity reforms have evolved since the 1990s into a dual system, with dominant state planning at the core while having a decentralized generation system at the periphery.[55] The first stage of Chinese electricity reforms took place from 1986 until 1996 and involved the raise of capital investment to keep up with the growth pace of the energy demand in the country.[56] This led to increased foreign investment and the breaking down of the monopoly energy supply structure in 1995. The second stage, from 1997 until 2001, led to market-oriented reformation with the structural (legal) separation of the electricity supply system. Since 2001 up until today, China is in its third reformation stage and is going through the process of introducing competition in all supply activities. Today, the electricity market in China remains partially liberalized with prevailing market access barriers for generation. Only a limited segment of the energy system is opened up fully to competition.

Japan segmented its electricity market since 1971 into ten regions where each region's electricity company sold its electricity exclusively under a regional monopoly structure.[57] Although Japan's economy has since the 1990's undergone a recession, the government adopted several macroeconomic policies to stimulate its economy and promote deregulation and restructuring policies.[58] Its energy system reform was part of a response on the inefficacy concerns related with this monopoly market structure.[59] This market structure was inefficient because, before the reforms of the Electricity Utility Industry Law in 1995, no company could enter the electricity generation market. The partial liberalization reform in 1995 introduced a competitive bidding system for generators in a wholesale market. Since then, a gradual liberalization process has been followed for the other sectors of the electricity supply system.[60] At the retail side, the partial liberalization boundary was extended to lower maximum power demands. The Japanese liberalization process aims to increase competition and transparency of the electricity market while maintaining vertical integration of the supply activities, i.e., generation, transmission and distribution, for reasons of security of supply.[61] Even though the partial liberalization process of the

[54] S. B. Cáceres, S. Ear, *The hungry dragon. How China's resource quest is reshaping the world,* New York, Routledge, 2013, 3.
[55] J. A. Cherni, J. Kentish, 'Renewable energy policy and electricity market reforms in China', *Energy Policy,* vol. 35, no. 7, July 2007, 3616-3629.
[56] H.W. Ngan, 'Electricity regulation and electricity market reforms in China', *Energy Policy*, Vol. 38, no 5, May 2010, 2142-2148.
[57] A. Sterlacchini, 'Energy R&D in private and state-owned utilities: An analysis of the major world electric companies', *Energy Policy*, Vol. 41, February 2012, Pages 494-506.
[58] M. Kanagawa, T. Nakata, 'Analysis of the impact of electricity grid interconnection between Korea and Japan – Feasibility study for energy network in Northeast Asia', *Energy Policy,* vol. 34, no. 9, June 2006, 1015-1025.
[59] M. Nakano, S. Managi, 'Regulatory reforms and productivity: An empirical analysis of the Japanese electricity industry', *Energy Policy*, Vol. 36, no 1, January 2008, 201-209.
[60] A. Sterlacchini, 'Energy R&D in private and state-owned utilities: An analysis of the major world electric companies', *Energy Policy*, Vol. 41, February 2012, Pages 494-506.
[61] A. Sterlacchini, 'Energy R&D in private and state-owned utilities: An analysis of the major world electric companies', *Energy Policy*, Vol. 41, February 2012, Pages 494-506.

retail market has taken effect since March 2000, the process is considerably slow.[62] As Japan experienced a shutdown of nuclear plants in 2003 and 2004, old thermal power plants were restarted to compensate for the deficit, however in the current process of liberalization it is foreseen that Japan will benefit from renewables such as wind, photovoltaic and biomass.[63]

iii) East Asia in the footsteps of the EU reform agenda

Following its deregulation, the EU has developed interconnected electricity grids. The Nord Pool especially, established in Northern Europe, was established successfully because the electricity sectors were liberalized enough in addition to differences to their power supply.[64] Such creation of interconnectors in a competitive market naturally seems to lead towards the creation of regional electricity markets, where previously centrally controlled national electricity markets trade electricity across regional borders depending on price and availability of resources, increasingly so with the implementation of renewable energies. For instance in the EU, interconnections between North and South started to emerge due to an abundance of wind in the North, which cannot be stored, and an abundance of sun in the South.

Hence, one could argue that regionalization has been a direct effect of liberalizing the market structure, which has allowed for new trading structures, where regions provide for optimal trading conditions due to differences in their energy portfolio. It has been argued that for a similar implementation of interconnectors in East Asia, the electricity sectors need to be fully deregulated.[65] The authors argue that on this basis a regionalization of the electricity markets in East Asia is on its way that may not follow the traditional Northeast Asia – Southeast Asia division, but rather where electricity markets are mature enough and the energy portfolio is diverse enough to sustain the cross-border exchanges, as was the case for the Nordic electricity market.

2. Micro-level: A trend of smart grids and microgrids at local level

While the current trend of regionalization seems to suggest that local/national electricity markets are expanding to a larger regional scale and, if interconnection capacity were to increase perhaps even a global scale, the place of microgrids, which operate at a local level, seems somehow self-contradictory to the trend the

[62] M. KANAGAWA, T. NAKATA, 'Analysis of the impact of electricity grid interconnection between Korea and Japan – Feasibility study for energy network in Northeast Asia', *Energy Policy,* vol. 34, no. 9, June 2006, 1015-1025.
[63] M. KANAGAWA, T. NAKATA, 'Analysis of the impact of electricity grid interconnection between Korea and Japan – Feasibility study for energy network in Northeast Asia', *Energy Policy,* vol. 34, no. 9, June 2006, 1015-1025.
[64] M. KANAGAWA, T. NAKATA, 'Analysis of the impact of electricity grid interconnection between Korea and Japan – Feasibility study for energy network in Northeast Asia', *Energy Policy,* vol. 34, no. 9, June 2006, 1015-1025.
[65] M. KANAGAWA, T. NAKATA, 'Analysis of the impact of electricity grid interconnection between Korea and Japan – Feasibility study for energy network in Northeast Asia', *Energy Policy,* vol. 34, no. 9, June 2006, 1015-1025.

authors are trying to describe. While the changes of the electricity market architecture in the past have generally related to wholesale markets, currently, the new advancing technologies are expected to change distribution network characteristics to the integration of a smart distribution level in electricity markets.[66] Distributed energy resources have become a focus of considerable inquiry around the globe and to capture the full potential of distributed energy resources, the modern architecture of the microgrid has been developed using distributed generation units with cogeneration and the optimal use of waste heat from local power generation to provide electrical energy as well as heating and cooling to multiple customers connected in a local network.[67] Indeed, this trend has caused that top-down power flows from the centralized generation plants connected to the transmission and distribution networks to consumers are being challenged by local distributed generation units, bottom-up power flows from the distribution network and local means of energy trading.[68]

The question if microgrids were to fit into the wider macro regional energy market cannot be answered without determining first where they would fit in as a player. The participation of all the grid actors needs to be guaranteed and determined in the future energy system. Hence, the microgrid needs to have a defined space within this future energy system. The grid actors in the future system on a regional scale are the following:

- Network operators, who are typically transmission and distribution system operators
- Grid users, who are generators, consumers, 'prosumers' and storage owners
- Other actors such as suppliers, metering operators, aggregators, etc

On a regional scale, distribution system operators (DSOs) can combine several roles, which could include network operators and metering operators. Also, the structures of the network operators differ according to the regional market at hand. If consumers would be allowed to participate, it would not only open a new revenue stream for them, selling electricity back to the main grid, but also potentially aid the wholesale electricity market balancing with the bottom-up service of ancillary services. That means within liberalized regional electricity markets, the network needs to enable the integration of users with new requirements, such as the integration of distributed energy resources including large and small-scale intermittent renewable generation, heat pumps and storage.

[66] I. PÉREZ-ARRIAGA, S. RUESTER, S. SCHWENEN, C. BATLLE, J.-M. GLACHANT, *From distribution networks to smart distribution systems: rethinking the regulation of European DSOs,* Draft report, THINK topic 12, 29 April 2013.

[67] D. E. KING, 'The regulatory environment for interconnected electric power micro-grids: insights from state regulatory officials', *Carnegie Mellon Electricity Industry Working Paper,* CEIC-05-08, www.cmu.edu/electricity (last consultation 12 March 2014).

[68] I. PÉREZ-ARRIAGA, S. RUESTER, S. SCHWENEN, C. BATLLE, J.-M. GLACHANT, *From distribution networks to smart distribution systems: rethinking the regulation of European DSOs,* Draft report, THINK topic 12, 29 April 2013.

At a distribution level there are two potential pathways for microgrids to develop. Microgrids can come in an isolated form, aiding to rural electrification, or in a grid-connected configuration in urban areas, evolving towards a future smart and highly interconnected grid. Microgrids are currently mostly established as off-grid systems, as part of the electrification of rural towns in developing countries, as high reliability systems or as trial and demonstration systems.[69] Grid-tied commercial microgrids with the option for islanding with seamless transition still experience challenges regarding protection systems, fault ride-through, reconnection as well as electricity regulations.[70]

In 2012, the global microgrid capacity was estimated to approximately 3200 MW.[71] Here, North America leads the way in microgrid research and test trials, having approximately 65% of the global capacity. The EU and East Asia are starting to catch up and selected established microgrid in these regions are subsequently discussed (*infra* IV). Microgrids are currently not often commercial yet since the cost of a microgrid is only justified in economic and regulatory environments with high utility energy prices, favourable climatic conditions, remoteness and support schemes. A major challenge for commercial microgrids, however, is the lack of standardization and regulation regarding both the interactions between the microgrid participants and the interactions of the microgrid with the central energy system.[72] To allow the widespread integration of microgrids in the central distribution network, technical standardization as well as a regulatory framework for microgrids needs to be developed to allow scalability of a microgrid network through a ‘plug-and-play’ approach. 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 standard to play a key role for microgrid interconnection standardization with intended islanding purposes.[73]

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[69] C. Marnay, N. Zhou, M. Qu, J. Romankiewicz, ‘International Microgrid Assessment: Governance, Incentives and Experience’, Ernest Orlando Lawrence Berkeley National Laboratory, June 2012, LBNL-5914E; M. Wolsink, ‘The research agenda on social acceptance of distributed generation in smart grids: Renewable as common pool resources’, *Renewable and Sustainable Energy Reviews*, vol. 16, no 1, January 2012, 822-835; Navigant Research, ‘Microgrid Deployment Tracker 4Q12’, http://www.navigantresearch.com. (last consulted 23 February 2014); N.W.A. Lidula, A.D. Rajapakse, ‘Microgrids research: A review of experimental microgrids and test systems’, *Renewable and Sustainable. Energy Reviews*, vol. 15, no 1, January 2011, 186-202.

[70] M. Wolsink, ‘The research agenda on social acceptance of distributed generation in smart grids: Renewable as common pool resources’, *Renewable and Sustainable Energy Reviews*, vol. 16, no 1, January 2012, 822-835.

[71] Navigant Research, ‘Microgrid Deployment Tracker 4Q12’, http://www.navigantresearch.com. (last consulted 23 February 2014).

[72] T. Ackermann, G. Andersson, L. Söder, ‘Distributed generation: a definition’, *Electric Power Systems Research*, vol. 57, no 3, April 2001, 195-204; M.F. Akorede, H. Hizam, E. Pouresmaeil,‘Distributed energy resources and benefits to the environment’, Renewable and Sustainable Energy Reviews, vol. 14, no 2, February 2010, 724-734.

[73] N.W.A. Lidula, A.D. Rajapakse, ‘Microgrids research: A review of experimental microgrids and test systems’, *Renewable and Sustainable. Energy Reviews*, vol. 15, no 1, January 2011, 186-202.

Microgrids can be characterized through several dimensions/drivers as displayed in Figure 1:

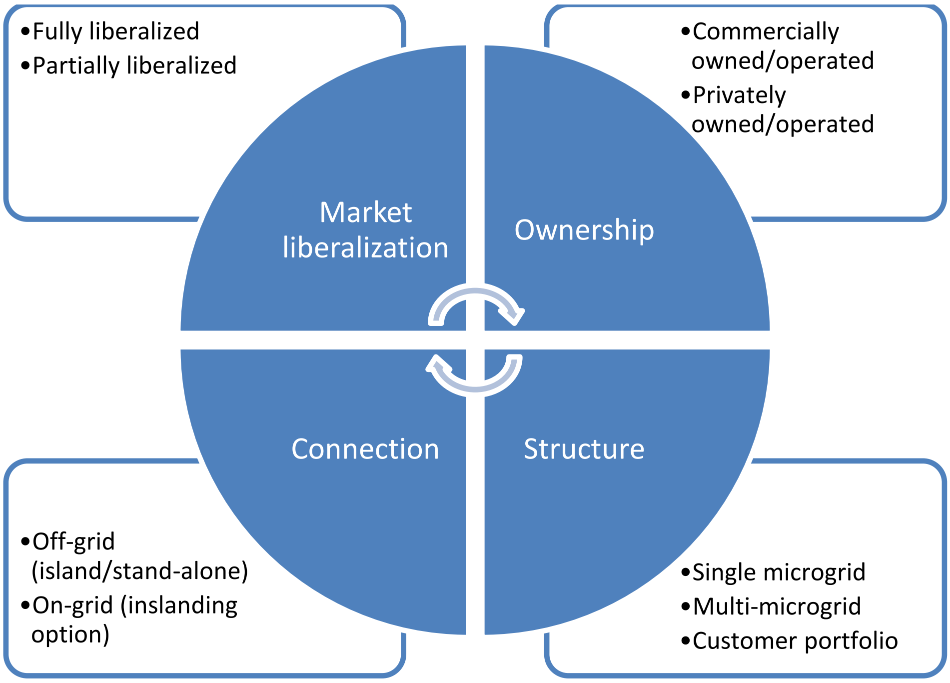

Figure 1: Microgrid configurations

- The first dimension is based on the *market structure* of the jurisdiction at hand where the microgrid is implemented. This can be a fully liberalized electricity market, which is the case for the EU, or can be a partially liberalized market, which is the case in the selected East Asian countries in this study.
- The second dimension can be formulated regarding *ownership*, i.e. whether the microgrid is commercially or privately owned and operated. The former refers to a microgrid that is (partially) owned and operated by a distribution retailer or DSO and has customers that receive their energy through a commercial agreement with the retailer/DSO. The latter refers to a microgrid, which is installed through governmental or private funding and is not a commercial site but rather a site for trial, demonstration or high reliability sites.
- The third dimension can be formulated regarding the *connection* of the installed microgrid with the distribution network. Either the microgrid is installed in an off-grid configuration, i.e. an island or stand-alone network, or the microgrid is installed with an active connection with the distribution network through which electric energy can be exchanged. The latter microgrid can also potentially have islanding options.
- The fourth dimension is based on the *structure* of the microgrid. This can be a microgrid that appears to behave as a single utility or a microgrid that consists out of several connected single microgrids, a so called ‘multi-microgrid’. Regarding the structure also a differentiation can be made regarding the customer portfolio: purely residential, commercial or industrial or a combination of either.

IV. Discussion of concrete microgrid examples in Europe and Asia

In Europe, the 'More Microgrids project' kicked off the development of microgrid trials and research in the EU with the initiation of the Kythnos island microgrid in Greece as well as the test microgrid at the National University of Athens, Greece around 2003 as part of the FP6 project.[74] This was followed by the Mannheim Wallstadt microgrid in Germany and the multi-microgrid installed on Bornholm island in Denmark mid 2000s initiating the FP7 project of 'More Microgrids'. Due to the last liberalization package, the electricity system in the EU places strong emphasis on increasing interconnection capacity and cross-border exchanges of electricity.

In the East Asian region, Japan started its NEDO (New Energy and Industrial Technology development Organisation) projects in 2003 developing grid-interconnected virtual and physical microgrids, both private and commercial.[75] China has followed Japan in starting up its microgrid research and trials around 2010 with mostly university test beds like in Hangzou University. Singapore started its microgrid projects only from 2010 onwards, supported by the Energy Market Authority as well as by both the Singapore Initiative on New Energy Technologies (SINERGY) Centre as well as the Singapore Agency for Science, Technology, and Research (A*STAR).[76]

The microgrids researched in this paper try to combine factors of each possible dimension or driver, given in Figure 1 (*infra* III), and analyze their specific regulatory characteristics. From a regulatory point of view, grid connected and commercial microgrids are most interesting since they require a framework for their 'internal market' as well as a framework for the grid connection. Based on the differentiation of the microgrid dimensions proposed in Figure 1, the microgrids addressed in this study are characterized below. The first subdivision between established microgrids is made based on the status of the market liberalization in the jurisdiction at hand. In

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[74] J. ROMANKIEWICZ, M. QU, C. MARNAY, N. ZHOU, 'International Microgrid Assessment: Governance, Incentives and Experience', Ernest Orlando Lawrence Berkeley National Laboratory, March 2013, LBNL-6159E.

[75] J. ROMANKIEWICZ, M. QU, C. MARNAY, N. ZHOU, 'International Microgrid Assessment: Governance, Incentives and Experience', Ernest Orlando Lawrence Berkeley National Laboratory, March 2013, LBNL-6159E; N.W.A. LIDULA, A.D. RAJAPAKSE, 'Microgrids research: A review of experimental microgrids and test systems', *Renewable and Sustainable. Energy Reviews*, vol. 15, no 1, January 2011, 186-202; S. MOROZUMI, 'Micro-grid Demonstration Projects in Japan', *Power Conversion Conference - Nagoya, 2007. PCC '07*, vol., no., 2-5 April 2007, 635-642.

[76] INTER-MINISTERIAL COMMITTEE ON SUSTAINABLE DEVELOPMENT, 'About the Sustainable Blueprint', http://app.mewr.gov.sg/web/contents/ContentsSSS2.aspx?ContId=1293 (last consulted 5 September 2013); A*STAR INSTITUTE OF CHEMICAL AND ENGINEERING SCIENCE, 'A*STAR's Experimental Power Grid Centre to spur R&D collaborations for future energy and smart grid solutions', http://www.ices.a-star.edu.sg/press-releases/astarstar%27s-experimental-power-grid-centre-to-spur-rd-collaborations-for-future-energy-and-smart-grid-solutions.aspx (last consulted 3 September 2013); Y. FAN, V. RIMALI, M. TANG, C. NAYAR, 'Design and implementation of Stand-alone Smart Grid Employing Renewable Energy Resources on Pulau Ubin Island of Singapore', *IEEE Asia-Pacific Symposium on Electromagnetic Compatibility - Singapore*, 2012. *APEMC'12*, vol., no., 21-24 May 2012, 441 – 444.

the EU, according to the Third Package, the electricity markets are assumed to be fully liberalized and unbundled. The addressed Asian countries are all in the process of liberalization and are therefore categorized under partially liberalized electricity market structures.

1. Fully liberalized electricity markets

The **Kythnos island microgrid in Greece** is an autonomous, stand-alone, off-grid microgrid located on the Kythnos island, part of the Cyclade islands in the Aegean Sea in Greece that has approximately 2000 inhabitants and experiences significant summer tourism energy consumption.[77] Table 1 summarizes the characteristics of this microgrid. The Kythnos Island Microgrid Project was funded by the 'More Microgrids' program of the EU (FP 5) in which the main goal was to test centralized and decentralized control strategies for islanding.[78]

Kythnos island, Greece	
Connection	Off-grid, stand-alone
Structure	Single microgrid Residential holiday customers (peak 12kVA)
Ownership	Privately ('More Microgrids')/Commercial (Public Power Corporation)
Technologies	Photovoltaic Battery storage Diesel generation set

Table 1: Kythnos island microgrid characteristics

The microgrid installed on Kythnos island as well as the specifications for the connections of the generation units and the households are in accordance with the specifications of the Public Power Corporation which governs the rest of the Kythnos island grid as well as the microgrid.[79] The rest of the Kythnos island is already advanced regarding renewable energy generation, storage and local control in a self-sufficient energy system.[80] Here, medium scale energy generating plants serve as central generation units on the island; a diesel power station, a wind park, a

[77] SMA, 'Kythnos Island', http://der.lbl.gov/sites/der.lbl.gov/files/SMA_Kythnos.pdf (last consulted 30 March 2014); N.HATZIARGYRIOU, H. ASANO, R IRAVANI, C. MARNAY, 'Microgrids: An Overview of Ongoing Research, Development, and Demonstration Projects', *IEEE Power and Energy Magazine*, vol., no., July/August 2007, 78-94.

[78] C. MARNAY, N. ZHOU, M. QU, J. ROMANKIEWICZ, 'International Microgrid Assessment: Governance, Incentives and Experience', Ernest Orlando Lawrence Berkeley National Laboratory, June 2012, LBNL-5914E; MORE MICROGRIDS, 'F2. Kythnos Microgrid', http://www.microgrids.eu/index.php?page=kythnos&id=2 (last consulted 30 March 2014).

[79] MORE MICROGRIDS, 'F2. Kythnos Microgrid', http://www.microgrids.eu/index.php?page=kythnos&id=2 (last consulted 30 March 2014).

[80] SMA, 'Kythnos Island', http://der.lbl.gov/sites/der.lbl.gov/files/SMA_Kythnos.pdf (last consulted 30 March 2014).

photovoltaic power plant combined with battery inverter systems. Kythnos has a large discrepancy between winter (300kW) and summer peak (2000kW) due to tourism.[81] With medium scale central generating plants on the island as well as load controllers and smart storage, this intermittency of the natural resources can be balanced and the demand on the island can be met. In the future, the Kythnos island microgrid will be connected to the grid that already connects other microgrids as well as medium central generating plants on the island. This will lead to a multi-microgrid in a smart grid configuration where renewable energy generation and storage holds a central role. Here the Bornholm island microgrid can act as an example (*infra* table 3).

The **Mannheim Wallstadt microgrid in Germany** is likewise the Kythnos island microgrid funded by the 'More Microgrids project' of the EU (FP 6) but here together with private investors as a long-term field test site.[82] The project is located in an ecological estate with about 1200 inhabitants and operated by MVV Energy in a medium voltage microgrid.[83] The system will comprise of generation units, storage units and load management for the customer site. The grid is set up with an interconnection with the central distribution grid as well as with future islanding options. Currently this project finished its first experimental goal. The initial objective was to prepare a suitable grid segment to function as a microgrid.[84] The first experimental goal was to experimentally show effective communication with loads and generators in a 'smart system'. This involved the engagement of the inhabitants with load management of the energy supply while installing photovoltaic systems and a combined heat and power unit in addition to central grid electricity supply. Also the islanding options with seamless transition of parts of the microgrid are already examined as the second goal of the experimental set up.[85] The third experimental goal was to test an agent model for internal 'market operation', i.e. the functionalities and negotiation abilities of several agents.[86] Table 2 summarizes the characteristics of this project.

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[81] SMA, 'Kythnos Island', http://der.lbl.gov/sites/der.lbl.gov/files/SMA_Kythnos.pdf (last consulted 30 March 2014).

[82] C. Marnay, N. Zhou, M. Qu, J. Romankiewicz, 'International Microgrid Assessment: Governance, Incentives and Experience', Ernest Orlando Lawrence Berkeley National Laboratory, June 2012, LBNL-5914E; H. Asano, R Iravani, C. Marnay, 'Microgrids: An Overview of Ongoing Research, Development, and Demonstration Projects', *IEEE Power and Energy Magazine*, vol., no., July/August 2007, 78-94.

[83] C. Marnay, N. Zhou, M. Qu, J. Romankiewicz, 'International Microgrid Assessment: Governance, Incentives and Experience', Ernest Orlando Lawrence Berkeley National Laboratory, June 2012, LBNL-5914E; N.Hatziargyriou, H. Asano, R Iravani, C. Marnay, 'Microgrids: An Overview of Ongoing Research, Development, and Demonstration Projects', *IEEE Power and Energy Magazine*, vol., no., July/August 2007, 78-94.

[84] More Microgrids, 'Advanced Architectures and Control Concepts for MORE MICROGRIDS (2009),' http://www.microgrids.eu/documents/661.pdf (last consulted 30 March 2014).

[85] More Microgrids, 'Advanced Architectures and Control Concepts for MORE MICROGRIDS (2009),' http://www.microgrids.eu/documents/661.pdf (last consulted 30 March 2014).

[86] More Microgrids, 'Advanced Architectures and Control Concepts for MORE MICROGRIDS (2009),' http://www.microgrids.eu/documents/661.pdf (last consulted 30 March 2014).

Mannheim Wallstadt, Germany	
Connection	Grid-connected, islanding options
Structure	Single microgrid Commercial and residential customers (peak ±80-230kW)
Ownership	Privately owned and operated generation park Commercially owned and operated LV distribution network ring (MVV Energy)
Technologies	Photovoltaic installations Combined Heat and Power Unit Flywheel storage

Table 2: Mannheim Wallstadt microgrid characteristics

Mannheim Wallstadt thus will not only serve as a technical microgrid test site but will also evaluate the socio-economic impact and influence under the form of customer awareness and engagement.[87] Since the microgrid is operated by a public utility, the Mannheim Wallstadt project aims to be a first grid interconnected, utility operated microgrid where customer awareness is a major factor in the development of microgrids and local generation, which can lead in the long term to a multi-microgrid and eventually a smart grid set up where large or medium scale renewable generation plants are interconnected with multiple single microgrids.

The **Bornholm island multi-microgrid in Denmark** is another field test site of the European 'More Microgrids' program, and functions as a multi-microgrid, middle voltage network.[88] The power system of Bornholm island is Danish and the DSO operating the grid on the island is ØSTKRAFT. The island has more than 28 000 customers, which is about 0.5% of Denmarks electricity demand and population.[89] Furthermore, the island consists out of several microgrids combined with large scale generation such as wind parks.[90] Wind turbines comprised in 2007 more than 30% of the energy supply of the island and are key units for the overall renewable energy generation aim of the island.[91] The island has one single interconnector which connects it to the Nordic interconnected power system and power market and the

[87] MORE MICROGRIDS, 'Advanced Architectures and Control Concepts for MORE MICROGRIDS (2009),' http://www.microgrids.eu/documents/661.pdf (last consulted 30 March 2014).

[88] MORE MICROGRIDS, 'DF7– Report on field test on MV island operating isolated (2009),' http://www.microgrids.eu/documents/663.pdf (last consulted 30 March 2014).

[89] J. ØSTERGAARD, J. N. NIELSEN, 'The Bornholm Power System – An Overview', http://ctt.sitecore.dtu.dk/upload/sites/powerlabdk/media/the_bornholm_power_system_an_overview_v2.pdf (last consulted 30 March 2014).

[90] MORE MICROGRIDS, 'DF7– Report on field test on MV island operating isolated (2009),' http://www.microgrids.eu/documents/663.pdf (last consulted 30 March 2014).

[91] J. ØSTERGAARD, J. N. NIELSEN, 'The Bornholm Power System – An Overview', http://ctt.sitecore.dtu.dk/upload/sites/powerlabdk/media/the_bornholm_power_system_an_overview_v2.pdf (last consulted 30 March 2014).

network has the characteristics of a typical Danish distribution system. The aim of the set-up in Bornholm is to establish islanding operation without disconnecting the wind turbines.[92] Bornholm island is thus the set-up of a future sustainable smart grid where local microgrids and large scale renewable energy generation units are interconnected and communicating and can deliver benefits such as active and reactive power back to the central energy system and electricity market. Bornholm island is also part of the platform for power and energy experiments, PowerLabDK to test for all sorts of smart grid technologies and characteristics.[93] The characteristics of the Bornholm Island multi-microgrid are provided in table 3.

Bornholm island, Denmark	
Connection	Grid-connected, market participating almost self-sufficient island
Structure	Multi-microgrid + central generation Mix customers (peak ±55MW)
Ownership	Privately and publicly owned and operated assets
Technologies	Wind power plants Combined Heat and Power/biomass plants Photovoltaic units Biogas plants Electric Vehicles District heating

Table 3: Bornholm Island multi-microgrid characteristics

The Bornholm island grid is thus a set-up for a future smart grid where large scale renewables are combined with electricity integration and heat integration of a multi-microgrid interconnected network with renewables and electric vehicles on the island and a connection with the central Nord Pool market and central power system and the option of islanding. This is an example of how a smart grid should be working on a larger middle voltage scale within the future energy system. Increased liberalization, like in the Nordic countries, and more specifically in the operation and establishment of the Nord Pool, opens up the market for more interconnected networks and higher bottom-up market participation through smart grids. The Bornholm island shows these features and interaction of a multi-microgrid with the central electricity system.

92 MORE MICROGRIDS, 'DF7– Report on field test on MV island operating isolated (2009),' http://www.microgrids.eu/documents/663.pdf (last consulted 30 March 2014).

93 J. ØSTERGAARD, J. N. NIELSEN, 'The Bornholm Power System – An Overview', http://ctt.sitecore.dtu.dk/upload/sites/powerlabdk/media/the_bornholm_power_system_an_overview_v2.pdf (last consulted 30 March 2014).

2. *Partially liberalized electricity markets*

The **Sendai microgrid in Japan** is one of the microgrid demonstration projects initially installed by the New Energy and Industrial Technology Development Organisation in Japan (NEDO). After its testing phase of providing heat and electricity to the Tohoku Fukushi University, the microgrid is currently under operation of the NTT Facilities inc., a company sponsored by the Nippon Telegraph and Telephone Corporation. Other microgrid demonstration projects of the NEDO are amongst others Kyotango and Yokohama.[94] The Sendai microgrid demonstration site, however, is particularly interesting since it proved its islanding microgrid operation capability after the earthquake on March 11 2011 in the Tohoku district in East Japan by disconnecting from the central grid and functioning autonomously for 2 days before the interruption of the gas supply main resulted in a power outage in the microgrid as well.[95] Furthermore, the Sendai microgrid is a Multiple Power Quality Supply System that provides electricity at various power quality levels according to customer needs both AC and DC.[96] The Sendai microgrid consists of a university zone with amongst others a hospital, a laboratory, dormitories and other high reliability customers and a city-owned zone with amongst others a school. The characteristics of the Sendai microgrid are provided in table 4.

Sendai, Japan	
Connection	Grid-connected with proven islanding capabilities
Structure	Single microgrid Mix customers (peak ±1.3 MW)
Ownership	Privately owned and operated assets
Technologies	Gas engine generators

[94] S. MOROZUMI, 'Micro-grid Demonstration Projects in Japan', Power Conversion Conference - Nagoya, 2007. *PCC '07* , vol., no.,, 2-5 April 2007, 635-642; N.HATZIARGYRIOU, H. ASANO, R IRAVANI, C. MARNAY, 'Microgrids: An Overview of Ongoing Research, Development, and Demonstration Projects', *IEEE Power and Energy Magazine*, vol., no., July/August 2007, 78-94.

[95] S. MOROZUMI, 'Micro-grid Demonstration Projects in Japan', Power Conversion Conference - Nagoya, 2007. *PCC '07* , vol., no., 2-5 April 2007, 635-642; K. HIROSE, 'Behavior of the Sendai Microgrid during and after the 311 Great East Japan Disaster', *Telecommunications Energy Conference 'Smart Power and Efficiency' (INTELEC), Proceedings of 2013 35th International* , vol., no., 13-17 Oct. 2013, 1-6; K. HIROSE, T. SHIMAKAGE, J. T. REILLY, HIROSHIIRIE, 'The Sendai Microgrid Operational Experience in the Aftermath of theTohoku Earthquake: A Case Study', http://der.lbl.gov/sites/der.lbl.gov/files/Sendai%20paper%20jan%2013.pdf (last consulted 31 March 2014).

[96] S. MOROZUMI, 'Micro-grid Demonstration Projects in Japan', Power Conversion Conference - Nagoya, 2007. *PCC '07* , vol., no., 2-5 April 2007, 635-642; K. HIROSE, 'Behavior of the Sendai Microgrid during and after the 311 Great East Japan Disaster', *Telecommunications Energy Conference 'Smart Power and Efficiency' (INTELEC), Proceedings of 2013 35th International* , vol., no., 13-17 Oct. 2013, 1-6; C. MARNAY, N. ZHOU, M. QU, J. ROMANKIEWICZ, 'International Microgrid Assessment: Governance, Incentives and Experience', Ernest Orlando Lawrence Berkeley National Laboratory, June 2012, LBNL-5914E; N.HATZIARGYRIOU, H. ASANO, R IRAVANI, C. MARNAY, 'Microgrids: An Overview of Ongoing Research, Development, and Demonstration Projects', *IEEE Power and Energy Magazine*, vol., no., July/August 2007, 78-94.

	Fuel cell Photovoltaic installation Battery storage

Table 4: Sendai microgrid characteristics

The Sendai microgrid thus demonstrates another benefit of microgrids and local generation in interconnection with centralized distribution systems. This microgrid is able to deliver several power quality levels to customers ranging from AC to DC with Uninterruptable Power Supply applications. Furthermore, an interconnection of the central grid together with bottom-up generation increases self-sufficiency of consumers and increases reliability levels due to islanding options. The islanding operation of the Sendai microgrid after the major earthquake, however, indicated the necessity for generation diversification with the interruption of the gas supply main after two days, resulting in an overall power outage.

The **Xianmen University microgrid in China** is a set-up for the first commercial DC microgrid in China. China is gaining increasing interest in energy efficiency and smart energy management systems. Therefore, China has been developing several microgrid demonstration projects, mostly at universities.[97] The Xianmen microgrid is here one demonstration site initiated in 2012 by a collaboration of major industry partners and grid operators at the School of Energy Research in Xiamen University (SER-XMU). This microgrid is especially interesting due to its goal to transform conventional buildings into smarter buildings by adding compelling, cloud-based energy load demand management and user engagement programs together with renewable energy technologies.[98] Table 5 gives an overview of the know characteristics of the Xianmen university microgrid.

Xianmen, China	
Connection	Grid-connected (High Voltage AC Connection)
Structure	Single microgrid (DC) Mix customers (peak -)
Ownership	Privately owned and operated by People Power
Technologies	Photovoltaic installation Battery storage Cloud energy management system

Table 5: Xianmen microgrid characteristics

[97] J. ROMANKIEWICZ, M. QU, C. MARNAY, N. ZHOU, 'International Microgrid Assessment: Governance, Incentives and Experience', Ernest Orlando Lawrence Berkeley National Laboratory, March 2013, LBNL-6159E.
[98] MARKET WIRED, 'Xiamen University Partners With Leading Technology and Energy Providers to Build China's First Direct-Current Microgrid', http://www.marketwired.com/press-release/Xiamen-University-Partners-With-Leading-Technology-Energy-Providers-Build-Chinas-1633316.htm (last consulted 30 March 2014).

The importance of the Xianmen University microgrid is that it will serve as a worldwide example for DC microgrids and their commercialization. More specifically, the microgrid could serve as an example for the transformation of university campuses regarding their building management and the control and consumption of on-site energy. This is an example of how, through government and private industry collaboration, microgrids can be established to aid building efficiency. The Xianmen microgrid serves as a real 'smart' grid with interconnection, local control of energy consumption and an in-cloud energy management system together with control applications.

The **Pulau Ubin microgrid in Singapore** is a smart microgrid based on a rural village island north-east of the urbanized main Singaporean island.[99] Previously, the inhabitants of the island received their electricity from diesel generators. The microgrid is designed, installed, owned and operated by a Singaporean based consortium (Daily Life Renewable Energy Pte Ltd and OKH Holdings Pte Ltd) and it gives the island the opportunity to electrify in a sustainable manner using locally available renewable energy resources in combination with back up generation and storage.[100] The jetty area of the island, included in the microgrid, comprises forty-two customers including households, temples, shops and other small enterprises. Table 6 gives the main characteristics of the Pulau Ubin microgrid test bed.

Pulau Ubin, Singapore	
Connection	Off-grid
Structure	Single microgrid Mix customers (peak ±138 kW)
Ownership	Privately owned and operated by Daily Life Renewable Energy Pte Ltd and OKH Holdings Pte Ltd
Technologies	Photovoltaic installation Battery storage Bio-diesel generation set

Table 6: Pulau Ubin microgrid characteristics

[99] F. YANG FAN, V. RIMALI, M. TANG, C. NAYAR, 'Design and Implementation of stand-alone smart grid employing renewable energy resources on Pulau Ubin Island of Singapore', *Asia-Pacific Symposium on Electromagnetic Compatibility - Singapore, 2012. APEMC'2012*, vol., no., 21-24 May 2012, 441-444; ENERGY MARKET AUTHORITY (EMA), 'Pulau Ubin Micro-Grid Test-Bed', http://www.ema.gov.sg/ubin-test-bed/ (last consulted 31 March 2014).

[100] F. YANG FAN, V. RIMALI, M. TANG, C. NAYAR, 'Design and Implementation of stand-alone smart grid employing renewable energy resources on Pulau Ubin Island of Singapore', *Asia-Pacific Symposium on Electromagnetic Compatibility - Singapore, 2012. APEMC'2012*, vol., no., 21-24 May 2012, 441-444; ENERGY MARKET AUTHORITY (EMA), 'Pulau Ubin Micro-Grid Test-Bed', http://www.ema.gov.sg/ubin-test-bed/ (last consulted 31 March 2014).

The Pulau Ubin microgrid aims to be a model of sustainable development of the rural off-grid electrification of not yet electrified areas in Asia.[101] The set-up test-bed is installed to test the reliability of the intermittent renewable energy supply within a microgrid. Additionally, it wants to be an example for local smart grid design with customer awareness, full system integration and an energy management system.[102] This microgrid can thus form a model for other off-grid communities in the region wanting to electrify in a sustainable manner.[103]

V. Lessons learned for the future role of microgrids within regional electricity markets

After looking at the trends both in the EU and East Asia (including Singapore) at macro- and micro-level currently -and potentially towards the future- a few lessons can be learned for policy makers across the globe towards driving a future regional energy market that would benefit from the integration of microgrids.

First of all, microgrids can only optimally function in a grid system that is highly interconnected and has free access to the grid in a total communicating system. Liberalization is here key to allow for energy generation on multiple levels as well as increasing trading on central as well as local level between different participating jurisdictions or areas.

Secondly, at a micro-level, the microgrids can contribute to achieving a few current policy drivers at macro-level – particularly security of supply, grid reliability, flexibility and sustainability:

- *Security of supply*: As the move towards an integrated regional energy market will include growing inter-dependence between the regions, microgrids can make sure that off-grid supply is guaranteed in case of outage.
- *Grid reliability*: As the grid will become more complex in that it will have to respond to different technical requirements, microgrids can be designed to meet specific customer power quality levels, potentially with the option for

[101] F. Yang Fan, V. Rimali, M. Tang, C. Nayar, 'Design and Implementation of stand-alone smart grid employing renewable energy resources on Pulau Ubin Island of Singapore', *Asia-Pacific Symposium on Electromagnetic Compatibility - Singapore, 2012. APEMC'2012*, vol., no., 21-24 May 2012, 441-444.

[102] Ministry of Trade and Industry Singapore, 'Mr S Iswaran at the Pulau Ubin Micro-Grid Test-Bed Inauguration Ceremony', http://www.mti.gov.sg/NewsRoom/Pages/Mr-S-Iswaran-at-the-Pulau-Ubin-Micro-Grid-Test-Bed-Inauguration-Ceremony.aspx (last consulted 31 March 2014); F. Yang Fan, V. Rimali, M. Tang, C. Nayar, 'Design and Implementation of stand-alone smart grid employing renewable energy resources on Pulau Ubin Island of Singapore', *Asia-Pacific Symposium on Electromagnetic Compatibility - Singapore, 2012. APEMC'2012*, vol., no., 21-24 May 2012, 441-444.

[103] F. Yang Fan, V. Rimali, M. Tang, C. Nayar, 'Design and Implementation of stand-alone smart grid employing renewable energy resources on Pulau Ubin Island of Singapore', *Asia-Pacific Symposium on Electromagnetic Compatibility - Singapore, 2012. APEMC'2012*, vol., no., 21-24 May 2012, 441-444; Energy Market Authority (EMA), 'Pulau Ubin Micro-Grid Test-Bed', http://www.ema.gov.sg/ubin-test-bed/ (last consulted 31 March 2014).

end-consumers in the microgrid to choose between AC or DC power supply at different quality levels.

- *Flexibility*: Since microgrids are tailored to a specific location, it provides flexibility to integrate diverse energy generation sources, including the integration of conventional generation technologies, high efficient energy technologies, renewable energy technologies and other features like storage for local balancing, electric vehicles and local control systems in addition to the conventional grid. With a ‘plug-and-play’ approach, microgrids can be more easily scaled up, expanded and interconnected into multi-microgrid and smart grid networks that allow active customer input and flexibility.
- *Sustainability*: Microgrids are able to integrate distributed generation technologies that use locally available renewable energy resources such as solar and wind. Microgrids could thus aid to the integration of renewable energy units and as such the development of sustainable future smart energy systems.

Thirdly, microgrids respond to the requirements of future smart energy systems as they will be able to provide for the needed flexibility within the energy system while at the same time guaranteeing the diverse energy portfolio from the different microgrids across the regions that is needed to diversify the mix.

Fourthly, policy drivers can be configured to respond to the requirements of microgrid characteristics to deploy their off- as well as on-grid capacity if policy makers would pay additional attention to the elements of connection, structure, ownership and market liberalization in relation to configuring the framework for microgrids. Based on the microgrids that were discussed in this paper, the following recommendations can be made for these policy drivers:

- *Market Liberalization*: For microgrids to operate to their fullest extent, the recommendation made is for countries to liberalize their electricity markets fully as this will allow for the needed interconnection capacity and competition for new market entrants necessary to deliver a different electricity portfolio that will allow different sources to penetrate the market, such as wind and solar photovoltaic units, which would ideally work within microgrids.
- *Ownership*: Most current microgrids are still privately owned and operated. For microgrids to operate to their fullest extent and to be interconnected into smart multi-microgrid networks in the long term with participation in the central energy system and market, utility and commercial ownership and operation of the network should be established.
- *Structure:* Microgrid sites should be initially developed as single microgrids configurations with one point of common coupling with the central grid. This should be done in a standardized manner to allow for microgrids and later smart multi-microgrids to operate to their fullest extent. Microgrids can in this way be interconnected and implemented in a ‘plug-and-play’ manner

speeding up the interconnection and scalability of the network at the bottom-up level, allowing for a broader customer portfolio where different customer needs and awareness can be accommodated for.

- *Connection:* Microgrids can be used for two main applications. First of all for the sustainable electrification of rural off-grid areas, and, secondly for fully regionally interconnected (smart) electricity networks. The latter will provide a pathway to the highly interconnected regional electricity market with active participation both at the top-down level as well as from the bottom-up level.

Finally, after investigating the different microgrid test-beds and their place within the macrogrid, it became noticeable that the first mature electricity markets in terms of liberalization and interconnections were the first to achieve an electricity pool and interconnect their microgrid successfully to the distribution network and the energy system as a whole, see the Nord Pool. The Bornholm island can here be put forward as an example of an interconnected sustainable smart multi-microgrid with full integration in the central energy system and active grid participation both top-down as well bottom-up. The rest of the EU is moving towards such a model. The Kythnos island is a microgrid that in the future could be part of such an interconnected multi-microgrid in a smart environment when interconnected to the main grid on the island. The Mannheim Wallstadt microgrid, then, serves as an example that includes the socio-economic impact of smart grids together with an example for the utility ownership and operation of microgrids.

The countries in the East Asian region (including Singapore) are still in the phase of moving from a partially liberalized electricity market towards their full reform agendas. This setting leads to a more directed microgrid demonstration site development that forms a concrete example for other areas in the region. The Sendai microgrid, for example attempts to present a structure which supplies several power quality levels and increases flexibility, reliability and security of supply through islanding capability. The Xianmen University microgrid aims to be an example for smart building management at university sites in the region through microgrid operation and customer awareness, and, lastly the Pulau Ubin microgrid serves as an example for rural sustainable electrification for similar environments in the area.

As the agendas of the East Asian countries move along, it is noticeable how these markets increase their interconnectors too and while this trend is discussed in research, emphasis is often on large-scale transmission systems without mentioning the place of microgrids within this trend.[104] This paper argues that while at first sight

[104] See for instance for China, Singapore and Japan: F. ZHU, Y. ZHENG, X. GUO, S. WANG, 'Environmental impacts and benefits of regional power grid interconnections for China', *Energy policy,* vol. 33, no. 14, September 2005, 1797-1805; Y. CHANG AND J. L. LEE, 'Electricity market deregulation and energy security: a study of the UK and Singapore electricity markets', *International Journal of Global Energy Issues,* vol. 29, no. 1-2, January 2008, 109-132; M. KANAGAWA AND T. NAKATA, 'Analysis of the impact of electricity grid interconnection between Korea and Japan – Feasibility study for energy network in Northeast Asia', *Energy Policy,* vol. 37, no. 9, June 2006, 1015-1025.

microgrids may seem to be a contradiction to this trend of regionalization, after full liberalization and increased interconnection, mature regional electricity markets have shown to pay attention to looking at options for the integration of microgrids, and later smart multi-microgrids, into their electricity networks. Future research could focus more on this aspect and for this purpose the development of East Asian electricity markets will be interesting to follow due to the presence of mature microgrid test-beds, especially in Japan and Singapore.

VI. Conclusion

This paper described how microgrids fit into our current and future energy system and what their benefits are within these roles. While at macro-level a trend of moving towards regional electricity markets is noticeable, at a micro-level the trend is moving towards a local level. This paper has demonstrated how those two trends do not have to contradict each other, but can be complementary in delivering secure energy within our future smart energy systems.

While in the EU, regionalization was a direct effect of deregulation as the market opened to competition and cross-border interconnections, a similar trend is expected in East Asia (including Singapore), which is currently achieving partially liberalized electricity markets and interconnected regions which points to a similar prospect of market integration at a regional level. It became apparent from this exercise that a mere opening up of the retail market to the consumer, or partial liberalization, is not sufficient to achieve full competition. Only after being fully liberalized which included additional steps in terms of institutional structures and unbundling, the interconnection and regional integration came full circle in the EU.

The conclusion of this research is that microgrids will fulfil a dual role within regionally integrated markets. They can guarantee supply security and increase flexibility in case of disruptions due to their islanding capability, but can at the same time be interconnected to and participate in the macro-grid interconnected system. Furthermore, microgrids can be tailored to specific customer needs as well as to local environments, delivering multiple power quality levels as well as increasing sustainable electrification. Therefore it is the recommendation of this research that governments pay more attention to the importance of microgrid connections to the distribution network and the central energy system and market as a whole and allow for the integration of the microgrid concept into the policy and legal framework by focussing on the four identified dimensions/drivers that are crucial for microgrid development and characterization.