100 % Renewable Energy System – Challenges and Opportunities for Electricity Market Design

Kaisa Salovaara, Samuli Honkapuro, Mari Makkonen, Olga Gore
School of Energy Systems
Lappeenranta University of Technology
Lappeenranta, Finland
Kaisa.Salovaara@lut.fi

***Abstract*—How energy is produced and consumed affects the whole society and cannot be dealt with as solely technical or economical issue. In this paper we look at the renewable energy systems in year 2050 through society scenario descriptions. We describe a framework for electricity market design in four transformative, qualitative scenarios and assess of possible market design outcomes. In the process, we highlight the key issues in determining applicable market designs.**

***Index Terms*—Market design, renewable energy sources, scenario**

I. INTRODUCTION

Energy industry is on the verge of a third industrial revolution that is now being paved by renewable energy sources (RES) [1]. As a result, technological and social changes, radically new innovations, services, and practices will emerge. In fact, a reliable 100 % renewable energy system in year 2050 seems to be technically and economically feasible [2], [3]. The resulting industry change will challenge the fundaments of the energy system. Current energy system is designed for centralized, large generating plants, where consumers are on the receiving end, and power balance is achieved by controlling the power supply of the generators. Transformation towards renewable system will require networks and markets to accommodate distributed, intermittent generation. How energy is produced and consumed affects the whole society. Customers' involvement in the system will increase as they have the opportunity to become producers themselves and to diffuse their values through to business. Eventually, this paradigm shift in power system will also require changes in the design of the electricity markets, as present design may not feasible.

In this paper, we will use top-down analysis to study how the changes in the energy system will affect the electricity market design. We base our analysis on four qualitative scenarios for neo-carbon society in year 2050. The scenarios have been produced using Futures Clinique workshop developed by Finland Futures Research Centre [4]. All of the scenarios are transformative, i.e. they imply fundamental change and differ more or less radically from the present. The main objective of the scenarios is to study possible socio-economic futures related to neo-carbon. Neo-carbon is defined as the combination of wind, solar and storages as synthetic hydrocarbons enabling distributed energy system. From the neo-carbon scenarios we have formed four conceivable views on energy sector's futures that answer the fully renewable challenge. The justification for the selected approach is that many past energy scenarios have not been able to account unexpected events such as the rate of technological development that could transform the economy significantly [5]. Commonly, scenario approaches have based on historical assumptions rather than attempted to solve future challenges [5]. In this paper we focus on following research questions: What kind of market design is feasible for neo-carbon society scenarios in year 2050, and which are required elements of the market design that enable the scenarios?

II. BACKGROUND – IMPACT OF RES ON MARKET DESIGN

Regardless of the market design, the (theoretically) optimal electricity market is a market that minimizes costs and power plants earn the rate of return on invested capital. Market design should provide sufficient incentives for meeting demand and supply in real time as well incentives for long-term capacity adequacy.

A. Challenges of fully RES electricity system

There are three underlying changes defining the future energy markets that are currently present: 1) push for decarburization through policy changes, 2) the integration of European electricity markets and 3) technical advances that enable extensive distributed small-scale renewable production [6]. The current electricity markets in many views struggle to sustain large renewable pallet. The fact that electricity cannot be stored but the demand and supply must meet at every instance, demand is inelastic and electricity flows according to physical not economical laws has to be addressed by electricity pricing [7]. Marginal cost based pricing has worked quite well for traditional market structure where fixed costs are low and variable cost high – market prices have risen to ensure cost recovery. Policies to further subsidize RES

This research is a part of "Neo-Carbon Energy" project funded by Tekes – the Finnish Funding Agency for Innovation.

decrease the operating times for these conventional power plants as the share of RES increases. RES typically have low marginal cost which pushes the base load power plants from the merit order. Market price is suppressed to a level where cost recovery is not sufficient as the higher market prices are set only in periods where RES are not producing the full demand. This creates a type of missing money problem for the investors as the market price does not provide long-term incentives for investment. There is also a question whether RES will be able to be profitable without subsidies even in the long run [8]. RES subsidies have guaranteed sufficient funding for power plants but most support mechanisms are designed to be temporary until grid parity is reached, and they are in many cases aimed only at new generation rather than the existing plants.

Renewable energy production is typically intermittent and unable to be dispatched similar to conventional power plants. High share of RES require complementary flexible capacity (production, demand or storages) to balance the system. Balancing/intraday adjustments are therefore likely to increase and the participation of dispatching plants needs to be incentivized. One option is developing transmission network to enable cross-border trade that would increase flexibility and alleviate capacity adequacy for a single country. For example, achieving EU market integration by increasing interconnection capacity is one precondition for facilitating high level of RES [8].

B. Market design options

There are several focuses to address large scale RES integration in the markets: By increasing flexibility and capacity adequacy in the day-ahead markets, developing balancing/intraday markets and/or capacity mechanisms. We have simplified the market design and focused on day-ahead market pricing mechanism and possible need for capacity mechanisms. Market designs that are considered likely to allow cost recovery in fully renewable electricity production are selected from [9] and [10].

Two of the most common pricing methods used are zonal and nodal pricing. Both apply the marginal pricing principle to determine the market price. **The zonal pricing** method clears the market based on marginal cost: Production with lowest marginal cost will be dispatched first and the highest last, until demand is met. Price is determined based on marginal cost for the last production brought online. Zonal pricing will be applicable if the transmission networks in the area are sufficient enough or necessary investments are being made, the borders of the zone follow the physical limits of the networks, and there are enough competing generators in the zone [11]. In fully RES markets zonal pricing would likely require capacity mechanisms (CM) to encourage investment in new power plants and/or ensure operation of existing plants. **Nodal pricing, or locational marginal pricing (LMP)**, sets the market clearing prices for a number of locations on the transmission grid (nodes). Price is the locational value of supplying electricity, i.e. marginal cost of energy as well as marginal cost of losses and congestion. LMP is therefore an effective way to manage network congestion and to provide power plants location signal. LMP markets are commonly joint with CM as the market prices are capped in order to avoid market abuse. **Dispatch based on marginal costs and pricing on leveled cost of energy (LCOE)** would retain the marginal cost dispatch of the present system but the generators would receive payments based on average production cost or long-term marginal cost. The information asymmetry between the generators and the market operator is evident and may influence the prices [9]. This complex bidding system could also lead to inefficient plant dispatch and an increase of technologies with low marginal costs.

An alternative to marginal pricing is to define the merit order by **pay-as-bid (PAB)** principle (i.e. discriminatory auction). Suppliers bid with their fixed operation costs and variable costs to assure cost recovery but ultimately bids reflect their estimates of expected market prices, not marginal costs [12]. Auction winners are paid according to their bids which leads to a higher price level than in a uniform marginal pricing situation and possible inefficient dispatch of generators [13]. PAB does not produce a common market price. **Cost of service** pricing bases on cost incurred. It is generally referred to in cases of vertical integration or utility service e.g. state-owned monopoly providing electricity would be responsible for efficient dispatch as well as for capacity investments. Extensive state involvement is often believed to produce overcapacity when securing for supply and therefore visions for the future rarely portray reduced competition and customer choice but competitive markets are seen as an effective tool to spur innovation. **Over the counter trading (OTC)** can be employed for arranging supply demand. Bilateral agreements can also be used as an additional method for market trading giving much freedom for the participants. Used alone OTC would require e.g. strategic reserves to be employed in order to guarantee capacity, depending on whether self-dispatching is employed [12].

C. Capacity mechanisms and add-ons

Increase in RES has raised concern over the sufficient investment signals and prompted considerations of adding CM to market design, see e.g. [14]. On the other hand, to achieve fully RES system add-ons such as feed-in tariffs (FiT) and premiums are used. CMs should not be considered as an autonomous mechanisms because there is a high motivation to participate simultaneously in complementary markets, typically wholesale markets. If the day-ahead markets do not provide sufficient cost recovery, producers rely more on the CMs and add-ons for cost recovery. In [10], market premiums and technology-specific auctions have been categorized as the most promising cost recovery mechanisms for fully renewable markets. Market premium paid for the intermittent renewable plants should guarantee cost recovery and investment incentives. Using ‘cap and floor’ approach, premiums allow market response for the generators while providing stable income [9]. In technology-specific auctions generators auction for long-term payments and for capacity availability. This mechanisms would solve the problem of cost recovery and investment incentives but incorporates a need to define the capacity for each technology, which can lead to technology lock-in or disregard for alternative technologies [10]. Summary of market design options for consideration in fully renewable system is presented in Table I.

TABLE I. MARKET DESIGN OPTIONS

Pricing mechanism	*Capacity incentives*
Marginal cost pricing: Zonal	CM, add-ons
Marginal cost pricing: Nodal	CM, add-ons
Marginal cost based dispatch and pricing on leveled cost of energy (MC & LCOE)	No
Pay-as-bid (PAB)	No
Cost of service	No
Over the counter trading (OTC)	No/defined by the state

III. FRAMEWORK FOR ELECTRICITY MARKET DESIGNS IN TRANSFORMATIVE SCENARIOS

The foresight part of the Neo-Carbon Energy project[1] produced four transformative, qualitative scenarios in Futures Clinique that utilizes several foresight methods including Futures Window, Futures Wheel and PESTEC Table (used to study the political, economic, social, technological, environmental and cultural aspects of a phenomenon), identification and impact analysis of weak signals and of black swans, for more detail see [1]. Scenarios were formed on two axes: Peer-to-peer and Ecological awareness see Fig. 1.

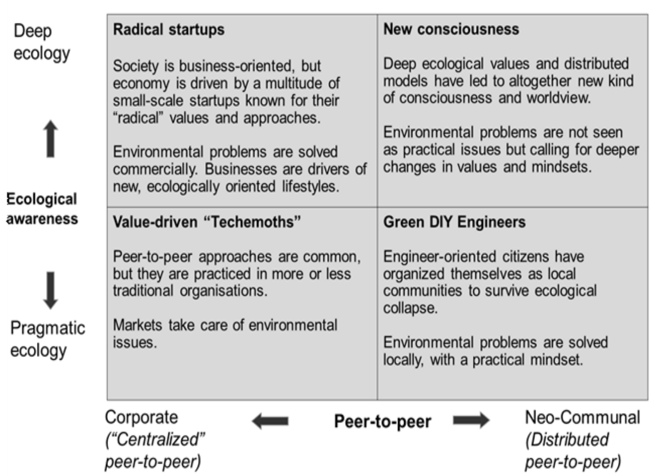

Figure 1. Transformative scenarios for Neo-Carbon Energy [1].

In neo-communal peer-to-peer individuals self-organize their joint efforts independently whereas in corporate peer-to-peer people self-organize freely within organizations that provide a platform. Pragmatic ecology sees nature as valuable resources that humans can utilize whereas deep ecology is a philosophy advocating inherent value of nature regardless of their utility to humans.

Scenarios are: 1) Radical start-ups where society is business-oriented, but economy is driven by a multitude of small-scale start-ups known for their radical, deep ecological values and approaches. Energy is produced in a scattered system. Transmission networks are interconnected with bottlenecks. 2) New consciousness where deep ecological values and distributed models have led to altogether new kind of consciousness and worldview. Energy is produced and stored in a centralized, integrated systems. Transmission network is strong. 3) Value-oriented "Techemoths" where peer-to-peer approaches are common, but they are practiced in more or less traditional, big corporations. Energy is produced and stored in centralized, large-scale integrated systems. Transmission has strong interconnections. 4) Green DIY Engineers where engineer-oriented citizens have organized themselves as local communities after an ecological collapse. Electricity is produced and used in highly distributed systems, even micro-grids that are equipped for off-grid operation. Energy storages are small-scale and transmission interconnections are weak. All scenarios have high share of solar and wind and assume fully RES production. Advanced demand response (DR) is in use except for scenario 4) where DR is assumed manual.

The transformative scenarios in Fig. 1. describe who or what the actors are in the decarbonized society and whether they are motivated by technologically enabled push, a pull from ecological awareness, a pragmatic approach or a need from external factors such as ecological collapse. The four transformative scenarios take societal and technological development as interwoven concept where technological development enables society's and individuals' values to be materialized in energy system. In order to outline what kind of electricity markets in year 2050 would be, the process for market design is performed top-down. We categorize approaches on electricity markets for each of the transformative scenarios by simplifying the market design to the following key questions:

1. Is there a common market for electricity?
    - Axes: Is the price formation open and public or fragmented with bilateral agreements?
    - Axes: Is the system integrated or scattered?
2. How is the needed generation and transmission capacity obtained?
    - Axes: Does the network adapt to the needs of the market?
    - Axes: Does the market adapt to the limits set by the network?
3. What are the driving forces for market development?
    - Axes: Are the markets consumer- or corporate-driven?

The approaches to market design set above define the market boundary conditions and form the basis for two separate illustrations that we propose for framework, see Fig. 2. We discuss the process further in the following text.

[1] The technological part of the project is to study and develop energy storage systems, and the related business opportunities.

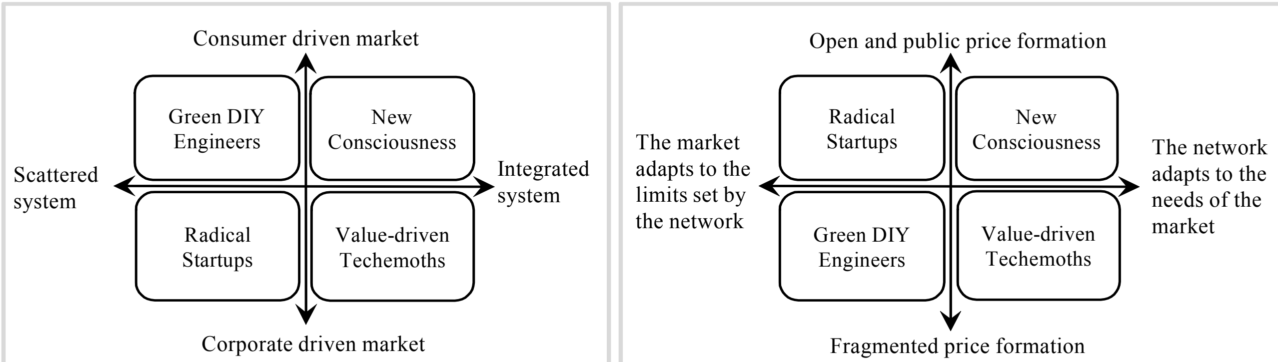

Figure 2. Framework for market design.

We have begun the process for constructing market design by taking two driving forces perceived from the transformative scenarios: Consumer activity and energy system design. In the 2050 neo-carbon energy markets a central concept related to consumer activity is prosumerism (producer + consumer). Consumers and corporates are the two polar ends of the axes that are the driving force of energy market development: In the one end customers are providing for themselves in a bottom-up approach and, in another end is the up-bottom, corporate-driven solutions. Energy system design is the logical continuation of customer involvement in the energy markets. The main question will focus on the markets ability to ensure adequate investments in the system. Unless markets provide clear investment incentives that are carried out by the established market participants there will be a shift to customer or society participation and, without functioning markets, production becomes self-organizing. Together with low cost technology enabled energy production the result will be a scattered energy system of small to medium scale solutions. Clear market signals for preferred technology, energy source etc. is likely to lead to integrated system where large scale solutions provide coordinated energy systems. The other option is centrally led system planning.

The second market design illustration takes more traditional approach to market design (adapted from [11]): Price formation and capacity adequacy. In a common markets, the price of electricity is based on balance between supply and demand. For instance, the Nordic power market employs marginal pricing principle to direct the merit order for generation. Price formation is central to market existence: Common market exists if there is a market where price is formed openly and that is informed to market participants. At the same time system state (power balance) information is available for all market participants. If the price is formed in bilateral agreements, price formation will be fragmented and so will be the information on system state. The balance between demand and supply in its current mode have to meet at all times in order for system stability to be reached. In an ideal market the transmission network and the power markets would align i.e. the network adapts to market's needs. In reality, transmission capacity limits the power flow, and the markets have to adjust by various markets mechanisms.

IV. MARKET DESIGNS FOR SCENARIOS

In this chapter we link the market design options from Table I to scenario descriptions using framework from Chapter III and Figure 2. In order to evaluate the applicability of the different market design options, we first analyze the pricing mechanisms qualitatively given the framework.

A. Assessment of market design characteristic

Integrated system can either refer to system that is centrally led and planned or to the energy production system itself. This would imply strong centrally led system operation, pool or vertically integrated structures where zonal, nodal and cost of service methods can be used. Scattered system accordingly refers to the distributed (and small-scale) energy system and dispatch management that can base on market mechanisms and bilateral trade. In these cases nodal, PAB and OTC would be preferred. On whether markets are consumer- or corporate-driven is determined on the ability of small-scale producer to participate in the markets. Zonal, nodal and OTC methods can particularly accommodate small participants. Corporate-led markets have more leeway on the method.

In the essence of market design is the question of pricing mechanism and how the generation and transmission capacity is adequately secured. Open and public price formation translates into liquid exchange and market design that enables small-scale participants, such as zonal and nodal. Fragmented price formation associates to bilateral or non-liquid markets such as in OTC, MC & LCOE and PAB. In these situations there may also be need for strong investment incentives that MC & LCOE and PAB provide. If network congestion is primarily handled by the markets, the preferable pricing mechanism would be nodal. If in these cases zonal pricing were to be selected, markets would have to rely on CM and add-ons for generation investment incentives and congestion management. Nodal pricing inherently handles these issues and gives locational signal for new generation that takes the constraints of the existing network into account. If the network adapts to the needs of the market, the network is capable of transmitting power from generation to consumption according to demand. In such case, the optimal pricing method would most likely be zonal.

B. *Scenarios' electricity market descriptions*

In radical start-ups –scenario the absence of investments in the networks has led to congestion, which impedes the functioning of markets. For markets that have to adapt to the limitations of networks, nodal method would be best suited. Zonal method would probably require CM and add-ons.

In Techemoths –scenario energy services are taken to the extreme: Techemoths are corporations that have become the new version of utility organization providing services in housing and transportation etc. where energy is included. This could be enabled by companies building power plants for their own use. Such strong market participants could be best accommodated with OTC or e.g. zonal with CM and add-ons.

DIY Engineers –scenario is perhaps the most radical one. Weak interconnections are result of ecocatastrophe that has taken affect globally. Network interconnections between communities are weak or useless because of demographic changes that result from climate changes. For this scenario, nodal or OTC could be employed, because of scarce transmission pathways that prevent creating large common market areas. Investments in energy infrastructure are generated by the communities' needs rather than the markets'. MC & LCOE could be employed to produce new generation capacity because of scarce investors.

The New Consciousness –scenario has strong ecological awareness that drives for strong networks and optimal production capacity and use. New investments are funded on socio-economical grounds which resembles state monopoly or strong central planning. Therefore the need for investment incentives is not strong and preferred market design could be cost of service, or if markets are needed zonal or nodal. Summary of selections is provided in Table II.

TABLE II. SCENARIOS' MARKET DESIGN SELECTIONS

Market design	***Radical start-ups***	***Techemoths***	***DIY Engineers***	***New Consciousness***
Zonal	++	++	no	++++
Nodal	+++	+	++	+++
MC & LCOE	no	++	++	no
PAB	+	no	no	no
Cost of service	no	no	+	+++
OTC	+	+++	++	+
Definitions: "no" = not at all suitable, "+" = slightly suitable, "++" = moderately suitable, "+++" = very suitable, "++++" = extremely suitable				

V. CONCLUSION

Qualitative approach on future energy system scenarios provides a novel and necessary view to considering fully renewable energy system. Traditional scenarios contemplate political change in the energy system but external ecological or economic shocks to society may expedite the solutions towards neo-growth society [5]. The Neo-Carbon scenarios share the common belief that energy system is able to function as fully renewable and that it is an economically viable option. In this paper we have linked theoretical electricity market designs with qualitative energy system analysis of four society descriptions in year 2050. The framework for market design addresses 1) the generation and transmission adequacy in relation to the market's needs, 2) price formation, 3) energy system layout (integrated or distributed), and 4) customer involvement in market development. Although the scenarios and the presented market designs can be considered radical as they exclude the business as usual approach, they can provide insight on possible futures or events made possible by present choices instead one linear, evolutionary development. In future research work we will carry out agent-based simulations on the impact of different market designs.

REFERENCES

[1] S. Heinonen, J. Karjalainen, J. Ruotsalainen. (Aug., 2015). Towards the third industrial revolution. Finland Futures Research Centre University of Turku, Helsinki. [Online]. Available: https://www.utu.fi/fi/yksikot/ffrc/julkaisut/e-tutu/Documents/FFRC-eBook-6-2015.pdf

[2] M. Child, T. Haukkala, C. Breyer. "The role of solar photovoltaics and energy solutions in a 100 % renewable energy system for Finland in 2050," in *Proc. 2015 31st European Photovoltaics Solar Energy Conf.*, pp. 2650-2671.

[3] M. Child, C. Breyer. "Vision and initial feasibility analysis of a recarbonised Finnish energy system," unpublished. Presented at the World Conference of Futures Research 2015: Futures Studies Tackling Wicked Problems, Turku, Finland, 11 June, 2015.

[4] S. Heinonen, J. Ruotsalainen. "Futures Clinique – method for promoting futures learning and provoking radical futures," *European Journal of Futures Research*, 15:3, 2013.

[5] J. Karjalainen, M. Käkönen, J. Luukkanen, J. Vehmas. (2014). Energy models and scenarios in the climate change era. Finland Futures Research Centre, University of Turku. [Online]. Available: http://www.utu.fi/fi/yksikot/ffrc/julkaisut/e-tutu/Documents/eBook_3-2014.pdf

[6] J.-M. Glachant, J. Vasconcelos, V. Rious. (2015). A conceptual framework for the evolution of the operation and regulation of electricity transmission systems towards a decarbonised and increasingly integrated electricity system in the EU. Florence Scholl of Regulation research report.

[7] F. Leuthold, H. Weigt, C. Hirschhausen. "Efficient pricing for European electricity networks – The theory of nodal pricing applied to feeding-in wind in Germany," *Utilities Policy,* 16 (4), 284–291, 2008.

[8] "Integration of renewable energy in Europe," DNV-GL Report No. 901 –700, June, 2014.

[9] J. Winkler, M. Altmann. (2012). "Market Designs for a Completely Renewable Power Sector," Z Energiewirtsch, 36:77–92

[10] R. Hartel, W. Fichtner, D. Keles. (April, 2015). Electricity market design options for promoting low carbon technologies. Insigh_e Rapid response energy brief 3.

[11] S. Viljainen, M. Makkonen, S. Annala, D. Kuleshov. (March, 2011). Vision for European Electricity Markets in 2030. Lappeenranta University of Technology Research report 13.

[12] S. Tierney, T. Schatzki, R. Mukerji. (2008). Uniform pricing versus pay-as-bid in wholesale electricity markets: Does it make a difference? New York ISO.

[13] P. Abid, D. Hurblut. (2008). "Market Power and Market Monitoring," in Competitive Electricity Markets - Design, Implementation, Performance, Sioshansi, F.P. (ed.), Amsterdam: Elsevier, pp. 267–296

[14] B. Tennbakk, P. Capros, C. Delkis, N. Tasios, M. Zabara, H. Noreng, A.B. Skånlund, A. Jenssen. (2013). Capacity Mechanisms in individual Markets within the IEM. DG ENER - DIRECTORATE B, European Commission. [Online]. Available: https://ec.europa.eu/energy/sites/ener/files/documents/20130207_generation_adequacy_study.pdf