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Electricity Markets Framework in Neo-Carbon Energy 2050 Scenarios

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PREFACE

This document has been prepared for the Neo-Carbon Energy project, WP 1. Our work is based on the four scenarios of Neo-Carbon world in 2050, on which we build four electricity market frameworks. The four original scenarios are all transformative, with each of the scenarios providing insights of how future, neo-carbonized world might be realized in radically different ways. This allows us to contemplate on electricity market design that employs fully renewable energy resources. Figure 1 illustrates the work carried out in WP 1.5.

Figure 1. WP 1.5 tasks.

The document first introduces some background to electricity markets, followed by general observations on differences between current market design and markets that operate on fully renewable resources. We then illustrate the process of building market designs for four transformative neo-carbon scenarios and finally, we discuss possible electricity market designs for each of the transformational scenarios and the roadmap to those.

Lappeenranta research group of WP 1

Lappeenranta 4.7.2016

EXECUTIVE SUMMARY

Neo-Carbon Energy scenarios share the common view that energy system is able to function as fully renewable, and that it is an economically viable option. However, transformation towards renewable system will require networks and markets to accommodate significant amount of distributed, intermittent generation. Eventually, this paradigm shift will also require fundamental changes in the design of the electricity markets, as present design may not be feasible.

In this study, we have linked theoretical electricity market designs with qualitative energy system analysis of four society descriptions in year 2050. Scenarios are called “Radical Startups”, “Value-driven Techemoths”, “Green DIY Engineers” and “New Consciousness”. We have considered the general applicability of different market designs in each of the scenario descriptions. 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.

In generally, electricity market design should provide sufficient incentives for meeting demand and supply in real time, as well incentives for long-term capacity adequacy. Marginal cost based pricing has worked quite well for traditional market structure, where fixed costs are low and variable cost high, and marginal prices have ensure cost recovery. However, 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 based generation is 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. Moreover, 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 the flexible resources needs to be incentivized.

Based on literature[1], there is no clear answer for what is the most feasible pricing mechanism for renewable markets. However, a uniform market price is seen important, as it is needed to ensure that power plants and demand response resources are given an incentive to be available when their value to the system is highest. Concerning the pricing mechanisms, it

[1] See for instance IEA (2016), Winkler and Altmann (2012), Borggrefe and Neuhoff (2011)

has been discussed that zonal pricing alone may not the best match, since the intermittent generation most likely increases network congestion and forecasting errors in the day-ahead timeframe which may lead to inefficient use of the networks. If the market design fails to account for physical constraints of the network, such as in the zonal method, the security of supply may become at risk, which would prefer nodal pricing.

In order to find out what kind of electricity market design would be potential for year 2050 transformative scenarios, the top-down analyses of the properties of different market designs are carried out. We have considered what are the required elements of the market design that enable each scenario, and from the other hand, what kind of market elements are possible in each scenario. As discussed, there is not one right answer for these questions, but the results here provide the framework for assessing the impacts of the societal transformation on the electricity market design. In future research work, we will provide quantitative results by carrying out agent-based simulations on the impacts of different market designs.

CONTENTS

ACRONYMS AND ABBREVIATIONS

Capex	Capital expenditure
CCS	Carbon capture and storage
CM	Capacity mechanism
CO_2	Carbon dioxide
DIY	Do-it-yourself
DR	Demand response
ICT	Information and communications technology
ISO	Independent system operator
LCOE	Leveled cost of energy
MC	Marginal cost
Opex	Operational expenditure
OTC	Over the counter (trading)
P2G	Power-to-gas
PAB	Pay-as-bid
PPA	Power purchasing agreement
R&D	Research and development
RES	Renewable energy source
SO	System operator
TSO	Transmission system operator
VRE	Variable renewable energy

1. INTRODUCTION TO NEO-CARBON ENERGY MARKET DESIGN

How energy is produced and consumed affects the whole society and cannot be dealt with as solely technical or economic issue. Renewable energy has taken over energy production and reliable, fully renewable energy system in year 2050 seems to be technically and economically feasible (Child et al. 2015; Child and Breyer, 2015). Transformation towards renewable system will require networks and markets to accommodate distributed, intermittent generation. Eventually, this paradigm shift will also require fundamental changes in the design of the electricity markets, as present design may not be feasible.

In this document, we consider renewable energy system's impact on electricity markets in year 2050, through society scenario descriptions. We base our analysis on four qualitative scenarios for neo-carbon society in year 2050, see Heinonen et al. (2015) for more detail. Scenarios are called "Radical Startups", "Value-driven Techemoths", "Green DIY Engineers" and "New Consciousness". The scenarios have been sketched using the following axes and their opposite values: The X axis is called "Peer-to peer" and its end values are Corporate ("centralised") peer-to-peer and Neo-Communal (distributed) peer-to-peer. The Y axis is called "Ecological awareness" and its end values are Pragmatic ecology and Deep ecology. The scenarios are summarized in the figure below.

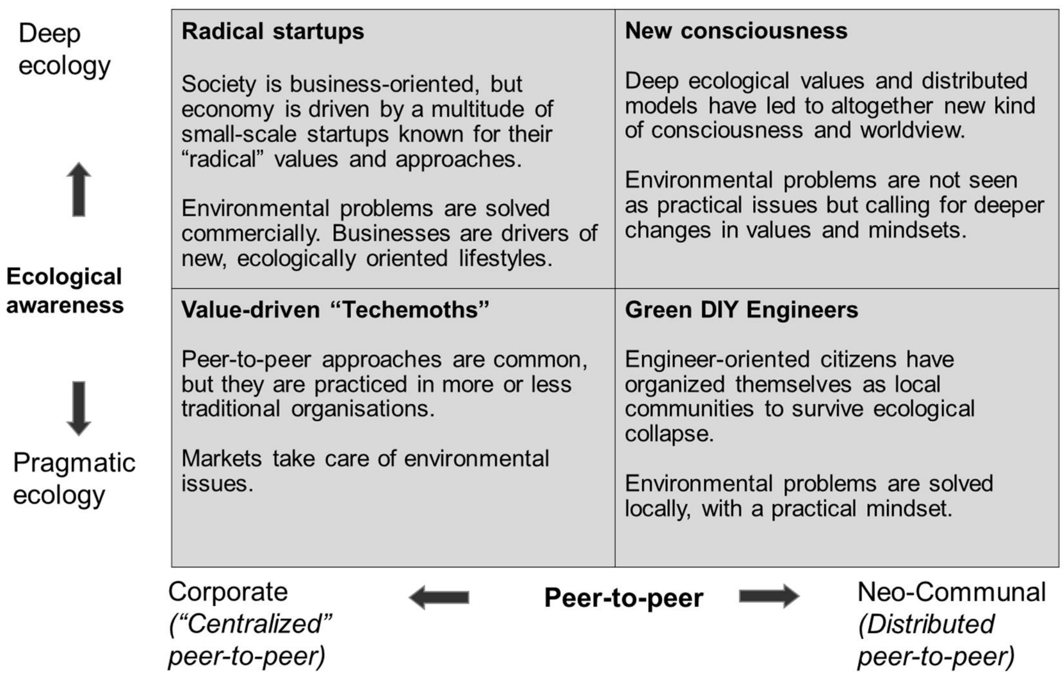

Figure 2. Transformative scenarios in 2050 for Neo-Carbon Energy project (Heinonen et al. 2015).

All of the scenarios are transformative, i.e. they imply fundamental change and differ 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 scenario approaches have based on historical assumptions rather than attempted to solve future challenges (Karjalainen et al. 2014). We describe a framework for electricity market design in four transformative, qualitative scenarios that all have high share of solar and wind and assume fully RES production. We then assess possible market design outcomes.

Key research questions in this report are, 1) what kind of market design is feasible in 100 % RES (renewable energy source) scenario, 2) how to provide incentives for building such RES based energy system, and 3) which are the required elements of the market model that enable such scenario.

2. ELECTRICITY MARKET DESIGN

Electricity market restructuring process (market liberalization) carried out in worldwide scale since the late 1980's has introduced competition to electricity generation and sales, whilst the networks have remained natural monopolies. In practice, this has meant transitioning from (national) monopoly model to competitive models[2]. The main goal of the electricity market liberalization was to promote competition in the markets, reduce governments' role, and strengthen the role of consumers in short- and long-term demand management, thereby making the market more efficient (Harris, 2006). Several sources also prefer privatization or reduced state involvement in the markets (Joskow, 2006; Littlechild, 2006; Harris, 2006). Competitive markets are also an efficient way to share scarce resources (Joskow, 2010). Other forces behind market liberalization include regulatory failures, high tariffs, and managerial insufficiency (Jamasb et al., 2005; Ma and He, 2008). European Union has set the guidelines for market liberalization in member countries and the ultimate goal is to create an integrated market for electricity with high level of competition. In the developing and transition countries, electricity market restructuring is mainly driven by the need for electrification of the whole country, an increase in service quality, transmission loss reductions, new (private) investments, and the effective collection of the payments (Jamasb et al., 2005).

Currently, there are three underlying changes defining the future energy markets: 1) push for decarbonization through policy changes, 2) the integration of European electricity markets, and 3) technical advances that enable extensive distributed small-scale renewable production (Glachant et al., 2015). Changes in electricity markets, such as the introduction of the emissions trading and the restructuring of the primary fuels markets create uncertainty with respect to future generator returns (De Vries, 2007).

The Neo-Carbon project bases from the idea that nuclear, fossil fuels and CCS (carbon capture and storage) are excluded and energy system relies on wind, solar, sustainable hydro and biomass. This poses a challenge to the energy system to maintain balance between the demand and supply, as well as to the electricity markets to act efficiently. Current energy system is designed for centralized, large generating plants, where consumers are on

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[2] Single buyer model allows competition between power generators to attain long-term power purchase agreements. Wholesale competition is denied and public utility controls transmission and most of the generating facilities.
The wholesale competition model allows competition for retail companies but electricity is provided as a bundled service of power and transmission. In retail competition the customers are able to choose their supplier.

the receiving end, and power balance is achieved by controlling the power supply of the generators.

2.1 Electricity markets

Electricity market design can be categorized into two dominant models, the poolco (or pool) model and the bilateral model (Rudnick et al., 1997). In the pool model, all energy and related transmission and ancillary services are traded in a central auction mechanism (exchange) in a coordinated manner, as opposed to bilateral model (or over the counter, OTC). Participation in the wholesale market can be mandatory when the exchange is said to have a 'power pool' structure where generators submit bids and the demand side is represented by a 'single buyer'. When participation is voluntary, term 'power exchange' is used and trade is made on standardized products. In practice, however, most wholesale electricity markets have characteristics of both models. Both pool and bilateral models recognize the need for a system operator (SO) who coordinates grid operations and preserves reliability. Transmission system operator (TSO) typically owns the transmission infrastructure and is responsible for constructing it and in many cases is also system operator. Network construction and operation are regulated to prevent the misuse of the monopoly position.

Present electricity markets are typically structured around three durations: short-term, medium-term and long-term (Cramton, 2015), see Figure 3. Long-term investment markets consist of two markets: markets for power production capacity, and long-term power purchasing agreements (PPA) for new power production. Capacity markets are a mechanism where typically system operator procures or imposes capacity requirements for availability, in three to four years in advance (IEA, 2016). Medium-term markets can be found in well-functioning markets: Most energy (even 90 % in liquid European markets) is traded before the short-term markets, from a few months in advance up to three or four years e.g. with future and forward standard products (IEA, 2016). Short-term markets generally consist of day-ahead and real-time markets. Price is determined based on marginal cost for the last production brought online for each hour next day. Intraday markets are needed to balance the supply and demand during delivery day. The time interval for the real-time markets can be e.g. an hour as in the Nordic markets or five minutes as in some USA markets.

Market participants can also operate in balancing markets where the system operator balances supply and demand during unexpected events. System operator also employs ancillary services and operating reserves to restore balance. Overall, short-term markets play a key role in mobilizing the flexibility of the power system, and the detail of their design affects the level of integration of renewables that can be reached (IEA, 2016).

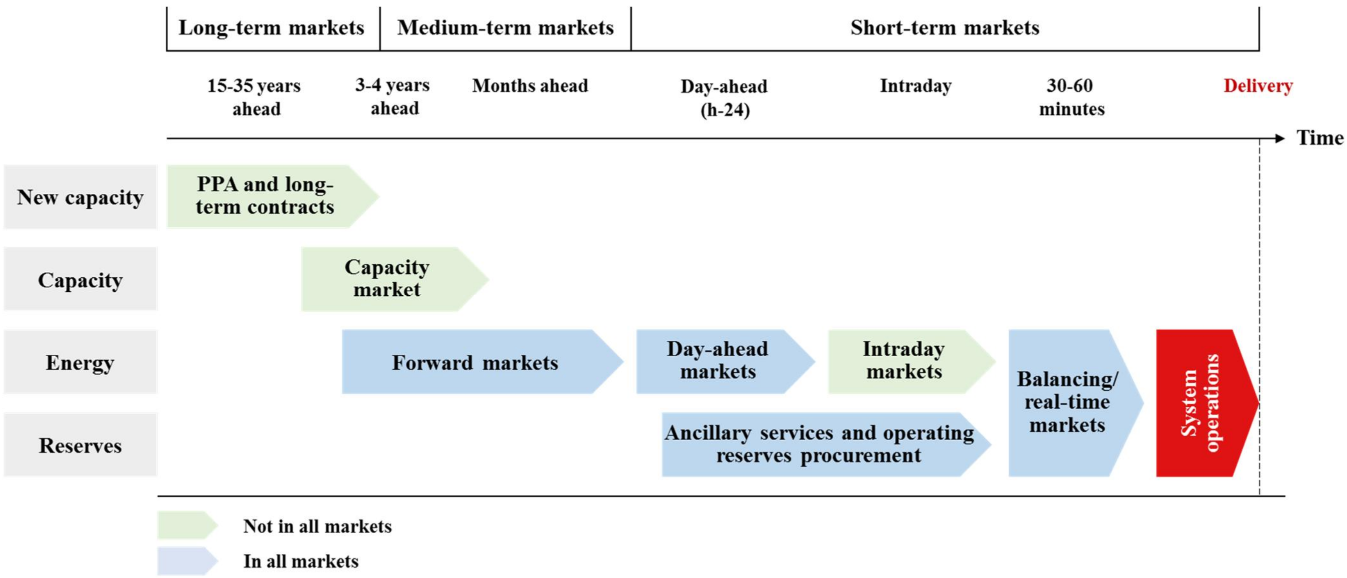


Figure 3. Overview of different building blocks of electricity markets (IEA, 2016).

Electricity markets are commonly categorized to energy-only and energy plus capacity markets. Energy-only markets should provide sufficient revenues to cover both fixed and variable cost of production while attracting new investments for future needs. When there is an excess in demand, prices are allowed to rise (scarcity prices) so that generators are able to recover their fixed costs and future investments are incentivized. Wholesale prices are usually capped, which reduces the scarcity revenues and at the same time causes a 'missing-money' problem for the generators. If markets fail to attract sufficient capacity to the markets, capacity mechanisms (CM) may be introduced. Capacity mechanisms refer to a group of mechanisms designed to provide additional revenue, which does not depend on electricity produced, but rather on power plant availability or installed capacity. Capacity mechanisms may also be needed to renew the system.

2.2 Impact of renewable energy sources on electricity markets

Conventional generation has typically set the marginal system price but renewable technology with low marginal cost reduces the operating hours of conventional generation while pushing it off the merit order and sets the price significantly lower. Only biomass has a fuel cost and is able to set prices higher. As wind and photovoltaics are likely to provide the base load, the wholesale prices remain low and there needs to be some additional mechanisms for cost recovery and to attract new investments. As a result of the reduced number of operating hours and suppression of real scarcity prices for peak generators fail to recover their fixed costs. Growing share of renewable energy sources (RES) add to the missing money issue by lowering the market price. Uncertainty to recuperate investments increases the investment risk and together with decommissioning of the existing plants may lead to a resource adequacy problem in energy-only markets.

Currently renewable energy is supported by various support mechanisms which will increase their number while the conventional capacity is also likely to be utilized less. Renewables still would require significant increase in capacity in order to meet future demand[3] as well as the emissions targets. High share of variable renewable energy (VRE) production can be accommodated with complementary flexible capacity (production, demand or storages) as the VRE does not contribute similarly to maintaining power balance or system reliability. Balancing/intraday adjustments are therefore likely to increase. 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 (DNV-GL, 2014).

Transmission infrastructure is in key role as market enabler. Increasing renewable generation often requires further transmission investments. The investment burden on penetrating RES can be allocated to society or to beneficiaries of the RES investment. In the network business the increase in distributed RES combined with demand side management will ultimately decline the revenue intake requiring them to increase rates[4] (or at least the fixed or capacity based portion of the charges) to recover declining usage. However, this may lead to a challenging cycle since an increase in customer rates over time to support investment spending in a declining sales environment will further enhance the competing technologies and supply/demand efficiency programs (Kind, 2013). This would lead to “utility death spiral” as there would be fewer customers remaining to support the costs of the infrastructure system. One solution to overcome the problems related to energy based distribution tariff is power/capacity based tariff. Power based tariff provides incentives to decrease the peak-power demand which would likely increase capacity utilization rate in distribution network. The result would be increased efficiency and decreased costs of the electricity distribution.

[3] Electricity demand is expected to be doubled by 2050 (Child and Breyer, 2015)
[4] Rates are usually a function of usage/unit sales

Part of the flexibility needed by the variable renewable production can be dealt with by demand response (DR). DR is a mechanism to compensate mismatches between production and consumption by reducing customer loads when needed. DR potential is expected to increase along with electrification of heat and transportation sector. DR reserves can participate in energy markets, capacity markets and in operating reserves similarly as power supplying plants. Also, by 2050 the technical development is believed to enable storing electricity both short- and long term basis. This will not eliminate the need to balance electricity supply and demand in real time, but storage has the potential to reduce the need for peaking and mid-merit capacity, and to ensure better use of other capital-intensive power plants (IEA, 2016). The following table summarizes some of the differences between fully renewable system and the present one.

Table 1. Summary of changes brought by the renewable energy in the electricity markets.

- Variable marginal cost for production decreases near zero
  - ✓ Merit order for demand-supply equilibrium changes and wholesale prices decrease
  - ✓ Cost recovery on new plants may be unfeasible
  - ✓ Investment signals are attenuated
- Increased volatility of production
  - ✓ Reduced security of supply (predictability)
  - ✓ Increased volatility of prices[5]
  - ✓ Changed load profile to non-variable plant
  - ✓ Dispatchable generation (hydro, biomass, energy storages) can recover high scarcity prices[6]
  - ✓ Need for balancing mechanisms is increased and subsequently their cost as VRE can offer fewer balancing services
- Generation relocation
  - ✓ Network topology changes
  - ✓ Congestion issues
- Small, scattered energy production
  - ✓ New market actors; prosumers, storage, demand response
- Need to redesign network tariff structures

[5] Negative prices will not occur in fully renewable system as there is no extremely inflexible plants (nuclear, lignite) (Winkler and Altmann, 2012).
[6] Scarcity effect is the price peaks, as fixed costs are recovered from a short period (Pöyry, 2011).

2.3 Market design with fully renewable system

In its current form the European energy markets may not be able to process 100 % renewable production (OECD, 2015; Vikk and Viiding, 2013) or to transmit energy without limitations from the networks[7]. The options for fitting advanced shares of renewables into the current market design are:

1) Introduce capacity mechanism
2) Improve existing trading
    a. in short-term or/and
    b. in long-term (medium-term)
3) Expansion of the transmission network
4) Introducing a new pricing mechanisms to replace the current marginal cost based.

The question is whether to develop energy-only markets instead of introducing capacity mechanisms (CM). Existing energy–only markets increasingly provide shorter investment signals which has driven politicians to push CMs so that security of supply is not left for market forces (Eurelectric, 2015). By increasing demand flexibility or developing ancillary services and financial markets, energy-only market may provide sufficient resource adequacy. Capacity markets have typically argued to be necessary for security of supply reasons. During transition phase towards fully renewable system capacity mechanisms provide a stable source of revenue for the producers but whether capacity markets along with markets for energy provide sufficient revenue in fully renewable market is unclear.

Increasing price volatility may shift the trade from day-ahead to balancing and real-time markets. Day-ahead markets and intraday markets may even merge (Norden, 2014). Market design that allows for more granularity over time and location, in the prices and dispatch, is able to integrate renewables better into markets (Hogan, 2010). Nevertheless, IEA (2016) expects that the energy markets will continue to be the main source of income for generators. Conventional generator will have the opportunity to receive payments from capacity markets and other ancillary markets if such exists but for VRE the prospects for participation may be slimmer. Changing to high time resolution (e.g. from hours to 15 min) enables trading close to operating hour and reduces the need for balancing operations. It also would ease the VRE and demand response participation in the markets. Allowing price spikes to occur has also been discussed as a solution for cost recovery but this would require hedging instruments. Improving short-time trading is beneficial to signaling investments, but they are unlikely to resolve the missing money problem. Improving long-term or medium-

[7] 80% of transmission network bottlenecks are related to the RES integration, but investments are also needed to enhance market integration and security of supply (TYNDP, 2012)

term markets, e.g. forward capacity markets would help investment climate and missing money issue (Lawrence and Cramton, 2010). The regulatory commitment needed to realize longer-term market functioning is a necessity.

Networks create the market place for electricity and trade is therefore limited by the restrictions of the networks. Expanding network would alleviate the variable production profile of the renewables as the opportunities for demand and production to meet are greater. Supergrid that would accommodate RES has been discussed in literature (Battaglini et al., 2009) but the current debate on the transmission network development has been limited to removing bottlenecks that impede trading.

Regardless of the market design, the (theoretically) optimal electricity market is a market where costs are minimized and all generation earn the market rate of return on invested capital. Market design should provide sufficient incentives for meeting demand and supply as well incentives for long-term capacity adequacy. In addition to the current energy-only market designs we have considered other designs that are considered likely to allow cost recovery in fully renewable electricity wholesale markets, selected from Winkler and Altmann (2012), Hartel et al. (2015) and Hogan (2010). Following table proposes market designs i.e. pricing mechanisms for wholesale markets, method for trading and the need for capacity mechanisms for fully renewable energy system. We discuss markets design options more closely below.

Table 2. Market design options for fully renewable electricity markets.

PRICING MECHANISM	TRADING	NEED FOR SEPARATE CAPACITY INCENTIVES
MARGINAL PRICING ZONAL	Exchange	Capacity mechanisms, add-ons
MARGINAL PRICING NODAL	Exchange and/or pool	Capacity mechanism, add-ons
DISPATCH BASED ON MARGINAL COST AND PRICING ON LCOE (LEVELED COST OF ENERGY)	Pool	No[8]
PAY-AS-BID	Pool	No
COST OF SERVICE	-	No
OVER THE COURTER TRADING (OTC) WHERE MARKET ACTORS DECIDE ON PRICING	Bilateral	No/defined by the state

[8] LCOE should in theory guarantee sufficient capacity incentives and therefore no additional capacity incentives are needed.

2.4 Pricing mechanisms

The most common pricing mechanisms used currently in competitive markets determine either a uniform marginal price, a few zonal marginal prices, or a set of nodal prices. Both zonal and nodal pricing apply the marginal pricing principle to determine the market price at a short-term (typically day-ahead) market. Marginal pricing directs the merit order to bring least marginal cost production first on line. The market price is formed on the basis of the marginal costs of the last production brought on line to satisfy demand, and it is the same for all forms of production and generators regardless of their bids and also for the demand side. Uniform price is formed unless there is congestion in the network. The difference between zonal and nodal pricing is that in the zonal markets trading is done only in energy markets. Nodal markets separate between electricity and generation capacity: Energy markets are used for trading electricity and to cover the variable cost of power production and capacity mechanisms cover the fixed costs of production.

Zonal pricing

Markets based on zonal pricing are typically known as energy-only markets. The primary market is the day-ahead market. Intraday market runs typically in hour intervals but there are discussions to shorten time-frame for better fit of VRE. Day-ahead trading is commonly done in extensive market areas that cover large number of producers that are 'price-takers'. If congestion occurs, market area is divided in predetermined zones based on network limitations. Within the price areas the price is uniform but can vary from area to another. Congestion inside the price area is allowed only in exceptional circumstances, and there has to be enough generators in the area. Internal congestions inside price areas cause a need for re-dispatching (rescheduling of generation or counter-trade), and repeated re-dispatching situations may enable the generators to game, which weakens competition in the market (Viljainen et. al, 2011). This model will be applicable if the transmission networks in the area are sufficient enough or necessary investments are being made, the borders of price area follow the physical limits of the networks, and there are enough competing generators in the area (Viljainen et al. 2011). If the price areas are large enough, the use of market power in the price area does not pose a significant risk. Market regulation, for instance company mergers and acquisitions, is carried out ex post.

The possibility of price spikes is a characteristic of the market; during the price spikes, the generators, especially peaking supplies, are able to earn money to cover some of their fixed costs (Wilson, 2000). Zonal pricing has in many European countries gone under review because of doubts whether it can sustain a market for larger share of renewables. Higher prices are set by fossil-fuel generators if RES are unable to cover full demand. Energy-only markets are theoretically able to provide adequate capacity in long-term but some have argued that energy-only markets are inherently flawed and need permanent capacity mechanisms (Cramton and Ockenfels, 2011). The market design can be corrected by introducing various add-ons, most commonly by capacity mechanisms, which are discussed later. The benefit of zonal model is that new (renewable) production is able to locate optimally without limitation from the network. The system operator is typically obligated to provide access to network for the new generation which allows RES to locate optimally.

Nodal pricing

Nodal pricing, or locational marginal pricing, provides detailed way to account for temporal and geographical price information about the transmission network constraints and marginal generation cost (IEA, 2016). The price is formed in each node and it is based on the power flows that take into account the marginal costs of generation, losses, and network congestion. Nodes represent points of the electricity system to which generation or load is connected. The number of nodes depends on the geographic spread of the market and the network topology. Nodal pricing is practically the only choice available, if there is scarcity of transmission capacity, and there are no intentions to invest sufficiently in this capacity because the market is local. If zonal pricing was selected in a situations like this, the price areas could become very small, or there could be congested lines inside the areas in any case. This would lead to inefficiency in the markets. In the short- term, pricing mechanisms simultaneously optimizes the use of the entire electricity system, consisting of the generation plants, the networks, and loads. In the long term, the fact that nodal prices contain strong signals to locate generation and demand may be beneficial in relieving network congestions. Wholesale market trading is done both in day-ahead and real-time markets. Real-time market runs both on hourly and five minute intervals (IEA, 2016). Short time interval has been considered to be more compliant with intermittent RES such as wind than the current EU market design (Borggrefe and Neuhoff, 2011), but the problem may be how to align transmission infrastructure investments with the generation facilities.

In nodal pricing, market regulation is carried out ex ante owing to the small size of individual submarkets; the control is also significantly stricter than in the zonal pricing model. The nodes have price caps, which the price may not exceed. Moreover, the bids of individual generation plants are monitored by various tests to prevent the exercise of market power. Detailed market surveillance can lead to the missing money problem for generators. Therefore it is quite common that the nodal pricing is joined with capacity mechanisms (e.g., in the

PJM and Russia). Price caps limit free price formation, and to guarantee revenues for existing generation and investments in the new generation, separate capacity markets are a necessity.

The key difference between zonal and nodal pricing lies in the method for calculating the price for electricity, as illustrated by Viljainen et al. (2011). In the zonal pricing model, the TSO is responsible for the main transmission grid to inform about the available transmission capacity, and the power exchange calculates the price for electricity based on the bids made by market parties. In the nodal pricing, the TSO is responsible both for the operation of the transmission grid and the electricity price calculation. In the nodal pricing, a major risk lies in the price differences between nodes caused by transmission congestions; this uncertainty can be hedged against by purchasing certain transmission hedge products, such as financial transmission rights. In zonal pricing model, electricity price volatility is one of the main risks for electricity traders. Common hedging instruments, such as forwards, futures and options, are used to fix a certain price level for electricity before the actual physical electricity trading takes place. Regardless of the market model, the SO is, in practice, always the body responsible for keeping balance between generation and consumption of power at every instant, which is a requisite for the system stability (Joskow, 2006). The following figure summaries the selection of the market model and the ramifications of that choice.

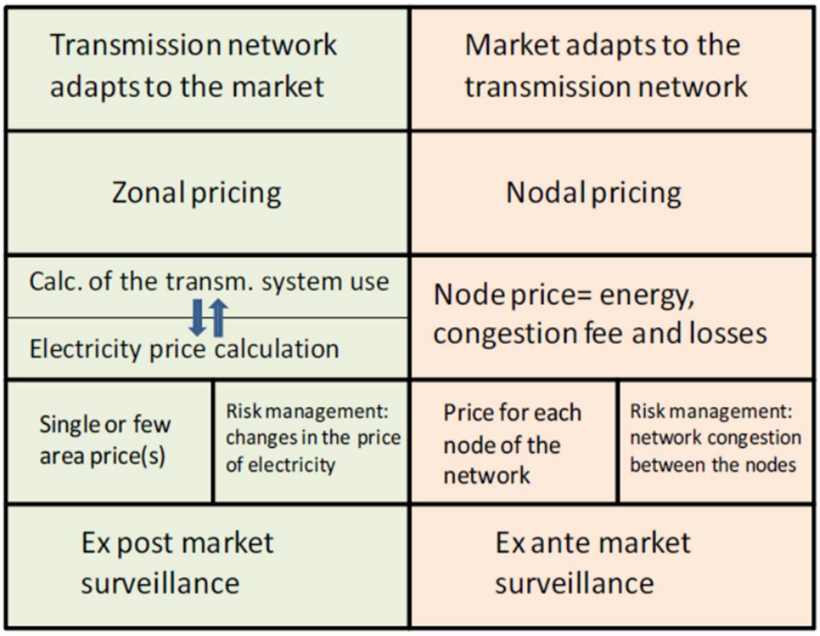


Figure 4. Electricity market pricing models (Viljainen et al. 2011).

Dispatch based on marginal costs and pricing on LCOE (leveled cost of energy)

Dispatch based on marginal costs and pricing on LCOE (leveled cost of energy) would change the wholesale pricing mechanisms by introducing complex bids. The dispatch of the plants would be organized according to rising marginal costs, whereas payments would be based on the average production costs. The system operator would be informed of the marginal as well as the average production costs of the market participants. This approach could lead to different problems. The information asymmetry between the generators and the market operator can be used to influence prices (Winkler and Altmann, 2012). This complex bidding system could also lead to inefficient plant dispatch and a disproportional increase of technologies with low marginal costs. Trading would most likely be done in the pool.

Pay-as-bid

An alternative method (to marginal pricing) is to define the merit order and the price of electricity using pay-as-bid principle (i.e. discriminatory auction). The producers are paid according to their offering price while the price for the demand side is an average of the generation bids (Tierney et al., 2008). It is assumed that market participants would bid to assure cost recovery. This method does not produce a common market price. The principle is likely to increase the uncertainty of the merit order making producers more likely to add risk premium to their offers: Suppliers' bids reflect their estimates of expected market prices, not marginal costs (Tierney et al., 2008). This leads to a higher average price level than in a uniform marginal pricing situation and possible inefficient dispatch of generators (Abid and Hurblut, 2008). Producers are also likely to dispatch more often to cover their costs. Trading would probably take place in pool rather than in an exchange.

Cost of service

Competitive markets are preferred because of their innovation incentives for generating facilities and the free choice of the consumers. However, according to OECD (2015) a lot of the investment in electricity worldwide is undertaken by vertically integrated utilities or under regulatory arrangements that do not rely on wholesale electricity markets. Pricing mechanism under vertical integration may be considered as cost of service where energy is priced based on the cost of providing it.

In some public considerations the issue of restoring vertical integration, i.e. state monopolies has been raised because of the complexity of the markets and heavy regulatory involvement. Restructuring did not deliver the promised price decreases (Sioshansi, 2008) which would justify nationalization. In vertical integration the state is responsible for efficient dispatching as well as adequate capacity investments. However, organizing decentralized and complex RES production can be difficult (Winkler and Altmann, 2012). On the drawbacks, Winkler and Altmann (2012) points out that state monopolies tend produce overcapacity as they focus on securing supply although according to IEA (2016) the cost of excess reliability cannot necessarily be considered relevant.

Over the counter trading

Supply demand can be arranged by over the counter trading (OTC). Bilateral agreements would secure production between market participants giving much freedom for the participants. OTC would require e.g. strategic reserves to be employed in order to guarantee capacity, depending on how dispatching is done (Generators could employ self-dispatching[9] (Barroso et al., 2005)). There would be a risk for market power abuse if the number of market participants is small. Also the question of arranging cross-border becomes an issue if markets are based solely on OTC.

2.5 Summary

There is no clear answer for what is the most feasible pricing mechanism for renewable markets. The IEA (2016), Winkler and Altmann (2012) and Borggrefe and Neuhoff (2011) consider that zonal pricing alone may not be the best match, but often requires new market mechanisms to accommodate increasing renewable share. The primary reasons are that the intermittent generation most likely increases network congestion and forecasting errors in the day-ahead timeframe which may lead to inefficient use of the networks (IEA, 2016). Also if the market design fails to account for physical constraints of the network such as in the zonal method, the security of supply may become at risk which would prefer nodal pricing. Most pricing mechanisms provide a uniform market price. The lack of common reference value impedes the efficient use of system resources and signaling preferred power generation. Electricity markets are needed to ensure that power plants and demand response resources are given an incentive to be available when their value to the system is highest (IEA, 2016). Winkler and Altmann (2012) points out that pool structure would be more advantageous with high RES because it would provide more liquid intraday market and simplify the market rules. Following table gives a summary of the characteristic of the pricing model discussed above.

[9] Self-dispatch means that generators decide on the dispatch of their own generating units under bilateral contracts models. Central dispatch of all generating units is related to mandatory pools. (Barroso et. al, 2005)

Table 3. Characteristics of pricing mechanisms.

	REQUISITES OF USE	TRANSMISSION CAPACITY	INVESTMENT INCENTIVES	MARKET POWER	RENEWABLES COMPATIBILITY
MARGINAL PRICING ZONAL	Sufficient transmission grid to establish single market area with common price and sufficient number of actors.	Congestion handled by SO who estimates the use of networks and decides on the zonal division. There is transmission capacity investment target to enhance grid so that single (or few) large market area can be achieved.	Market price and scarcity prices according to ascending marginal cost. Remunerative mechanisms for RES integration as a permanent fixture of market design.	Dividing markets into zones may affect competition. Countertrading can be seen as a subsidy to entrants in the zone with deficiency. Participation in complementary markets e.g. balancing market may cause gaming.	New generating plants can locate optimally without limitation from the network. Simple price mechanism. Extensive price areas → producers are price-takers. High share of RES lowers market price → e.g. capacity mechanisms for cost recovery.
MARGINAL PRICING NODAL	Suitable for network that is meshed and fragmented.	Potentially high grid congestion between nodes; new investments are not primarily to relief congestion (i.e. congestion is acceptable)	Pricing mechanism provides investment signals for locating generating plants but price caps set due to market surveillance may create a need for capacity markets.	Local market power issues in each node creates a need for constant monitoring.	New power plant investments should be located to deficit nodes as transmission investments are not prioritized according new plants. Optimal dispatch and use of system.

DISPATCH BASED ON MARGINAL COST AND PRICING ON LCOE	Sufficient knowledge on power plants' cost structure.	Requires some method to trade transmission capacity (explicit/implicit method and SO) and investors to guarantee transmission capacity investments (TSO/merchant).	Generators can cover all the costs → supports investments.	Enough market participants and transparent market needed. Information asymmetry issues.	Low marginal cost have priority in dispatch. Guarantees cost recovery for investments.
PAY-AS-BID	Need for new generating capacity.	New investments by TSO/merchant.	Generators can cover all costs in pricing procedure which would imply no separate add-ons are needed.	Enough market participants needed. Risk of overpricing. High capex and low opex or marginal costs have an incentive to dispatch as often as possible.	Can support RES if all kind of generation can cover costs.
COST OF SERVICE	State control implies distrust in the functioning of markets.	SO decides and invests.	State defines the needs and guarantees new investments. State control may result in overcapacity.	Controlled by the state.	Can support RES if all kind of generation can cover costs.
OTC	Sufficient amount of market participants to avoid oligopoly/monopoly.	TSO/merchant transmission capacity investments. Explicit transmission capacity method in cross-border trading.	Generators can cover all costs but state can also guarantee some investments (security of supply).	Small number of market actors can cause market power abuse.	Bilateral trading gives opportunities for full cost recovery for all generation types.

2.6 RES support policies

Large scale deployment of renewable technology is mainly result of the support policies. Support policies increase the profitability of new low-carbon technology but also increase the regulatory intervention in the markets. There is generally two main policy options considered for fully renewable markets: wholesale electricity markets with strong carbon price (e.g. emissions trading) or technology-specific policies and regulations (IEA, 2016). The current support policies either increase the revenue for selected energy sources or set a quota to be met. The prices of RES technologies show decreasing trend making them comparable to conventional technology and eligible for competition (Child et. al, 2015). That being said, some subsidies mechanisms may be a permanent addition to the market design. Different renewable energy subsidies are briefly illustrated below, adapted from Hogan (2010) and Hartel et al. (2016). For more on the differences between schemes, see e.g. Winkler et al. (2016).

Table 4. RES subsidies.

EMISSIONS TRADING SYSTEM (ETS)	'Cap and trade system'. Total amount of greenhouse gases are capped for emitting entities and the cap is reduced in time. Emissions permits are traded in markets after allocating or auctioning.
GREEN CERTIFICATES	RE producers receive certificates according to their actual production and can sell them in a special market or directly. Purchasers have quota obligation as a predetermined percentage of their electricity sales or use.
FEED-IN TARIFFS (FIT)	Producer of a given RES technology is entitled to dispatch all generated power to the grid at fixed, constant payment Typically set for extensive periods (10-20 years).
FEED-IN PREMIUM	Producer is guaranteed to receive electricity price + premium for produced electricity (fixed premium). The premium can vary according to electricity price (sliding premium) or can be capped and floored.
GREEN UNECONOMIC DISPACT	Changing the merit order for production by preferred order. Effect on market design disruptive.
TECHNOLOGY-SPECIFIC AUCTION	Auction establishes a maximum price for particular technology investments. The level of support determined competitively.
TAX INCENTIVES	State promoted RE through direct or indirect fiscal incentives for the producers. Tax credits can be sold to third parties (production tax credits).

2.7 Capacity mechanisms

In an energy-only markets investors expect return that provides adequate cost recovery and, without regulatory intervention such as price caps, this could be achieved (Newbery, 2016). RES typically decreases the price level in the electricity markets and creates concern over capacity adequacy. If markets fail to attract sufficient capacity to the markets, capacity mechanisms may be introduced. Capacity mechanisms have been designed to strengthen investments incentives, risk mitigation, market abuse power mitigation or a necessary addition to energy markets in long-term market design. Main advantage is that if capacity adequacy is secured, the risk of outages is reduced as well. Capacity mechanism also ensure the profitability of the existing power plants and guarantee or at least support investments in new power plants.

European Commission (2015) distinguishes six categories of capacity mechanisms which can be grouped to targeted and market-wide mechanisms. Targeted mechanisms focus on the additional capacity that will meet the capacity requirements expected by the markets. In market-wide mechanisms capacity, both existing and new, that ensures security of supply receive payments. Both targeted and market-wide mechanisms can be further split between volume-based and price-based intervention, see figure below. A price-based mechanism incentivizes investments by providing direct support for investments in the form of capacity payments. In a volume-based (or quantity-based) mechanism, regulator sets a desired amount of installed capacity, and the price evolves from the market clearing.

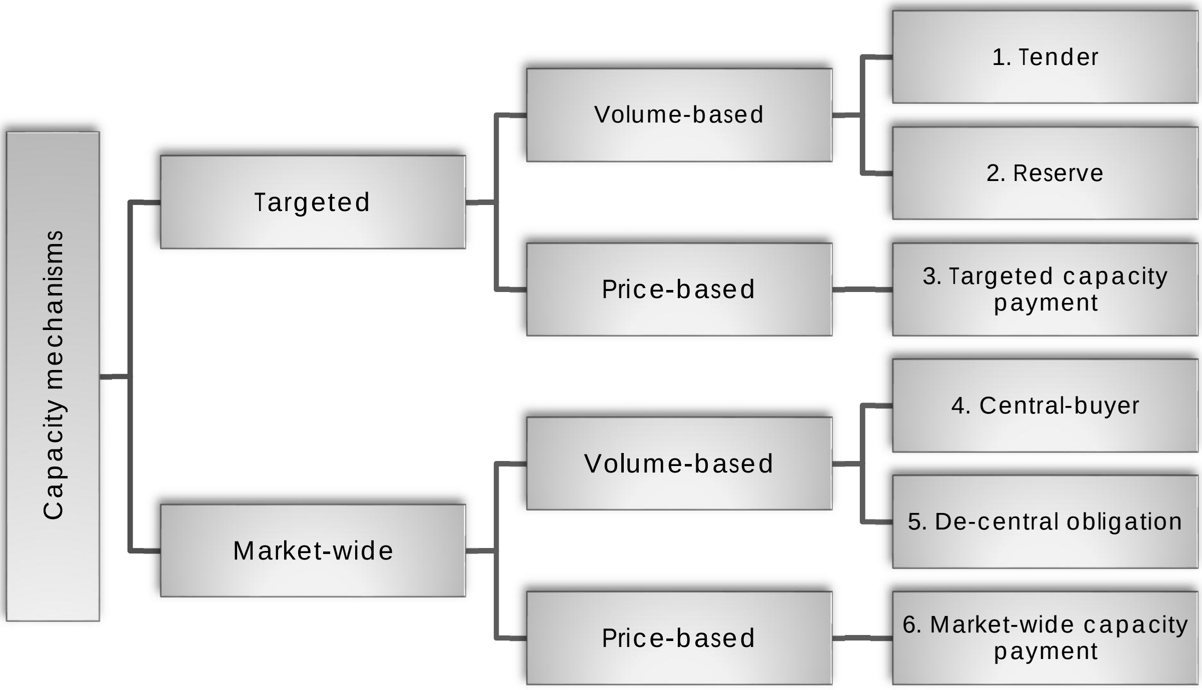


Figure 5. Classification of capacity mechanisms (European Commission, 2015).

There are further variations beyond this listing. Often the term *capacity markets* is used when employing following capacity mechanisms: capacity obligations, single buyer (auctions) or reliability options[10]. They also provide the markets long-term investment signals better than other mechanisms. Centralized capacity markets are implemented in the US, by PJM and ISO-NE, and in Colombia (Pfeifenberger et al., 2009). Capacity markets are often compulsory for all market participants. Capacity mechanism have been considered and implemented within EU internal energy market. Currently there are no harmonization between different mechanisms and countries have proceeded based on their individual needs.

New elements in the market design are always a potential source of risk and CMs are no exception. For example, generators may engage in withholding capacity and thereby manipulating prices in the short-term. Another disadvantage is that a CM may lead to a sub-optimal volume of generating capacity (most likely overcapacity), a risk that must be weighed against the risk of under-investment (De Vries, 2007). The combination of different support mechanisms as well as storage technology development and/or demand flexibility may also lead to excess capacity. Most of the CMs also require that the regulator has to

[10] Reliability options are a quantity-based, market-wide capacity mechanism which aims to secure capacity availability at times of scarcity. The TSO or the regulator purchases call options (reliability contracts) from generators on behalf of consumers. The option is called as the spot price is higher than strike price and the generator pays for the difference. The volume of reliability options subject to procurement is defined usually as a forecasted peak demand plus the reserve margin

address the level of required capacity during peak load periods and the extent of demand side participation which may prove difficult. Renewables in capacity markets receive lower capacity value on account of their intermittent production characteristics which may present problems for larger RES shares.

Cross-border trade

Efficient cross-border trade facilitates the efficient use of resources and an increase in the social welfare. Sharing of resources enables consumers in high-cost regions to have access to low-cost electricity generation in other regions. This results in a more efficient use of resources and increases the probability that the demand is met by the least-cost production. Moreover, opening the national markets to foreign participants would enhance market competition and strengthen the security of supply (Creti, 2004).

Varying capacity market models in adjacent market areas may hamper efficient cross-border trading. Capacity payments in another market area can be so high that they prevent the trading across the border even though the day-ahead electricity prices could justify the trades. Capacity mechanisms may in the worst case discard cross-border capacity and cross-border trade, thereby introducing new market distortions (Tennbakk et al. 2013). The degree to which individual capacity mechanisms could impact the cross-border trade depends on the degree of interconnectivity between markets, the correlation of prices and scarcity situations between the markets, and coordination on the possible cross-border impacts with the neighboring market (ACER, 2013).

2.8 Risk distribution between actors

Different market designs and policy instruments allocate risks differently. For instance, CO_2 price risks, renewable deployment, fossil fuel and demand risks all have an impact on the outcome of wholesale market price risk, and it is usually not possible to assess these risks individually (IEA, 2016). The introduction of new policies and market mechanisms are always a potential source of risk. Generally, moving from a regulated environment to a market-based approach considerably raises the risk to which investors are exposed (IEA, 2014). The risk borne by the ratepayers similarly decrease. The purpose of support policies is to lower the investor risk to initiate low-carbon production. As the increase in investor's risk increases the cost of capital, risk level has a clear impact on the price of the electricity generated by RES, where capital costs are dominating cost parameter. Risk is affected by the design of support, see Fig. 6. Auctions often provide long-term power purchasing agreements that lower the generator's risk. Also, feed-in tariffs are relatively low risk for the power producers because they offer fixed price and sales volume for a given time period. Subsidies on top of markets revenues (such as tax incentives or market premiums) generally leave more risk exposure.

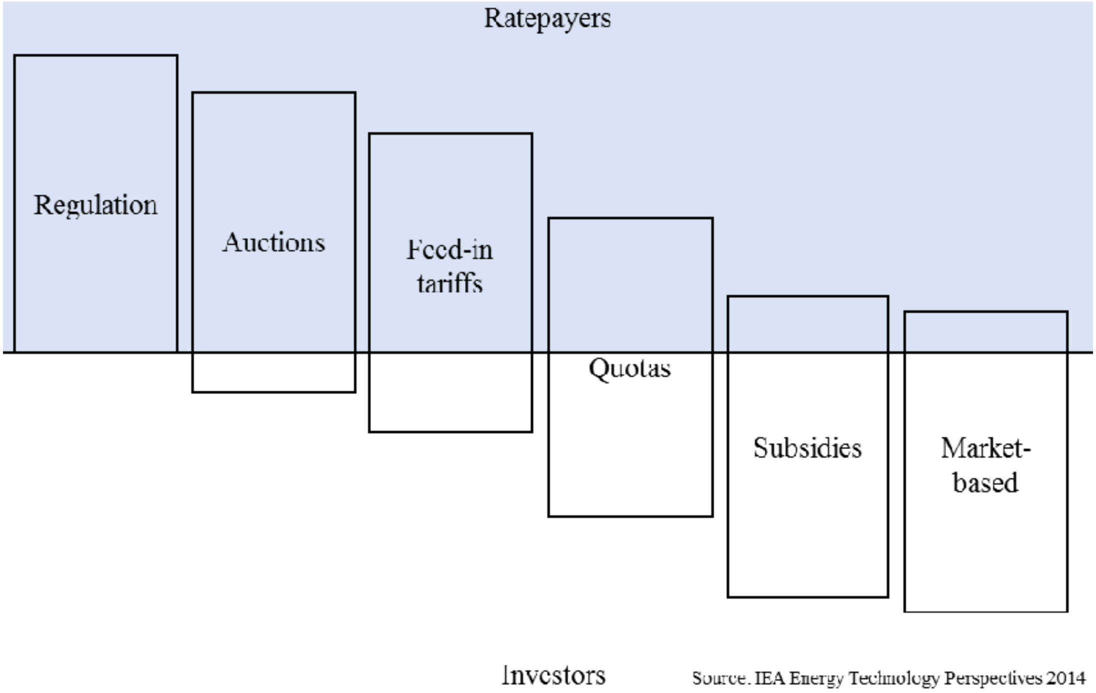


Figure 6. Support policies and risk distribution (Supponen, 2014).

The risk exposure between different market designs also varies. In cost of service pricing state, i.e. the ratepayers are the owners bearing all the risk. In zonal and nodal markets the risk is allocated to investors but the situation may vary depending on support mechanisms or capacity mechanism. Long-term purchasing agreements that can be used in OTC trading also transfer some of the risk from the investors but not all. Pay-as-bid would also leave much risk to ratepayers but the investor risk would be significantly reduced to spur investments.

3. MARKET DESIGN BUILD UP FOR TRANSFORM-ATIVE SCENARIOS

The transformative scenarios in Heinonen et al. (2015) describe who or what the actors are in the neo-carbonized society in 2050 and are they motivated by technologically enabled push, a pull from ecological awareness, a pragmatic approach or a need from external factors such as ecological collapse (see also Appendix 1 for Energy issues in scenarios). 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 set out what kind of electricity markets in year 2050 would be, the process for market design is performed top-down. First we look what are the required elements of the market design that enable each scenario – what kind of market elements are possible in each scenario? We categorize approaches on electricity markets for each of the transformative scenarios by simplifying the market design to the following key questions:

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?

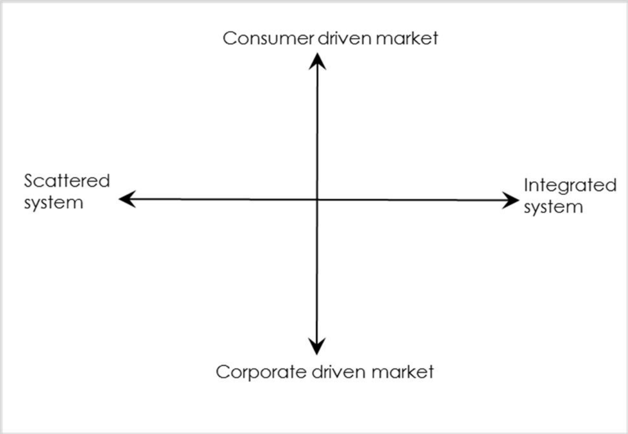
How is the needed generation and transmission capacity obtained?

- Axes: Does the network adapt to the needs of the market or markets to the limits set by the network?

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. 7. We have placed the scenarios on the axes and discuss the approach in more detail below.



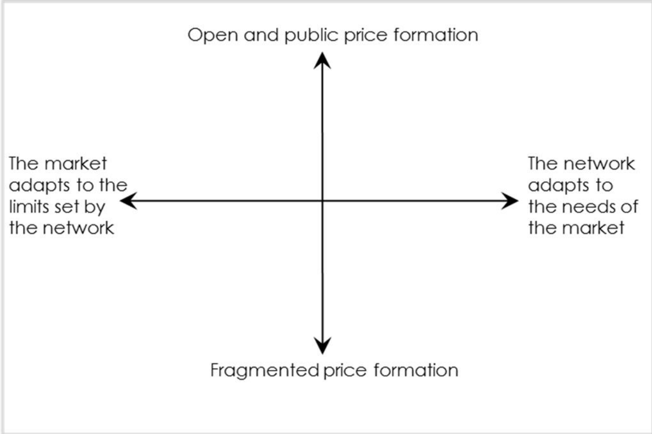


Figure 7. Framework for market design.

3.1 Market design approach #1 – consumer activity and energy system 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 investments 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 central led system planning. The four transformative scenarios are placed on axis labelled consumer activity and energy system design to illustrate the forces of market development.

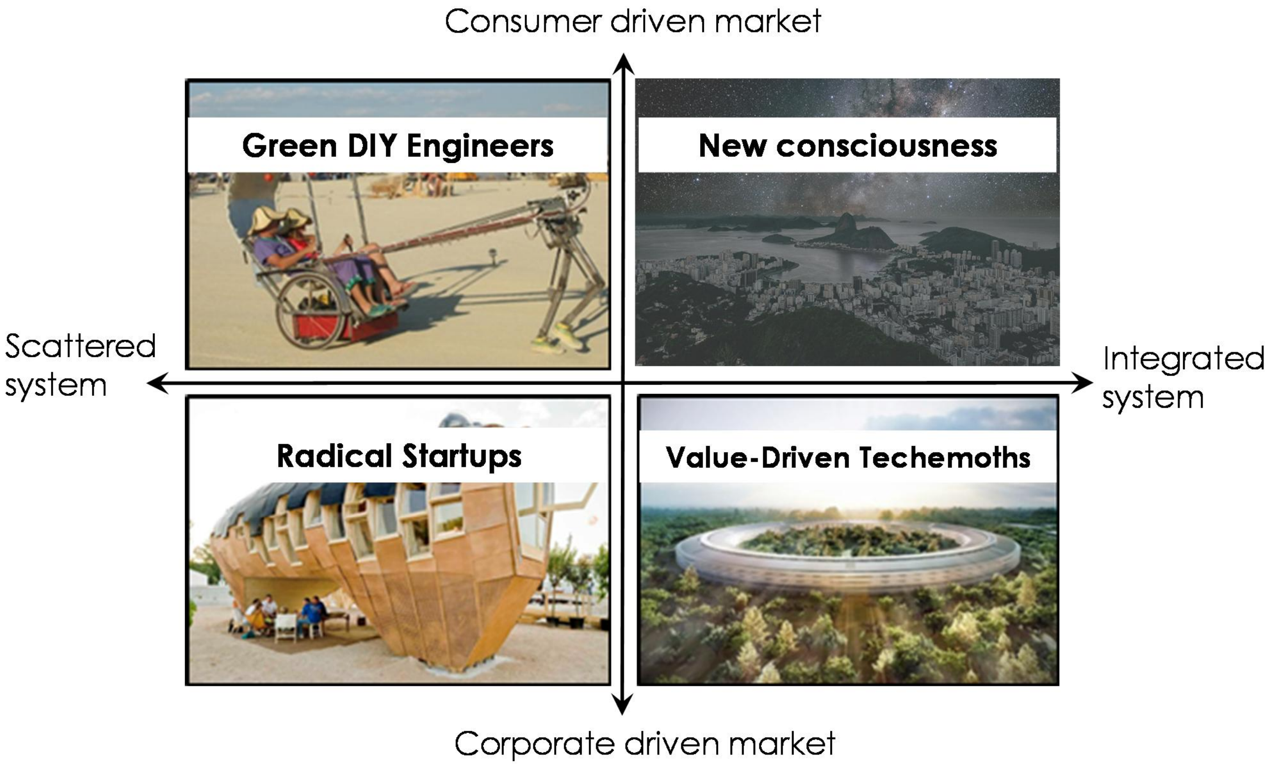


Figure 8. Market design approach #1: Energy system for consumer activity and energy system design.

Next we link the market design options from Table 2 to scenario descriptions using above approach.

- Integrated system refers to energy production system that is used, planned and led centrally. Integrated energy system enables particularly the use of zonal, nodal and cost of service methods.
- Scattered system accordingly refers to the distributed (and small-scale) energy system where dispatch management can base on market mechanisms or bilateral trade. In these cases nodal, PAB and OTC would be preferred.

- Consumer driven market. The market development is driven by the consumers need rather than the corporates'. Customers are allowed to participate the markets directly or by representatives. The most extreme case would be microgrids or customer-scale production and more typical case in present energy markets would be public ownership. Zonal, nodal and OTC methods can particularly accommodate small participants whereas cost of service pricing would be suited for vertically integrated energy services.
- Corporate-led markets have more leeway on the method, allowing most of the methods under consideration. Companies participate in the markets to make profit and drive market development.

3.2 Market design approach #2 – balance between generation and consumption

The second market design illustration takes more traditional approach to market design (adapted from Viljainen et al. 2011): 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. The four transformative scenarios are placed on axis labelled price formation and capacity adequacy to illustrate the market functioning.

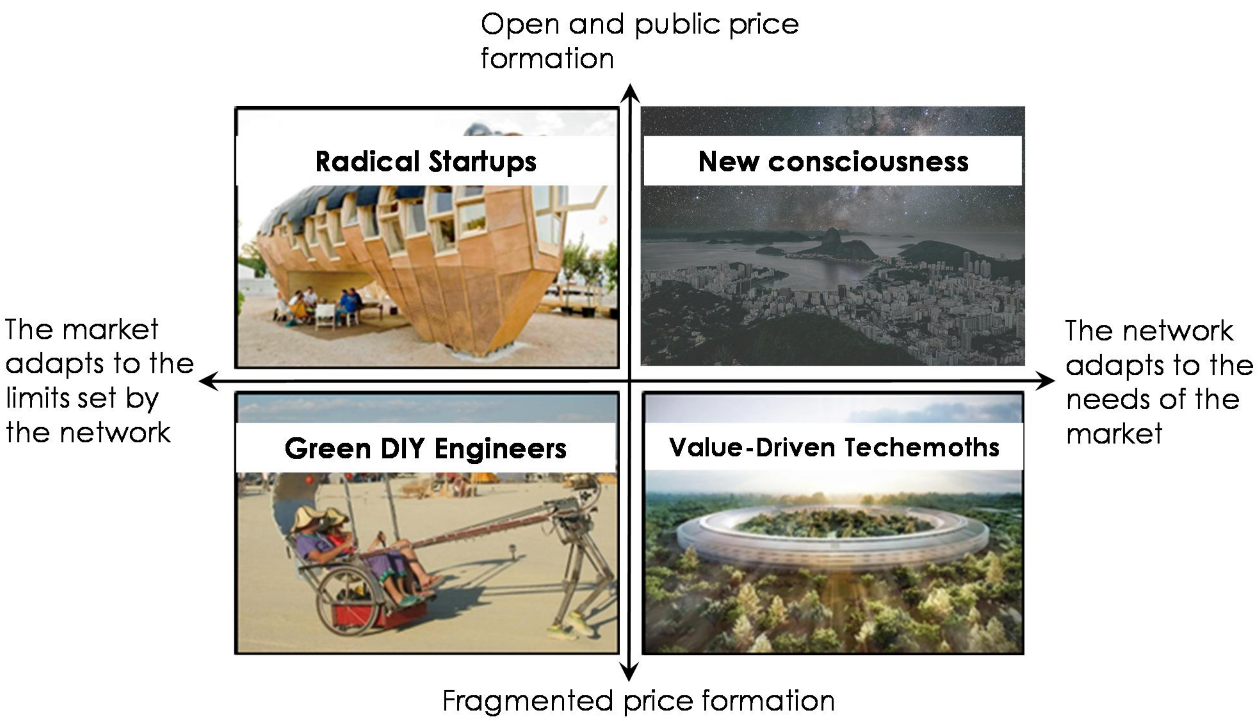


Figure 9. Market design approach #2: Price formation and capacity adequacy.

Next we link the market design options from Table 2 to scenario descriptions using above approach.

- Open and public price formation translates into liquid exchange and market design that enables large scale participation of diverse actors, e.g. small-scale producers. Zonal and nodal would in particular enable these.
- Fragmented price formation associates to bilateral or non-liquid markets such as in OTC, MC & LCOE and PAB. In these situations there also may be need for strong investment incentives that MC & LCOE and PAB provides.

- The market adapts to the limits set by the network. In ideal situation networks do not limit the power flow. In reality, network congestion limits the market areas and even the choice of market design. In highly congested network, market functioning may be affected and markets have to adopt to the network constraints. 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.
- Network adapts to the needs of the market. 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. Large markets areas are usually needed to gain sufficient number of market participants (especially generators) so that markets do not develop too concentrated. However, inside broad energy regions where the price is uniform congestion can become hidden and market signals for investments are weak or absent (Hogan, 2010).

4. ELECTRICITY MARKETS IN NEO-CARBON SCENARIOS

We have based out analysis of market design on the Neo-Carbon Energy scenarios in 2050 and particularly Energy issues in the scenarios, see Appendix I. Following table is a synthesis of Neo-Carbon Energy researchers' views on scenarios set-up differences, for more information on scenario differences see Appendix 2.

Table 5. Scenario set-up information.

ENERGY PRODUCTION AND CONSUMPTION STRUCTURE	RADICAL START-UPS	VALUE-DRIVEN TECHEMOTHS	GREEN DIY ENGINEERS	NEW CONSCIOUSNESS
CENTRALIZED/ DISTRIBUTED	Distributed energy system, Scattered system	Centralized solutions, large-scale, Integrated system	Highly distributed energy system, Scattered system	Distributed-centralized, Integrated system
SHARE OF SOLAR/WIND	From high to very high	From medium to high (limited by high potential for centralized solutions)	From medium to high (limited by high potential for traditional biomass)	From high to very high
P2G OPTION	Small-medium scale P2G	Centralized P2G	Small-scale P2G	Centralized P2G/ small-medium-centralized P2G
DEMAND RESPONSE	Advanced automation	Advanced automation	Manual demand response	Advanced automation
TRANSMISSION BETWEEN AREAS	Interconnected with areal bottlenecks	Strong interconnections	Weak interconnections	Strong grid
BIOMASS USE	Consumer-driven small and medium scale circular economy	Advanced bio economy, circular economy by advanced technology	High utilization in traditional uses and by traditional, small-scale technology	Global circulation economy, high recycling rates
ENERGY MARKETS				
ENERGY MARKET INTEGRATION	Integrated markets	Corporate-sized self-sufficient energy systems, integrated markets	Localized markets, limited energy trade	Global markets
CO_2 POLICY	At least regional policies	Global CO_2 agreement	No climate agreement	Global CO_2 agreement
ENERGY, CLIMATE, AND INNOVATION POLICIES	Regional policies	Minimal regulations, market-orientation Industry-driven innovations	Self-sufficiency targeted Communities regulate themselves	Global energy and climate policy Global, efficient innovation policy

We have considered the general applicability of each market design in each of the scenario descriptions, see Table 6.

Table 6. Scenarios' market design assessments.

PRICE MECHANISM	RADICAL STARTUPS	VALUE-DRIVEN TECHEMOTHS	DIY ENGINEERS	NEW CONSCIOUSNESS
MARGINAL PRICING WITH ZONAL (ZONAL)	◑	◑	○	●
LOCATIONAL MARGINAL PRICING (NODAL)	◕	◔	◑	◕
PAY-AS-BID (PAB)	◔	◔	◑	○
MARGINAL COST BASED DISPATCH AND PRICING ON LCOE (MC & LCOE)	○	◑	◑	○
COST OF SERVICE (CoS)	○	○	◔	●
OVER THE COUNTER TRADING (OTC)	◔	◕	◑	◔

○ Not at all suitable

◔ Slightly suitable

◑ Moderately suitable

◕ Very suitable

● Extremely suitable

Given the framework for market design described in the previous chapters the following market design sketches have been drawn (mainly concerning the EU region).

4.1 Radical Startups

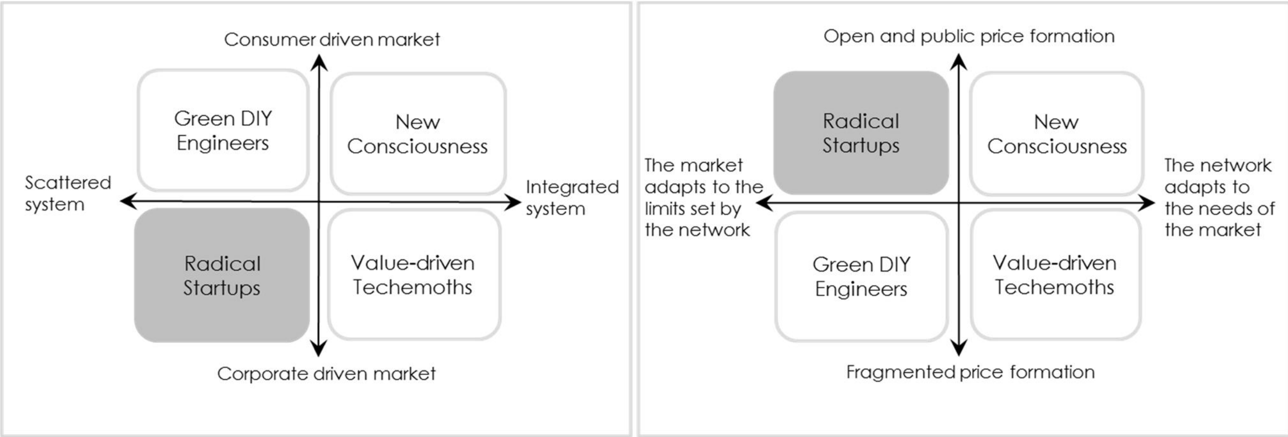


Figure 10. Market design framework in “Radical Startups” scenario.

World of radical startups provide consumers ubiquitous smart technologies with carbon-negative business models. Startups are active in the field of power generation, power aggregation, sales, and energy storage etc. using novel small-scale and medium-scale technology solutions. Technology development on renewables production and storage has made power generation scattered and reduced the size of generating facilities. Energy systems move towards distributed and prosumer type of behavior, where consumers self-produce a major part of their energy and centralized energy production has only a marginal role. The customers will to participate in cleaner energy production is not necessarily driven by cheaper energy supply but ecological values. This has led to electricity markets co-driven with users and startups.

Electricity networks are developed at national or region level to optimize the utilization of smart distribution infrastructure and demand response. SOs lead the network optimization. Electricity markets are integrated but the lack of investments have led to bottlenecks in the networks that limit the market integration. Cross-border connections provide regulating power for the scattered energy production. For electricity markets that have to adapt to the limitations of the network development, nodal pricing method would probably be best suited. Nodal method would also optimize the use of regional energy sources and transmission capacity efficiently to avoid the congestion that is caused by large share of renewables. The combination of wholesale markets and capacity markets are used to signal for new generation facilities and the main market is intraday/balancing market. Ubiquitous ICT, advanced automation and smart pricing enable significant volumes of real-time (local) energy trade between small-scale consumers and producers. However, consumers still acquire some amount of the power from the markets. The role of energy market regulator is fairly strong in protecting the interest of consumers. International emissions trading has not fully taken effect but startups are committed to offering emissions free solutions.

Major topological changes have occurred in energy distribution, as consumers have relocated to cities leaving rural areas unoccupied. The absence of investments in infrastructure combined with the enabling role of the startups has led to a situation where the monopoly status of distribution networks has been weakened or at least there are regional differences in the responsibilities assigned to distribution companies. Startups have stronger role on account that electricity distribution now have de facto substitutes (customers' own generation and storage provided by startups compete with network connection). Customers' role has become so strong that electricity distribution companies need to offer more services to consumers in order to keep them. Distribution companies have, in fact adopted the role of investors. Startups draw investments leaving little room for traditional energy sector actors (e.g. electricity retailers). Startups use new financing opportunities[11] to electrify rural areas are emerging.

Demand for energy is relatively high, although housing is zero-energy. Wind and solar energy are mainly used as energy sources but also biomass is available for consumer level producers. Integration of solar and wind with smart utilization of heating/cooling and transportation sectors increase their economically feasible potential. This enables solar and wind power production to reach high levels. Customers are able to participate in demand response through markets mechanisms.

Pathway to Radical Startups scenario

2020:

- Support policies for renewables and energy efficiency are developed towards market-based solutions. They boost the stagnant energy investments.
- The impact of international climate negotiations is not as effective as thought. Nevertheless, e.g. Finland is to become carbon-neutral by 2050.
- Customer are demanding more action from the energy industry to deliver emission-free energy.

[11] http://www.bloomberg.com/news/articles/2016-01-12/african-sunshine-can-now-be-bought-and-sold-on-the-bond-market

- External costs are included in consumer prices, which offers startups competitive advantages in relation to traditional, less green businesses. Small-scale energy production is booming.
- TSO are reluctant to make necessary transmission investments to fully integrate the markets and congested grid makes the use of zonal pricing complicated. Also, some countries have difficulties in adjusting to increasing share of VRE as their existing generation asset are ageing and they make the decision to switch to nodal pricing in order to secure reliability[12].

2030:

- Startups are increasingly taking over some of the responsibilities in electricity supply. Larger energy companies lose their markets shares, medium and small sized companies are dominant in the electricity markets.
- Customer are demanding more from their energy suppliers, in fact more that the industry is prepared to deliver. Start-ups fill the cap and gain ground in the energy field.
- Electricity prices become volatile.
- Regional independent System Operators are established to handle the grid/price calculations.

4.2 Value-driven Techemoths

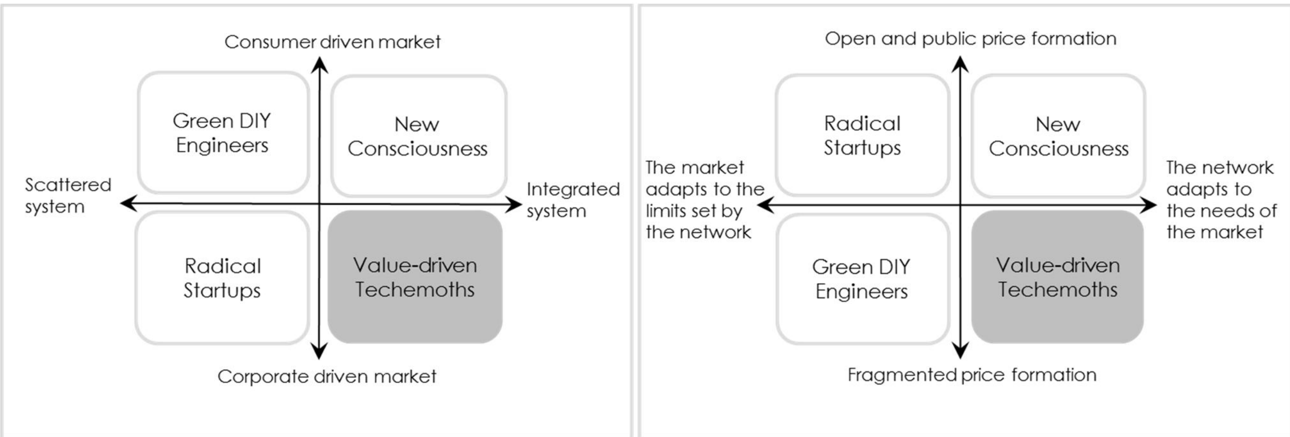


Figure 11. Market design framework in "Value-driven Techemoths" scenario.

12 See for example the Polish consideration on swithcing to nodal pricing: http://www.elforsk.se/Documents/Market%20Design/conference/2011%20Papers/11_Sikorski.pdf the ERCOT, Texas experience on switching form zonal to nodal: http://www.fortnightly.com/fortnightly/2007/09/best-little-nodal-market-texas?page=0%2C1

In this scenario large corporations, Techemoths, have become the new version of utility organizations that are active in energy generation, storage, sales, transmission and distribution and also providing services in housing, transportation etc. Energy services are included in corporations' products and services. Energy is produced in centralized, large scale solutions run by the Techemoths. They provide services for consumers within their sphere of influence making the most out of modern technological development and the data accumulated to them (big data). Despite the dominant market positions, Techemoths act as hubs for individuals' shared projects, making Techemoths in the frontier of R&D. The energy platforms that Techemoths offer are company-specific, so buying products and energy in a bundle is typically the only option. All-encompassing presence of the Techemoths has weakened the role of national regulators. There is global CO_2 agreement and the price for CO_2 is high but in general the energy sector is market-orientated with little regulation.

The dominating role of the Techemoths has diminished the relevance of electricity markets in providing energy services. Significant part of energy supply is done outside the markets. Where markets exist, majority of trade can be done bilaterally, over the counter. Also, Techemoths build and produce major part of their energy to their own use. Techemoths invest in needed generation capacity, to ensure that there is enough low-cost energy, which enables the selling of their other products (similarly as why Google invests to new computing centers). If Techemoths operate only regionally and there are other market players, zonal pricing with capacity mechanisms and add-ons could provide incentives for Techemoths participation in the markets and in providing sufficient security of supply. Zonal pricing allows locating power plants optimally according to energy sources available and given the extensive network, and can operate with minimal regulation. There is however a need for TSO that builds and operates interconnections. Marginal cost based dispatch and pricing on LCOE would also give large corporations leeway on pricing electricity to cover expenses and it would produce incentives sufficient generation capacity. On the other hand, the role of SO/TSO would probably be stronger. Although transmission pathways are fairly well-established in this scenario, the public infra is in many cases being neglected as Techemoths may have an interest to build their own networks without bottlenecks.

Distribution networks in cities are mainly within Techemoths sphere of influence and are being developed to serve Techemoths needs. Spot pricing[13] in electricity distribution does not exist anymore. Consumers produce their own energy only if they are compelled to do so for ideological reasons (do not want to participate in Techemoths' operation by giving them

[13] uniform price, which is not depending on geographical location of customer, similar as postal stamp tariff system

their personal data) or out of necessity (consumer is located out of Techemoths sphere). Governments require some energy services to be delivered to customers in rural areas outside Techemoths reign. The disparity between customers has however led to price and quality differences based on location and status as there is absence of strong independent regulatory influence. States provide some capital and sureties to newcomers in energy production, to mitigate the power of large corporations and to provide utilities services people outside Techemoths influence.

Pathway to Techemoths scenario

2020:

- Integration of EU electricity markets proceeds steadily and there are coordinated transmission capacity investments made at EU level.
- Energy companies struggle to find new business opportunities as the electricity price remain low and consumption decreases.
- Large technology corporations increasingly invest in own renewable generation.
- Although household solar and wind generation is growing popularity, more often people buy or rent shares of large wind and solar farms.

2030:

- As markets are fully coupled, there is only one power exchange in the Europe. Techemoths eventually will be dominant market participants hampering the market development severely.
- ICT-Techemoths start gaining ground from the energy sector giants. Techemoths have gathered comprehensive data from their customers which allows them to optimize energy use. The benefits from big data use are seen greater than the loss of functioning electricity markets. Regulation in the energy sector is reduced.
- Techemoths' influence has made the societies fully renewable. Techemoths start to offer services that incorporate housing or transport where the energy is included in the services.

4.3 Green DIY Engineers

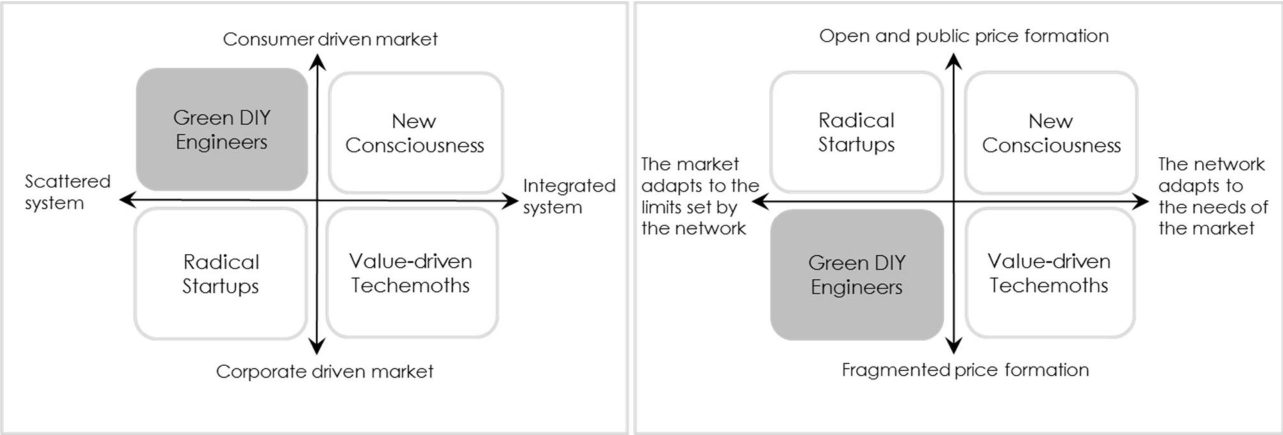


Figure 12. Market design framework in “Green DIY Engineers” scenario.

The DIY Engineers –scenario is perhaps the most radical one. Ecocatastrophe that has taken affect globally has changed the way energy is being produced and transmitted. The energy system is scattered and led by individuals in their communities.

Network interconnections between communities are weak or useless and generation assets obsolete because of climate change that has forced people and infrastructure to relocate. This set up enables the birth of numerous microgrids that would otherwise be too expensive to retrofit. The electricity system is therefore based on highly local, practical solutions where the existence of markets is not meaningful. If there are no organized markets, the approach taken by the communities is to invest based on needs rather than market profits and to rely on OTC when needed. In order to build extensive common markets, large investments in energy infra should be made. Additional market mechanisms could be used in order to incentivize the investments, but for highly local markets they can be considered too expensive and difficult to use. Networks would be built by regional SO or merchants. One suitable pricing model for limited market areas is nodal pricing. It can be executed locally but it requires constant market monitoring. In practice, every micro-grid is a separate node in nodal pricing scheme. Smaller market areas can lead to price spikes and misuse of market power. PAB or MC & LCOE-model could also be used to incentivize capacity investments in highly scattered system whit scarce investors.

Energy is produced and used on site, which means that the electricity distribution networks have been modified into smaller stand-alone micro-grids[14] run by communities. Energy is

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[14] Microgrids are generally defined as low-voltage networks with distributed generation sources, together with local storage devices and controllable loads.

used efficiently and energy solutions are affordable. Consumers are willing to endure quality shortcomings in electricity supply, to ensure the low cost of the electricity. Readily available energy storages for different uses mitigate the intermittent electricity supply and quality fluctuations.

Pathway to Green DIY Engineers scenario

2020:

- Local energy communities' movement continues to gain ground (Yildiz et al., 2014; Marsh, 2014). Similar development is witnessed in national level: Energy self-sufficiency is becoming more important and national energy policies diverge. Transmission networks are not developed sufficiently. Finnish energy production increases the share of bioenergy sources.
- Taxation is removed from renewable energy, which drives the national energy transformation.

2030:

- As more people decide to leave the network and become prosumers, rest of the customers bear increasing cost of distributing energy. As a result, even more customers will go off-grid. Unstable situation aggravates the reliability of electricity supply and the development of integrated networks. Experimental microgrids and decentralized energy system are challenging the traditional network design.
- Aim for energy self-sufficiency is continuing on national and household level - either as a choice or out of necessity.
- Energy storages are becoming common and enable decentralized energy systems. They have become a central part of providing security of supply.
- Once the climate change is beginning to erode the basis for energy system infrastructure, necessary network investments have not been done. Integrated network development is seen unmanageable as there is a large need for new power generation. Zonal marginal pricing is not seen suitable for virtually rebuilding the energy system and managing extreme congestion.
- Communities become the main actors in the field of energy. Common markets are not required as system is decentralized (lots of small and local generation units) and local trading can be done bilaterally.
- Cross-border transmission is minimal.

4.4 New Consciousness

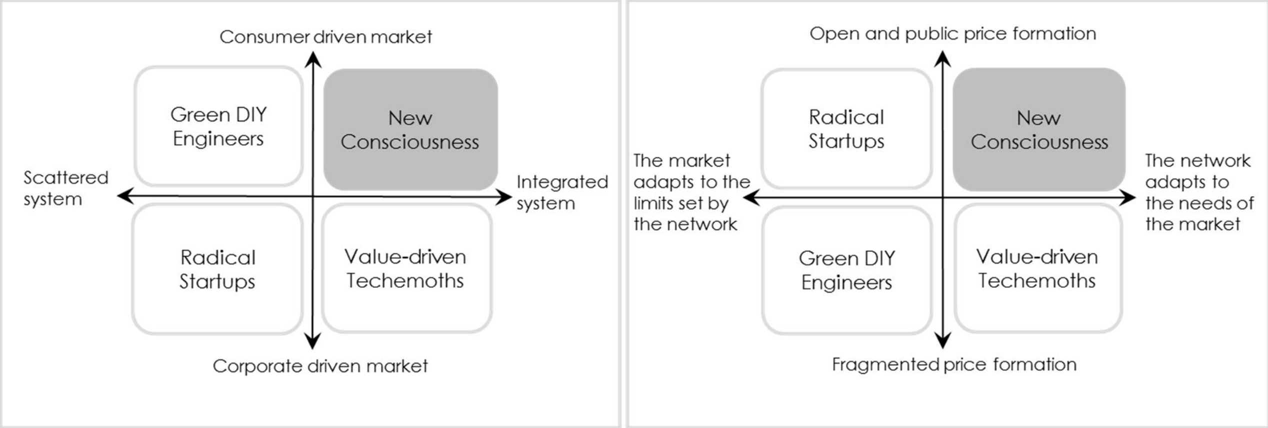

Figure 13. Market design framework in "New Consciousness" scenario.

The New Consciousness –scenario has strong ecological awareness that has spurred the building of strong interconnected network and optimal production capacity and use[15]. Transmission networks are ideal and deeply interconnected with very few congestion in the system. The development of networks is led by independent system operator (ISO) to balance production and demand. ISO also owns the network assets and allocates the cost of network investments. In New Consciousness society energy is produced where and when it is the most cost-efficient, and demand response is automated so that energy is consumed as little as possible. In practice, this means that states have taken over the energy supply. Energy systems move to a direction showing characteristics of both distributed and centralized nature but energy system optimization is centrally led. Support policies have been removed from all power generation and emissions price has become the main driver for investments. The energy system in many respects resembles state monopoly or strong central planning where services are provided on cost basis. Vertical integration makes the co-ordination of scattered small gains easier (IEA, 2016).

Instead of private companies, trading takes place between states. Strong transmission network and abundant generation facilitates allow the use of zonal pricing. Extensive networks enable the use of marginal pricing in fully renewable system; bio energy and storage set the price in the markets. Markets are set mandatory to ensure efficient market function. Strong grid enables efficient cross-border trade and also is the main component in providing

[15] http://www.bloomberg.com/news/articles/2016-01-25/cutting-pollution-from-u-s-power-plants-cheaper-than-you-think

security of supply. As the society's support for energy infrastructure is strong, market instruments would not be needed to incentivize investments.

Pathway to New Consciousness scenario

2020:

- A successful global climate agreement in Paris 2015 brings tangible changes in the generation structure. International collaboration of energy agencies (TSOs, regulators, energy producers) brake the boundaries of national security of supply –thinking. Massive work on building much stronger transmission network or even supergrid[16] is seen as a solution to manage increasing renewables intake.
- Transmission system operators have deepened their co-operation to interconnect European networks. Cross-border investments are carried out to finalize the integrated energy markets.
- Societies and nations strongly encourage renewable energy production by subsidies and climate policies. The share of renewables increases sharply.

2030:

- Ecosystem catastrophes led to the collapse of world trade, and thus, business and states were paralyzed. This initiated the reborn of the ideas of the deep ecology. Values adopted to protect the environment were used to solve energy issues globally and the nations' borders ceased to fence renewables deployment.
- European-wide independent transmission system operator is formed. Gradually, it received possession of the national network assets.
- The network infrastructure is being reinforced to transmit power from large wind and solar installations to areas of high demand. There are also small-scale solutions that show efficient utilization of local energy resources.

[16] http://spectrum.ieee.org/energy/the-smarter-grid/lets-build-a-global-power-grid
http://www.montefiore.ulg.ac.be/~ernst/uploads/news/id140/Global_Grid_RENE_final.pdf

5. CONCLUDING REMARKS

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. Based on these assumptions, we have linked theoretical electricity market designs with qualitative energy system analysis of four society descriptions in year 2050. Scenarios are called “Radical Startups”, “Value-driven Techemoths”, “Green DIY Engineers” and “New Consciousness”. 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.

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 capacity mechanisms 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 in other services. This could be enabled by companies building power plants for their own use. Such strong market participants could be best accommodated with Over-the-Counter (OTC) trading or e.g. zonal model with capacity mechanisms and add-ons. DIY Engineers –scenario is perhaps the most radical one. Weak interconnections are result of ecocatastrophe that has affected 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. Marginal cost based dispatch and pricing on leveled cost of energy (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-economic 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 7. In future research work we will carry out agent-based simulations on the impact of different market designs.

Table 7. Summary of scenario market designs.

MARKET DESIGN	RADICAL STARTUPS	VALUE-DRIVEN TECHEMOTHS	GREEN DIY ENGINEERS	NEW CONSCIOUSNESS
PRICE FORMATION	Nodal/zonal	OTC If common market are needed: zonal/MC & LCOE	Nodal/PAB/MC &LCOE/OTC	Zonal model with ISO/CoS
TRADING	Exchange but bilateral trading is also allowed	Bilateral or pool/exchange if needed	Pool/exchange with strong role of bilateral trading	Exchange but bilateral trading is also allowed
CAPACITY MECHANISM	CM needed, add-ons	Not necessary if LCOE or OTC used in the common markets.	Not necessary	Public investments
NETWORK INFRASTRUCTURE	Public investments	Private and public investments	Public (community) investments	Public investments

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APPENDIX 1: ENERGY ISSUES IN SCENARIOS

Energy in Radical Startups Scenario (synthesis)

In Radical Startups scenario the industrial structure changes radically from the existing, acting as a driver for development of the energy sector. In line with the move towards innovative local and regional production, the production volumes of bulk products decrease due to increased challenges in the global markets. Instead, new value added products and related services increase the productivity of industries.

Technology development shows dispersed nature – it is not driven by one-fits-for all but tailored solutions according to local circumstances.

Energy technology development is driven by startup-originated innovative high tech small-scale solutions. Penetration of local energy solutions are driven by startup companies' rationalization with characteristics of local energy resources. Energy systems move towards distributed and prosumer type of behavior, where consumers self-produce a major part of their energy.

Electricity transmission between areas is interconnected but with limitations. This supports development of smart distribution infrastructure and demand response. Integration of solar and wind with smart utilization of heating/cooling and transportation sectors increase their economically feasible potential. Thanks to these developments, solar and wind power production reaches high levels. As urbanization moves on, utility-scale PV solutions appear particularly interesting in many urban areas

Power to gas and other energy storage technology breakthrough is led by small and medium scale solutions. Biomass use is consumer-driven and can be characterized as "small and medium scale circular economy". That is, as solar and wind reach high levels, biomass is increasingly available for customer products compared to highly industrial-oriented usage in developed countries today.

Steps forward in open data and advancements in industrial ecosystems support utilization of waste streams also in small scale companies. Ubiquitous ICT, advanced automation and smart pricing enable significant volumes of real-time energy trade even between small-scale consumers and producers

In a world of regional production, digitalization and ubiquitous ICT, the demands for transport of goods and people reduce compared to the current trend. 3D printers enter in households, industries, and other sectors. Smart city concepts enable modular shift of mobility towards public transport, walking and cycling.

Private houses become 0-energy and in the longer term plus energy buildings. The energy efficiency for heating increases while buildings become higher and the urban density increases making low temperature district heating cost efficient. Solar and other renewables are the major primary sources of energy.

Energy in Value-Driven Techemoths Scenario (synthesis)

"Techemoths", large technology companies operating in many business areas, are dominant actors in society. They cast the model for not only companies to come, but for the whole society. Large companies exploit economies of scale in production, leading to material intensive production.

Development in societies is largely market-driven: there is a global CO_2 agreement, and price of CO_2 is high. Furthermore, CO_2 price is included in the price of end-user products and services. Innovations and technology development are highly industry-driven. The development can be characterized being of high technological level, business-driven "big" solutions.

Energy services are included in corporations other products and services (e.g. electric vehicle is sold/leased with electricity included). Energy platforms are company specific, so buying product and energy in bundle is typically only option. Hence, traditional energy companies, such as electricity retailers, do not exist anymore in larger scale.

Electricity generation is mainly based on solar and wind, and hence energy storage and intelligent control of the demand are in essential role in energy system. Because of that, companies are eager to sell/lease products and their energy as a bundle, so that they have possibilities to control energy usage and energy storages of these devices (e.g. electric vehicle with corporate controlled smart charging and discharging). Eventually, energy issues are more and more invisible for end users. PVs are everywhere in cities as standard rooftop and wall material. However, they are mostly owned by big companies.

Energy storage system is centralized. There are centralized P2G systems in cities. In addition, batteries of electric vehicles are used as distributed, but centralized controlled energy storages.

Transmission system operators' (TSOs) role is weaker than today, as Techemoths have started to construct their own transmission lines for their own use. However, transmission networks connecting different regions are strong.

Price of energy is significantly higher in rural than urban areas, while quality of supply in public infra is quite low. Spot pricing in electricity distribution (uniform price, which is not depending on geographical location of customer, similar as postal stamp tariff system) does not exist anymore.

Some people are outside of the Techemoths energy services (some of them due to their own decision not to give away their personal information to corporations). As electricity price for them is high and quality low, these people have incentives to develop their own DIY solutions for energy generation.

In a world of large enterprises and material intensive production, there is an increasing demand for transport of goods between areas. Buildings are highly energy efficient in urbanized areas that are dense but relatively uncompact.

Energy in Green DIY Engineers Scenario (synthesis)

In the Green DIY engineers' world global trade has plummeted, leaving communities to cope with mostly low-tech solutions. Efficient use of resources and recycling are key drivers for enabling communities to thrive.

The level of technological advancement is dependent on the knowhow of the community. Lots of innovative, but actually low-cost low-tech energy efficiency solutions are in-use (e.g. earth architecture, simple biomaterials). Needed technology is produced and developed in communities by groups of engineers. People use barter economy, open source and 3D printing to help reduce the gap to those who are in the technical frontier. With the help of 3D printing people can get personalized energy solutions and store energy in self-made batteries. Low cost, portable energy solutions are used in the rare instances when travelling.

Prosumers are busy with wind, solar and biomass energy solutions conceived from available resources. Energy is produced by the people, for the people making energy systems widely scattered. Relative scarcity of resources drives towards more diverse energy pallet giving energy production cultural value as well, as it strengthens the identity of communities. Wasting energy and resources are a taboo and people thrive when consuming as little energy as possible.

Waste is not a problem but a resource for recycling and upcycling. However, waste can also be seen as an energy resource, and hence, there is sometimes a disagreement over the primary use of the waste.

Interconnections between communities are weak and some of the communities are off-grid and totally self-reliant. Investments in energy infrastructure are community-based, energy is produced and used on site.

Energy storage comes in different sizes and cost, there is a personalized solution for every need, including small-scale and off-grid P2G systems.

Harsh environment means pragmatic solutions in ensuring energy efficiency. In a survivalist ethos people are willing to endure quality shortcomings in electricity supply. Readily available energy storages for different uses mitigate the intermittent electricity supply and quality fluctuations.

Due to local production, trading of goods has been replaced by trading of knowledge. Because of localized living and manufacturing, the energy demand of transportation sector is very low.

There are lots of shared public spaces, which offer also shared public electricity, generated for instance by innovative energy harvesting solutions. Buildings have been retro-fitted against the unpredictable weather making them energy efficient or even 0-energy houses.

Energy in New Consciousness Scenario (synthesis)

New consciousness society is organized as open global collaboration and sharing of resources and information. Structures of industries and the whole economy move towards knowledge intensive production, radically different than today. Global circular economy with high recycling rates increases resource efficiency of economies.

Technology development is boosted by a society-wide commitment towards renewable options. This radiates into giving large-scale, capital intensive solutions relatively high importance in the energy system.

Energy systems move to a direction showing characteristics of both distributed and centralized nature. That is, advanced integration of grids and information exchange guarantee tempting conditions for efficient large-scale production (with e.g. concentrated solar power as a promising option). On the other hand, small-scale solutions are driven by citizens' commitments towards efficient utilization of local energy resources. The development reflects to utilization of different type of storage technologies.

Power to gas technology breakthrough has led to employment of P2G solutions in several scales, and there a variety of P2G solutions are in use in societies.

Advanced automation utilizing ubiquitous ICT helps integrating renewable electricity in the system.

Solar and wind power production reaches high or even very high levels as solutions in all scales develop favorably and they can be efficiently integrated to global energy markets.

Transmission networks are strong with only few bottlenecks.

Transportation volumes face a pressure upwards due to globalized world with wide opportunities for trade of goods and mobility of people. However, resource efficient production, as well as virtual reality and advanced public transportation have the potential for dampening the trend. Both electricity and gas driven vehicles largely replace conventional ICE vehicles.

Buildings are largely “plus-energy-buildings” as smart energy systems enable solar and other renewable energy integration.

APPENDIX 2: SCENARIO SET-UP INFORMATION

Table 8. Scenario set-up information, continued from Table 5.

	RADICAL START-UPS	VALUE-DRIVEN TECHEMOTHS	GREEN DIY ENGINEERS	NEW CONSCIOUSNESS
ENERGY MARKET INTEGRATION	Integrated markets	Corporate-sized self-sufficient energy systems, integrated markets	Localized markets, limited energy trade	Global markets
CO_2 POLICY	At least regional policies	Global CO_2 agreement	No climate agreement	Global CO_2 agreement
TECHNOLOGY DEVELOPMENT	High-tech, innovative small-scale solutions	High technological level, business-driven "big" solutions	"Low-tech", traditional solutions	High technological level, global solutions
ECONOMIC DEVELOPMENT, ECONOMIC STRUCTURE	High economic development. Developed service sector, small and medium scale enterprises.	Very high economic development. Large enterprises, material intensive production.	Slow GDP growth/even decline economic development. Microenterprises, self-production, low production volumes.	High economic development. Knowledge intensive production, radically different than today.
BIOMASS USE	Consumer-driven small and medium scale circular economy	Advanced bio economy, circular economy by advanced technology	High utilization in traditional uses and by traditional, small-scale technology	Global circulation economy, high recycling rates
TRANSPORTATION	High transportation volumes, service-oriented industry affecting goods transportation	Local transportation-oriented passenger transportation, transportation of goods between areas	Low transportation volumes, shared vehicles	High transportation volumes, advanced public transportation
REGIONAL AND URBAN DEVELOPMENT	Highly urbanized, dense but compact	Urbanized, dense but relatively uncompact	Urban exodus	Split between urban areas and areas outside them
BUILDINGS	Highly energy efficient buildings	Highly energy efficient buildings	Low energy efficiency of buildings	Highly energy efficient buildings
ENERGY, CLIMATE, AND INNOVATION POLICIES	Regional policies	Minimal regulations, market-orientation Industry-driven innovations	Self-sufficiency targeted Communities regulate themselves	Global energy and climate policy Global, efficient innovation policy

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