# Chapter 4

## Smart Grid

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# CHAPTER 4

# Smart Grid

## 4.1. Smart Grid Systems for an Eco Town

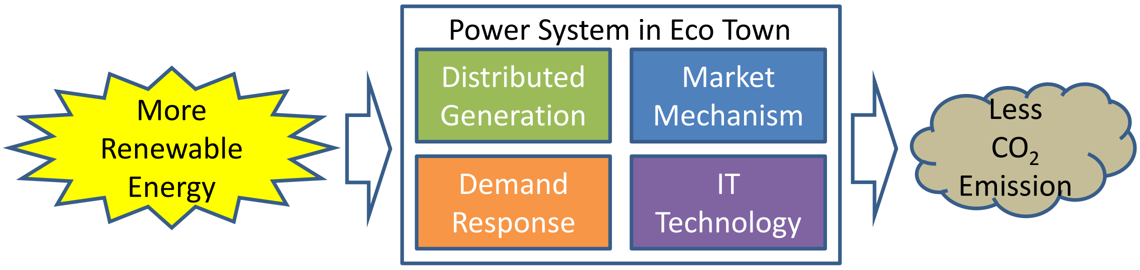
### 4.1.1 Power System in Sustainable Society

Carbon dioxide ($CO_2$) emissions and economic growth, expressed in terms of gross domestic product (GDP) are strongly correlated for countries worldwide. Similarly, GDP and energy consumption are also correlated. This implies that energy consumption needs to increase in order to achieve higher economic growth. As such, $CO_2$ emissions caused by the consumption of energy from fossil fuels are unavoidable. A notably large contribution to $CO_2$ emissions comes from coal power plants and, in fact, about 75 percent of global coal consumption is in the power sector. Yet many countries, including Japan, has set an energy policy goal of halving $CO_2$ emissions to contain the increase in temperature to within 2 degrees Celsius by 2050. This emissions reduction is required to establish a sustainable society in the future. To achieve this goal, the largest reduction in $CO_2$ emissions is expected in the power sector, by introducing renewable energy as much as possible.

Figure 40 depicts a power system with its components in a sustainable society. This system integrates more renewable energy to emit less $CO_2$ through the interaction of these components, each still new but nonetheless in place: distributed generation (wind power plants, mega-solar photovoltaic (PV) plants, rooftop solar PV systems on buildings), market system, demand response technologies and information technology (IT, i.e. data acquisition and communication).

The power system which enables to coordinate the interplay of the above-mentioned components is also known as a smart grid system. A smart grid is defined differently by several institutions, such as the European Union, World Economic Forum (WEF), US Department of Energy, and the International Energy Agency (IEA). The IEA defines a smart grid as an electricity network system that uses digital technology to monitor and manage the transport of electricity from all generation sources to meet the varying electricity demands of end-users (OECD/IEA, 2015). Such grids can coordinate the needs and capabilities of end-users and electricity market stakeholders in such a way that they can optimise asset utilisation and operation and, in the process, minimise both costs and environmental impacts while maintaining system reliability, resilience and stability.

**Figure 40: Power System in a Sustainable Society**



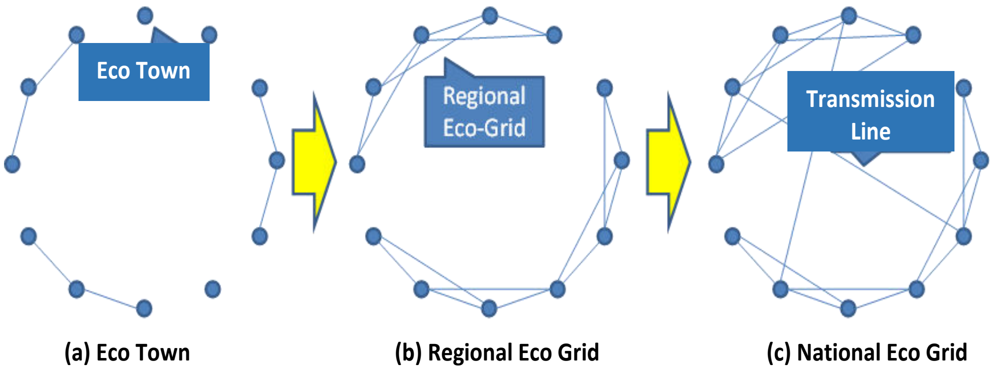

Source: Author.

### 4.1.2 Goal of the Smart Grid in an Eco Town

The goal of the smart grid in an eco town is to put into practice five key power system functions: (i) sustainability, (ii) dependability, (iii) flexibility, (iv) affordability, and (v) scalability.

'Sustainability' means avoiding climate change and limiting the use of fossil fuel and other natural resources. 'Dependability' means to supply stable and quality power for use in technology-intensive industries such as semiconductor device manufacturing and automotives. 'Flexibility' is also related to the sustainability and stability of the power system. Integrating variable renewable energy such as wind and solar power requires flexibility to establish a demand and supply balance using a dispatchable power source such as thermal and hydropower plants. 'Affordability' is obtained by avoiding extremely expensive technologies, such as nuclear fusion reactors, global super-grids, space solar PV, and artificial photosynthesis. 'Scalability' is especially important for the development of an eco town. Figure 41(a) shows an eco town in its early stage. Most eco towns are independent and a few are connected by transmission lines. Then, regional eco-grids are formed by connecting adjacent eco towns, as depicted in Figure 41(b). Finally, many transmission lines are added between regional eco grids to form a national eco grid, as in Figure 41(c). Scalability thus means that this evolution can be accomplished at a reasonable cost proportional to the system size. This scalability is obtained if each eco town has the four key elements from the early stage of the evolution. In particular, the market mechanism is essential even if the size of the power system is very small.

**Figure 41: Scalable Evolution of Eco Towns**




Source: Author.

## 4.2. Smart Grid Systems and Technologies, Including Storage Systems and Cost

### 4.2.1 Smart Grid Infrastructure

A smart grid system involves a complex arrangement of infrastructure whose functions depend on many interconnected elements. A smart grid system can be visualised as having four main layers whose elements are combined to create grid features that improve the grid's ability to achieve certain goals such as integrating more renewables, improving reliability, and reducing energy consumption (Madrigal and Uluski, 2015):

- The first layer is the 'hard' infrastructure, which is the physical component of the grid. This covers generation, transmission, and the distribution network as well as energy storage facilities.
- The second layer is telecommunications, which represent the telecommunication services that monitor, protect, and control the grid. This includes wide area networks, field area networks, home area networks, and local area networks.
- The third layer is data management, which ensures proper data mining and utilisation of data to facilitate smart grid applications;
- The fourth layer consist of tools and software technologies that use and process collected information from the grid to monitor, protect, and control the hard infrastructure layer and reinforce the grid to allow integration of renewable energy.

### 4.2.2 Reduction in Fossil Fuels with the Integration of Renewable Energy

The operation of conventional electric power systems is briefly described. The imbalance of supply and demand in electric power may cause a failure in production due to a power frequency problem or a blackout due to the ensuing shutting down of thermal power plants.

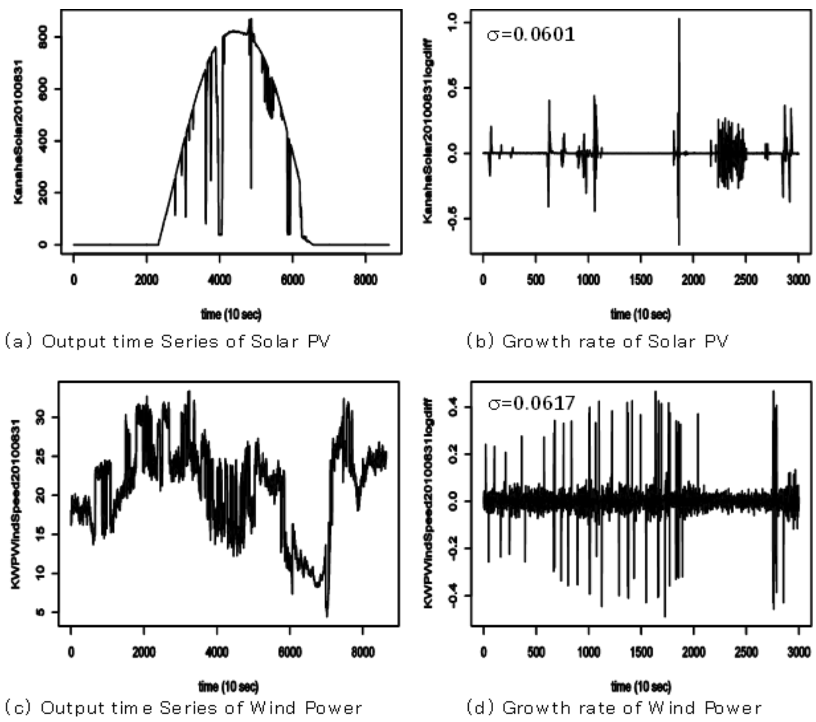
The usual operation of an electric power system requires centralised energy management to avoid the above failures and to maintain a stable supply of power.

Facilities such as power plants, power substations, and distribution and transmission lines have to play their own roles effectively for balancing supply and demand. For this purpose, rigorous operating procedures are determined and the central load dispatching office monitors the overall system and orders various load-dispatch instructions, such as parallel, parallel-off, power control, and operating switch.

The integration of renewable energy, including wind power, solar power, hydropower, biomass, and geothermal, into the power system to reduce the consumption of fossil fuels has been increasing in recent years. Wind and solar power notably have a characteristic not possessed by other renewables, which is output fluctuation, as depicted in Figure 42. Panels (a) and (c) show an output time series for solar PV and wind power, respectively, and panels (b) and (d) are the corresponding growth rate time series. The variability of output makes wind and solar power difficult to integrate into the conventional power system.

In the conventional system, load fluctuations are caused by fluctuations in demand. Load balance is restored by thermal and hydropower plants (Figure 43a). When wind power and rooftop solar PV power are integrated, load fluctuations increase as this characteristic of wind and solar PV power combines with demand fluctuations. If thermal and hydropower plants do not have a sufficient balancing capability, large electric storage devise such as batteries would be required (Figure 43b). However, if demand side management is introduced, electric storage on a moderate scale suffices to restore load balance. This implies that managing demand introduces additional balancing capability to the supply side of the system (Figure 43c).

**Figure 42: Output Fluctuations of Renewable Energy**



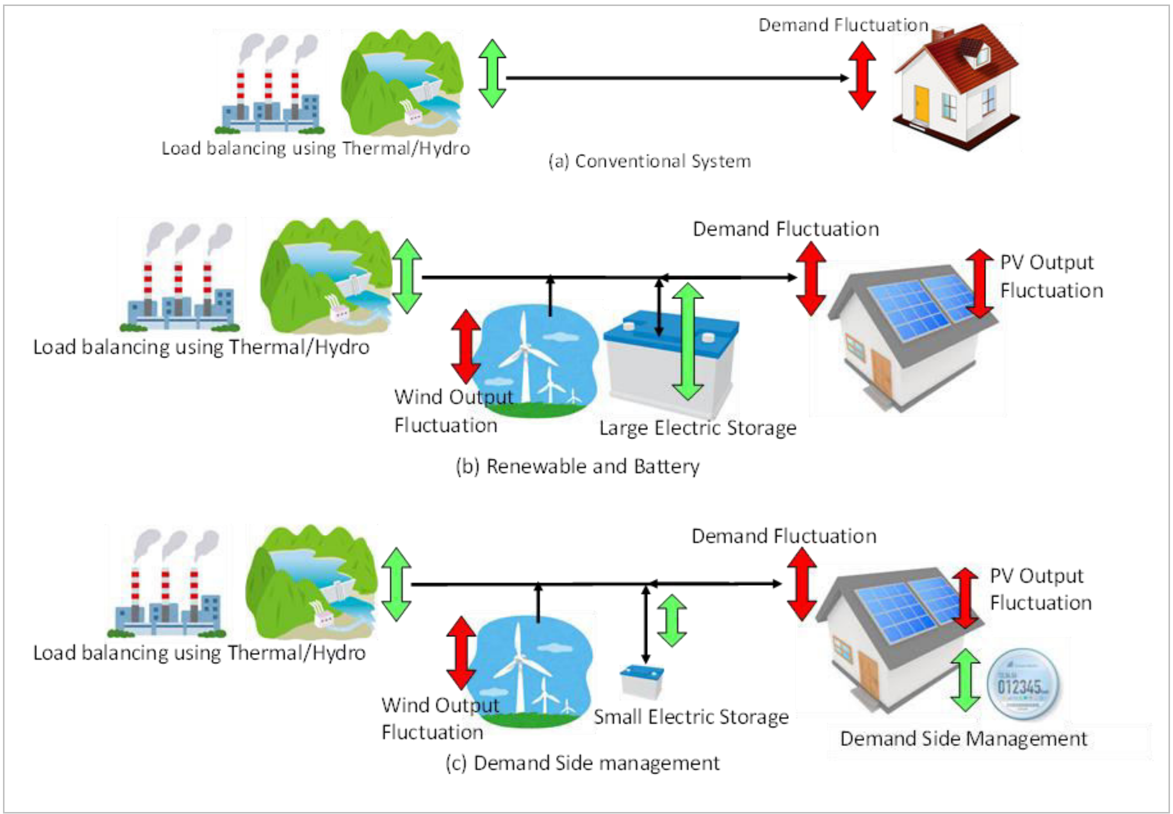

PV = photovoltaic.

Source: Author.

In an eco town, renewable energy will be integrated as much as possible to reduce fossil fuel consumption in order to establish a sustainable society. This is shown in Figure 44.

The first stage of an energy market is marked by long-term bilateral contracts. Generating companies and retailers conclude long-term bilateral contracts based on their own long-term forecasting of demand. Long-term bilateral contracts between generating companies and retailers will take up the largest share in the energy market.

**Figure 43: Grid Integration of Wind and Solar PV**




PV = photovoltaic.

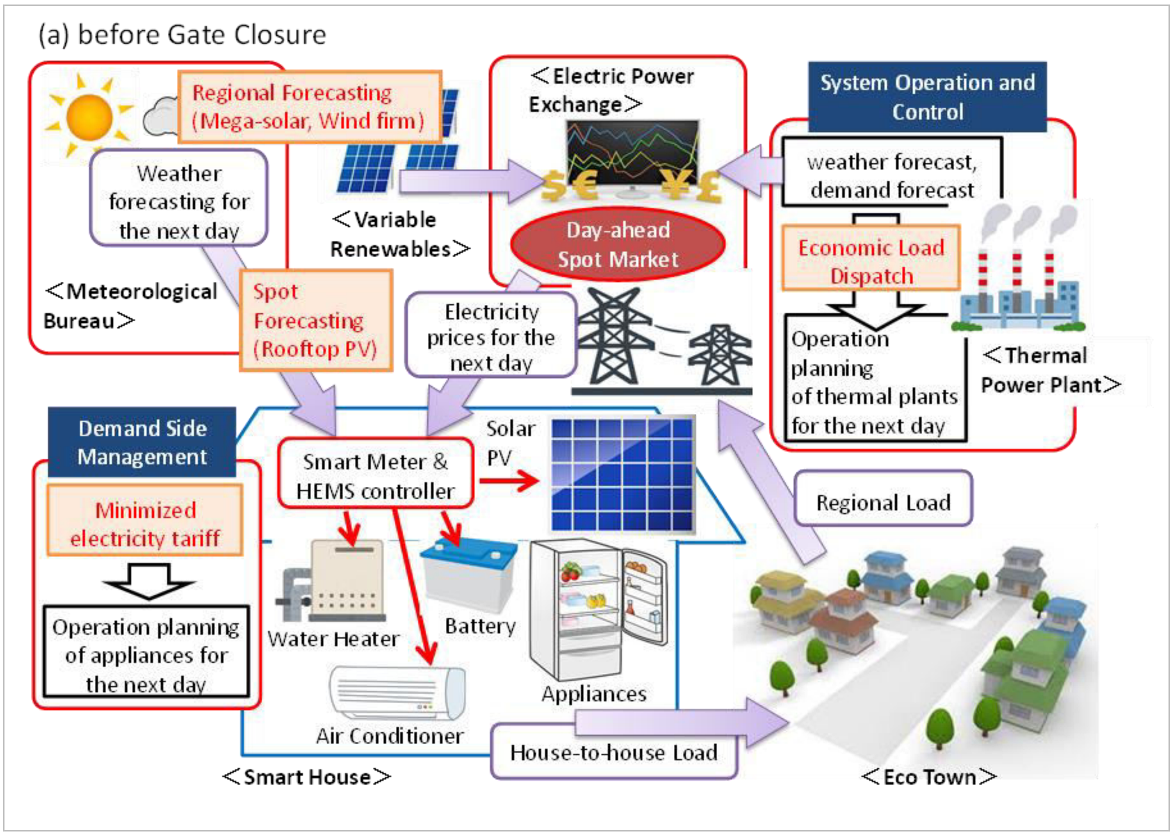
Source: Original drawings based on personal communication from Kazuhiko Ogimoto, University of Tokyo.

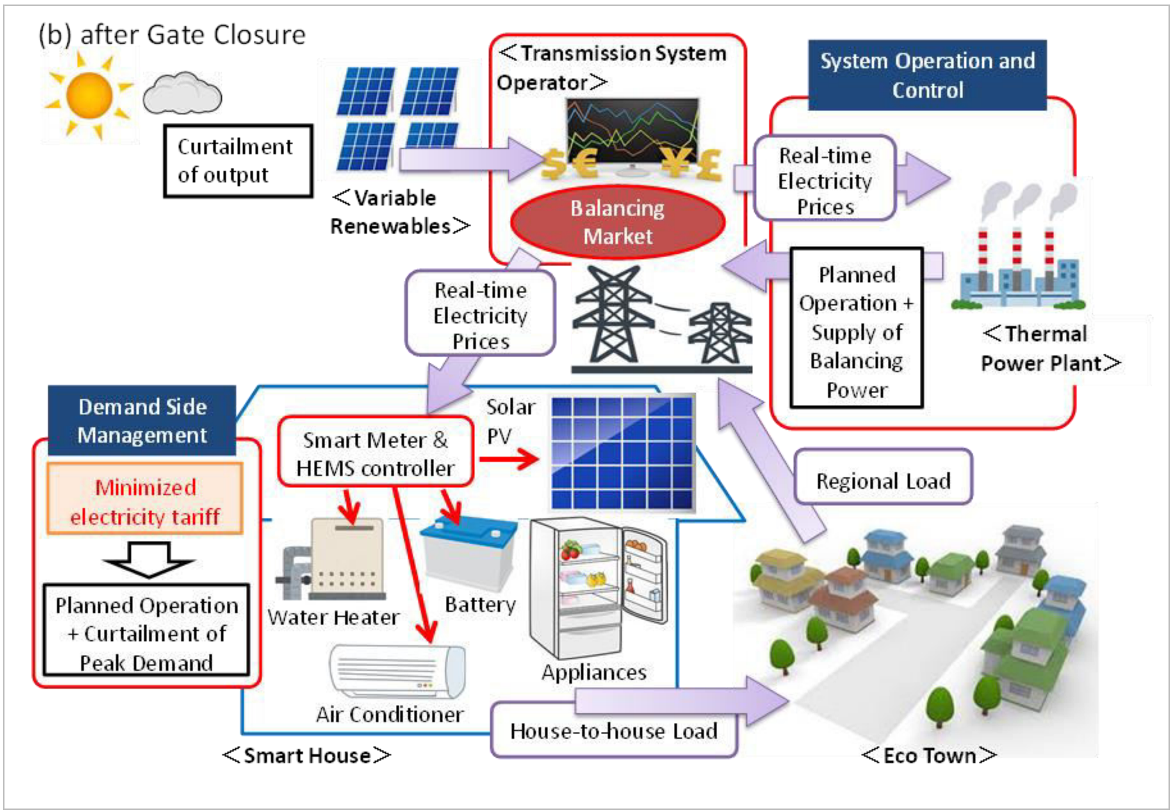
The second stage of the energy market is the day-ahead spot market (see Figure 44(a)). First, the meteorological bureau announces the weather forecast for the next day. Mega solar plants place their output electricity, estimated using the weather forecast, on the market. Home energy management systems (HEMS) located in smart houses estimate the house-to-house load by taking into account the output from rooftop solar PVs. Retailers estimate their regional load in eco towns by aggregating the load for all eco towns and bid on the market. Companies operating thermal power plants forecast demand and make operation plans based on economic load dispatch and place their supply on the market. The electric power exchange is responsible for operating the day-ahead spot market. The gate of the day-ahead spot market is closed before a certain time.

After the gate closure, the balancing market is opened by the transmission system operator (TSO). IT is key to making the balancing market possible, measuring demand in real time using smart meters and capturing the system-wide demand–supply imbalance through the supervisory control and data acquisition (SCADA) system. HEMS located in smart houses curtail peak demand to minimise the electricity tariff in each house, if the real-time electricity price rises. Companies operating thermal power plants place their balancing power on the market if they have extra capacity for generation. The TSO is responsible for operating the overall power system in the eco town, keeping demand and supply in balance. If PV output is too much to maintain a balance, the TSO can order mega solar plants to curtail their output.

As explained earlier, distributed generation, the market mechanism, demand response, and IT technology are the keys to integrating more renewable energy to emit less $CO_2$. Note that the power system in an eco town is clearly at the opposite end of the system operated by the central load dispatching office of an oligopolistic utility company.

**Figure 44: Image of Eco Town before and after Gate Closure**






Source: Original drawings based on discussions with Kazuhiko Ogimoto, University of Tokyo.

## Table 10: Investment Cost and Levelised Cost of Electricity (LCOE) for Solar PV

| | | Investment Cost in 2015 (USD/kW) | LCOE in 2013 in California (USD/MWh) |
|---|---|---|---|
| Mega-Solar PV | Min | 1522 | - |
| | Max | 2913 | - |
| | Ave | 2043 | - |
| Rooftop PV | Min | 1609 | 200 |
| | Max | 4739 | 316 |
| | Ave | 2130 | - |

PV = photovoltaic.
Source: International Energy Agency (IEA) (2014), *Energy Technology Perspective 2014*. Paris: IEA.

## Table 11: Investment Cost and Levelised Cost of Electricity (LCOE) for CSP

| | | Investment Cost in 2015 (USD/kW) | LCOE in 2015 (USD/MWh) |
|---|---|---|---|
| CSP w/o storage | Min | 3739 | 158 |
| | Max | 6348 | 263 |
| | Ave | 4609 | 191 |
| CSP with 6-hour storage | Min | 6348 | 146 |
| | Max | 9130 | 213 |
| | Ave | 7304 | 168 |

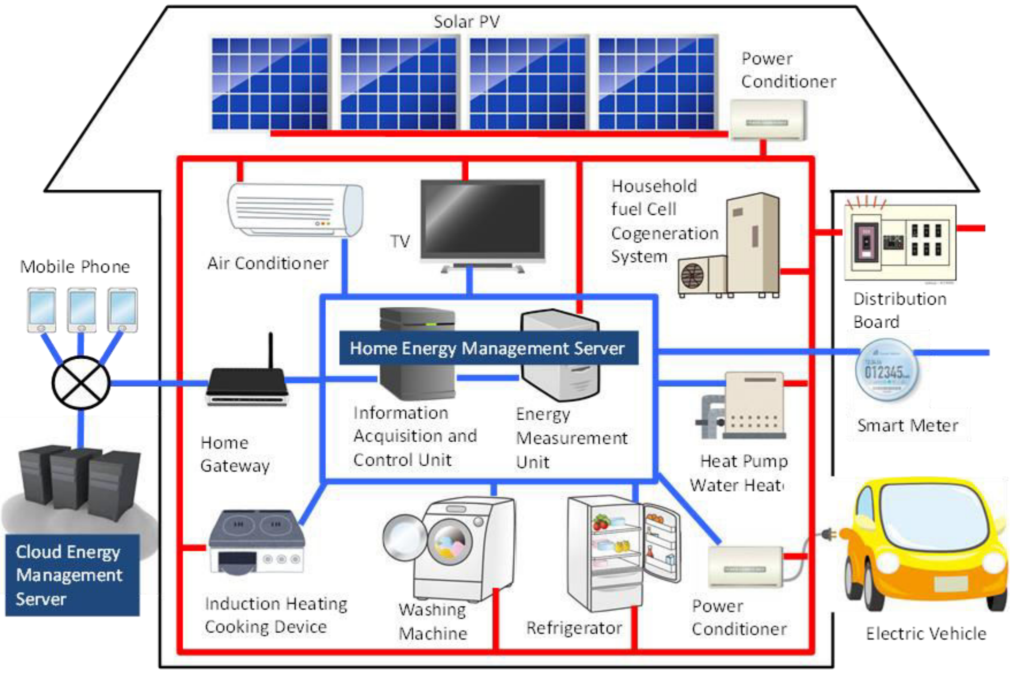
CSP = concentrated solar power.
Source: International Energy Agency (IEA) (2014), *Energy Technology Perspective 2014*. Paris: IEA.

Cost is another important factor to deploy renewable energy on a large scale. The investment cost and levelised cost of electricity (LCOE) are shown in Tables 10 and 11 for solar PV and concentrated solar power (CSP), respectively. The investment cost for solar PV is lower than that for CSP, but the LCOE for solar PV is higher than that for CSP. This means that solar PV is economically easy to implement, but recouping the investment takes longer. Note that the LCOE for CSP with storage is lower than that for CSP without storage, although the investment cost is higher. This is because storage allows for separating the acquisition of heat in the day and power generation after the sun sets. In a country where peak demand is in the early evening, this capability has a considerable economic advantage.

#### 4.2.2. Key Technologies of Demand Side and Supply Side Management

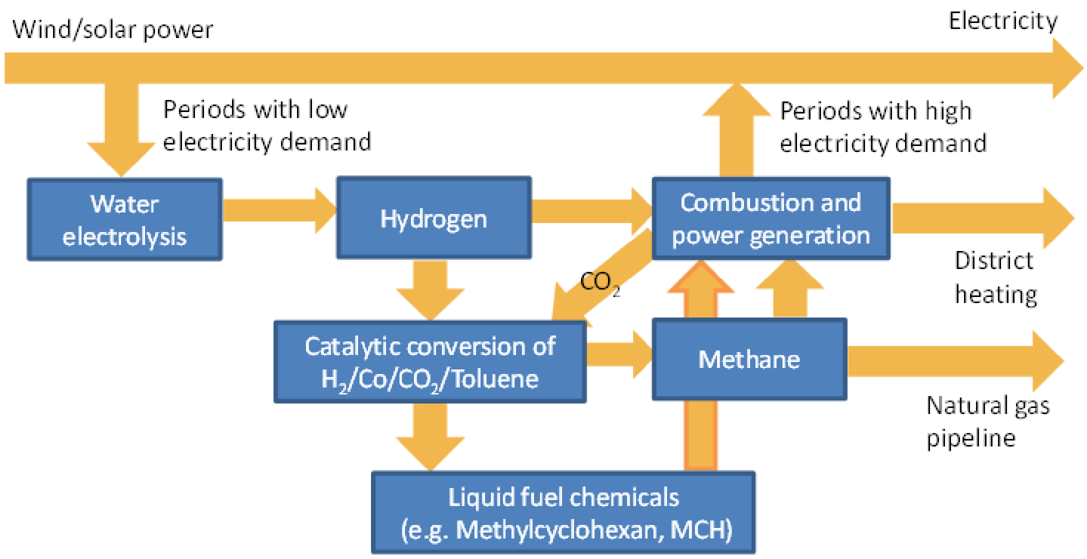
At the heart of demand side management is the HEMS, consisting of an energy measurement unit and an information acquisition unit (see Figure 45). The HEMS currently assumes time-based pricing, but it is ideal for dynamic pricing in the balancing market. The system makes it possible to manage power saving operations during the day (high price) and automatic operation at night (low price). In this system, smart appliances such as refrigerators, washing machines, air conditioners, television sets, heat pumps, water heaters, household fuel cell cogeneration systems, and induction heating cooking devices are controlled through a home gateway and a cloud energy management server via a mobile phone while outside the home. In addition to these appliances, DC air conditioners are efficient for residences or offices with a rooftop solar PV panel. This is because solar PV generates DC power and air conditioners use a DC brushless motor.

**Figure 45: Key Technologies of Demand Side Management**




Source: International Energy Agency (IEA) (2014), *Energy Technology Perspective 2014*. Paris: IEA.

**Figure 46: Hydrogen Production in Wind and Solar Power**

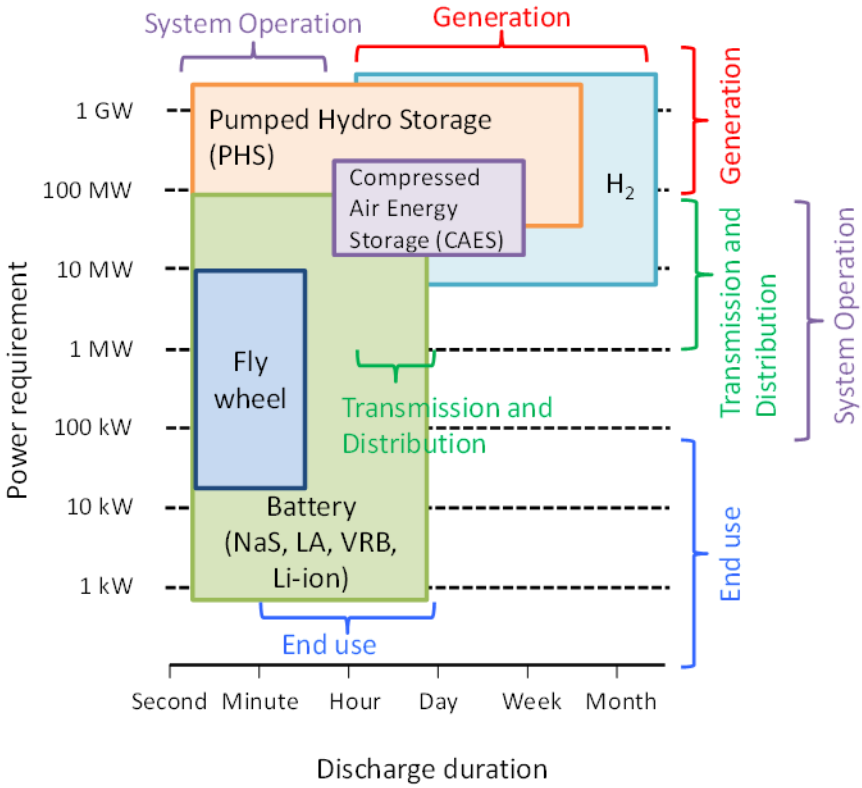



Source: Chiyoda Corporation (2014), 'SPERA Hydrogen System', IEA H2 Roadmap Asia Workshop, 26–27 June.

When the power system is modernised using market mechanism technology, demand response technology, and IT, but the system does not have adequate flexibility, technological innovations using various electricity storage technologies are needed. One of the most promising storage technologies is hydrogen production using extra wind or solar power (see Figure 46). During periods with low electricity demand, extra wind or solar power is used for water electrolysis to produce hydrogen instead of curtailing output power (IEA, 2014). The produced hydrogen can be stored in a high-pressure tank or as liquefied hydrogen. The stored hydrogen is combusted during periods with high electricity demand. Alternatively, methane is produced from a catalytic reaction of hydrogen and $CO_2$ in the exhaust gas of thermal power plants. Methane is liquefied at low temperatures and is stored in a tank in the same manner as storing natural gas. Another promising technology is a chemical reaction between toluene and hydrogen to synthesise methylcyclohexane (MCH), which is in a liquid state in an ambient environment (normal temperature and atmospheric pressure) (Chiyoda, 2014). Therefore, MCH is easy to store and easy to transport. This means that MCH could be exported, just like oil and natural gas.

Storage applications and technologies are characterised by the two-dimensional space of discharge power (MW) and discharge duration (hour) (IEA, 2014). For instance, application in generation is (100 MW–1 GW, hour–month), system operation is (100 kW–100 MW, second–hour), transmission and distribution is (1 MW–100 MW, hour–day), and end use is (100 W–100 kW, minute–day) (see Figure 47). Applications with large economic values are arbitrage in generation (US$80/MWh), load following in system operation (US$150/MWh), investment deferral in transmission and distribution (US$100/MWh), and off-grid in end use (US$330/MWh), where figures in parentheses are the economic value. Arbitrage in generation is storing low-priced power for later sale at a higher peak price, load following in system operation is charging power when generation exceeds demand or discharging power during times when demand exceeds generation, and investment deferral in transmission is the rescheduling of transmission investments.

**Figure 47: Applications and Technologies of Electricity Storage**




Source: International Energy Agency (IEA) (2014), *Energy Technology Perspective 2014*. Paris: IEA.

Meanwhile, distribution is relieving congestion on grid by placing storage units at the connection bottleneck and off-grid in end use is supplying power using solar PV with storage for small-scale users.

The appropriate technologies for the applications are shown in Figure 47 by coloured boxes, based on their characteristics of discharge power (MW) and discharge duration (hour). The investment costs for pumped hydro storage (PHS), $H_2$, and compressed air energy storage (CAES) are low in comparison to other storage technologies (Table 12). These three technologies are suitable for arbitrage applications in generation due to those most competitive levelised costs, PHS, CAES, and batteries (NaS) are suitable for a load following application in system operation. PHS, H2, and CAES are suitable for investment deferral application in transmission and distribution, and batteries are best for off-grid in end use. LA, VRB, and Li-ion batteries are relatively expensive but are easy to implement for small-scale users.

**Table 12: Investment Cost and Levelised Cost of Electricity Storage**

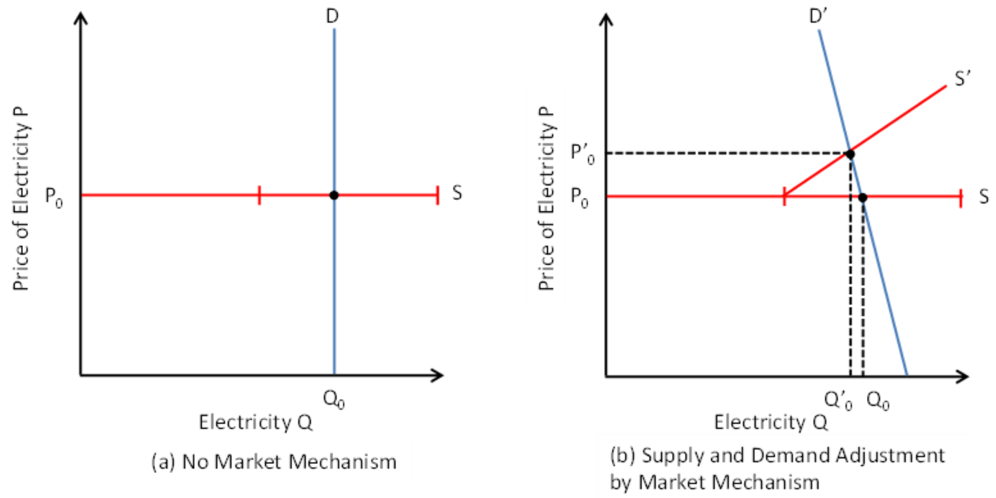
| | Investment Cost | | Levelised Cost of Electricity | | | |
|---|---|---|---|---|---|---|
| | Power (USD/kW) | Energy (USD/kWh) | Arbitrage | Load Following | T&D investment deferral | Off-grid |
| Pumped Hydro | 500-4600 | 30-200 | 89-156 | 133-267 | 89-156 | - |
| CAES | 500-1500 | 10-150 | 67-178 | 111-289 | 89-178 | - |
| Hydrogen | 600-1500 (Electrolyser) 800-1200 (CCGT) | 10-150 | 156-267 | 356-622 | 233-356 | - |
| NaS Battery | 300-2500 | - | - | 333-467 | - | |
| Li-ion Battery | 900-3500 | - | - | - | - | 767-1011 |
| LA Battery | 250-840 | - | - | - | - | 489-756 |
| VRB | 1000-4000 | - | - | - | - | 678-1011 |
| Flywheel | 130-500 | - | - | - | - | |

Source: International Energy Agency (IEA) (2014), *Energy Technology Perspective 2014*. Paris: IEA.

### 4.2.4. Competitive Market and Renewable Energy

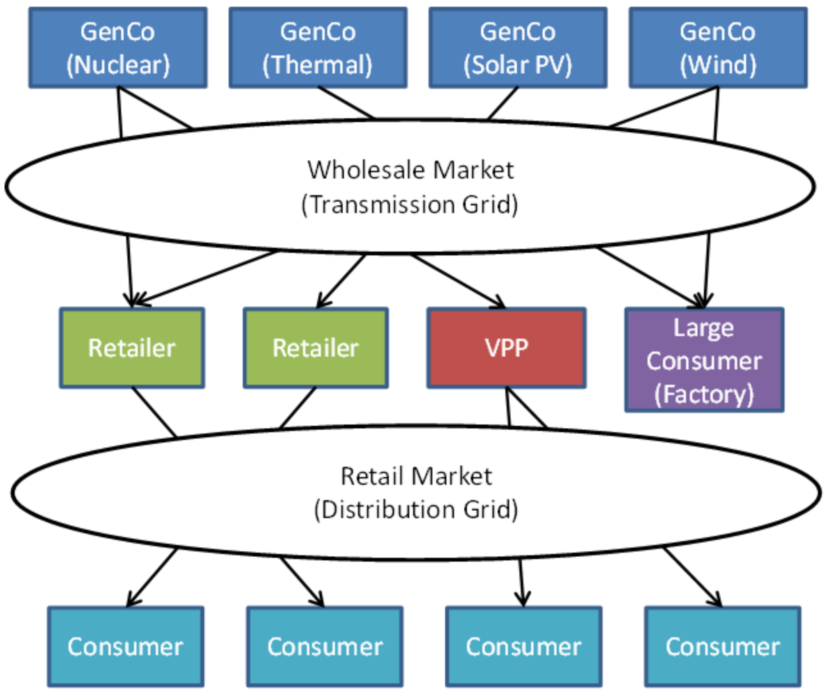
Energy is one of the factors of production of an economy. When there is no market mechanism, demand for electricity is presented graphically in Figure 48(a) by a vertical line D, which has no price elasticity of energy demand. Utility companies have the obligation to supply electricity $Q_0$ regardless of price $P_0$. On the other hand, when we have a market mechanism, demand for electricity is presented by the slant line D', which has price elasticity of energy demand (see Figure 48b). If the supply decreases due to output fluctuations in solar PV, a standby thermal power plant with higher costs supplies electricity S'. As a result, the price increases from $P_0$ to $P'_0$ and demand decreases from $Q_0$ to $Q'_0$.

**Figure 48: Electricity Demand and Price**




Source: Author.

**Figure 49: Competitive Power Market**




VPP = virtual power plant.
Source: D. Kirschen and G. Strbac (2004), *Fundamentals of Power System Economics*. Chichester, UK: John Wiley & Sons.

Prior to the liberalisation of the electricity industry that has been advanced by industrialised countries since the 1990s, regional monopolies were the most common electricity market structure globally. These monopolies lacked the flexibility to integrate renewable energy.

After liberalisation, competitive power markets were introduced (Kirschen and Strbac, 2004). One of the key market features of a competitive market is the existence of virtual power plants (see Figure 49) which mainly functions in balancing the market. They produce power by aggregating small-scale generating companies to supply balancing power. In a similar way, they produce negative power (decrease demand power) by aggregate consumer demand response to supply balancing power. This flexibility accelerates the integration of PV and wind power by promoting investment in balancing power. However, there are important new issues that arise with power markets. Liberalisation does not always lead directly to a lower electricity price. In Europe, electricity prices became higher because of the increase in fuel prices after the deregulation in the late 1990s. It has also been noted that investment in transmission and balancing capabilities is not sufficient for Europe's near-term needs.

### 4.3. Policy and Regulations

With one of the core objectives of ensuring sustainability through the integration of supply side and demand side measures, an eco town requires a robust and flexible grid structure that could be realised through the implementation of a smart grid. A smart grid controls and optimises electricity flow from both the demand side and supply side. It also provides better planning and management of existing and future electricity distribution and transmission grids, actively manages supply and demand, and enables new energy services and energy efficiency improvements (Connor et al., 2014).

In general, the benefits of a smart grid include the following: (*a*) deliver energy more efficiently, (*b*) provide the capacity to integrate more new renewable energy into existing networks, (*c*) provide the ability to manage increasing numbers of electric vehicles; (*d*) enable customers to have greater control of their energy; (*e*) provide a considerable capacity to reduce global carbon emissions, and (*f*) stimulate an array of new business models in the energy sector (WEF, 2010).

The establishment of an eco town provides a strategic direction and mandate to initiate smart grid development or pilot smart grid technologies. An eco town blueprint that specifies target reductions in consumption, carbon emissions, and generation from variable renewable energy technologies could form a basis for investments and set key parameters for policy and regulation related to smart grid deployment. The following identifies at least three main concerns in smart grid deployment that require policy and regulatory interventions: (i) funding smart grid investments, (ii) smart grid standards, and (iii) smart consumer policies.

#### 4.3.1 Funding Smart Grid Investments

One of the key policy and regulatory concerns of smart grid development under an eco town framework is funding for smart grid investments. The costs of deploying smart grid technologies is often viewed as too high (high capital investment, high maintenance costs, and complex management requirements) given the uncertainty of return of investments associated with new technologies which is considered as the main economic barrier to smart grid deployment (OECD/IEA, 2015). Public utilities who will be responsible for smart grid investments must be assured of financial and regulatory support allowing them to recover their investments. Smart grid technologies can be broadly classified those that have been proven and largely tested whose risks of deployment are low and those that are more advanced but less tested whose risks of not achieving expected benefits may be high (Madrigal and Uluski, 2015; WEF, 2010).

Utility investments on proven and largely tested technologies should be considered as part of utilities expenditure programmes, and investments on deployment should be recovered through electricity tariffs. This may not require an additional regulatory process beyond what is being practiced under existing cost recovery models. On the other hand, for less tested technologies, this should require special funding schemes such as government grants (Madrigal and Uluski, 2015) or through public–private partnerships (WEF, 2010).

Large deployment of smart-grid technologies may also reduce electricity sales of utilities and will affect the service provider's financial viability. This may warrant a special regulatory treatment to ensure viability, and various cost recovery and performance incentive programmes may be employed (Madrigal and Uluski, 2015).

One of the cost recovery measures is the lost margin recovery scheme in which utilities are compensated for investments that cause reductions in electricity sales. Performance incentive programmes that make energy efficiency a profitable investment include performance targets and shared savings schemes.

#### 4.3.2 Standards and Interoperability

With integration of variable renewable energy sources in eco towns, smart grid systems need to maintain optimal electrical conditions at all times. This can be achieved through coordinated operation of intelligent and flexible protection and control devices that can adapt to meet continuously varying system-level conditions and varying operating objectives (Madrigal and Uluski, 2015).

Communicating sensors and devices exchange information and interoperate. In order to interoperate effectively, a framework of interfaces, protocols, and consensus standards would be needed. Standards already exist for devices and sensors for distribution systems that require integration and interoperability. For smart grids, some of the interoperability standards are evolving and some are still being developed (Madrigal and Uluski, 2015; WEF, 2010; IEC, 2010). Interoperability standards that are still being developed include those of demand response technologies, smart inverters, electric vehicle charging standards, communication standards, and internet protocol (Madrigal and Uluski, 2015).

Smart grid deployment in eco towns, particularly those in developing countries, as much as possible should refer to and conform with smart grid standards that are developed by international standards institutes or agencies. Regulatory agencies should provide clear guidance on the use of existing standards and directions with respect to new and evolving standards.

### 4.3.3 Smart Consumer Policies

Smart grid benefits can be fully realised when customers are fully aware of incentives or service options that warrant behavioural changes. This would be the case for industrial customers and, to some extent, commercial customers where knowledge on energy management is high. For eco towns, most customers are residential customers and they are most often not aware of service options or pricing options needed to manage their demand. Smart grid customer policies could be categorised into feedback policies, pricing, and customer protection (OECD/IEA, 2011).

Under feedback policies, customers are expected to modify their behaviour when information related to energy services are visible. Consumer feedback could be provided through monthly electricity bills or through devices that provide information related to consumption and prices. Smart grid systems aim to optimise benefits by providing an automated response to consumption and demand according to price or other signals. This could be achieved through devices that are pre-programmed based on parameters set by customers. Smart grid and smart metering schemes are measures that provide automated end-user demand and energy efficiency response.

One of the objectives of smart grid deployment is to promote efficient consumption through pricing signals. Various smart customer studies have shown that time-differentiated pricing schemes stimulate behavioural changes and trigger demand response resulting in reduction of peak electricity demand. Smart grid deployment should be accompanied by pricing schemes that generate demand response benefits.

Under electricity pricing, at one end of the spectrum is flat-rate pricing while at the other end is real-time pricing. In between is time-of-use (TOU) pricing. Flat-rate pricing, which charges customers the same price throughout the day, does not encourage customers to shift demand to different times, while under real-time pricing, in which price is based on actual costs of generation, transmission, distribution, and supply, customers may not be able to reduce electricity demand during peak times. TOU pricing, on the other hand, takes advantage of the predictability of electricity costs on a daily and seasonal basis and thus reduces risks for customers by providing certainty (OECD/IEA, 2011).

There are other concerns related to consumer protection that need to be addressed when implementing a smart grid program. These include (*a*) privacy, ownership, and security issues associated with the availability of detailed customer data; (*b*) customer acceptance and social safety net issues associated with new types of electricity tariff rates; and (*c*) customer protection issues associated with remote disconnections made possible by smart grids (OECD/IEA, 2011). Regulatory agencies could take into consideration various lessons learnt in several pilot projects implemented internationally and take into account the emerging best industry practice in addressing these issues for eco towns.

## 4.4. Road Map and Guidelines

A road map is defined as 'a specialised type of strategic plan that outlines activities an organisation can undertake over specified time frames to achieve stated goals and outcomes' while the process by which a road map is created, implemented, monitored, and updated as necessary is termed road mapping (Madrigal and Uluski, 2015). Entities develop a road map when embarking on smart grid programmes. An officially sanctioned road map with an implementation plan becomes the basis for future smart grid activities.

### 4.4.1 Methodologies

Various methodologies and approaches exist for the preparation of a smart grid road map and can be found in the literature, including those from Sandia National Laboratories, the Electric Power Research Institute (EPRI), and the International Energy Agency summarised in Tables 13, 14, and 15, respectively.

**Table 13: Sandia National Laboratory Phases of Technology Road Mapping**

| | |
|---|---|
| **Phase 1: Preliminary activities** | ● Satisfying essential conditions<br>● Providing leadership/sponsorship<br>● Defining the scope and boundaries for the technology road map |
| **Phase 2: Development of the technology road map** | ● Identifying the focus of the road map<br>● Identifying critical system requirements and targets<br>● Specifying major technological areas<br>● Specifying drivers and targets<br>● Identifying alternatives<br>● Recommending technology alternatives<br>● Creating a road map report |
| **Phase 3: Follow-up activities** | ● Providing critique and validation of the road map<br>● Developing an implementation plan<br>● Reviewing and updating |

Source: Author's compilation.

**Table 14: EPRI Methodology for the Development of Smart Grid Road Maps**

| | |
|---|---|
| **Step 1: Defining the vision** | ● Summarising what the utility intends to accomplish. Includes a mission statement that provides how the vision statement will be accomplished. Defining a vision statement begins with evaluating the essential business objectives and drivers that can be addressed by technology investments. |
| **Step 2: Identifying the requirements** | ● Identifying and defining the requirements which include the needs and interactions of various actors and logical interfaces with the relevant attributes such as timing, accuracy, volume, and so on. |
| **Step 3: Assessing and selecting the technology** | ● Ranking the technology by impact and effort. Selecting technology candidates for road map implementation. Conducting a gap analysis to identify the gaps between the current and desirable technology state. |
| **Step 4: Planning** | ● Establishing fishbone diagrams that show the current situation as fish tail and the future objective as the head of the fish. The steps to be taken are the scales of the fish. |
| **Step 5: Implementing the road map** | ● Delivering a report document, distributing to stakeholders, and performing project implementation and governance. |

EPRI = Electric Power Research Institute.

Source: Author's compilation.

**Table 15: IEA Methodology for the Development of Smart Grid Technology Road Maps**

| | |
|---|---|
| **Step 1: Goals** | ● Clear concise set of targets that if achieved will result in the desired outcome |
| **Step 2: Milestones** | ● Interim performance targets for achieving the goals, pegged to specific dates. |
| **Step 3: Gaps and barriers** | ● List of potential gaps in knowledge, technology limitations, market structural barriers, regulatory limitations, public acceptance, or other barriers to achieving the goals and milestones |
| **Step 4: Action items** | ● Actions that could be taken to overcome any gaps or barriers that stand in the way of achieving the goals |
| **Step 5: Priorities and timelines** | ● List of most important actions that need to be taken to achieve the goals and the time frames taking into account interconnections among those actions and stakeholder roles and relationships |

Source: Author's compilation.

The above-mentioned methodologies vary in detail but have common features in terms of the flow and sequencing of activities:

- The first steps in the preparation of the road map are the definition of visions, goals, and objectives.
- The last steps are often the preparation of the implementation and monitoring plans.
- In between could be a single step or a series of steps that identify drivers; gaps and barriers; identify, prioritise, and select technologies; and identify actions to be undertaken.

The use therefore of any of these methodologies would generate an appropriate smart grid road map for an eco town project.

#### 4.3.2 Road Map Elements

Smart grid road maps vary from utility to utility, but they also have common elements: vision, drivers, theme areas, and pillars of action. Visions and objectives could be narrow, focusing mainly on the technology or the quality of services of the utility such as those of Pacific Gas and Electric in San Francisco and the State Grid Corporation of China. Alternatively, they could be broad, combining global, environmental, and social concerns at the national and utility levels such as those of Toronto Hydro-Electric System, the Provincial Electricity Authority of Thailand, and in France. This is shown in Table 16.

**Table 16: Smart Grid Visions/Objectives of Selected Utilities**

| | |
|---|---|
| Pacific Gas and Electric, California (United States) | ● Provide customers safe, reliable, secure, cost-effective, sustainable, and flexible energy services through integration of advance communications and control technologies |
| Toronto Hydro-Electric System (Canada) | ● Climate protection and sustainable energy<br>● Energy security<br>● Customer satisfaction |
| Provincial Electricity Authority (Thailand) | ● Increase energy efficiency and maintain the environment<br>● Improve quality of life<br>● Provide intelligent and green community in the future |
| State Grid Corporation of China | ● Ultra-high voltage (UHV) grid as a backbone network and coordinated development of subordinate grids at all levels |
| France | ● Attain emissions reduction objectives for greenhouse gases set for 2020<br>● Compliance with European objectives for the integration of renewable energy |

| | |
|---|---|
| | • Maintaining the quality and security of supply in the electricity system<br>• Consideration of social issues related to electricity supply |

Source: Author's compilation.

A similar pattern can also be observed for smart grid drivers. Smart grid deployment can be driven by micro utility level concerns, by the structure of electricity markets or physical infrastructures, or by global environmental or national concerns. Drivers can be expressed as principles or can be initiatives or programmes of government agencies. This is shown in Table 17.

**Table 17: Smart Grid Drivers of Selected Utilities**

| | |
|---|---|
| Pacific Gas and Electric, California (United States) | • Safety, reliability, and security<br>• Customer empowerment<br>• Efficient and flourishing electricity markets<br>• Environmental sustainability<br>• Consumer and technological advancement |
| Toronto Hydro-Electric System (Canada) | • Ontario Smart Grid Forum that promotes the industry's visions for the city's grid of the future<br>• City of Toronto's 'Change is in the Air: Clean Air, Climate Change and Sustainable Energy Action Plan' that has a goal to make Toronto the renewable energy capital of Canada |
| Provincial Electricity Authority (Thailand) | • Energy security and environmental awareness<br>• Customer demand for informative decisions<br>• Society's demand for a safe and eco-friendly grid<br>• Provincial Electricity Authority officers' demand for a safe and pleasant working environment |
| France | • Degree of intelligence in the electricity system and grids and the range of products and services associated with this capacity<br>• Degree and type of decentralisation in the system and grids<br>• Regulatory choices, business models, and the role of players affecting smart grids and electrical systems |

Source: Author's compilation.

Pillars of actions of a smart grid road map could be presented under programme areas or functional priorities. As shown in Table 18, programme areas and functional priorities differ by utility and this is influenced mainly by the vision and the objectives in the deployment of smart grid systems. Table 19 presents the case of Pacific Gas and Electric where smart grid pillars of action are classified according to programme areas. On the other hand, a number of utilities present their activities in a time frame representing the deployment plan. Table 20 presents the smart grid deployment plan for Toronto Hydro-Electric System and the Provincial Electricity Authority of Thailand.

**Table 18: Smart Grid Programme Areas/Functional Priorities of Selected Utilities**

| | |
|---|---|
| Pacific Gas and Electric, California (United States) | ● Engaged customers<br>● Smart grid energy markets<br>● Smart utility<br>● Cross-cutting smart grid infrastructure |
| Toronto Hydro-Electric System (Canada) | ● Climate protection and sustainable energy<br>● Energy security<br>● Customer satisfaction |
| San Diego Gas and Electric (United States) | ● Customer behaviour/education<br>● Demand response<br>● Rate design |
| United States National Institute of Standards and Technology | ● Wide area situational analysis<br>● Demand response<br>● Electricity storage<br>● Electric vehicles<br>● Applications (distribution grids management, advance metering infrastructure)<br>● Cross-functional areas (cybersecurity, network communications) |

Source: Author’s compilation.

**Table 19: Pacific Gas and Electric Smart Grid Programme Areas and Pillars of Action**

| Engaged Customers | Smart Energy Markets | Smart Utility | Cross-Cutting Smart Grid Infrastructure |
|---|---|---|---|
| ● Leverage smart metres technology<br>● Improve demand response resources<br>● Support electric vehicles | ● Improve forecasting techniques<br>● Integrate large-scale renewable energy resources | ● Enhance grid outage detection, isolation, and restoration<br>● Enhance grid system monitoring and control<br>● Manage grid system voltage and losses<br>● Manage transmission and distribution asset condition | ● Provide foundational and cross-cutting utility systems facilities and programmes necessary to continuously improve the application of smart grid technologies |

Source: Author's compilation.

**Table 20: Deployment Plan Phases and Pillars of Action**

| Toronto Hydro-Electric System | | |
|---|---|---|
| **Phase 1 (0–3 years)** | **Phase 2 (3–10 years)** | **Phase 3 (10–25 years)** |
| ● AMI integration<br>● Early DR programmes<br>● Cyber security systems<br>● Early DA systems integration<br>● Early DG programmes | ● Substantial growth of DG installations<br>● Integration of distributed energy storage systems<br>● Early implementation of V2G<br>● DA enhancement<br>● Use of smart appliances at homes will grow | ● Creation of micro-grids<br>● Fully electrified transport<br>● Decentralisation of energy generation will be completed<br>● Fault anticipation |
| **Provincial Electricity Authority of Thailand** | | |
| **Planning and pilot project phase (2012–2016)** | **Phase 2 (2017–2021)** | **Phase 3 (10–25 years)** |
| ● Micro-grids<br>● Integration of energy storage technologies<br>● AMI implementation | ● Large expansion of planning and pilot projects started during phase 1 | ● Decentralisation of power generation<br>● Customers can buy or sell electricity |

| | | |
|---|---|---|
| ● Integration of customer-owned distributed generation technologies<br>● Enable options for information usage of electricity<br>● Use of smart appliances<br>● Incorporation of EVs and charging stations<br>● Electricity generation from waste<br>● Increase use of electric transport | | ● Virtual power plants creation<br>● Self-healing network<br>● Two-way power supply of electricity for EVs (V2G)<br>● Peak demand reduction through EV usage |

AMI = advanced metering infrastructure, DA = distributed automation, DG = distributed generation, DR = demand response, EV = electric vehicle, V2G = vehicle to grid.
Source: Author's compilation.

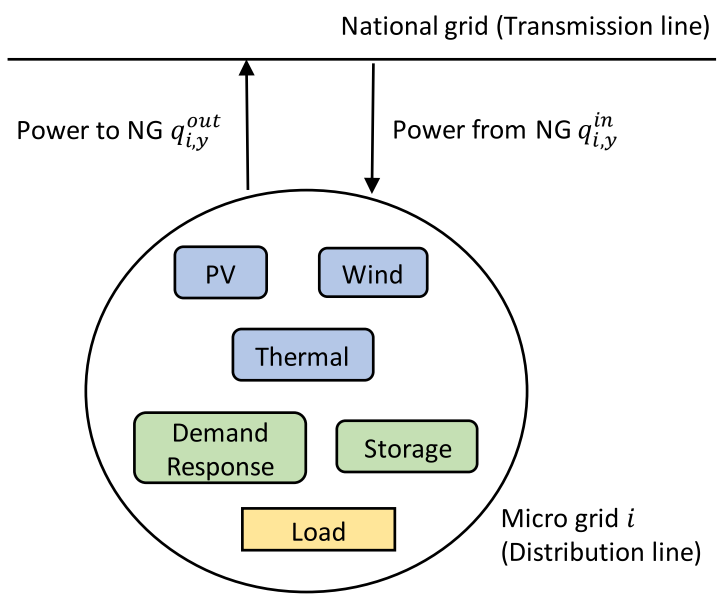
The review shows that though most road maps share common features, there is no standard format in presenting elements of a smart grid road map. Based on the existing smart grid road maps, Madrigal and Uluski (2015) in a study for the World Bank reviewed smart grid road maps of various utilities globally, and proposed five steps in defining the priorities of a road map:

- Step 1: Establish a vision and identify pillars. Under this stage, the long-term vision for smart grids is established which is based on energy sector goals. Also, key roles and responsibilities are defined.
- Step 2: Establish a timeline and goals for each phase. The timeline, either incremental or phases, for achieving smart grid vision is established.
- Step 3: Establish pillars of action. Pillars of action are established based on the road map vision. Also under this stage, risks, costs, and potential barriers are analysed.
- Step 4: Propose technology and functional applications. Under this stage, policies, regulations, and technology for each period and each pillar are suggested. The challenges associated with smart grid implementation are addressed.
- Step 5: Develop metrics and monitoring. This stage develops smart grid performance metrics to measure the success of implementation.

## 4.4. Cost Analysis of Smart Grid System in Eco Town

The following provides an outline of a methodology for analysing the cost and benefits of the smart micro grid system shown in Figure 50 (Rangarajan and Guggenberger, 2011; Morris et al., 2012). The methodology assumes the following basic parameters are obtained: (*a*) initial investment cost and maintenance schedule and cost per kilowatt for thermal power plants, transmission line (national grid), distribution line, solar PV power generation system, wind power generation system, electric storage system, and demand response equipment; (*b*) parameters of thermal power plants, such as generation capacity, fuel consumption rate, minimum up-time constraint, and minimum down-time constraint; (*c*) parameters of electric storage system, such as minimum discharge power, maximum discharge power, minimum stored energy, maximum stored energy, and efficiency; (*d*) scenario of fuel price used in thermal power plant (high, medium, low); (*e*) load profile (hourly and monthly) and growth rate; and (*f*) wind and solar profiles and fluctuation (hourly and monthly).

**Figure 50: Smart Micro Grid System Connected to National Grid**




NG = national grid, PV = photovoltaic.

Source: Author.

The outline of the methodology consists of the following six steps:

- Step 1: Selecting the case

We consider five cases in our cost–benefit analysis of smart micro grid systems. In the base case, all electric power is generated using only thermal power plants. The micro grid system is isolated from the national grid (transmission line) and therefore only a distribution line is used to supply power to consumers. In case 1, we consider the base case to connect the national grid, as depicted in Figure 50, in which electric power is transacted between two grids. In case 2, we consider case 1 with the integration of variable renewable energy, such as solar PV power and wind power. This means that we need fewer thermal power plants compared with case 1. In case 3, we consider case 2 with the addition of electric storage. This means that more variable renewable energy is integrated compared with case 2. We need fewer thermal power plants for the integration of variable renewable energy. In case 4, we consider case 3 with the addition of demand response capability. We need less electric storage for the integration compared with case 3.

- Step 2: Estimating the initial investment cost

We estimate the initial investment cost for the selected case at step 1 using basic parameters: initial investment cost per kilowatt for thermal power plants, transmission line (national grid), distribution line, solar PV power generation system, wind power generation system, electric storage system, and demand response equipment.

- Step 3: Setting the price parameter $\alpha$

The parameter α is introduced to calculate the area price of electrical power $p_{i,t}$ in micro grid $i$ at time $t$ from generation cost $c_{i,t}^{j}$ of thermal power plants ($1 \leq j \leq K$) operating to supply power to consumers in micro grid $i$ at time $t$,

$$p_{i,t} = \alpha \max_{1 \leq j \leq K} \{c_{i,t}^{j}\}. \quad (1)$$

The initial value of α is set slightly larger than 1.

- Step 4: Calculating the yearly profit of generation $P_{i,y}$ in micro grid $i$

Effective load: The actual load subtracted by base load (hydro and nuclear power) $l_{i,t}$ in micro grid $i$ at time $t$ is defined by

$$l_{i,t} = q_{i,t}^{g} + q_{i,t}^{in} - q_{i,t}^{out}, \quad (2)$$

where $q_{i,t}^{g}$, $q_{i,t}^{in}$, and $q_{i,t}^{out}$ are power generated by thermal power plants, power from the national grid to micro grid $i$, and power from micro grid $i$ to national grid, respectively. $q_{i,t}^{j}$, $q_{i,t}^{in}$, and $q_{i,t}^{out}$ are calculated using the unit commitment model by minimizing the objective function,

$$\sum_{i=1}^{N} (C_{i,t} - E_{i,t}). \quad (3)$$

The unit commitment model for the smart grid with variable renewable energy, electric storage, and demand response was formulated as a mixed integer problem (Ikeda et al., 2012; Ikeda and Ogimoto, 2013, 2014). Power generated by thermal power plants at time $t$ is $q_{i,t}^{g}$ is summed power from each thermal power plant ($1 \leq j \leq K$),

$$q_{i,t}^{g} = \sum_{j=1}^{K} q_{i,t}^{j}. \quad (4)$$

The price of $q_{i,t}^{in}$ is calculated as the maximum of area price among area with $q_{i,t}^{out} > 0$,

$$p_t^{NG} = \max_{1 \le i \le N, q_{i,t}^{out} > 0} \{p_{i,t}\}. \quad (5)$$

The profit of generation in micro grid $i$ at time $t$ is calculated using

$$P_{i,t} = S_{i,t} - C_{i,t} - E_{i,t} - M_{i,t}, \quad (6)$$

where $S_{i,t}$, $C_{i,t}$, $E_{i,t}$, and $M_{i,t}$ are sales revenue $S_{i,t} = p_{i,t} q_{i,t}^{g} - p_t^{NG}(q_{i,t}^{in} - q_{i,t}^{out})$, operation cost $C_{i,t} = \sum_{j=1}^{K} q_{i,t}^{j} c_{i,t}^{j}$, $CO_2$ emission cost $E_{i,t} = p_{CO2} \sum_{j=1}^{K} e_j q_{i,t}^{j}$, and maintenance cost $M_{i,t} = \sum_{j=1}^{K} m_{i,t}^{j}$, respectively. Here, $p_{CO2}$is $CO_2$ price per unit volume and $e_j$ is the emission coefficient for thermal power plant $j$. $m_{i,t}^{j}$ is scheduled maintenance cost at $t$ for thermal power plant $j$. Finally, the yearly profit of generation $P_y$ in micro grid $i$ is calculated using

$$P_{i,y} = \sum_{t=1}^{T} P_{i,t}. \quad (7)$$

- Step 5: Checking economic constraints

The economic constraints for investment for smart micro grid $i$ are given by the positive net present value,

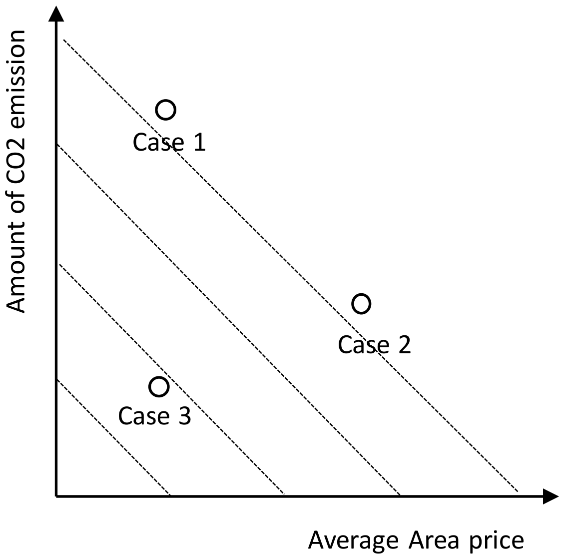
$$\mathrm{NPV} = \sum_{y=1}^{Y} \frac{P_{i,y}}{(1+r)^y} - I_i \ge 0. \quad (8)$$

Here, the investment cost for the national grid is not included. If the constraint (8) is not satisfied, we return to step 3 to increase parameter $\alpha$, and then repeat steps 4 and 5. If the constraint (8) is satisfied, the calculation is complete.

- Step 6: Obtaining the price of electric power $p_y$ and amount of yearly $CO_2$ emissions $e_y$

The location of cases is obtained in the plane of average area price and amount of $CO_2$ emissions. This is depicted in Figure 51. Equi-cost curves are shown by the dotted lines. This plot provides policymakers with information to decide which case is suitable for their purpose.

**Figure 51: Image of Location of Cases in the Plane of Average Area Price and Amount of $CO_2$ Emissions**




Source: Author.

### 4.5. Challenges and Recommendations

A smart electricity grid is an essential component of a fully functioning eco town or system of eco towns. A smart grid system allows optimal interaction of key elements such as distributed generation, demand response, IT, and market mechanism, and ensures that the overarching goal of establishing a sustainable society would be achieved in each eco town.

The deployment of smart grid technologies, however, faces major challenges for eco towns. As discussed, they include funding smart grid investments, interoperability of technologies, and consumer participation. The deployment as well as optimal operation and utilisation of smart technologies therefore requires policy and regulatory interventions.

Electric utilities are mainly responsible for investments of key smart grid technologies. Demonstration projects could be funded by grants from either public or private entities, but the replication of these projects in a system of eco towns requires a sustainable source of funding. Policy and regulatory mechanisms thus need to be established to ensure that utilities would recover their investments, whether on direct smart grid investments or to recover lost revenues due to energy efficiency improvements from smart grid deployment.

Smart grid technologies include communicating sensors and devices that exchange information and interoperate. Standards exist for some of these technologies but are still evolving for others. Regulatory agencies should ensure that smart grid technologies used in eco towns conform to existing international standards and should provide clear guidance and directions with respect to technologies that have new or evolving standards.

Smart grid technologies also elicit automated end-user demand and energy efficiency responses. To promote efficient consumption, this must be accompanied by the introduction of consumer incentives through pricing schemes. Time-differentiated pricing schemes are found to stimulate behavioural changes and trigger demand response.

To further promote consumer participation in demand response, regulatory agencies must also assure consumer protection, especially regarding privacy, ownership, and security issues related to access to detailed consumer data and other issues related to the social safety net associated with the introduction of new tariff rates, as well as protection associated with remote disconnections made by smart grid technologies.

Decentralised renewable electricity in eco towns, on the other hand, could be supplied not only by utilities or independent power producers but also by electricity consumers who are allowed to generate their own supply or to supply to the grid. Policy and regulatory interventions such as feed-in tariff and net metering schemes would also be required to provide incentives to consumers to invest in renewable energy technologies and be allowed to interconnect to the grid.

Considering the required level of investments and the evolution of technologies, the deployment of smart grid technologies should progress on an incremental basis. The development of a smart grid road map for eco towns is therefore critical. The road map could vary from one eco town to another and this will be influenced mainly by the priority objectives. If the main objective is for higher deployment of renewable energy technologies, smart grid technologies that could be rolled out initially would be those that facilitate higher integration of renewables. On the other hand, if the objective is to improve energy efficiency, then smart metering and other technologies that facilitate demand response would be prioritised for implementation.

Overall, in order to achieve a fully functioning smart grid system in an eco town that facilitates an interaction between variable energy supply and flexible demand through a smart distribution network, a strong policy and regulatory intervention is required to incentivise (*a*) the supply side, i.e. consumers to become producers of variable renewable electricity supply; (*b*) utilities to invest in standardised smart grid technologies; and (*c*) the consumption side, i.e. consumers to modify consumption patterns in response to time-differentiated pricing schemes.

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