Study on the Energy Mix in Future Smart Electricity Systems in Japan

Qi Zhang* and Tetsuo Tezuka

PhD (Energy Science), Research Fellow

Graduate School of Energy Science, Kyoto University, Kyoto 606-8501, Japan,

Tel: 81-75-753-4750; Email: ZhangQi@energy.kyoto-u.ac.jp

Abstract The future developments of nuclear and renewable energy need to be considered together in Japan to realize a safe and clean future electricity system after the Fukushima Nuclear Accident under continuing policies of CO_2 emission reduction. On the other hand, one of the most crucial elements of future electricity systems will be the capability for "smart" controls on both supply and demand sides to perform under real-time dynamics. Therefore, the purpose of the study is to propose energy mix scenarios in smart electricity systems and penetration of electric devices under their smart control strategies from reliability, economy, security and environment aspects. The scenario analysis was conducted using an input-output hour-by-hour simulation model to derive supply-demand balance subject to constraints from technological, economic and environmental perspectives. The obtained excess electricity, CO_2 emissions, operation patterns of various devices, etc. in different scenarios were compared and analyzed. The results of the analyses make us understand quantitatively the technological and environmental impacts of the different mixes of renewable and nuclear energy, as well as the corresponding operation patterns of controllable devices under their smart control strategies in different scenarios.

Keywords: Electricity mix, Nuclear, Renewable, Smart electricity system, Control Strategy

1 Introduction

Nuclear is viewed as the backbone power source in efforts to reduce the high rate of dependence on overseas energy imports and CO_2 emission in Japan with the restrictions of minimal domestic energy resources [1][2]. However, the Fukushima Nuclear Accident happened on March 11, 2011 led to many criticisms on nuclear power again, and renewable energy is expected to penetrate electricity systems as quickly as possible. However, we argue that, from a long-term viewpoint, apart from the safety issues of nuclear power, there are also very serious energy security problem, global warming pressure and renewable energy penetration bottlenecks from technological, systemic and economic perspectives in Japan. Energy supply in Japan is more than 95% dependent on overseas imports, and the price of energy resources is still increasing in international markets. Building new coal-fired and oil-fired power plants are not desirable choice even in an electricity shortage situation due to CO_2 emission increase. On the other hand, renewable energy - mainly including photovoltaics (PV) and wind power - the potential is limited in Japan due to physical-geographic limitations. There are still many bottlenecks for the high level penetration of renewable energy into the electricity system particularly from the systematic perspective due to the possibilities for too much excess electricity happen [3][4]. Therefore it is crucial to consider both renewable and nuclear energy in Japan to realize future clean and safe electricity systems. The nuclear reactors mentioned here would be new generation technology that incorporates “passive” safety features intended to avoid disasters like the one in Fukushima.

However, renewable and nuclear energy pose a significant problem to traditional grid systems, which cannot cope with rapid, intermittent and uncontrollable peaks and falls in electricity demand depending on the time of day and season. Electricity production from renewable energy mainly PV and wind depends highly on weather conditions which are unstable and cannot be adequately predicted. Nuclear power as a base load generation source with high capital cost and low operation cost cannot readily alter its power output for technological and economic reasons. Therefore, load levelling and fluctuation absorption remain a problem that power suppliers are unable to overcome by themselves [5]. On the other hand, new electric devices such as battery, electric vehicle (EV) and heat pump (HP), etc. will soon be added to the electricity system in future, and their operation pattern can be controlled in real time [6][7][8]. The new electric devices are expected to help electricity systems to integrate more nuclear and renewable energy by absorbing excess electricity and supplying deficient electricity. For this reason, smart control strategies of the electric devices are of vital importance to integrate renewable and nuclear energy into future electricity systems.

In order to find the property mix of nuclear, renewable and thermal power in future electricity system with various new electric devices under their control strategies, this study presents scenario analysis of the Japanese electricity system with different penetration levels of power sources and electric devices in 2030 using a model which incorporates aspects of technology, economy and environment. The model is organized into an input-output framework, and is realized using an hour-by-hour computer simulation to derive a supply-demand balance under smart control strategies. Finally, the appropriate electricity mix can be selected based on the obtained performance data and operation patterns in different scenarios.

2 Methodology

2.1 Future Smart Electricity Systems

In future electricity systems, many new electric appliances and devices will be integrated on both supply and demand sides such as PV panel, battery, EV, HP, etc. Here, we define “smart” as that electric appliances and devices can be controlled in real time to absorb excess electricity and supply deficient electricity to realize a low-waste and effective electricity system with renewable energy penetration. In practice, renewable energy particularly PV and electric devices are distributed in individual locations, and many individual locations form a region/nation. In some situations, some individual locations use their own distributed electricity systems which isolate from big grid system. However, we assume that all the electric devices in individual locations are integrated into the big grid system and the electric power company can monitor and manage all of them using smart meter and smart control device. In the proposed methodology, target future electricity systems are in region/nation level, and we assumed that smart controls are realized automatically in all individual locations in the target region/nation.

2.2 Analysis Model

Therefore, we proposed the model shown in Fig.1. It is organized in an “Input-Output” framework and realized by hour-by-hour computer simulation to derive demand-supply balance. The “Input” includes basic physical data and predefined operation rules (control strategies). Main input data are historical traditional electricity load, solar irradiation, wind speed, fuel supply, installed capacity, CO_2 emissions factor and basic cost information, etc. A number of alternative regulation strategies emphasis on control strategies of new devices, blackout permission, generation priority of various technologies, upper limitation of excess electricity, range of capacity factor, cost, CO_2 emission constraints, etc.

New electricity devices (battery, EV, HP, etc.) and their combinations are optional, and their control strategies are also defined as optional rules. The “Output” includes mainly energy balances, annual electricity production, fuel consumption, total/average cost, total/average CO_2 emission, operation patterns of the new devices under their defined control strategies, etc. All the basic data is hourly, however, through statistics, daily, weekly, monthly and annul data can be obtained. Some models have been developed for analysis of the energy (electricity) mix with renewable energy penetration [9]. However, there is still not a model mainly focusing on penetration of both renewable and nuclear energy into future electricity systems with various electric devices under their smart control strategies.

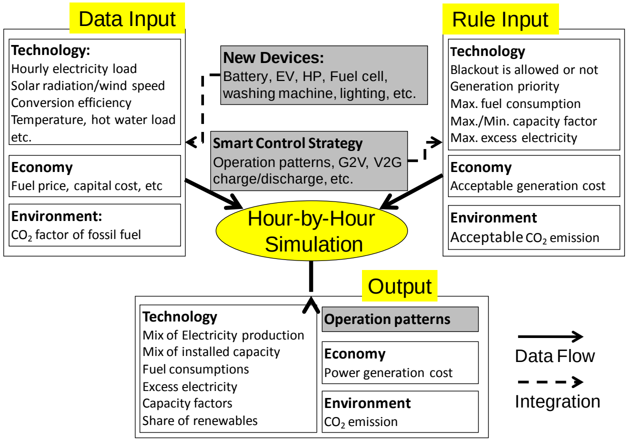

Fig. 1 Model for analyzing future smart electricity system

The model is developed as an operable software, and the hour-by-hour simulation flow is shown in Fig.2. Electricity generations from renewable, nuclear, thermal and hydro are considered as basic supply, when it becomes more than traditional electricity load, excess electricity will be used to drive HP and/or charge batteries. On the other hand, when basic electricity supply from renewable and nuclear energy is less than traditional load, battery is discharged to meet the deficient electricity. If no blackout happens, the system is considered as technology feasible, otherwise initial data will be changed and new iterative will start. Finally, the results are obtained through statistics on hourly data.

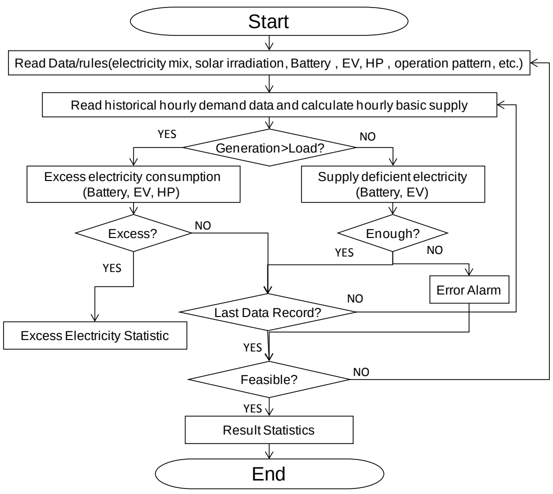

Fig. 2 Concept flow chart of hour by hour simulation for future smart electricity systems

3 Data

3.1 Electricity Load

The hourly distribution of traditional electricity load in 2001 is shown in Fig.3 [10]. The electricity productions increased by about 30% from 740 TWh in 1990 to 960 TWh in 2001. However, on the demand side, energy saving is the key focus especially since the Fukushima accident [11], and possible population reduction is also predicted [12]. Therefore, we assume that demand remains at 2001 level in the demand scenario.

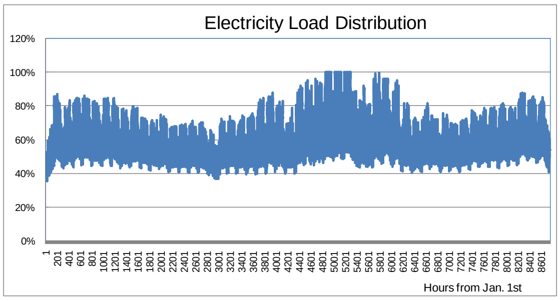

Fig. 3 Hourly electricity load distribution in Japan

The electricity consumption of EV and HP is new load. There are about 120 million people, 50 million households [12], and 70 million passenger cars in Japan in 2030 [13]. A part of cars are assumed to be substituted by EV and HP is installed in a part of households for hot water production. The efficiency of EV in Japan uses data from the practical EPA value-5km/kWh in average [14], and daily travel distance is considered as 30km per EV in their moving patterns [15]. HP is used to supply 450 liters of hot water at 40°C according to revised M1 mode (hot water is 65 ºC)[16] to meet hot water load [17]. The hourly electricity consumption of HP for making hot water can be obtained using COP (Coefficient of Performance) calculation [18]. However, the impact on the electrical load would be different according to the patterns of EV charge and HP operation patterns.

3.2 Nuclear Power, Thermal Power and Renewable Energy

Three different nuclear power development cases in light of the Fukushima nuclear accident are proposed: (1) negative nuclear power; (2) conservative nuclear power; and (3) active pursuit of nuclear power as shown in Fig.4. In the S1, the stopped NPPs in this earthquake will be closed permanently, all NPPs under construction and in planning will be canceled and the NPPs in operation will be closed in their early lifetime 35-40 years. On the other hand, in the S2 and S3, all NPPs under construction and in planning will be continued according to the schedule and all NPPs will operate for a long lifetime 40-50 years and very long lifetime 50-60 years, furthermore, in the S3 Fukushima Daiichi NPPs will be rebuilt before 2030.

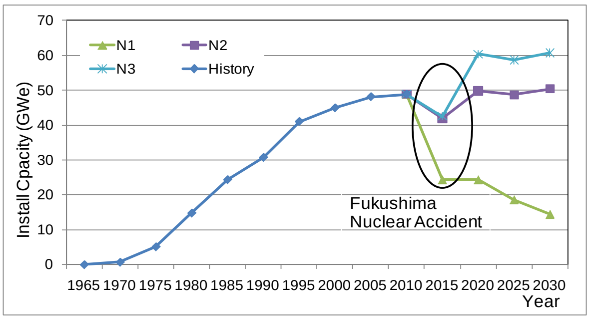

Fig. 4 Nuclear power development cases to 2030

If all the thermal power plants (coal, LNG, oil) are stipulated to have 45 year lifetimes, and there will be no new construction of thermal plants up till 2030, the installed capacities of thermal power plants are shown in Fig.5 based on historical installed capacity data [10]. This is the basic installed capacity for thermal power, and in the scenario analysis, new LNG power plants can be built when necessary to provide sufficient capacity.

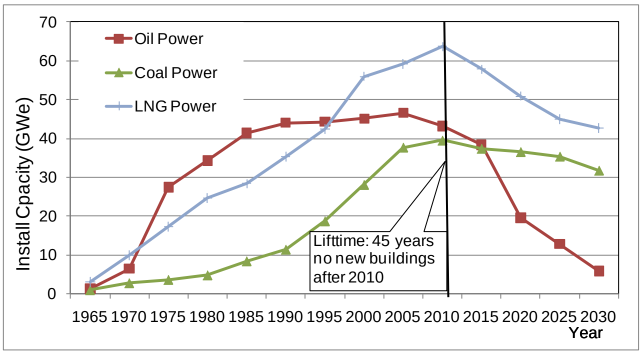

Fig. 5 Thermal power development to 2030

Japan will have to increase substantially the amount of electricity provided by renewable sources, especially "new" sources such as wind, solar, and biomass, because the country's hydroelectric potential has already been largely exploited. At present, the installed capacity of hydro power is 21 GWe [10]. We assume the value will remain constant and pumped hydropower will be replaced by batteries in this study. The potential of renewable energy in Japan is listed in the following table [19][20], and the solar irradiation and wind speed historical data in 2001 same year with historical load provided by JMA (Japan Meteorological Agency) are used [21]

Table 1 Renewable energy potential in Japan

Renewables	PV	Wind	Biomass	Hydro
Potential	100GWp	50GWe	2GWe	21 GWe

4 Rules

The main defined rules are shown in Table 1, which includes five aspects. Battery, LNG, oil and biomass can alter their output 100% in one hour to absorb fluctuations of PV and wind power. In the target electricity systems, when excess nuclear power appears, heat pumps come into operation, and the batteries are charged. On the other hand, during the demand peak of daytime or on a cloudy/rainy day, heat pumps are on standby status, and available batteries could be used to provide electricity to the grid. In case of EV is used, the processes of charging and discharging are called G2V (Grid to Vehicle) and V2G (Vehicle to Grid). There are many uncertainties in the cost information of facilities such as V2G and G2V, and distribution of battery's capital cost between EV and electricity system. Therefore, economic performance of electricity system is not considered in the study, although the model has the economy analysis function. In environment aspect, the CO_2 emission in electricity generation sector is calculated using CO_2 emission factor [22], and 1990 level is used as a indicator here. CO_2 emission reductions in transportation sector from replacing gasoline cars using EV and in residential sector from replacing gas driven hot water producer by electricity driven HP for hot water production are not accounted into electricity systems.

Table 2 Summary of main defined rules

	Defined Rules
Supply-demand	1. Blackouts is not allowed 2. Only PV&wind power can become excess power 3. Excess power ratio < 15% in total 4. New building of LNG power plant is allowed
Power generation and storage	1. Generation priority: hydro, Nuclear, coal, PV&Wind, Battery, LNG, biomass, oil, EV 2. Capacity factor of coal-fired power can be lowered to zero for more renewable energy penetration 3. Battery(EV):10%(30%)≦SOC≦95%, 4. charge speed<30%SOC/h, discharge speed<50SOC/h
Resource Availability	1. Renewable energy penetration≦ physical potential 2. Fossil fuel demand≦Max. supply capability 3. Facilities and resource can be imported from overseas
Capacity factor load-following	1. Capacity factor: 75%≦Nuclear≦100%, coal≦ 85% 2. Battery, LNG, oil and biomass operate in load-following mode
CO_2 emission	1. Average annual CO_2 emission per kWh≦1990 level

5 Results

5.1 Scenario Design

As shown in Fig.6, there are three nuclear power development cases in the supply side, and five electric device combinations in demand side.

Supply Side (S1-S3)

Nuclear	(GWe)
N1	14.3
N2	50.4
N3	60.8

Renewable	Potential (GWp/e)
PV	100
Wind	50
Biomass	2

Other (Gwe)	Coal	LNG	Oil	Hydro
	31.8	≧42.6	5.8	21

×

Demand Side (D1-D5)

	Battery (GWh)	HP (Million)	EV (GWh)
D1	×	×	×
D2	500	×	×
D3	500	20	×
D4	×	×	500
D5	×	20	500

Fig.6 Scenario design in supply and demand sides of electricity systems in Japan in 2030

5.2 Results

The electricity mix, excess electricity and CO_2 emission of all scenarios are shown in Fig.7, Fig.8 and Fig.9 respectively. If the "N1" is selected, even renewable is developed as much as possible; Japan will have to use LNG to supply more than 30% its electricity, and thus face CO_2 emission/climate change pressure. On the other hand, in case of the "N3", much more excess electricity happens and the people in the country have to face more potential dangers of nuclear power. Furthermore, electric devices (battery, EV and HP) operated under their smart control strategies can reduce greatly excess electricity and CO_2 emission, and thus help the system to integrate more renewable and nuclear energy. However, the scenarios - especially the nuclear development policy - will ultimately be self-selected by the people, government and industry in Japan.

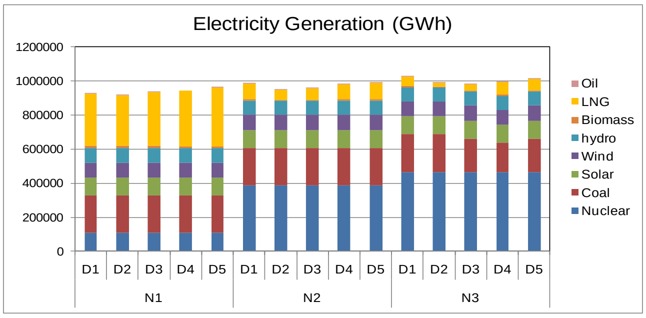

Fig. 7 Electricity mix in all scenarios

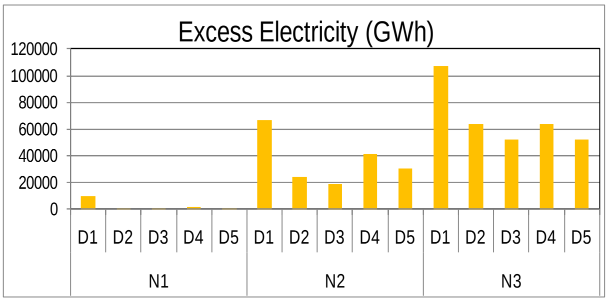

Fig. 8 Excess electricity comparison in the scenarios

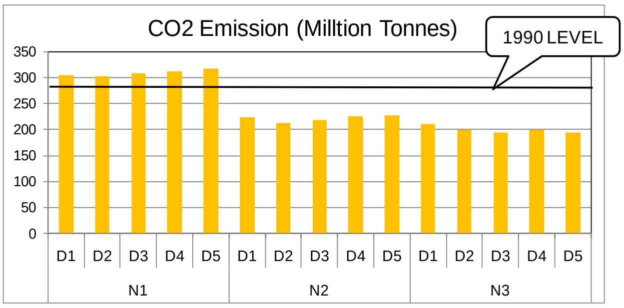

Fig. 9 CO_2 emission comparison in the scenarios

6 Conclusion

Scenario analysis was conducted on the electricity systems with electric appliances and devices operated under their smart control strategies in Japan in 2030 using an input-output hour-by-hour simulation model. Three development cases of nuclear power were proposed after the Fukushima Nuclear Accident in supply side and five electric device combinations were assumed in the demand side. The simulation results of the electricity mix, excess electricity and CO_2 emission in all scenarios were obtained based on the input data and predefined rules. The analysis results show that (i) negative nuclear policy will lead to more fossil fuel consumption and CO_2 emissions increase comparing with 1990 level; (ii) however very active pursuit nuclear power policy will lead to more excess electricity; (iii) excess electricity and CO_2 emissions can be reduced greatly in various scenarios with the help of electric appliances and devices (battery, EV and HP) under their smart control strategies.

7 Acknowledgement

The authors would like to thank the GCOE program in Graduate School of Energy Science, Kyoto University and Kan Gen Kon for the great support and helpful comments.

References

[1] METI (Ministry of Economy, Trade and Industry of Japan) (2010) The Strategic Energy Plan of Japan, <http://www.meti.go.jp/english/press/data/pdf/20100618_08a.pdf>.

[2] JAEA (Japan Atomic Energy Agency) (2009) 2100 nuclear vision. [in Japanese]

[3] Denholm P, Margolis MR (2007) Evaluating the limits of solar photovoltaics (PV) in traditional electric power systems. Energy policy, 35: 2852-2861

[4] Lund H (2006) Large-scale integration of optimal combinations of PV, wind and wave power into the electricity supply. Renewable Energy, 31:503–515.

[5] Hall PJ, Bain EJ (2008). Energy-storage technologies and electricity generation. Energy policy, 36-12: 4352-4355.

[6] Yoda S, Ishihara K (1997) Global energy prospects in the 21st century: a battery-based society. Journal of Power Sources, 68-1:3-7.

[7] Lund H, Kempton W (2008) Integration of renewable energy into the transport and electricity sectors through V2G. Energy policy, 36:3578-3587.

[8] Hewitt NJ (2011) Heat pumps and energy storage – The challenges of implementation. Applied Energy, doi:10.1016/j.apenergy.2010.12.028.

[9] Connolly D, Lund H, Mathiesen BV, Leahy M(2010), A review of computer tools for analysing the integration of renewable energy into various energy systems. Applied Energy, 87:1059-1082.

[10] FEPC (Accessed June 2011) Electricity power statistic information, available at <http://www.fepc.or.jp/library/data/tokei/index.html> .

[11] KEPCO (Accessed July, 2011), Electricity Usage Graph, available at <http://www.kepco.co.jp/setsuden/graph/index.html>

[12] National Institute of Population and Social Security Research (2008) Future population prediction in Japan. [in Japanese]

[13] AIRIA (Automobile Inspection &Registration Information Association) (Accessed July, 2011) Automobile holding data in Japan, available at <http://www.airia.or.jp/number/index.html>.

[14] US Environmental Protection Agency (Accessed July, 2011), Fuel Economy of Electric Vehicles, Available at < http://www.fueleconomy.gov/feg/evsbs.shtml>

[15] JSTE (Japan Society of Traffic Engineers) (2007) Road Traffics census OD Investigation, [in Japanese].

[16] IBEC (Institute for Building Environment and Energy Conservation) (2009) Energy consumption calculation.

[17] Imamura E and Asano H (2007) Optimal hot water supply technology sect analysis in residential house under load survey data, Socio-economic Research Center, CRIEPI, Rep.No.Y06025. [In Japanese]

[18] Mita Y, Ikeya T, Miyashiro H and Kobayashi Y (2009) Development of Prototype of Battery Energy Storage System Coupled with Heat Pump Water Heater. Materials Science Research laboratory Rep. No.Q08018. [in Japanese]

[19] ME (Ministry of Environment of Japan) (2011) study of Potential for the Introduction of Renewable Energy. [in

Japanese]

[20] JWPA (Japan Wind Power Association) (2011) Roadmap of long-term introduction of wind power in Japan, available at <http://log.jwpa.jp/content/0000289019.html>.

[21] JMA (Japan Meteorological Agency), 2001-2005, Amedas data.

[22] Imamura E, Nagano K (2010) Evaluation of Life Cycle CO_2 emissions of Power Generation Technologies, CRIEPI, p. 34. [In Japanese].