6 Simulating the Dynamics of ERJ

The SimRen simulation was developed to study the dynamics of an energy supply system consisting solely of renewable energy sources. SimRen was used to plan and optimise the supply system for Japan. The objective of this optimisation was to assure a reliable supply at all times and to supply Japan with electricity without importing energy from outside of Japan. The simulation calculates the deliverable energy from installed power plants using time-resolved methods. The installation of power plants was adjusted until the optimal amount of installed power plants was found. (further information see Appendix)

The year 1999 was taken for the reference year of the ERJ Demand Model and therefore the time span that was simulated. A time span of a whole year had to be simulated in order to ensure that seasonal variations and critical weather situations were included and tested.

According to the Japan Meteorological Agency the year 1999 had weather conditions that are a little below the average. The average wind speed and the solar irradiation were below the average for the years 1975-2000.

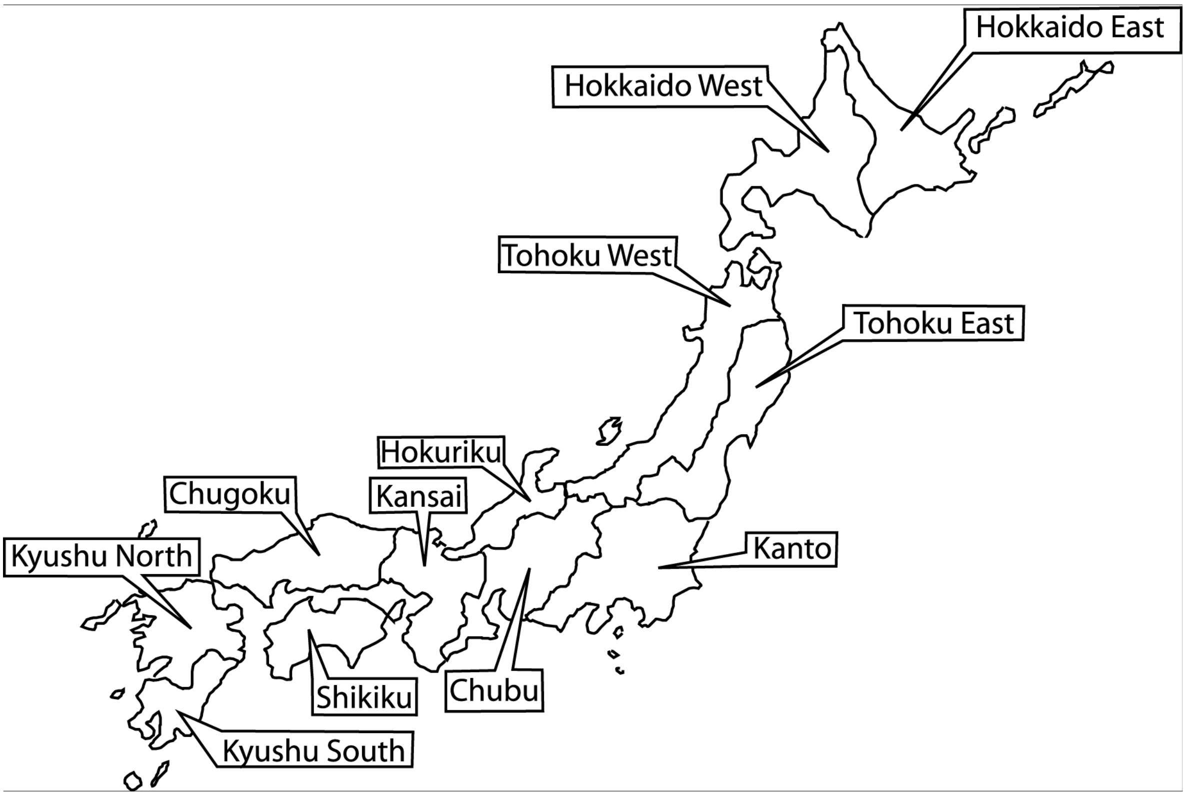
	Average 1975-2000	**Average 1999**
Wind speed	3.2 m/s	2.9 m/s
Solar irradiation	12.9 MJ/qm	12.5 MJ/qm
Temperature	13.7 °C	14.2°C

Source: Japan Meteorological Agency.

Table 22 : Average wind speeds and solar radiation in Japan

A well thought-out spatial resolution was also seen as important for the significance of the results, as all weather-dependent effects had to be simulated with a high resolution to be as realistic as possible. Consequently, all available weather data was taken into consideration for the SimRen Simulation for Japan. The information from 153 weather stations uniformly distributed over the whole country was available. The potential photovoltaic production was calculated using 66 of these stations, which also measured solar radiation.

All the other data integrated into the model of Japan was available from the ten Japanese districts. Some regions were divided into two, because of differing meteorological and geographical characteristics. These were Hokkaido East and West, Tohoku East and West and Kyushu North and South. Thus the ERJ Electrical System Model has 12 regions as shown in the picture below. The energy consumption of Okinawa was only available combined with Kyushu and is therefore included in the Kyushu demand. Since most of the southerly islands cannot be integrated in the Japanese electrical grid, only the islands of Yakushima and Tanegashima were used. The more southerly islands can be used to produce hydrogen, because they have very high wind speeds and solar radiation but this was not included in the simulation. Some regions were divided into two, because of differing meteorological and geographical characteristics. These were Hokkaido East and West, Tohoku East and West and Kyushu North and South. Thus the ERJ Electrical System Model has 12 regions as shown in the figure below.

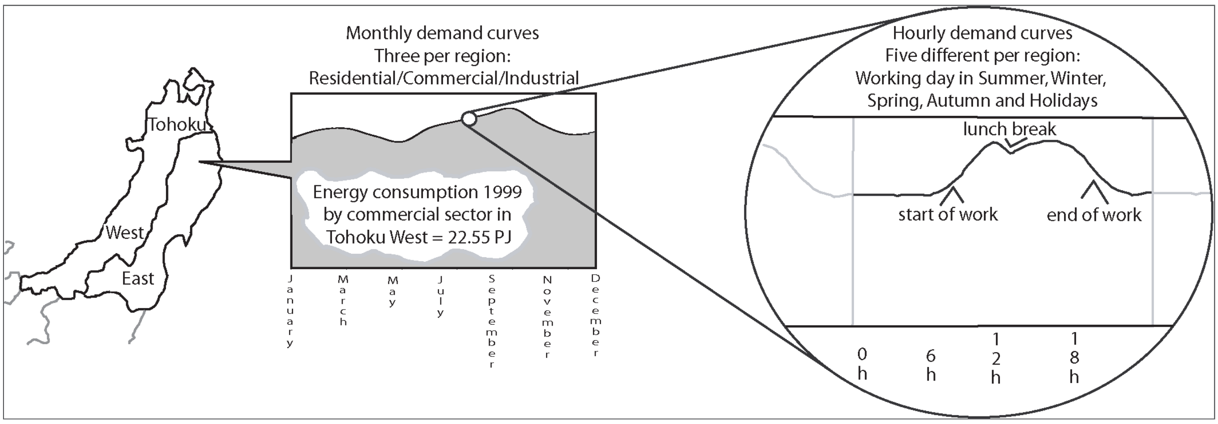


Source: ERJ.
Figure 43 : The 12 regions of the ERJ Electrical System Model

6.1) The ERJ Electrical Demand Model

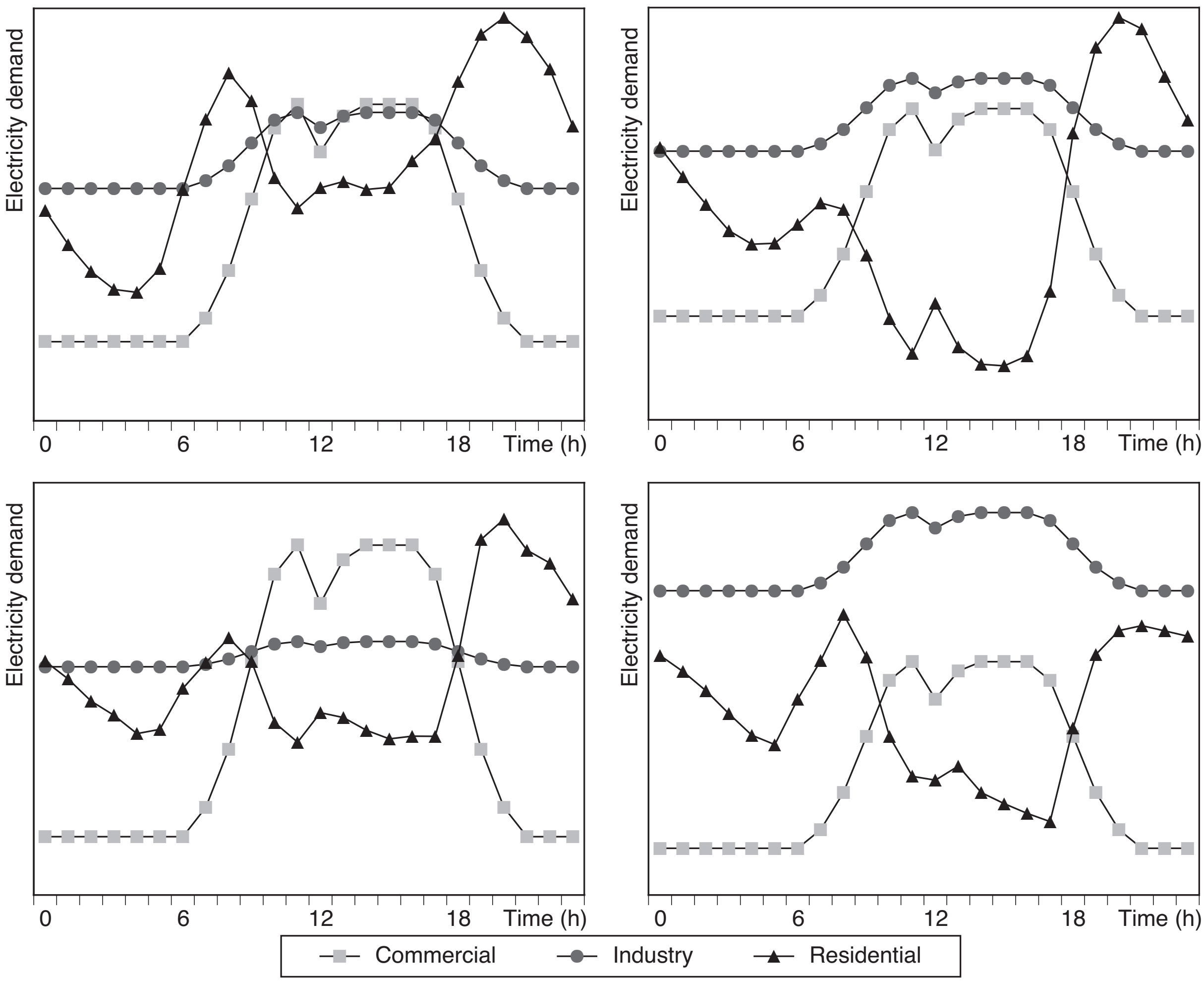
SimRen calculated the energy demand of a consumer group at a certain point in time using typical daily and yearly demand curves. The consumer groups were residential, commercial and industrial consumers. The way this was done is illustrated in the figure below.

A unique yearly demand curve was developed for each consumer sector and district in Japan, which indicated how much electrical energy was consumed in a certain month in that sector of that region. In addition, the ERJ Demand Model contained information about the amount of energy consumed in a whole year in the residential, commercial and industrial sectors.



Source: ERJ.

Figure 44 : Analysis of annual demand in Tohoku East showing daily fluctuations



Source: ERJ.

Figure 45 : Examples of hourly demand curves

A monthly resolution of the demand data was considered far too low for meaningful research. SimRen therefore used daily demand curves that were combined into a yearly curve resulting in the correct sum total for the whole year. In addition, the daily demand curves were scaled with the yearly curves as they also included monthly tendencies. For Japan, daily demand curves for spring, summer, autumn and winter, and a curve for public holidays were developed. These curves differed from region to region and demand sector to demand sector.

The final demand curve SimRen used included a random fluctuation of five percent to reproduce more realistic consumer behaviour, as consumers are not entirely predictable.

6.2) The ERJ Electrical Supply System

An intelligent regulation of the adjustable energy suppliers was vital in order to realise a good working electrical supply system. Electricity suppliers in SimRen were categorised as fluctuating or adjustable.

6.2.1) Fluctuating Energy Suppliers

Wind and photovoltaic are fluctuating energy suppliers because they depend on the wind and solar radiation respectively. In addition to these two suppliers, cogeneration plants in the residential and commercial sector were also classified as fluctuating energy suppliers as the heat needed in that sector determined the energy production. The residential and commercial consumers used combined heat and power plants to heat houses or water. Electricity production therefore depended on atmospheric temperatures in the region.

Photovotltaic

According to existing technologies, which reach an efficiency of 15%, we used this efficiency as well. After calculation of the irradiation on a declined surface having regard to the shading effects the energy output is calculated using the efficiency of 15% and the thermal change of the efficiency.

The photovoltaic areas we used for ERJ Japan had the alignment shown in the Table 23.

Solar-thermal Energy Calculation

The heat that can be produced with solar thermic areas has also been calculated with SimREN, although it has nothing to do with the electrical supply of Japan. Its calculation utilises the same formulas as the calculation of the photovoltaic electricity production. We assumed an efficiency of

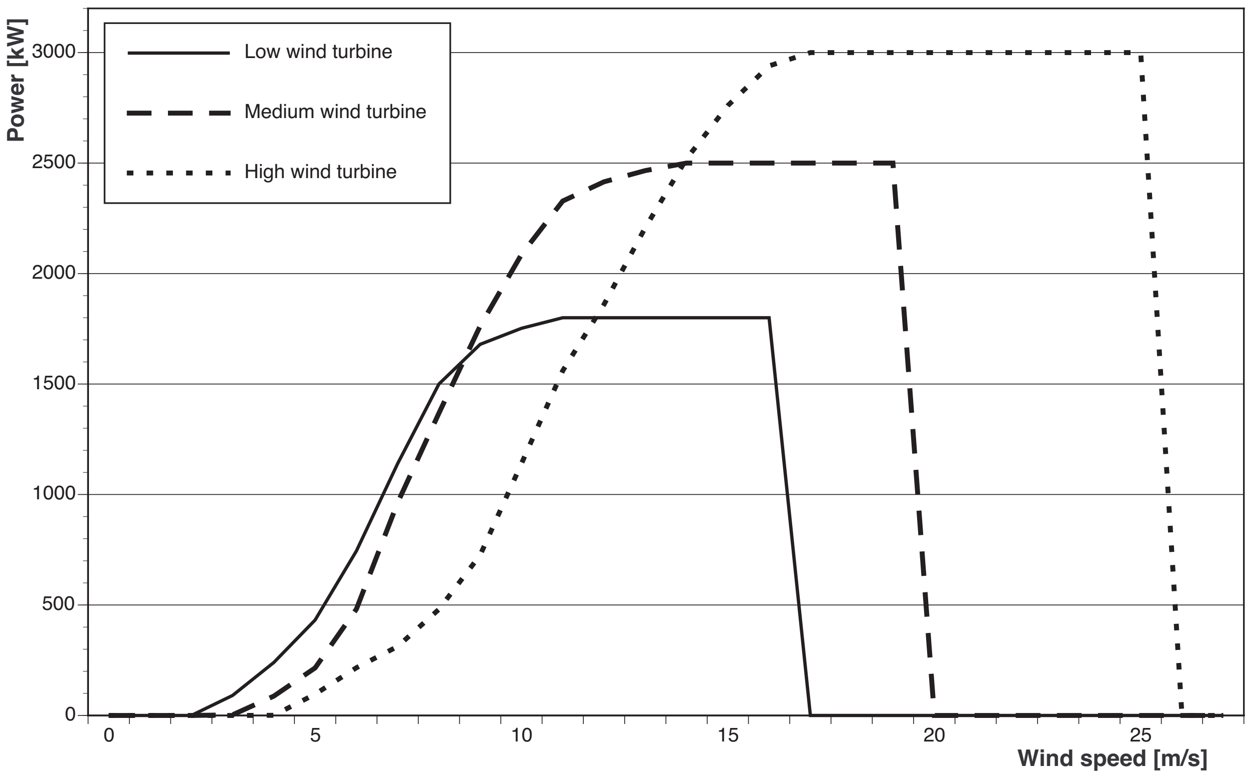
50% for the solar thermic areas in the commercial and residential sector, where temperatures up to 50°C are needed, and an efficiency of 25% in the industrial sector, where mostly higher temperatures up to 150°C are needed. The distribution of the alignments of the areas is the same as for photovoltaic and is shown in the Table 23.

Percent of all photovoltaic areas	Inclination	Adjustment	Type of roof
50 %	Degree of latitude + 10°	South	Flat roof Shading
25 %	Degree of latitude + 10°	South	Sloping roof No shading
12.5 %	Degree of latitude + 10°	South + 30°	Sloping roof No shading
12.5 %	Degree of latitude + 10°	South - 30°	Sloping roof No shading

Source: ERJ.
Table 23 : Photovoltaic areas and their alingments

Wind Energy Calculation

The simulation of the energy output by wind turbines is based on typical power curves of windmills. We used three different types of windmills in SimREN, from which two are used offshore and onshore. The power curves of these types are shown in the Figure 46



Source: ERJ.
Figure 46 : Three wind turbine power curves

The two bigger windmills are used onshore and offshore. It seems that it is not profitable to install the smaller ones offshore, because of the high wind speeds offshore, the high expenses and the low energy output. The technical details of the different types are summarized below.

	Low wind turbine	Medium wind turbine	High wind turbine
Nominal output	1,800 kW	2,500 kW	3,000 kW
Height of hub	108.6 m	80 m	95 m
Cut-in wind speed	2 m/s	3 m/s	4 m/s
Cut-out wind speed	17 m/s	20 m/s	26 m/s
Nominal wind speed	11 m/s	14 m/s	17 m/s
Regulation type	Pitch	Pitch	Pitch

Source: ERJ.

Table 24 : Wind turbine technical details

The roughness used in this formula can be classified by the different kinds of landscapes. For the conversion of the wind speed in measurement height to hub height we used a roughness of 0.1. This accords to an area with bushes.

Information about offshore wind speeds was not available. Therefore it had to be calculated using the weather data from stations close to the sea. The fundamental difference between onshore and offshore is the lower roughness of the ground and consequently higher wind speeds offshore. As measurements in Denmark and Germany show the offshore wind speed is approximately 33% higher than onshore, thus we also used a 33% higher wind speed offshore than measured at the onshore weather stations. To calculate the wind speed offshore we first converted the wind speed onshore to the wind speed in hub height using the formula above, then we raised this wind speed 33% to reflect the offshore location.

Cogeneration Heating Plants Calculation

The energy production of the cogeneration heating plants in households and commercials depends on the outside temperature in the regions and the hot water demand in the households and commercial buildings. We suggest that hot water can be stored throughout the day and therefore only the production of heat for heating fluctuates. If the outside temperature falls under a predefined start temperature, the cogeneration heating plants start heating up to a target temperature. These temperatures differ between night and day. During the day the plants start heating if the temperature falls under 18°C. If this happens they heat the houses to a target temperature of 20°C. During the night the target temperature is about 15°C and the heating starts at about ten degrees centigrade, but not all rooms that are heated during the day are heated during the night. Therefore we assumed an average starting temperature of 5°C and an average target temperature of ten degrees centigrade in the whole house, to make the simulation easier. Night heating begins at 23:00h and ends at 7:00h.

The plants run at least one hour, because it makes no sense to turn them on and off every time the temperature curve crosses the start temperature. The dispensable heat is stored and can be used later.

According to existing technologies we assumed an electrical efficiency of 30% and a thermal efficiency of 50%.

6.2.2) Adjustable Energy Suppliers

Adjustable energy suppliers used in SimRen included hydropower plants, geothermal power plants, fast reacting power plants and cogeneration power plants for high and low temperature heat. The power output of the pumped storage plants was also adjustable but depended on the fill level. Although the maximum power output of the hydropower plants fluctuated with the water level of the rivers, at least the power output was controllable up to that level.

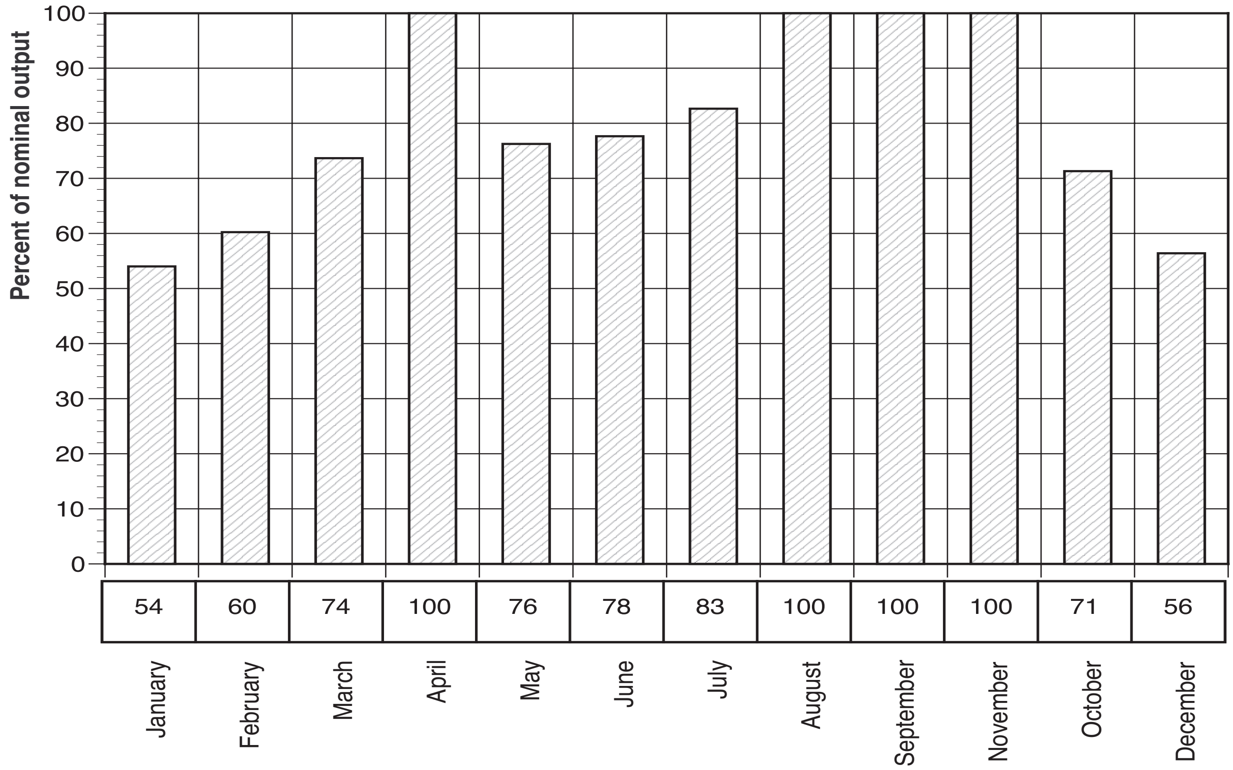
Cogeneration Heating Plants in Industry

As cogeneration heating plants have a predefined maximum power output that has been described in the ERJ supply part, their power output can be adjusted up to this output without restrictions. This applies for low temperature heat produced by motors just like for high temperature heat by steam turbines. The assumptions about efficiencies are the same as for the cogeneration in households and commercial buildings, 50% for thermal and 30% for electrical energy.

Hydroelectric Power Plants

The graph below shows maximum fraction of power that can be produced by a hydropower plant in a certain month in Kanto. This fraction depends on the water flux in big rivers in the regions. We assumed that a maximum electricity production is possible, when the water flux in big rivers is above the average flux of the whole year. If the rivers carry less water, the maximum electricity production goes down as well.

The Figure 47 shows the maximum electricity production by hydropower plants in Kanto. The possible output in April, August, September and October is 100% of the installed power, because the water flux in big rivers was higher than the average flux of the year. What cannot be seen in this graph is that August has the highest water flux of all months of the year. In winter the water flux and consequently the maximum output is much lower than in summer and autumn. These curves have been developed for every region of the simulation. The only region that differs markedly from the others is Kyushu, where the water production is low in August and September and high in the spring.



Source: ERJ.
Figure 47 : The maximum power output of hydropower plants in Kanto.

Geothermal Power Plants

The maximum electricity output of geothermal power plants does not vary over the year, because the supply with geothermal heat does not fluctuate either. Up to the installed amount of producable energy the power plants can be adjusted freely. The amount of installable power plants and their size was published by the Institute for Energy and Total Engineering and was therefore available for the simulation.

Pumped Storage Power Plants

The pumped storage power plants can convert electrical energy into potential energy of water, i.e. they pump water in a reservoir to a higher position using electrical energy. This water can later be used to produce electrical energy again by driving a turbine. Each of these conversion processes has an energy leakage of 10.5%. This leads to an energy loss of 20% for the whole process of storing the energy and reconverting it to electrical energy.

Fast Reacting Power Plants

The fast reacting power plants are hydrogen burning fuel cells (although steam turbines have similar characteristics), which use the hydrogen that has been produced from energy surpluses Their production can be adjusted up to the nominal power output as long as there is hydrogen available. The efficiency for the fast reacting power plants is set to 50%.

6.3) The Dynamics of the ERJ Electrical Model

The energy demand was calculated first. The energy demand of consumers is not adjustable by energy demand management[100]. The electricity production of fluctuating suppliers in every region was then determined and subtracted from the energy demand. The remaining demand had to be covered by adjustable suppliers and storages.

An energy manager was used in the simulation to control the adjustable energy suppliers. This energy manager controlled the cogeneration plants, the hydropower plants and the geothermal power plants. Cogeneration power plants consisted of motors for low temperature heat and steam turbines for high temperature heat. They supplied the industrial sector with enough heat for its processes. Two thirds of these cogeneration plants operated constantly throughout the day. The others were adjusted to meet the electricity demand in the regions. This mode of operation was possible as the heat could be stored in the industry and then consumed when heat was needed.

Firstly, the energy manager powered up the cogeneration plants in the industry in order to cover the remaining electricity demand. If their production did not meet demand, geothermal power plants were used to produce more energy. The hydropower plants were powered up last as their energy production depended on the water level in the dedicated river and was therefore restricted by the amount of usable water.

Regions with a high population density such as Kanto or Kansai are not self-sufficient in energy production. In these regions, the energy deficit is very high because of the large energy demand, with little space for windmills and other energy suppliers. Other regions with a very low population density have a large amount of windmills because of the available space and therefore can export energy to these densely populated regions. This energy exchange has to be managed.

The Import-Export Manager distributed the surpluses over the regions that lacked energy, until all the energy was used or all the regions were fully supplied. The Manager attempted to use the

100.It would be possible to alter consumer behaviour by sending information to consumers about varying prices according to demand. But this kind of demand management is not included in this program version, although it would improve the energy system.

shortest possible distances in order to minimise transportation losses. If the electricity production was still insufficient, a fast reacting hydrogen power plant with one Gigawatt peak output was powered up. The Manager then emptied the pumped storage plants in order to produce more energy and finally another two Gigawatts of fast reacting hydrogen power plants could be powered up if required. The Manager could also command the energy managers in the regions to produce more energy than required for their own region in order to supply other regions. This ensured that all potentials were used up to a maximum to supply Japan with energy. After many simulation runs this strategy turned out to best meet the supply. This strategy had the advantage that pumped storages always contained some energy for critical times and fast reacting power plants did not burn too much hydrogen.

In this program version of SimRen, Japanese holidays were treated as normal working days, as integration in the simulation was not possible. During the optimisation process it became clear that the introduction of a summer time adjustment would be favourable as the electricity demand peaks would much more closely match the peaks in the solar radiation much better. That is why in the ERJ Electrical Supply Model a time shift of one hour between March 28th and November 31st is included.

Energy supply curves for certain weeks in 1999 were included below to illustrate the dynamic and reliable nature of the supply system[101]. The curves show the supply situation in the third week in January from Monday 14th to Sunday 20th. No shortages occurred during the whole simulation period of one year.

The curves include all energy suppliers and show the power output in Gigawatts over time. The X-axis shows the day of the year and the vertical lines isolate the days from each other at midnight.

The first graph in the figure shows electricity consumption (demand) compared to production (supply). It can be seen that production is always greater than consumption. The energy production is the sum of all energy suppliers shown in the other four graphs. The second graph shows the energy production of geothermal and hydropower plants. Below these adjustable suppliers is a curve containing photovoltaic and wind energy. The fourth curve contains the cogeneration heating plants in the industrial sector and the commercial and residential sectors. The cogeneration plants in the commercial and residential sectors fluctuate due to changes in the outside temperature (Sunday was a very cold day). The high fluctuations in the production occur because the target heating temperature is usually lower at night than during the day, and therefore less heat and less electricity is produced during the night. The development of pumped storage plants and fast reacting power plants is plotted in the last graph. The graph also contains the resulting hydrogen production in this week, although it is not included in the first graph. In this graph, storage charge

101.All the curves for 52 weeks of the simulation are included in the appendix.

and hydrogen production are drawn negative as they consume energy and can then easily be summed with the producers to the production curve on top.

On the 15th and 16th, the first curve shows a surplus of energy. This energy comes from a very high wind energy and photovoltaic as shown in curve three. Hydrogen was generated from the energy surplus. The second curve shows that the geothermal and hydropower plants produce less energy on those days, as not as much energy is needed. They are not powered down completely because some regions still need this energy.

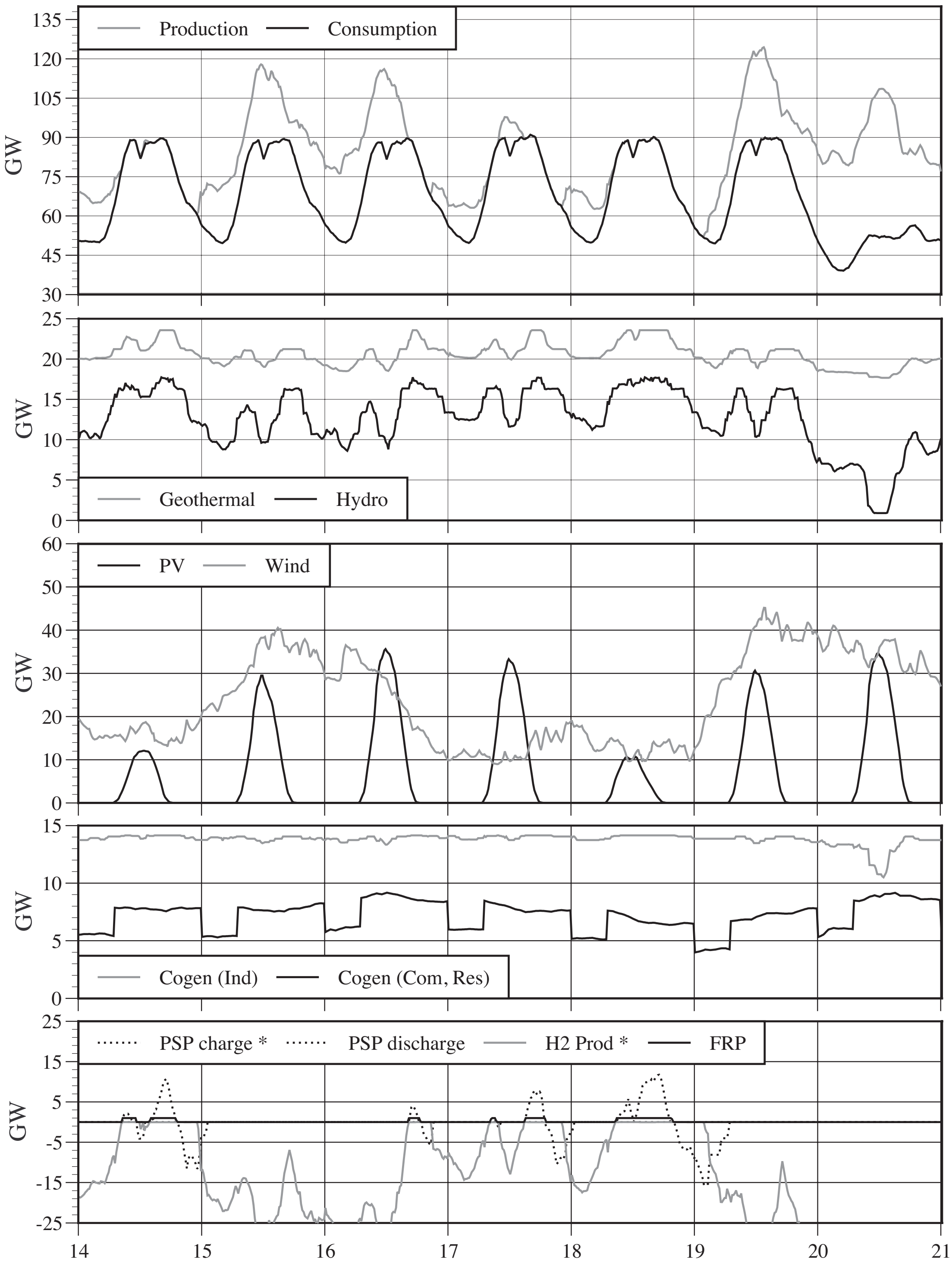
On the 18th, the energy production matches the demand exactly. The ERJ Electrical Supply Model achieved this by adjusting the hydropower and geothermal power plants. The wind and photovoltaic production is much lower on Friday than on the other days. Therefore the adjustable suppliers have to run at full capacity. Of particular note is the fourth graph, which shows the charging and discharging of the pumped storages and the fast reacting power plants. As described above, the fast reacting power plants produce one Gigawatt before the storages are powered up. The pumped storages were then the last technology to prevent Japan from having an energy deficit but, as the graph shows, they were capable of providing the missing energy (see Friday evening) and they were replenished when a surplus of energy became available (see Friday night).

Sunday 20th shows what happens if far too much energy is available. On Sundays the energy demand is always lower than during the week because most of the offices are closed and many industry branches do not work. As this does not affect the fluctuating energy suppliers, most Sundays are oversupplied with electrical energy. The storages are filled mostly over the weekend and can be used again to fill energy deficits. All the adjustable energy suppliers are powered down. Even the production of cogeneration plants in industry can be reduced as shown in curve four.

By analysing these curves, the electrical energy supply system was optimised until it was finally proved that a complete supply of Japan with electrical energy from renewable sources was possible. Two other weeks were also included to show the behaviour in summer and autumn.

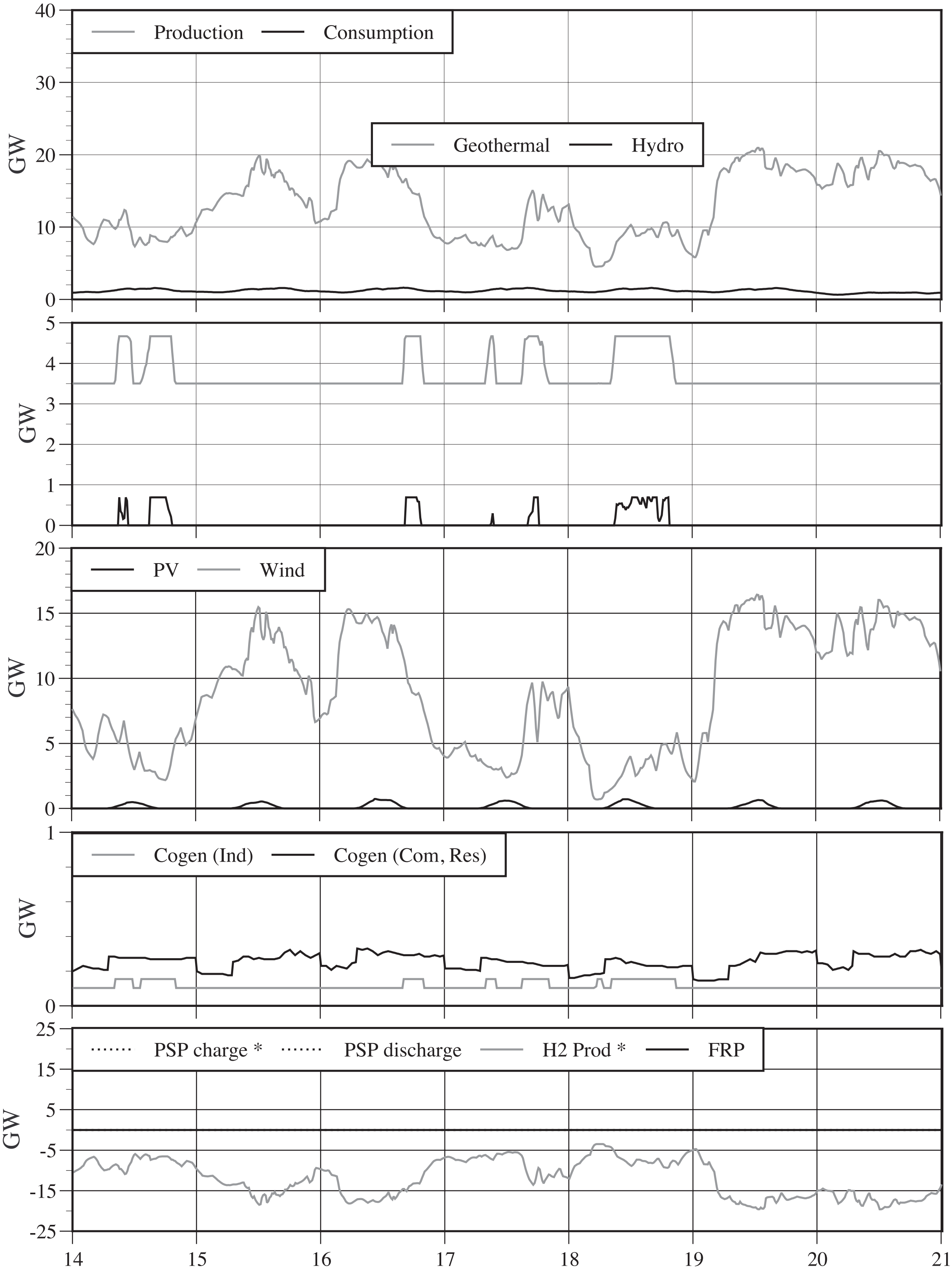
The set of curves above show the region Hokkaido West, where the energy production exceeds the energy consumption most of the time. The graph shows the immense amount of electricity that is produced by windmills and geothermal power plants, because there is such a high potential in Hokkaido West. The photovoltaic electricity production is very low, because Hokkaido has a low population density and therefore very little area for photovoltaics. Energy production by cogeneration is very low for the same reason. On days when the energy production by fluctuating suppliers is low (like Friday or Monday in this week) the geothermal power plants are powered up, although there is no energy needed in Hokkaido West. Even the water power plants produce energy at those times.

The next set of graphs above shows the same week in Kanto. The proportions are reversed in this region, because the population density is extremely high and therefore the spaces for windmills are few. In the week that is shown the energy demand can be met only on Sunday, because the energy consumption is lower than during the week. Due to the high population density the suitable area for photovoltaics on buildings or parking lots is very big. This leads to high energy production by photovoltaic areas. The high industrialisation leads to a large number of cogeneration power plants that also supply the region with energy, but the extremely high energy demand and the few wind mills lead to a undersupply that has to be met by the other regions. In the shown week the geothermal and hydro power plants can only be powered down on Sunday. On Thursday, when the photovoltaic energy production is very low even the pumped storages have to be discharged.



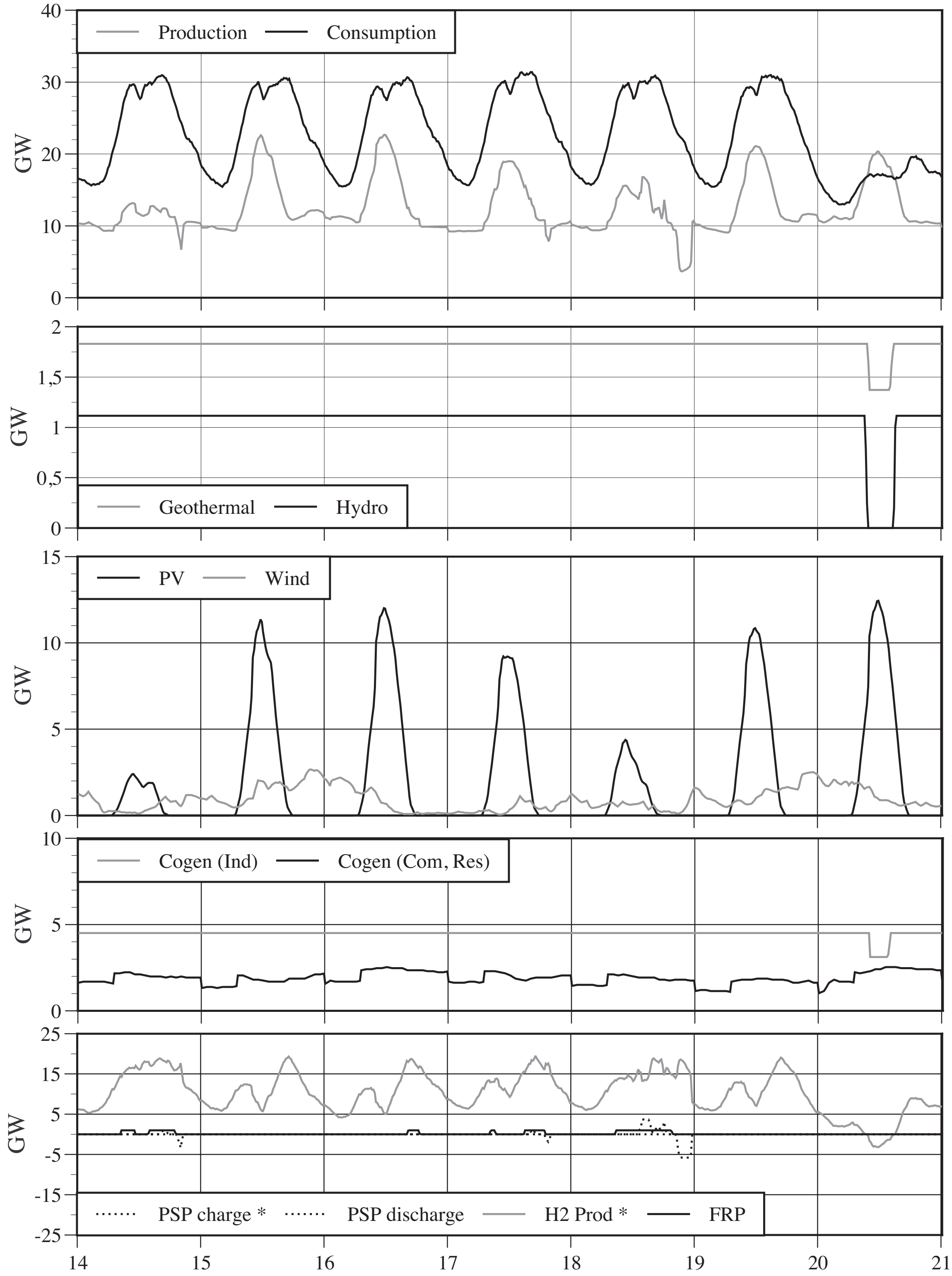
Source: ERJ.

Figure 48 : Energy supply and demand over one week in January in gigawatts.
The figure shows the energy supply by different technologies, the total demand and the storage of electrical surplus in hydrogen or pumped hydropower



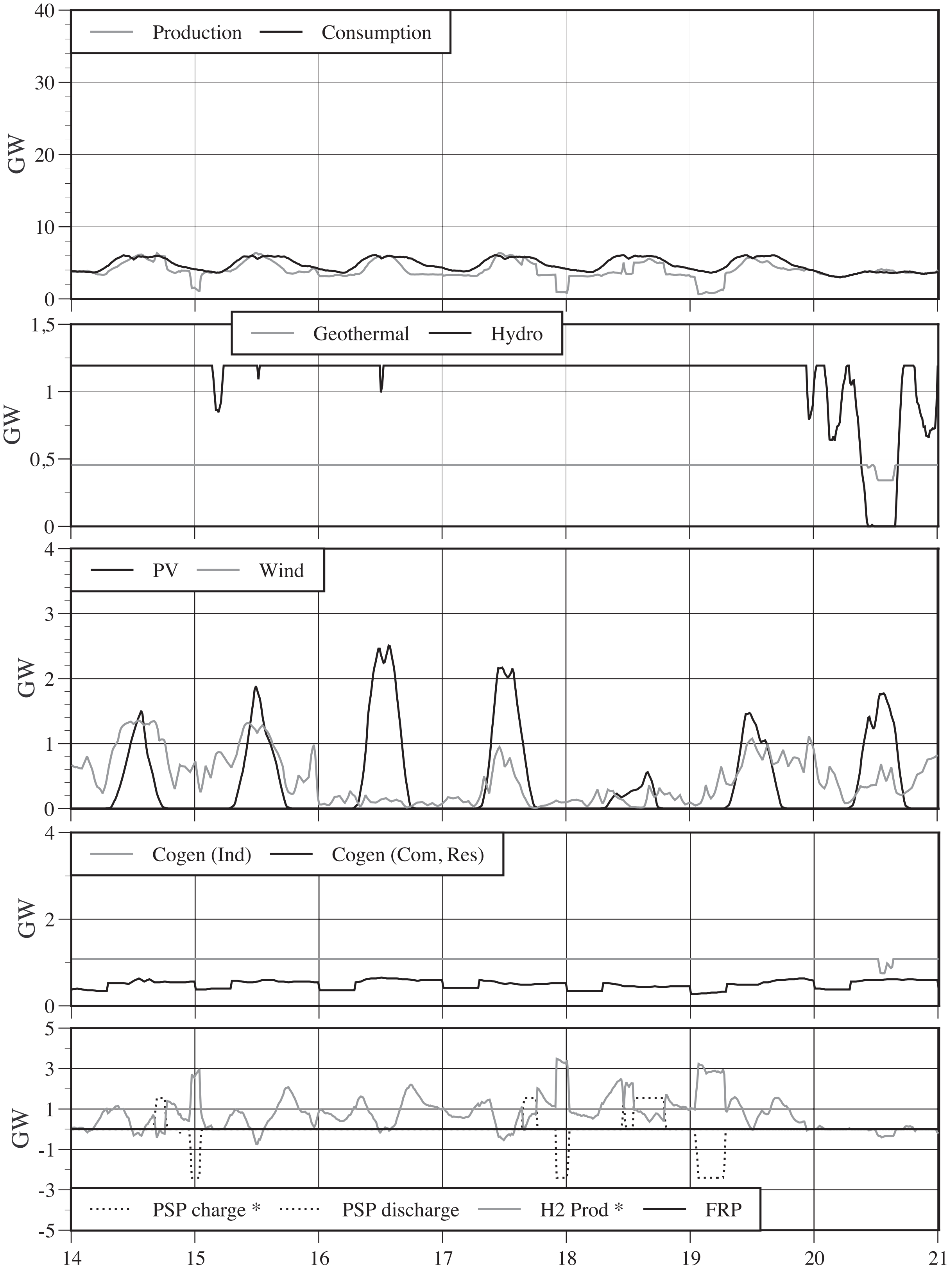
Source: ERJ.

Figure 49 : Energy supply and demand in Hokkaido West over one week in January in Gigawatts.The figure shows the energy supply by different technologies, the total demand and the storage of electrical surplus in hydrogen or pumped hydropower



Source: ERJ.

Figure 50 : Energy supply and demand in Kanto over one week in January in Gigawatts. The figure shows the energy supply by different technologies, the total demand and the storage of electrical surplus in hydrogen or pumped hydropower



Source: ERJ.

Figure 51 : Energy supply and demand in Chugoku over one week in January in Gigawatts.The figure shows the energy supply by different technologies, the total demand and the storage of electrical surplus in hydrogen or pumped hydropower

The third set of graphs above shows Chugoku. It is included because Chugoku has an energy production that nearly supplies the energy demand out of the region itself. The area that is already sealed allows a high installation of photovoltaic areas and there are many hydropower plants in Chugoku. The energy consumption is only a fifth of Kanto. Thursday and Friday night the storages are filled although the region itself does not produce too much energy. This is because the rest of Japan has an energy surplus. And during the day the Import-Export manager orders the storages to produce energy in order to supply Japan. The storages are not discharged when Chugoku is undersupplied but if energy is needed for Japan as a whole.

By analysing these curves, the electrical energy supply system was optimised until it was finally proved that a complete supply of Japan with electrical energy from renewable sources was possible.

The curves of all 52 weeks of the year 1999 are included in the appendix. It is interesting to look at the 2nd week in April, because the energy production by wind parks and photovoltaic areas is very high in this week and the supply exceeds the demand nearly the whole week. The effects of the wind and irradiation can also be seen in the 3rd week in August, because in this week the energy production by these sources is very low and the adjustable suppliers have to cover the demand. It can be seen that the storages are charged nearly every day during the day and discharged during the night. And the fast reacting power plants have to supply the adjustable suppliers in order to meet the demand.

6.4) Conclusions of the Simulation

Using the SimRen simulation of the ERJ Electrical supply Model, it has been proved that Japan can cover its whole electrical energy demand with renewable energy sources that are available within Japan.

The installed capacities and the full load hours of the technologies in the ERJ Electrical System are summarised in the table below. Fast reacting power plants and pumped storage power plants have the least full load hours, as they are only used when the other technologies cannot cover the energy demand. Wind turbines and cogeneration in the commercial and residential sectors have low full load hours compared with the other technologies because they are not adjustable, and depend on wind speed and outside temperatures. The simulation's full load of 2,890 hours is quite high compared with windmills actually installed. This is because the amount of windmills installed offshore is very high. Cogeneration has full load hours of 8,573, which is certainly high, but additional backup plants lower this amount. It is important to allow some time for maintenance.

Technology	Installed Power	Energy output GWh	Full load hours
Cogeneration in industry sector	14.2 GW	121,737	8,573 h
Geothermal power plants	25.4 GW	180,645	7,112 h
Water power plants	23.7 GW	125,705	5,304 h
Cogeneration in commercial and residential sector	10.9 GW	38,728	3,553 h
Wind turbines	56.9 GW	164,441	2,890 h
Fast reacting power plants	3.0 GW	1,287	429 h
Pumped storage power plants	19.4 GW	4,055	209h

Source: ERJ.

Table 25 : Renewable energy sources used in the ERJ Scenario One, their installed power, energy output and full load hours

The highest electricity production from wind turbines was on the 9th of January. On that day, wind turbines had a power output of 49 GW, which is 86% of the installed power. Because of the low temperatures, the maximum output of the cogeneration power plants in the residential and commercial sector of 9.8 GW was on February 4th, while in August the output of these plants was only 2.5 GW due to the high temperatures in this month.

Pumped storage plants and fast reacting plants run mainly in the afternoon and evening when the sun sets and photovoltaic production declines. At this time most people come home from work and need energy, which then has to be produced without photovoltaic support. Therefore, the introduction of a summer time is highly recommended and is included in the simulation[102]. The storages are filled mainly during the night and on Sundays, because the energy consumption is very low at these times.

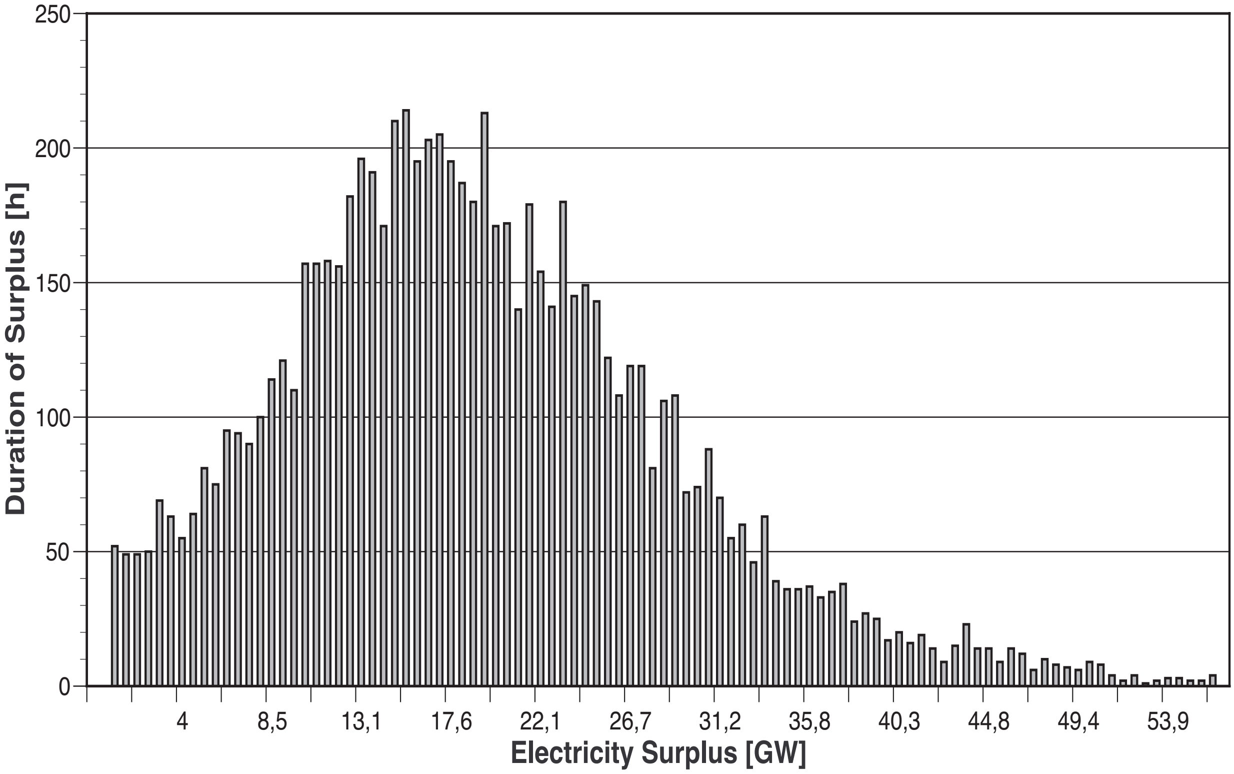
The graph above shows how long certain amounts of energy surplus lasted. This surplus is the energy that is used to produce hydrogen. This means pumped storage and fast reacting power plants are already included in the production. Therefore the graph only shows the overproduction. If we include the Fast reacting Powerplants and pumped storage plants in the optimised energy supply system no energy under supply occurs.

Out of 8,760 hours in a year 91.1% of the time more electricity is produced than the demand. This energy is used to generate hydrogen or stored in pumped water for hydropower. The other 8.9% of time when there is no surplus of energy, the energy production meets the demand exactly. This is possible, because the controllable suppliers can be precisely adjusted, if the fluctuating suppliers do not produce too much energy. In 5,700 of these hours (65% of the year) the energy surplus lies between ten and 30 GW. As the graph shows a surplus of more than 40 GW is very rare (only

102.The introduction of “summertime”, sometimes known as “daylight savings” artifically sets the clock forward during summer months to enable people to make the most of daylight in the working day and immediately after work. It also has the effect of adjusting peak demand time of day favourably for solar power.

three percent of the year). An overproduction of this size is mainly on Sundays, when the energy consumption is very low.

Using the SimREN simulation of the ERJ Electrical Supply Model it has been proved that Japan can cover its whole electrical energy demand by renewable energy sources that are available within Japan.



Source: ERJ.

Figure 52 : Duration of overproduction of electricity in Japan