

## 10 Appendix : SimRen Simulation of the dynamics of energy systems

The program ‘Simulation of Renewable Energy Networks’ (SimRen) has been developed in order to study energy systems that are based largely or entirely on renewable sources of energy. SimRen is based on the experience gained while creating scenarios for the European supply area <sup><108></sup>. In the analysis of the dynamics of the scenarios, it was found that the existing tools (simulation programs, database) were not sophisticated enough to make assertions that are precise to the hour or minute about the security of supply of such a system. This meant that only a limited optimization of the system was possible, and the estimates necessary as a consequence probably led to much greater plant capacity being needed in the scenarios than would have been necessary for reliable operation.

With the help of the SimRen simulation, it is possible to model and study in detail the structure of an energy supply system within the simulation environment. SimRen enables one to investigate the dynamics of the system, the optimization of the geographical distribution of the different technologies, and to simulate a country or a supply area over a period of an entire year.

The dynamics of the system are of great interest, since one must ensure that the energy demand can be met simultaneously, especially in the field of electrical power supply. Renewable sources of energy are dependent to a large degree on external weather conditions. For that reason, a large part of the energy supply cannot be controlled, or only to a limited extent. These fluctuations can be compensated for to a large extent by good geographical distribution. Therefore it is important to simulate a high spatial resolution, so as to be able to optimize the distribution of the technologies. If power consumption and power production do not coincide at some point in time, frequency fluctuations or supply bottlenecks can occur in the electricity grid. It is thus necessary to simulate the system with a sufficiently high temporal resolution, so as to examine whether security of supply is guaranteed at all times.

### 10.1) Necessary temporal and spatial resolution of the simulation

In order to prove that a region can be supplied at all times with electric power from renewable sources, a meaningful temporal resolution of the simulation is important. For example, a temporal

---

108.LTI (1998).

resolution of one day would provide few useful results, since insufficient supply during the course of a day, due to fluctuating suppliers, could not be detected. A resolution of one value per hour is the usual resolution in which weather and power-consumption data are available. A resolution at least this fine should be chosen in order to be able to make reliable statements about security of supply. However, in view of the technologies to be simulated, it makes sense to choose a resolution of fifteen minutes, since they typically need that long to react to changes.

A high spatial resolution is decisive for exact investigations of spatially dependent and weather-dependent effects. The effects of a high resolution on the simulated production of wind power becomes clear in the following graphs.

Figure 56 shows the normalized electrical output of nine wind turbines, in an example from the 'Energy Rich Japan' study. The black curve is computed on the basis of nine different sets of weather data<sup><109></sup>, while the grey curve is based on only one average set of data. So while the black curve is composed of the weather data at nine different locations, only the weather data for one location were used for the grey curve. The curve calculated using nine different sets of weather data is more even, since wind turbines are scattered about the countryside, and thus each wind turbine does not experience the same weather. The fluctuations of the weather-dependent suppliers cancel one another out in part if a higher spatial resolution is chosen. This results in a substantially higher base load, which corresponds more to real-life operations.

The Figure 56 confirms the hypothesis formulated by other authors that fluctuations in periods less than fifteen minutes are canceled out by a high spatial resolution. However, this smoothing of the curve representing the energy produced only affects fluctuations that propagate spatially, or local fluctuations that do not occur over larger areas.

A meaningful spatial resolution is obtained from the speed of movement of clouds or wind fronts. The spacing between the meteorological measuring points should not be smaller than the distance that a wind front can cover between two measurements. So for a temporal resolution of the weather data of one hour, and an average wind speed of 4 m/s, the weather stations should be located at least 15 km apart.

Another, usually much more decisive, limitation is the existence of correlated weather data in a suitable resolution, on the one hand, and the computing time needed for the simulation, on the other. For the Energy Rich Japan simulation, weather data from 175 weather stations with a resolution of 1 hour was available.

---

109.Japan Meteorological Agency (2001)

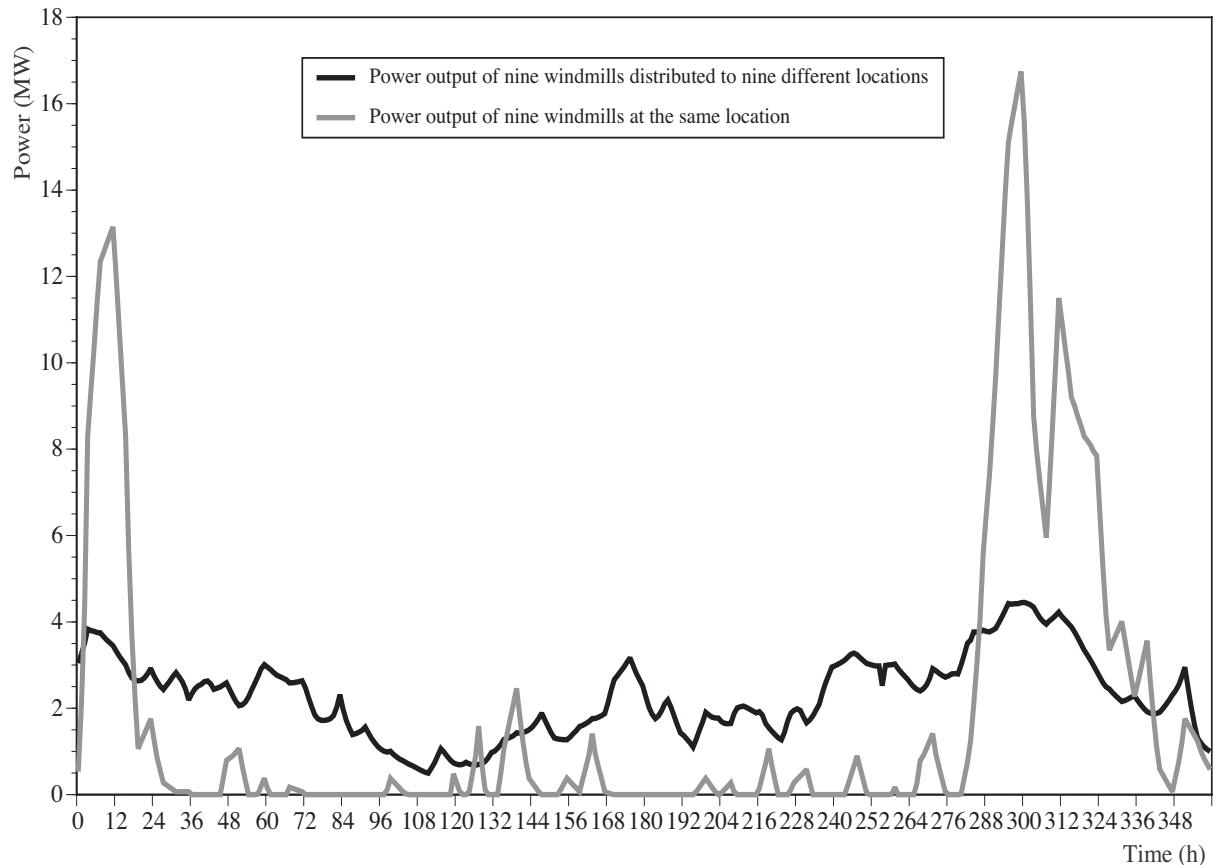


Figure 56 : Power output of several wind turbines computed for different spatial resolutions. Source: ISUSI

## 10.2) Structure of the simulation model

The simulation is subdivided into energy supply, demand, and distribution models. These three parts have been integrated in a “bottom-up” structure. Just as a real energy supply system is made up of many different energy suppliers and consumers, the simulation is composed of many small units, such as wind turbines, hydroelectric plants, geothermal power plants, or energy consumers, which are combined into regions. In SimRen, a supply area is composed of regions, which each have their own supply, demand, and distribution components. Thus the overall model is built up from the “bottom” (the consumer or supplier) to the “top”, the overall system.

The lowest level of the model in SimRen consists mainly of technologies that convert primary energy into electrical energy or heat. One example for such a technology is a wind turbine that converts the energy of the wind into electrical energy by the wind driving a turbine. The electrical energy can then be transmitted via the electricity grid.

The following are currently available for the simulation: wind, photovoltaic installations, hydroelectric plants, solar thermal power plants, geothermal power plants, biomass power plants, con-

ventional fossil-fuel power plants, solarthermal collectors, peak-load power plants, and cogeneration of electricity and high-temperature or low-temperature heat. Pumped-storage reservoirs and hydrogen reservoirs for storing electrical energy over longer periods are also integrated. However, due to the modular, bottom-up structure, it is easy to add additional components to this nucleus.

There are differing meteorological data associated with the energy suppliers having weather-dependent energy production in the various regions. In principle, an unlimited number of sites with differing meteorological data is possible for each region.

In order to map the dynamics of an energy system realistically, it is necessary to simulate the energy consumption side as well. Since figures for energy consumption are usually not available with an hourly resolution for a whole year, the energy consumption must be calculated from typical day and year load curves with the help of a demand model. The curves must be available separately for the various energy demand sectors which one wishes to simulate. From these load curves, the energy consumption for each simulation step in each region is calculated with the help of a demand model, which can be weather-dependent. The total energy consumption is the sum of the energy consumption of the individual regions, which in turn is subdivided into the various energy consumption sectors. The simulation offers the ability to compute statistical fluctuations into the energy demand. This reflects realistic deviations from standardized daily load curves, and also offers the opportunity of studying the sensitivity of the results to fluctuations, for example due to varying consumer behavior.

Besides the modules for energy production and energy consumption named, there must also be control mechanisms in the simulation, to ensure that the energy suppliers are adjusted sensibly to one another. These control mechanisms control the adjustable energy suppliers and the consumers, if a demand management is possible in to be simulated. In each region, there is an “energy manager”, which controls the controllable energy suppliers. Interactions between the individual regions are directed by an “import-export manager”, which exchanges energy between the regions, and can make individual regions increase production within the limits of their reserve capacity.

The modular structure of the simulation allows the elements described to be combined into larger units, which can then be used repeatedly in a simulation. Thus, several wind turbines are grouped into a wind farm; such wind farms combine with other energy suppliers to form an energy supplier group. The largest units in SimRen are the “regions”, which contain all the energy suppliers and consumers of a region. These regions are also modular, and interact with one another.

### 10.3) Course of the simulation

SimRen calculates energy consumption and production separately for each time increment. First, the non-controllable energy demand is simulated, then the non-controllable share of the supply is calculated. Afterwards, the controllable shares of the energy supply and consumption are calculated. These calculations are performed at the regional level first, and then combined for the entire country. The production of the individual components within the regions is coordinated by the “energy manager”. The import-export manager coordinates production between the regions.

The energy consumption is simulated in SimRen by energy sector and region. Parts of the demand are oriented to the climatic conditions, such as the amount of heat needed for heating.

SimRen is capable of simulating demand management. In this case, some of the energy demand must be simulated together with the controllable energy suppliers, so as to enable the energy manager to control it, as well. This makes it possible to coordinate demand with the energy production of the fluctuating suppliers.

By means of demand management, one can reduce the demand for energy in periods of lower energy production by the fluctuating energy suppliers, thus helping to reduce the capacities that are only provided for peak-load periods.

After the uncontrollable consumers, the fluctuating electricity producers are simulated. The sets of meteorological data belonging to the sites of the respective producers are used for this.

In order to ensure sensible control of the controllable suppliers and consumers, an “energy manager” is integrated into each region. The energy manager attempts to cover the energy demand in the region from local sources as far as possible, in order to minimize transmission losses. If it is not possible to produce the energy needed, the energy manager discharges reservoirs or throttles back consumers. If that is still not enough, the energy manager notifies the “import-export manager” that there is a shortage.

All the regions are subordinate to an “import-export manager”. This exchanges power from regions with unused supply capacities or surpluses with under-supplied regions. Thus regions that cannot supply themselves sufficiently can still be supplied with electric power. The manager attempts to obtain the power from adjacent regions, so as to minimize transmission losses. If not enough power is available in total, the import-export manager requests more power from regions that are able to produce more than they consume themselves.

With this redistribution of electrical energy, it is possible to include in the balancing the transmission losses that occur during the transmission of the electricity. For this, the import-export manager needs information on the length and number of lines between the individual subregions.

## 10.4) The demand model

With the help of daily and annual demand curves, SimRen can compute the energy demand at any time in a year, with a 15-minute resolution, from the total annual demand. At present, a German and a Japanese demand model exist. The Japanese model is used here to explain the way in which the consumer model operates.

In the Japanese model, the consumer sectors household, industry, commerce, and services are implemented.

The goal of the consumer model is to compute the energy demand of a consumption sector and within a region, with a temporal resolution of fifteen minutes. This is necessary because demand data with such a temporal resolution for an entire year are not available for most regions and sectors.

Typical annual and daily load curves and the total annual consumption of the sectors in the regions serve as the basis for the calculation. The annual load curve should have a temporal resolution of one month, and reflect the average consumption of the sector. Daily load curves have an hourly resolution, and represent the average consumption within this hour. At least a weekday curve and a weekend curve for each season is needed for the daily load curves. The algorithm is more accurate if more daily load curves are available. For example, it is helpful to have different daily load curves for each month, and different curves for Saturdays and Sundays. Examples of annual load curves are shown in Figure 60. Examples for daily load curves are in Figure 57, Figure 58 and Figure 59. These were prepared in the ERJ research project, coordinated by the ISEP Institute.

In SimRen, normalized curves, in which the area under the curve is normalized to 12 or 24, are derived from the daily and annual load graphs in order to compute the consumption. Thus the values of the individual curves can be multiplied by one another, while preserving the shape of the individual curves. If this is then linked with the desired total annual consumption, a value for each step of the simulation is obtained, and the shape of the specified curves is retained. The load curves are then combined in such a way by the algorithm that the shape of the individual daily and annual load curves is preserved, and the integral under the consumption curve gives the total annual energy consumption.

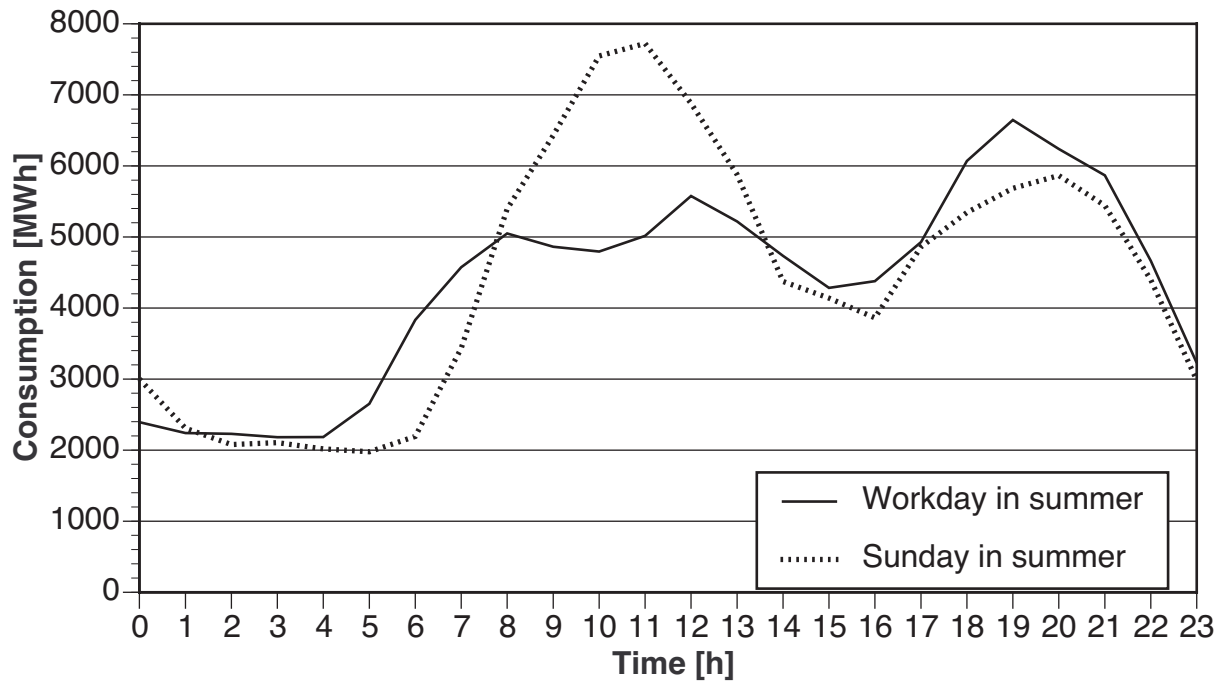


Figure 57 : Daily load curves for households in Japan in summer. Source: ISEP

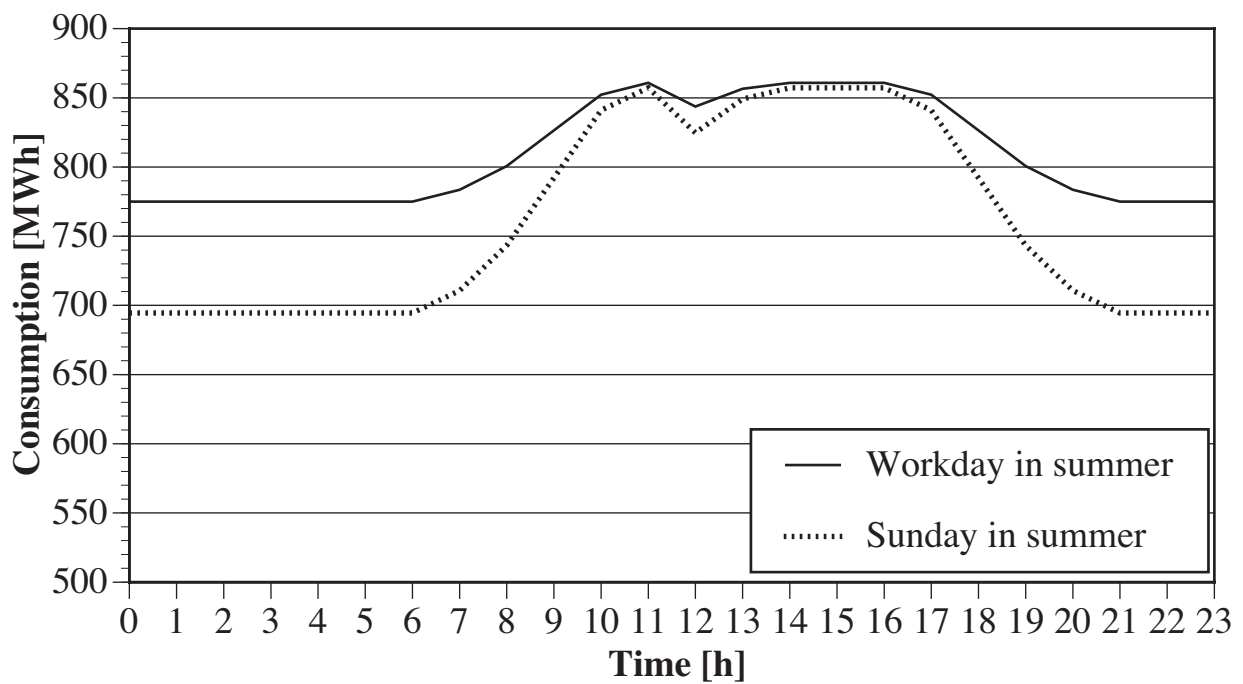


Figure 58 : Daily load curves for industry in Japan in summer. Source: ISEP

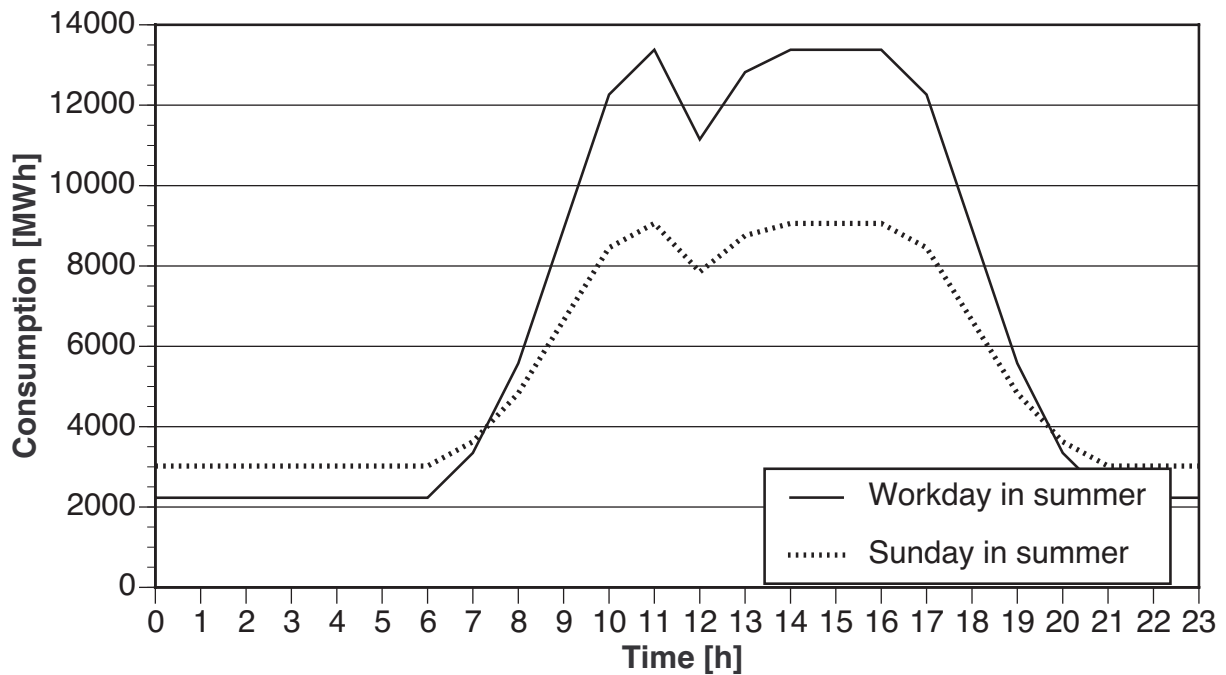


Figure 59 : Daily load curves for commerce and service sector in Japan in summer. Source: ISEP

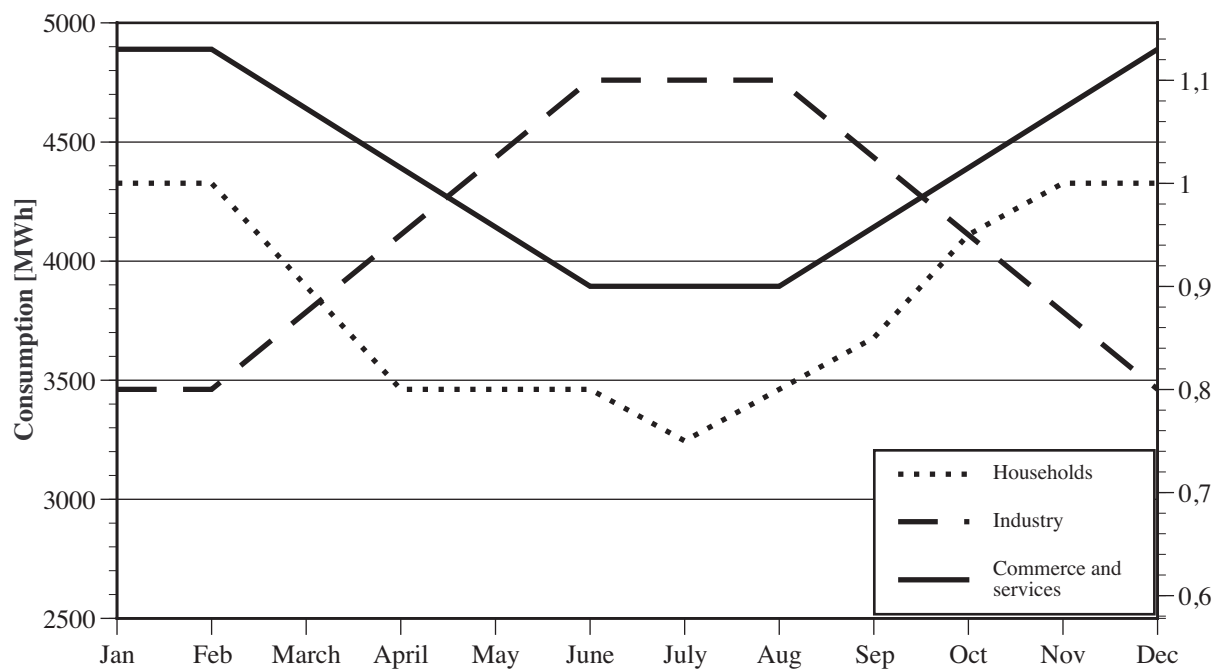


Figure 60 : Annual load curves of various energy-consumption sectors on an absolute and a normalized scale. Source: ISEP



### 10.4.1) The computational algorithm

In Figure 57 and the subsequent figures, one can see that there is sometimes a pronounced difference between the holiday and workday consumption. Since only the shape of the curves is preserved when they are normalized, and the absolute values are lost, the computation algorithm requires the ratio of workday to weekend power consumption. Then the differing consumption on holidays and workdays can be taken into account, by reducing the consumption on weekends by this factor.

First, the annual envelope curve, which normally corresponds to the monthly consumptions of a previous year, is converted into a normalized curve. The sum of all the values in this annual curve then equals 1. This is done by forming the mean of the individual monthly consumption figures, and then dividing each individual value by this mean (see Figure 60, "Annual load curves of various energy-consumption sectors on an absolute and a normalized scale. Source: ISEP").

Daily weighting factors for each day of the year result. It is assumed that the value for each month is reached exactly on the first of that month. After this, the daily weighting factor approaches the value for the coming month linearly. This ensures that no discontinuities occur in the resultant function. Thus one can multiple a twelfth of the desired total consumption with the respective monthly value, and obtain precisely the desired total consumption over a year. The daily envelope curves are converted into normalized curves via the same algorithm.

The power consumption on weekends is usually considerably less than during the week. Therefore, another factor is introduced for weekends and workdays. This factor is calculated by adding the number of workdays to the number of holidays, which are multiplied by the ratio of consumption.

$$[\text{Holiday}] = \frac{[\text{HolidayConsumption}]}{[\text{WorkdayConsumption}]}$$

$$[\text{Mean}] = \frac{[\text{NumberOfWorkingDays}] + [\text{NumberOfHolidays}] \times [\text{Holiday}]}{365}$$

The workday and holiday weighting factor then amounts to:

$$[\text{WorkdayWeightingFactor}] = \frac{1}{[\text{Mean}]}$$

$$[\text{HolidayWeightingFactor}] = \frac{[\text{Holiday}]}{[\text{Mean}]}$$

The consumption at a specific time of year is then:

$$P_V = [\text{DailyWeightingFactor}] \times [\text{WorkHolidayWeightingFactor}] \times [\text{HourFactor}]$$

Since the daily load curves can differ widely, and the end of an autumn curve does not necessarily fit the beginning of a winter curve, for example, discontinuities that are not realistic can occur at the transition from one day to the next. This may be the case at a change in season or the change from weekday to holiday curves, for example. Therefore, the hourly weighting factors are adjusted between 9:00 p.m. and 3:00 a.m. so that the proportion of the previous day's function declines linearly, while the proportion of the coming day's function increases. This ensures that no discontinuities occur at the change from one day to the next. The consumption for the respective time of the previous day is added to the consumption of the next day with a linear factor.

In other words:

$$\begin{aligned} 10:00 \text{ p.m.: } & \frac{1}{6}[\text{AutumnConsumption}(10\text{pm})] + \frac{5}{6}[\text{SummerConsumption}(10\text{pm})] \\ 11:00 \text{ p.m.: } & \frac{2}{6}[\text{AutumConsumption}(11\text{pm})] + \frac{4}{6}[\text{SummerConsumption}(11\text{pm})] \\ & \cdot \\ & \cdot \\ 3:00 \text{ a.m.: } & \frac{5}{6}[\text{AutumConsumption}(03\text{am})] + \frac{1}{6}[\text{SummerConsumption}(03\text{am})] \end{aligned}$$

Figure 61 shows the difference between a change in season with and without gradual adjustment of the curves to one another. The daily load curves of the last day of summer are shown in the first 24 hours, and those of the first day of autumn in the second 24 hours. In the upper curve, the curve for the last day of summer joins directly to the curve for the first day of autumn. A discontinuity between 11 p.m. and midnight can be seen clearly. This discontinuity no longer occurs in the second curve, since here the values have been adjusted to one another. The same behavior occurs upon changing from one month to another, since the curves are based on differing daily weighting factors. Therefore, a single monthly weighting factor is not sufficient; instead, the monthly weighting factors must merge into one another smoothly.

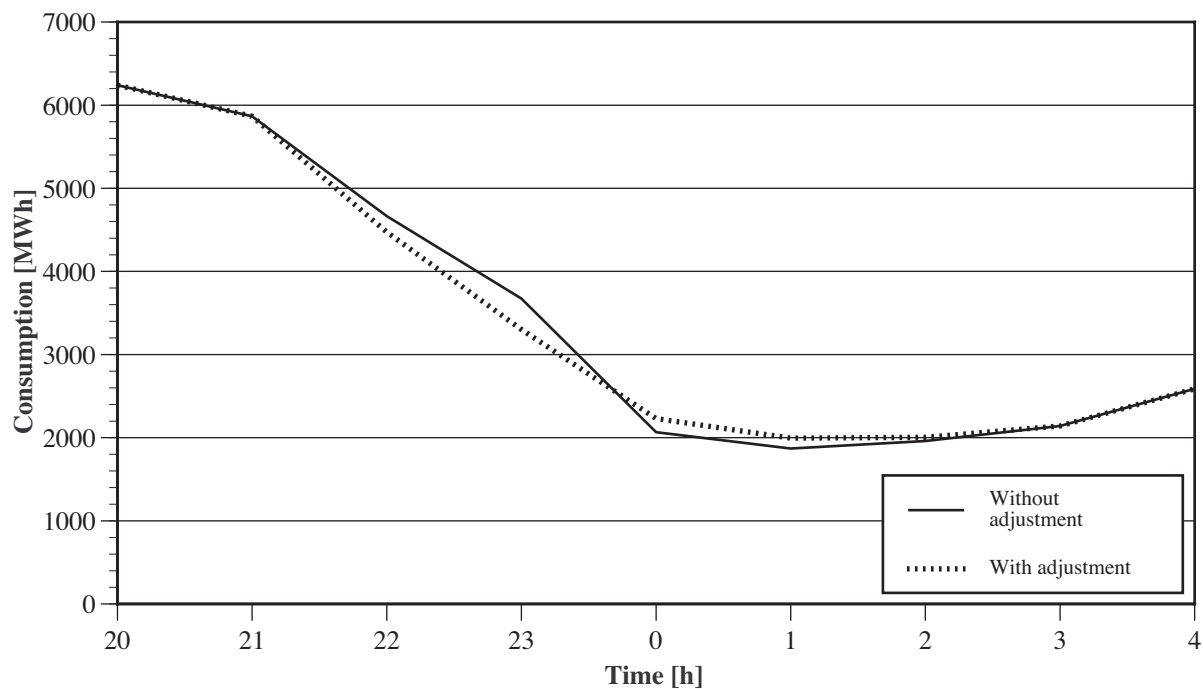


Figure 61 : Comparison of a season change with and without adjustment. Source: ISUSI

If time steps of less than an hour are simulated, the consumption values are interpolated from the two adjacent values.

The consumer module in SimRen is also capable of taking daylight savings time [summer time] into account. It simply repeats the consumption at the time the clocks are set back, and skips an hour in the load curve at the time the clocks are set forward again.

Using the consumer module described, various test runs have been performed, which showed that the total annual energy consumption specified is maintained. Furthermore, the shapes of the daily and annual curves are preserved, except for the adjustments required.

- Random fluctuations

Since SimRen is intended to ensure the security of supply of an energy supply system, the consumption module must be capable of superimposing random fluctuations on the consumption, thus allowing for the fact that consumption based on normalized curves does not reflect the real consumption that varies from day to day.

Various statistical fluctuations of the behavior pattern are possible with SimRen. The following algorithm, with which the maximum percentage change of the demand value, and the probability of achieving that value can be set, has proven itself in practice. If one does not wish to included fluctuations in the computation, the maximum excursion can simply be set to zero. The excursion of the following time step is calculated making use of the excursion of the previous step, so as not

to create any discontinuities. A maximum percentage change of the excursion is defined, such as a one-percent change from one time step to the next. Then a random number between -1 and +1 is generated, and multiplied by the desired maximum excursion in percent. If the excursion in the previous step was larger than this number, the step size is deducted from the previous excursion again, giving the new excursion. Otherwise, the step size is added to obtain the new step size. This means that it is always more probable that the excursion shifts towards zero again than that it shifts away from it. This is important to keep large excursions from being maintained over considerable lengths of time.

In this algorithm, the step size is a measure of the probability of the maximum excursion actually being achieved. If a small step size is chosen, the excursion will tend to shrink towards zero again, rather than towards its maximum value.

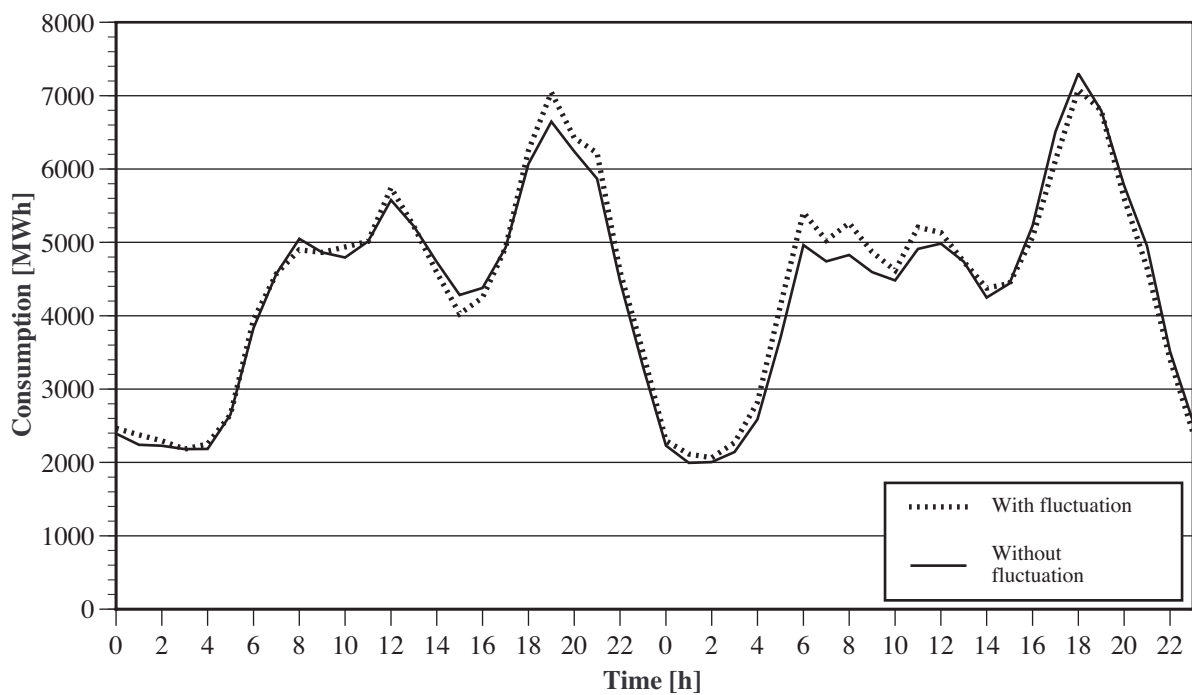


Figure 62 : Effects of random fluctuations on the curves. Source: ISUSI

Figure 62 shows the difference between a curve with and without fluctuations. Fluctuations of up to 50% of the initial value are included, and the step size is 3%. It is evident that the peak load on the first day is also shifted significantly upwards. Although the maximum possible fluctuation is 50%, values of such magnitude do not occur on those two days, since it is very improbable that the deviation would become that large. An increase of the fluctuation would need to occur for 17 time steps, which becomes more and more improbable the larger the deviation in the preceding step was.

From the static input parameters, such as the total annual energy consumption and the load curves, a dynamic energy consumption model is developed in SimRen. Tests have shown that the total annual energy consumption of the dynamic model corresponds to the static input parameter again. And the shapes of the annual and daily curves in the dynamic final result are also analogous to the input again. The random fluctuations do not change the total annual consumption substantially, either, since the fluctuations in both directions balance out. Noticeable differences only occur over shorter periods, such as a day.

General		Daily envelopes	Advanced Settings																								
Please enter a name for the group of consumers that is represented in this block		Year envelope (0=Jan;11=Dec )																									
<input type="text" value="Residential"/>		<table border="1"> <tr><td>0</td><td>8827879,00</td></tr> <tr><td>1</td><td>7707917,00</td></tr> <tr><td>2</td><td>7553900,00</td></tr> <tr><td>3</td><td>7093684,00</td></tr> <tr><td>4</td><td>5839455,00</td></tr> <tr><td>5</td><td>5422044,00</td></tr> <tr><td>6</td><td>6316919,00</td></tr> <tr><td>7</td><td>7845868,00</td></tr> <tr><td>8</td><td>8329610,00</td></tr> <tr><td>9</td><td>6393954,00</td></tr> <tr><td>10</td><td>6016115,00</td></tr> <tr><td>11</td><td>6626715,00</td></tr> </table>		0	8827879,00	1	7707917,00	2	7553900,00	3	7093684,00	4	5839455,00	5	5422044,00	6	6316919,00	7	7845868,00	8	8329610,00	9	6393954,00	10	6016115,00	11	6626715,00
0	8827879,00																										
1	7707917,00																										
2	7553900,00																										
3	7093684,00																										
4	5839455,00																										
5	5422044,00																										
6	6316919,00																										
7	7845868,00																										
8	8329610,00																										
9	6393954,00																										
10	6016115,00																										
11	6626715,00																										
Energy consumption for this kind of consumers in a whole year (PJ) :		<input type="button" value="OK"/> <input type="button" value="Cancel"/>																									
<input type="text" value="172,92"/>																											
Saturday=Holiday ? <input checked="" type="checkbox"/>																											
Please enter a multiplier for holidays. I.e. if the energy needed on a holiday is 80% of a working day please enter 0,8:																											
<input type="text" value="0,68"/>																											
January 1st is a (0=Monday; 6=Sunday):		<input type="text" value="0"/>																									
The Consumption varies from -10% to 10% around the standart curves. Please enter the stepsize for this variation in percent.		<input type="text" value="1"/>																									

Figure 63 : The input dialog of a consumer module. The total consumption, the weekend factor, and the variation are entered here. The annual load curve is also entered on this page. The daily load curves are entered on the 'Daily envelopes' page. Source: ISUSI

## 10.5) The energy supply model

The energy suppliers in SimRen can be classified in controllable and fluctuating energy suppliers. The energy production of the fluctuating energy suppliers cannot be regulated, due to their dependence on weather, irradiation, and demand. Therefore, they are simulated immediately after the unregulated energy consumers, since no control of the components is possible, and their output must be known in order to control the controllable suppliers. Intelligent control of the control-

lable energy suppliers is absolutely necessary for implementing a well-functioning electrical supply system, since they must produce precisely the amount of power the consumers are still lacking at any time.

Wind, solar thermal and photovoltaic facilities are fluctuating energy suppliers, since their output depends on the supply of wind or solar radiation. Apart from these obviously fluctuating electricity producers, combined-heat-and-power (CHP, or cogeneration) plants in the industrial, domestic, commercial, and services sectors are counted among the fluctuating suppliers if they are controlled according to their heat output. This classification makes sense, since the output of electric power from such power plants only depends on the demand for heat in the sectors named. The power plants produce heat for hot water and heating, and are thus oriented to the outdoor temperatures in the respective regions.

The controllable energy suppliers that have been used in SimRen are hydroelectric plants, geothermal power plants, peak power plants, and combined-heat-and-power plants that are controlled according to their electricity output. Biomass and coal-fired power plants are controllable if enough fuel is available. Otherwise, their control range is limited by the supply of fuel. Pumped-storage power plants are also controllable, apart from their dependence on the level of the reservoirs. The output of the hydroelectric plants depends on the water level of the rivers on which they lie, but can be adjusted freely below this upper limit.

The energy manager controls the energy output of the controllable energy suppliers and the energy consumption of the controllable consumers within a region. The control logic can be adjusted easily. Apart from the non-controllable energy demand and the non-controllable energy consumption within a subregion, it also depends on the demand from the import-export manager. Thus the import-export manager is able to request energy from or provide energy to an energy manager within a region.

The feedback control that proved to make sense for the Japanese energy system is explained below. In ERJ, the combined-heat-and-power facilities are engines and steam turbines that supply industrial plants with the necessary process heat. Two-thirds of this capacity runs constantly all day long, while the remaining third can be adjusted to the demand for electricity.

This mode of operation is possible because the hot water and steam produced by the plants can be stored well, and does not necessarily have to be produced exactly at the moment it is needed.

First, the energy manager starts up the CHP units in the industrial plants, and attempts to meet the energy demand with them. Next, geothermal power plants are brought on line. Since the power available from the hydroelectric plants depends on the water level of the rivers, and is thus subject to limitations, those power plants are started up last.

It often happens that individual subregions are not able to provide themselves with an autonomous supply of energy, while in others, there is surplus production or unused capacity available. Balancing out these production deficits and surpluses at a supraregional level is the responsibility of the import-export manager, which is superior to all the regions and coordinates them.

General Settings
Advanced Settings

Please enter the Distances and number of cables between the different regions. Use the upper right corner to enter your data. The block will copy everything to the other side.

**Cable matrix:**

	Region1	Region2	Region3	Region4	Region5	Region6
1	100000	100000	100000	10000 0	100000	10000 0
2	100000	100000	100000	10000 0	100000	10000 0
3	100000	100000	100000	10000 0	100000	10000 0
4	100000	100000	100000	10000 0	100000	10000 0
5	100000	100000	100000	10000 0	100000	10000 0
6	100000	100000	100000	10000 0	100000	10000 0
7	100000	100000	100000	10000 0	100000	10000 0
8	100000	100000	100000	10000 0	100000	10000 0
9	100000	100000	100000	10000 0	100000	10000 0
10	100000	100000	100000	10000 0	100000	10000 0
11	100000	100000	100000	10000 0	100000	10000 0
12	100000	100000	100000	10000 0	100000	10000 0
13	100000	100000	100000	10000 0	100000	10000 0
14	100000	100000	100000	10000 0	100000	10000 0
15	100000	100000	100000	10000 0	100000	10000 0

**Distance matrix:**

	Region 1	Region 2	Region 3	Region 4	Region 5	Region 6
1		100000000	100000000	10000000 0	100000000	10000000 0
2	100000000		200	1081	764	681
3	100000000	200		1281	964	881
4	100000000	1081	1281		317	635
5	100000000	764	964	317		318
6	100000000	681	881	635	318	
7	100000000	1240	1440	272	476	756
8	100000000	1054	1254	492	353	373
9	100000000	100000000	100000000	10000000 0	100000000	10000000 0
10	100000000	2029	2229	948	1265	1578
11	100000000	1663	1863	582	899	1217
12	100000000	1349	1549	268	585	898
13	100000000	2350	2550	1269	1586	1899
14	100000000	1719	1919	638	955	1268
15	100000000	100000000	100000000	10000000 0	100000000	10000000 0

Figure 64 : Dialog of the import-export manager. The lengths and numbers of lines connecting the subregions can be entered here. The import-export manager calculates an energy distribution matrix with the minimum transmission losses from this information. Source: ISUSI

First, the import-export manager distributes the surpluses from individual regions (if there are any) to the undersupplied regions, until all the surplus power has been used up, or all regions have been supplied. It uses the shortest possible distances for this distribution. The energy losses can be estimated by the import-export manager, and included in the balance as energy consumption. The

transmission losses can be calculated as a percentage of the total energy produced, or from the information on line lengths in the import-export manager.

The import-export manager is able to start up the peak power plants and to empty the reservoirs if the potential total output is not sufficient to cover the total demand. Various control algorithms can be implemented for this purpose.

For the ERJ study, it proved to make sense to start up 1 GW of the peak power plants' capacity first, if there is a risk of under-supply. Next, the pumped-storage reservoirs can be used to produce energy; and if this is still not enough, there is another 2 GW of peak power plants' capacity available to meet the demand for power. In addition, the import-export manager can order the energy managers in the individual regions to produce more power than they need, in order to cover the demand for energy in other regions. This ensures that the installed power plants are utilized optimally. The strategy described proved to be a good solution for the Japanese energy system; in combination with a sensible distribution of the facilities, it allows the demand for energy to be met with the minimum of installed capacity. However, this algorithm can also be adjusted easily by means of a small alteration in the import-export manager. The combination of peak power plants and pumped-storage reservoirs results in the pumped-storage reservoirs usually still containing an emergency reserve if power plants fail unexpectedly, and not too much hydrogen is burned in the peak power plants.

### 10.5.1) Simulation of the energy supply components

#### 1. Computation of the energy output of photovoltaic systems:

In order to calculate the power output of a photovoltaic array, detailed data on the solar irradiance are essential. The irradiance is categorized as “direct” and “diffuse” radiation. Direct radiation reaches the Earth's surface directly from the Sun, while diffuse radiation is scattered by clouds or dust particles. Since weather stations mainly measure “global” (= direct + diffuse) radiation, the irradiation must be divided up. This splitting can be done by means of an algorithm that requires the sun's current position in the sky. Once the position of the sun has been calculated, the split between diffuse and direct radiation can be calculated by the following equations<sup><110></sup>:

$$k_T = \frac{E_{g, \text{hor}}}{E_0}$$

$$E_{\text{diff, hor}} = E_{G, \text{hor}} (1.020 - 0.254 k_T + 0.0123 \sin \delta_s) \text{ for } k_T \leq 0, 3$$

---

110.Quaschnig (1999)



$$E_{\text{diff, hor}} = E_{G, \text{hor}} (1.400 - 1.749k_T + 0.177\sin \delta_s) \text{ for } 0, 3 < k_T < 0, 78$$

$$E_{\text{diff, hor}} = E_{G, \text{hor}} (0.486 k_T + 0.182 \sin \delta_s) \text{ for } k_T \geq 0, 78$$

$E_{g, \text{hor}}$  is the global radiation impinging on a horizontal plane,  $E_0$  the solar constant,  $\delta_s$  the position of the sun, and  $E_{g, \text{diff}}$  the diffuse radiation impinging on a horizontal plane.

Since the irradiance of a horizontal plane differs from that of an inclined plane, the irradiance must be converted. This conversion can be done using Lin and Jordan's equation.

$$E_{g, I} = R \cdot E_{\text{dir, hor}} + \left( \frac{1}{2}(1 + \cos n) \right) \cdot E_{\text{dir, hor}} + p \cdot E_{G, \text{hor}}$$

$E$  = Irradiance

$p$  = Reflection coefficient (must be estimated)

$n$  = Angle of inclination

$R$  = Ratio of the direct radiation onto an inclined and a horizontal plane

The temperature dependency of the efficiency has been taken into account using a model by Fuentes. This model calculates the module temperature from the irradiance and the wind speed.<sup><111></sup>

And it is also possible to simulate elevated solar arrays that shade one another when the sun is in certain positions. For calculating them, flat roofs with a width of 10 m, and solar arrays 1 m long spaced 2 m apart were assumed. Shading losses amount to about 1.5% compared to a simulation that does not take shading into account.

---

111.Fuentes (1987)

General Settings
Advanced Settings

This block simulates a photovoltaic power station. The effectiveness decreases with higher temperatures. OK

Cancel

Latitude  Longitude  Height over sealevel (m)

Reflexion coefficient of surroundings

Degree of effectiveness

Decrease of effectiveness due to higher temperatures  %/K

Reference temperatur:  °C

Area 1 is adjusted like a standard area for the NOCT temperature. It's not changeable.

Inclination 1	<input type="text" value="52,16"/>	Adjustment 1	<input type="text" value="0"/>	Area 1 (qm)	<input type="text" value="639100"/>
Inclination 2	<input type="text" value="52,16"/>	Adjustment 2	<input type="text" value="0"/>	Area 2 (qm)	<input type="text" value="319550"/>
Inclination 3	<input type="text" value="52,16"/>	Adjustment 3	<input type="text" value="-30"/>	Area 3 (qm)	<input type="text" value="159775"/>
Inclination 4	<input type="text" value="52,16"/>	Adjustment 4	<input type="text" value="30"/>	Area 4 (qm)	<input type="text" value="159775"/>
Inclination 5	<input type="text" value="90"/>	Adjustment 5	<input type="text" value="-45"/>	Area 5 (qm)	<input type="text" value="0"/>
Inclination 6	<input type="text" value="45"/>	Adjustment 6	<input type="text" value="45"/>	Area 6 (qm)	<input type="text" value="0"/>
Inclination 7	<input type="text" value="90"/>	Adjustment 7	<input type="text" value="45"/>	Area 7 (qm)	<input type="text" value="0"/>

Calculate radition from global
 NOCT temperature:

Radiation input is diffuse/direct
 Module height over ground:

Please enter the number of the weatherstation: 
Height of wind measurement :

Figure 65 : Dialog for a photovoltaic module. Various surfaces with differing alignments, that are all connected to the same weather station, can be entered here. In addition, the module requires information on the position of the module and its efficiency. More than one angle of inclination and declination (“Inclination” and “Adjustment”) with solar arrays of different sizes can be set. The setting “Radiation input is diffuse/direct” means that the meteorological data are available divided into diffuse and direct radiation, in contrast to “Calculate radiation from global”, where these data must be computed from the global irradiance. The “number of the weatherstation” identifies the set of meteorological data pertaining to the module. Source: ISUSI

## 2. Calculation of solar-thermal heat output:

The heat produced by solar thermal collectors can also be calculated with SimRen. It is calculated using the same equations as for the photovoltaic output, but without temperature dependence of the efficiency. SimRen computes the diffuse and direct radiation impinging on an inclined surface, and multiplies this with the efficiency of the solar thermal system.

In ERJ, 50% was assumed as the efficiency for temperatures up to 50°C. Such temperatures are needed in all consumer sectors while higher temperatures are often needed in industry. So an efficiency of 25% has been assumed for temperatures up to 150°C. These efficiencies are overall system efficiencies. Only storage losses have to be accounted for separately. In ERJ, the storage losses were calculated after the simulation, from the duration of storage and a loss factor. The dialog for this module offers the same possible inputs as for a photovoltaic module, except that no temperature-dependent efficiency can be specified.

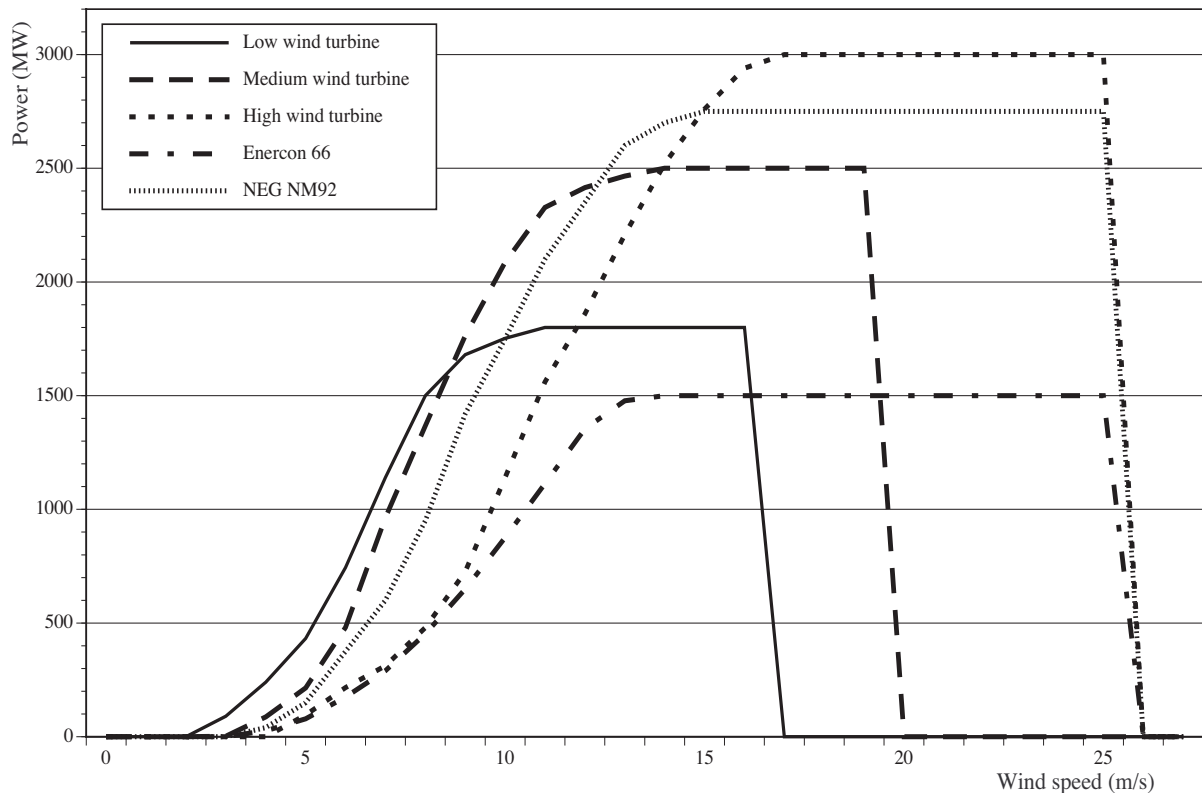


Figure 66 : Typical output curves of wind turbines. Source: ISUSI

### 3. Calculation of wind energy output:

The simulation of the power output of aerogenerators is based essentially on typical output curves for wind turbines. Any number of different kinds of wind turbine can be integrated into SimRen. At present, the SimRen libraries contain wind turbines from Enercon, Tacke, NEG Micon, and artificial wind turbines, whose performance is oriented to the output curves of various units. It is possible to integrate additional wind turbines. Due to the modular construction of the software, wind farms can be combined from various models of wind turbines.

Figure 67 : Typical dialog for a group of wind turbines. The number of wind turbines, the height of their hubs, and the roughness of the surroundings can be entered. Some information from the adjacent weather station is also required. Thus each wind turbine can have its own set of meteorological data assigned to it, which is given in the field “Number of the weatherstation”. Source: ISUSI

Using the output curves in Figure 66, it is easy to determine the output of the wind turbines, as long as the wind speed at hub height is known. The weather stations usually do not measure the wind speed at hub height, therefore the wind speed must be converted to hub height, using the logarithmic height equation<sup><112></sup>.

$$v(h_2) = v(h_1) \cdot \frac{\ln\left(\frac{h_2}{z_0}\right)}{\ln\left(\frac{h_1}{z_0}\right)}$$

where  $h_{1,2}$  is the respective height,  $v_{1,2}$  the speeds, and  $z_0$  is the roughness length.

112.Quaschnig (1999)

The roughness length in this equation categorizes the various types of landscape. For the conversion to hub height, a roughness length of 0.1 metres has been used. This corresponds to a landscape with bushes.

Since sometimes no meteorological data from offshore weather stations are available, the wind-turbine module is capable of computing the wind speed at sea from the wind speed on land. As measurements in Germany and Denmark confirm, the wind speed at sea is about 33% higher than on land. In order to compute the wind speed of the offshore installations at hub height, SimRen therefore first calculates the wind speed at hub height on land, and then multiplies this by 1.33. Then the achievable output can be calculated using the output curve. The multiplication factor can be adjusted, if necessary.

#### 4. Calculation for the heat-oriented combined-heat-and-power plants

The electrical energy generated by combined-heat-and-power plants in the household, commercial, and services sectors is oriented to the outdoor temperature in the respective regions and the demand for hot water. It is assumed that hot water can be stored all day, and that the demand is thus constant the whole day. Therefore, only the energy demand for heating systems fluctuates. The control of heating systems can be adjusted to the respective needs in SimRen.

In the ERJ study, the CHP plant begins to heat the houses up to a particular target temperature when the outdoor temperature falls below a particular value. These starting and target temperatures differ for daytime and nighttime. The values for the starting and target temperature and the times of day can be set as desired in the component.

The energy required to heat up the households and commercial and service buildings by 1°C must be defined beforehand. In addition, a thermal and an electrical efficiency must be assumed, in order to calculate the electrical energy. In the Japanese energy supply model, the electrical efficiency is 30%, and the thermal efficiency is 50% in SimRen. So the electrical energy can be calculated by the following equation:

$$\Delta T = T_{\text{target}} - T_{\text{outside}}$$

$$P_{\text{out}} = \frac{\Delta T \cdot P_C \cdot \eta_{\text{el}}}{\eta_{\text{th}}}$$

$T_{\text{target}}$  = target temperature,  $T_{\text{outside}}$  = outdoor temperature,  $P_{\text{out}}$  = power output,

$P_{\text{°C}}$  = energy requirement per °C,  $\eta_{\text{th}}$  = thermal efficiency,  $\eta_{\text{el}}$  = electrical efficiency

In the ERJ study, the units heat houses in the daytime as soon as the temperature falls below 18°C, up to a temperature of 20°C. The heating keeps running for at least an hour, in order to prevent constant switching on and off due to fluctuating temperatures. At night, the target temperature is 15°C, and the starting temperature 10°C; but since not all rooms are heated at night, an average starting temperature of 5°C and a target temperature for the whole house of 10°C was assumed. In other words, the 5°C and 10°C nighttime temperatures are an average temperature for the rooms in the house, not all of which are heated at night. The reduction to nighttime levels begins at 11 p.m. and ends at 7 a.m. In the ERJ study, only one reference temperature for cogeneration electricity production was assumed per region. Using more than one is possible in principle, and would make control easier.

General Settings	Electricity Settings	Advanced Settings
		OK
		Cancel
Covered qm:	1,0093e+09	
Thermal power rating per qm (MW):	0,015	
Electrical efficiency:	0,3	
Thermal efficiency:	0,5	
Starting temperature (Day Night):	18,00	5,00
Target temerature (Day Night):	20	10,00
Power needed per °C per qm per plant (W)		0,1
Day heating begins	7 :00h and ends	23 :00h.
First month in summer:		7
Last month in summer (1=Jan;12=Dec) :		8
Minimum minutes of operation:		60

Figure 68 : Dialog for CHP plant in the household and industrial sectors. The times of day and target temperatures for daytime and nighttime heating can be entered here, for example (“Day heating begins ... and ends ...”, “Starting temperature”, “Target temperature”), as well as the thermal and electrical efficiency. What rated capacity per square metre is installed is entered in “thermal power rating per qm”. This value, multiplied by the “Covered qm”, gives the total rated capacity of the CHP plant module. The field “Minimum minutes of operation” can be used to specify the shortest time the installation will run after being switched on, in order to avoid constant switching on and off. This block does not require any information on the set of meteorological data, since the temperatures are passed on to the CHP plant module from a separate meteorological data module. Source: ISUSI

## 5. Calculation for the electricity-oriented combined-heat-and-power plants

The electricity-oriented combined-heat-and-power plants are installed with a particular capacity, and can be run up to and down from this capacity at will. In SimRen, internal-combustion engines are used to generate low-temperature heat, and steam turbines to generate high-temperature heat.

In the ERJ study, these power plants were only employed in the industrial sector, since industrial plants are usually capable of storing the heat they produced for a short time, and have a high demand for electricity in addition to the demand for heat. It was assumed that control of electricity generation in the industrial plants was performed by a variable tariff for the electricity fed into the grid. The respective electricity price must then be communicated to the industrial plants via a data network. (For further details, see the consumer model.) The efficiencies in the ERJ study are 50% thermal efficiency and 30% electrical efficiency, just like the CHP plants in the household sector and commercial and services sector.

Figure 69 : Dialog for CHP plants in industry. Here, the rated capacity and thermal and electrical efficiencies can be specified. Nothing more is needed to calculate the output.  
Source: ISUSI

## 6. Hydroelectric plants

Hydroelectric plants are initialized with a certain maximum output, which depends on the turbines installed. However, they cannot produce this amount of energy at all times, since the power output depends on the water level in the river on which they lie. In order to allow for this, the hydroelectric-plant module in SimRen is provided with a monthly fluctuation curve. This curve indicates what proportion of the installed capacity can be utilized in the respective month. If such curves are not available, as in the ERJ study, they can be computed from the flow rates in large rivers of the region. In the ERJ study, the mean of the flow rate was calculated, and it was assumed that the power plants are designed for this flow, in other words, that they can achieve their rated output at an average flow. If the flow is below average, it was assumed that the ratio of the flow in that month to the average flow is equal to the ratio of the output achievable to the rated capacity.

$$P_{\max} = P_{\text{Nenn}} \quad \text{for } \hat{m}_{\text{mom}} \geq \hat{m}_{\emptyset}$$

$$\frac{P_{\max}}{P_{\text{Nenn}}} = \frac{\hat{m}_{\text{mom}}}{\hat{m}_{\emptyset}} \quad \text{for } \hat{m}_{\text{mom}} < \hat{m}_{\emptyset}$$

$P_{\max}$  = Maximum achievable output in the month being calculated

$P_{\text{Nenn}}$  = Installed capacity

$\hat{m}_{\text{mom}}$  = Flow rate in the month being calculated

$\hat{m}_{\varnothing}$  = Average flow rate

Maximum power output of hydroelectric plants in the ERJ model for the Kanto region shows the proportion of the installed capacity of the hydroelectric plants that can be utilized each month, due to the flow rates in the Kanto region according to the ERJ simulation.

General Settings    **Advanced Settings**

This block simulates a number of water power plants. Please enter the installed maximum production and a multiplier between 0 and 1 for every month of the year.

Maximum production in MW:

Availability of the maximum per month 0=Jan. Please enter values between 0 and 1.

	Multiplier
0	0,540117731
1	0,602443168
2	0,736634583
3	1
4	0,762594654
5	0,776484133
6	0,826477731
7	1
8	1
9	1
10	0,713136154
11	0,564153689

Comments

OK    Cancel

Figure 70 : Dialog for a hydroelectric plant. In addition to the rated capacity, the envelope curve for maximum energy output can be specified. Source: ISUSI

In the ERJ study, it was assumed that the output of the entire installed capacity can continue to be generated if the flow rate is greater than the annual average. If there is less water in the rivers than the annual average, the proportion of the electricity that can be generated is less to the same extent that the flow rate lies below the average. Examples for water power curves are in the Appendix.

## 7. Geothermal power plants

The geothermal power plants are able to produce energy up to their rated capacity. As for the hydroelectric plants, an annual curve can also be filed for the geothermal power plants.



In SimRen, it has been assumed that the achievable output of the geothermal power plants does not vary over the course of the year. The output achievable can be set freely up to the installed capacity.

Figure 71 : Dialog for a geothermal power plant. Input of rated capacity and the thermal and electrical efficiencies. Source: ISUSI

## 8. Pumped-storage power plants

Pumped-storage power plants can store energy by converting it into the potential energy of water and storing the latter in a reservoir. This water can then be used later to drive a turbine, thus generating electrical energy again. During these conversion processes, energy losses occur, which are specified beforehand.

In the ERJ study, the energy loss per conversion was about 10.5%, resulting in a total loss of 20%. In other words, when the energy is stored, 10.5% of the energy to be stored is lost as a storage loss, and the same proportion is lost again when the reservoir is discharged due to the efficiency of the turbines and similar aspects.

Figure 72 : Dialog for a pumped-storage power plant. The input parameters are the maximum level, the level at the start of the simulation run, and the efficiency. In addition, the maximum storable and available capacities can be specified. The momentary level is an output parameter. Source: ISUSI

## 9. Conventional power plants

SimRen is capable of simulating conventional combustion power plants. Such power plants can be fueled with coal or biomass. These power plants must be connected to a fuel store, where information is stored on how much fuel is available per simulation step. The modules are initialized with a rated capacity and the amount of fuel that is consumed for that output. If enough fuel is available, they are able to produce outputs that are less than or equal to their rated capacity. If not enough fuel is on hand, the maximum output achievable is proportional to the supply of fuel. The conventional power plants use the same module in principle as the electricity-oriented combined-heat-and-power plants. Therefore, the dialog offers the same possible inputs.

## 10. Peak power plants

In SimRen, the peak power plants are fuel cells or steam turbines. The energy outputs of the power plants can be adjusted freely up to their rated capacity, as long as fuel is available. The efficiency of the electricity generation can be selected freely. Peak power plants do not have a dialog screen of their own, since they are simulated in the import-export manager.

# 10.6) Results

The SimRen simulation generates several files in a simulation run, which contain all the information on the run. All this information is stored in a directory that contains the date, time, and name of the simulation run. This directory contains, divided up by regions, one file for each block in the simulation. These files contain the initialization data of the block, such as the number of wind turbine units belonging to a particular set of meteorological data, or the alignments of the solar-cell surfaces in a photovoltaic module.

A results directory is also created, containing the result data for each region and an aggregate file for all regions. The date and time of day of the time step are filed in this file for each time step. It contains the solar radiation, wind, and temperature data from a representative weather station from the region. In addition, the energy output data for the individual technologies, and the energy consumption of technologies that store energy or convert it into fuels, are printed to the file. So it contains the average output for each time step in megawatts for wind turbines and similar energy producers. The amounts stored and discharged and the available levels of reservoirs are filed. For units that produce hydrogen from electricity, the average power input in megawatts for each time step is stated. The file also contains the mean output and input per time step.

Besides these files, the simulation environment also creates another file that also stores all the results. When the simulation is reloaded, this file is also loaded. So when one loads the simula-

tion, all the data of the last simulation run are accessible again. In the simulation, these data can also be analysed with their own block, and a desired printout can be generated. For example, the results for one region can be displayed, or the energies produced by different technologies on particular weekdays or at particular times of day.

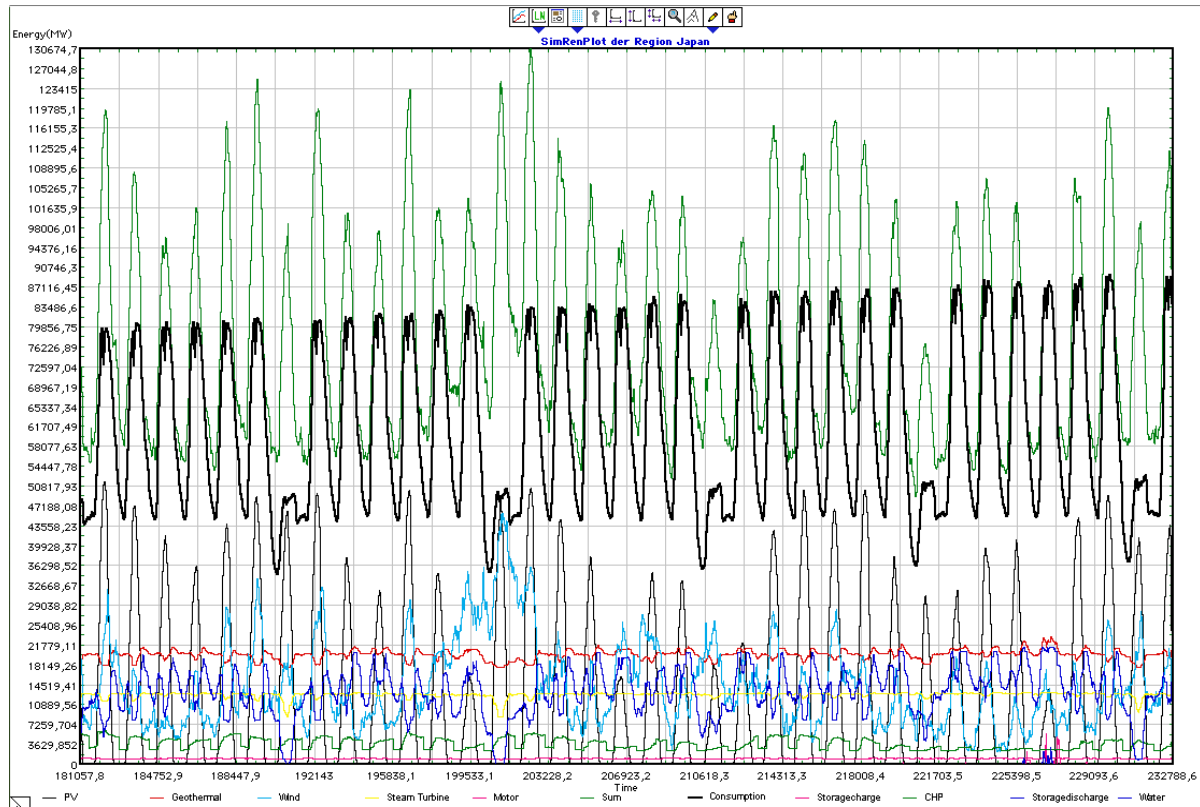


Figure 73 : Representation of a selection of the results of SimRen within the simulation environment. Source: ISUSI

## 10.7) Tests of the modules

For each of the energy supply and consumption modules described above, a test system has been set up for checking the computational algorithms and the results<sup><113></sup>.

The SimRen simulation was developed with the help of the simulation environment Extend® , which provides its own programming language. A standard simulation environment was chosen in order to minimize the possible sources of error from programming.

113.Spangardt (1999).

The modules in SimRen are simple input-output modules, which can be tested well independently of the rest of the SimRen model. The photovoltaic block, for example, computes the amount of electricity generated as an output from meteorological data as an input.

In the photovoltaic module, the most complicated one, the correct calculation of the sun's position and the conversion of solar radiation onto solar-cell surfaces was tested by comparing 'manually calculated' and simulated values. The temperature-dependent reduction in efficiency is also taken into account according to the cell temperature determined. By comparison with the cell temperatures measured by ISET, the simulated cell temperatures show a very good approximation to reality <sup><114></sup>. Furthermore, the shading calculation for elevated modules and the time shift of the radiation data were checked. In conclusion, time series of the power output from photovoltaic arrays with various erection geometries as measured by ISET were compared to simulated time series. Reflected radiation was not taken into account in the simulation. A satisfactory to good agreement of the time series was found.

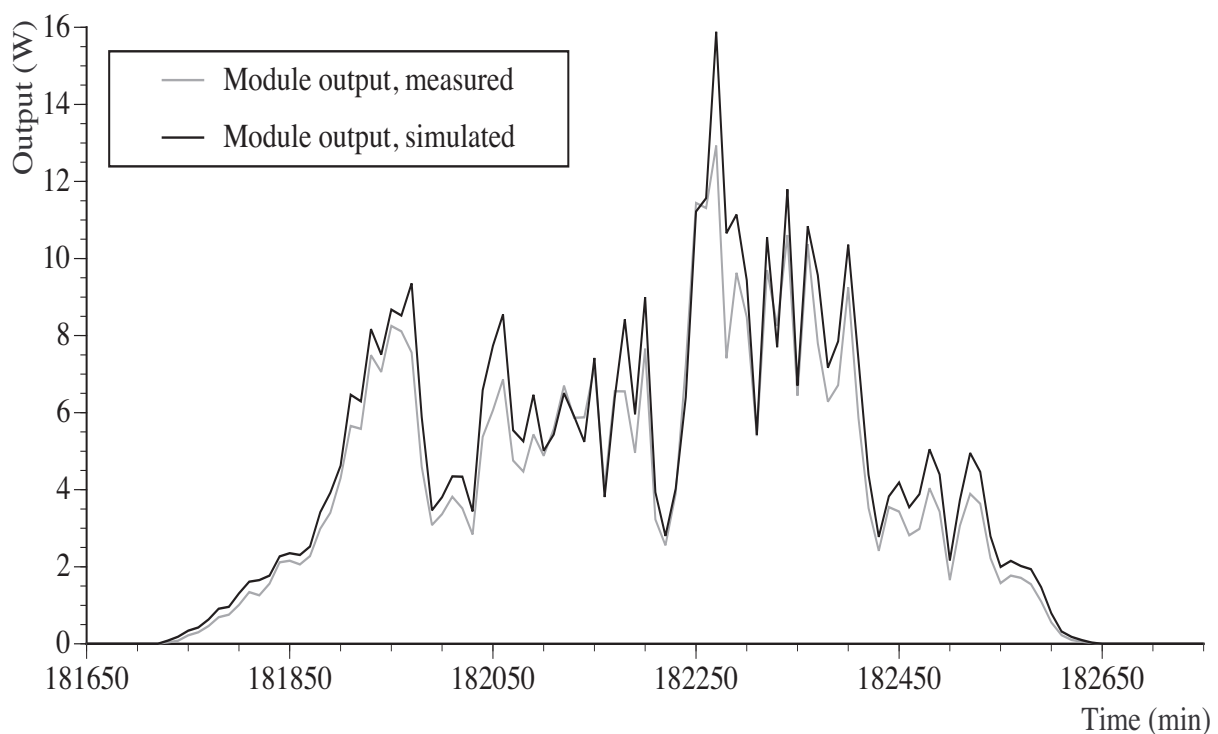


Figure 74 : Test of photovoltaic module: Comparison of simulated with measured values.  
Source: Spangardt (1999).

It is noticeable that for small outputs, the simulated output is somewhat higher than the measured one. The reason is probably because a constant efficiency of the power inverter is assumed in the simulation, whereas real inverters can feature losses in the part-load range. This could only be taken into account in a simulation of individual photovoltaic installations, not in the simulation of

114.ISET (1998).

an assemblage of installations. For high irradiance and larger mounting angles, the measured radiation is higher than the simulated one. This may be attributed to the reflected radiation that is left out of account, which is of increasing importance as the mounting angle increases.

In the simulation modules for wind turbines, the correct entry of the output curves was checked first. In addition, the behavior of a simulation module on a sample day was analysed. A correct conversion of the wind speed to the hub height of the simulated wind turbines, and a correct application of the output curve to compute the output to the grid were found. Unfortunately, comparisons with real installations were not possible, since the institutes that have measured the wind turbine data are not authorized to release these data. Since, however, the output curves of the wind turbines were derived from just those data, errors in the simulation can only result from the conversion of the wind speed to the hub height of the aerogenerators. If one assumes that the logarithmic elevation equation reflects the circumstances correctly, the possible source of error is in the assumption concerning the surroundings, i.e. in the assumption of the roughness length. If one considers the roughness length 0.01 m of open terrain, and of 0.1 m of a landscape with bushes, the height conversion factor for a measurement height of 10 m for the wind speed and a hub height of 70 m has a value of 1.28 or 1.42, respectively. So if one takes the roughness length of open terrain for wind turbines in a landscape with bushes, one makes an error of 10%. It must also be taken into account that this height equation can only properly be used if the measuring station and the wind turbine are located in comparable surroundings.

The power plant options of coal, gas, solid biomass, and biogas-fired power plants have been tested with regard to the correct control of the power plant assembly, and thus the correct calculation of fuel consumption. In these tests, it was found that the modules behaved according to the specifications.

The hydroelectric and geothermal power plants were tested to see whether the power plants produce the expected output if controlled appropriately, and whether this agrees with the rated capacity. In the case of the hydroelectric plants, it was also necessary to examine whether the limitations on output due to the water level are taken into account.

Cogeneration in the household and services sectors was simulated with a test set of meteorological data, and the results were compared with manually calculated values.

In checking the storage simulation modules, the charging and discharging of the storage systems was tested. As intended, the stored energy was diminished in accordance with the efficiency of the storage systems. So the charging and discharging of the storage systems is simulated according to the specified strategy. In these modules, the source of error is presumably the assumption of constant efficiency of the storage options. If one wishes to take into account the efficiency of the stor-

age systems as a function of the load, each storage unit must be taken into account individually for each storage option.

In the case of the simulation of the electrical load curve, it was checked whether the electrical demand is simulated correctly from the specified curves. The load-curve simulation was checked with the help of a spreadsheet program for various consumer groups on sample days.

Since the peak power plants are integrated into the import-export manager module, and respond to the demands of all regions, they were tested together with the import-export manager.

The import-export manager and the energy manager can only be tested in the context of an overall system. No errors in these modules were found during repeated simulation and evaluation of the results. As part of the tests, the energy balances were calculated by hand repeatedly, and the control response of the two modules was studied and improved.

## 10.8) Example of a simulation of a supply system

In the following, the energy supply curves for a few weeks are shown to illustrate the dynamics of a supply system. The examples are taken from the simulation of the Japanese power system. Energy supply of Japan in the 3rd week of the year shows the third week in January, from Monday the 14th to Sunday the 20th.

The results show the energy output of all energy suppliers in gigawatts, plotted against time. The day of the year is given on the horizontal axis, and the vertical lines separate the days from one another at midnight. Hydrogen production is not always shown completely, because it is very high at times.

The top (first) graph shows energy consumption compared with energy output. Energy output is the sum of the energy suppliers shown in the other four curves. Potential supply deficiencies can be detected there, and surplus output estimated. In the third week of January shown in the graph, we can see that a full supply is ensured at all times. Since the supply system was optimized for that goal, this full supply is available throughout the year. The second graph shows the output of the geothermal power and hydroelectric plants. The photovoltaic and wind power outputs are plotted below this. The next graph contains a results curve for the cogeneration plants in the industrial sector, and one for those in the household, commercial and services sectors. The CHP plants in the household, commercial and services sectors fluctuate according to the outdoor temperature, as described previously. The major jumps in output are due to the change-over between daytime and nighttime heating. The last graph shows the energy output or demand of the pumped-storage and peak power plants and the hydrogen production. The energy used to charge the reservoirs and for

generating the hydrogen is negative in these graphs, since it is consumed. In order to obtain the course of hydrogen production, one can simply take the sum of the individual energies produced (except for the hydrogen production curve).

In the first (top) section, one can see a surplus of energy on the 15th and 16th of January. This energy comes from the high outputs from wind energy and photovoltaic systems, as one can see in the third figure. Hydrogen is generated from the energy surplus. In the second curve, one can see that hydroelectric and geothermal power plants are producing less energy at that time, since less energy is required from controllable suppliers. They are not shut down completely, since a few regions need this energy.

On January 18th, energy production and demand coincide exactly. This is made possible by precise adjustment of the controllable energy suppliers. The wind energy and photovoltaic output is considerably less on that day than on the other days, and for that reason the controllable energy suppliers run almost at full capacity. The last graph, which covers the charging and discharging of the reservoirs and the peak power plants, is very interesting in this context. As described previously, 1 gigawatt capacity of the peak power plants is started up before the reservoirs are discharged. If that is not enough, the pumped-storage turbines are used to cover the remaining demand. This happens on Friday evening, for example. They are then refilled when there is a surplus of energy, for example Friday night.

On Sunday, January 20th, one can see what happens if much too much energy is available. On Sundays, the demand for energy is considerably less than on weekdays, since most offices are closed and many energy consumers are not working. Since this does not affect the fluctuating energy suppliers, there is a surplus of energy on most Sundays. The reservoirs can be refilled over the weekend. In addition, all the controllable energy suppliers can be throttled back. Even the output of the cogeneration plants is lowered. In the last curve, one can see that hydrogen production is especially high on that day.

The results in Figure 76 show the supply of the Hokkaido West region from the ERJ model. Let us consider these results in order to examine a region whose energy supply exceeds demand for almost all the year. As one can see, a very large proportion of the energy is generated by wind turbines and geothermal power plants. This is possible because the region has a very low population density and pronounced geothermal anomalies. The photovoltaic output is so low because there are hardly any roof surfaces on which photovoltaic arrays could be installed.

As one can see, many controllable energy suppliers produce energy although no more energy is needed at all in the region. This shows clearly that the import-export manager takes over control partially, and starts up the power plants because power is still needed in other regions.

The results for a region of the ERJ model that, due to its high population density, is not able to supply itself completely for most of the year are shown in Figure 77. These graphs show the same week in Kanto. Here, conditions are exactly the opposite. There is very little room for wind turbines, since the region is very densely populated. However, much energy can be obtained from cogeneration plants, since the population also needs a lot of heat, and electricity can be generated during the production of heat. In the results shown, the energy demand can only be met on Sundays, since energy consumption is considerably lower on that day than on any other day of the week.

As one can see, on days with low photovoltaic output, the energy manager in the region switches on the pumped-storage power plants, in order to generate electricity from their stored energy. The energy manager is only able to throttle back the hydroelectric plants on Sunday, since enough energy is available on that day. Since this region is hardly able to supply itself, energy production here is only influenced by the import-export manager inasmuch as it imports energy into the region when needed, in order to ensure supply.

Figure 78 shows the Chugoku region in the same week. These graphs are discussed here because they show once again the influence of the import-export manager on the charging and discharging of the storage systems. Chugoku is largely able to cover its energy demand itself, without generating a surplus in the process. The region is able to have large areas of photovoltaic arrays, and already has numerous hydroelectric plants. Furthermore, demand is only about one fifth of Kanto's energy demand.

As one can see, the reservoirs are filled on Thursday and Friday night, although the region does not produce surplus energy. The reason is that there is a surplus of output in Japan as a whole. The import-export manager stores this in the reservoirs in Chugoku, since there is still free capacity here. In the daytime, the reservoirs are discharged partially, although there is no lack of supply in Chugoku. This is done in order to supply the rest of Japan with power. Here too, the import-export manager controls the energy output of the pumped-storage power plants.

The double peak in the photovoltaic output is due to the fact that in Chugoku most of the solar-cell surfaces are computed from meteorological data from two different longitudes. Therefore, the maximum irradiance of a day occurs first at the eastern, and a little later at the western weather stations. The result is this double peak in the curve.

Figure 79 shows a summertime result of the ERJ simulation. Due to the high temperatures, the cogeneration plants are not used for space heating in this month, but only to heat water. Therefore, the course of the curve for the cogeneration plants in the household and services sector ("Cogen(Com,Res)") in the results is no longer weather-dependent, nor does one see the nighttime lowering of temperature. Energy supply just meets demand during the summer months, and



cannot be used for hydrogen production. But this is due less to the low CHP output than to the poorer wind conditions than in the rest of the year.

The results in Figure 80 and Figure 81 are good examples of what the energy supply of a model region might look like if coal-fired and gas-fired power plants are included in the energy system. The control mechanisms are the same as in the ERJ simulation. In the graphs shown here, the gas-fired power plants are always regulated before the coal-fired ones, so that their output varies considerably more within the weeks shown than that of the coal-fired power plants. In Figure 80 there is a very large surplus throughout the week, while in Figure 81 the output of the fossil-fuel power plants has to be increased towards the end of the week because of the low wind-energy output. The week shown in Figure 81 is a week in summer, as well. Therefore, the cogeneration plants in the household and services sector are not run for heating purposes during this week.

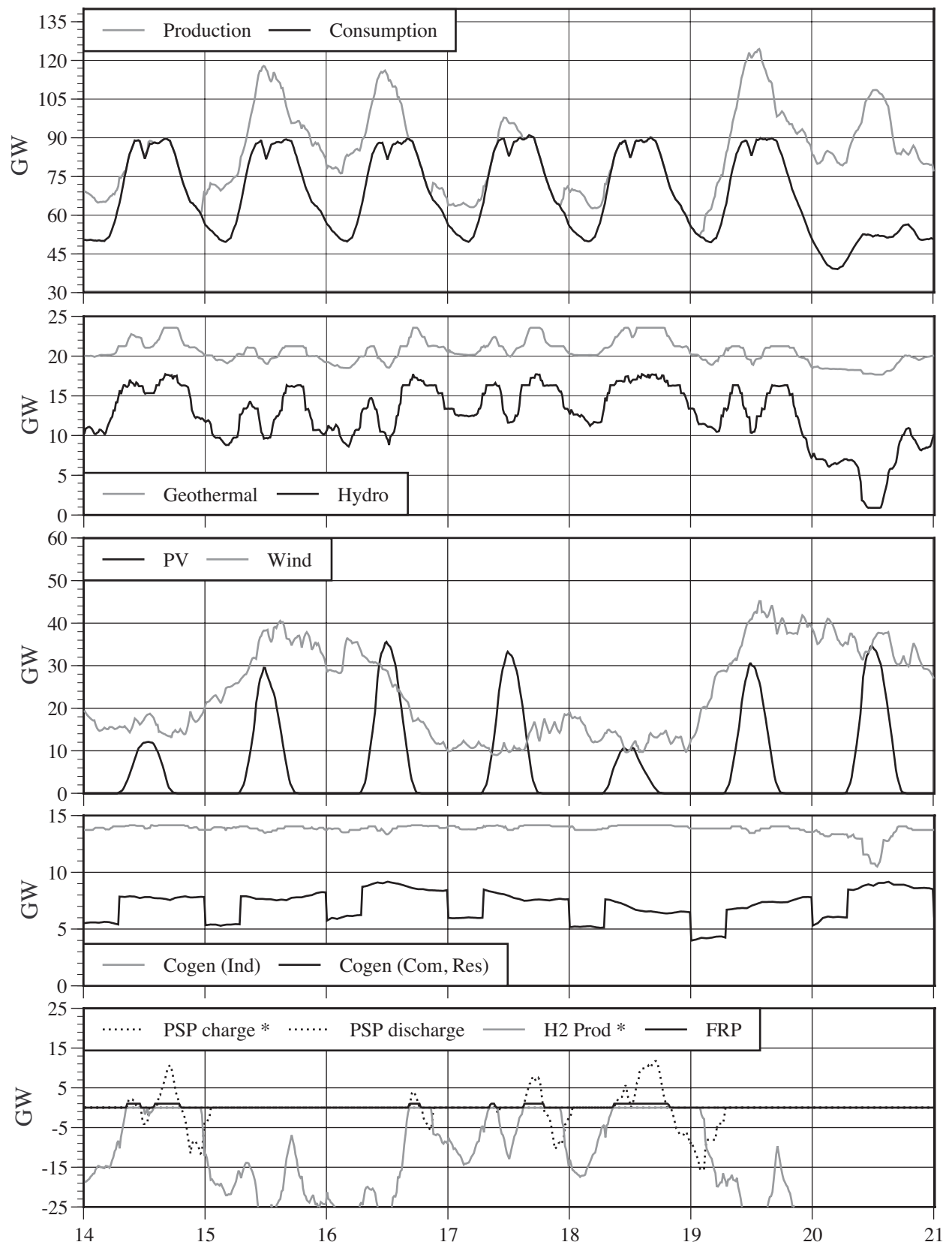


Figure 75 : Energy supply of Japan in the 3rd week of the year. Source: ERJ.

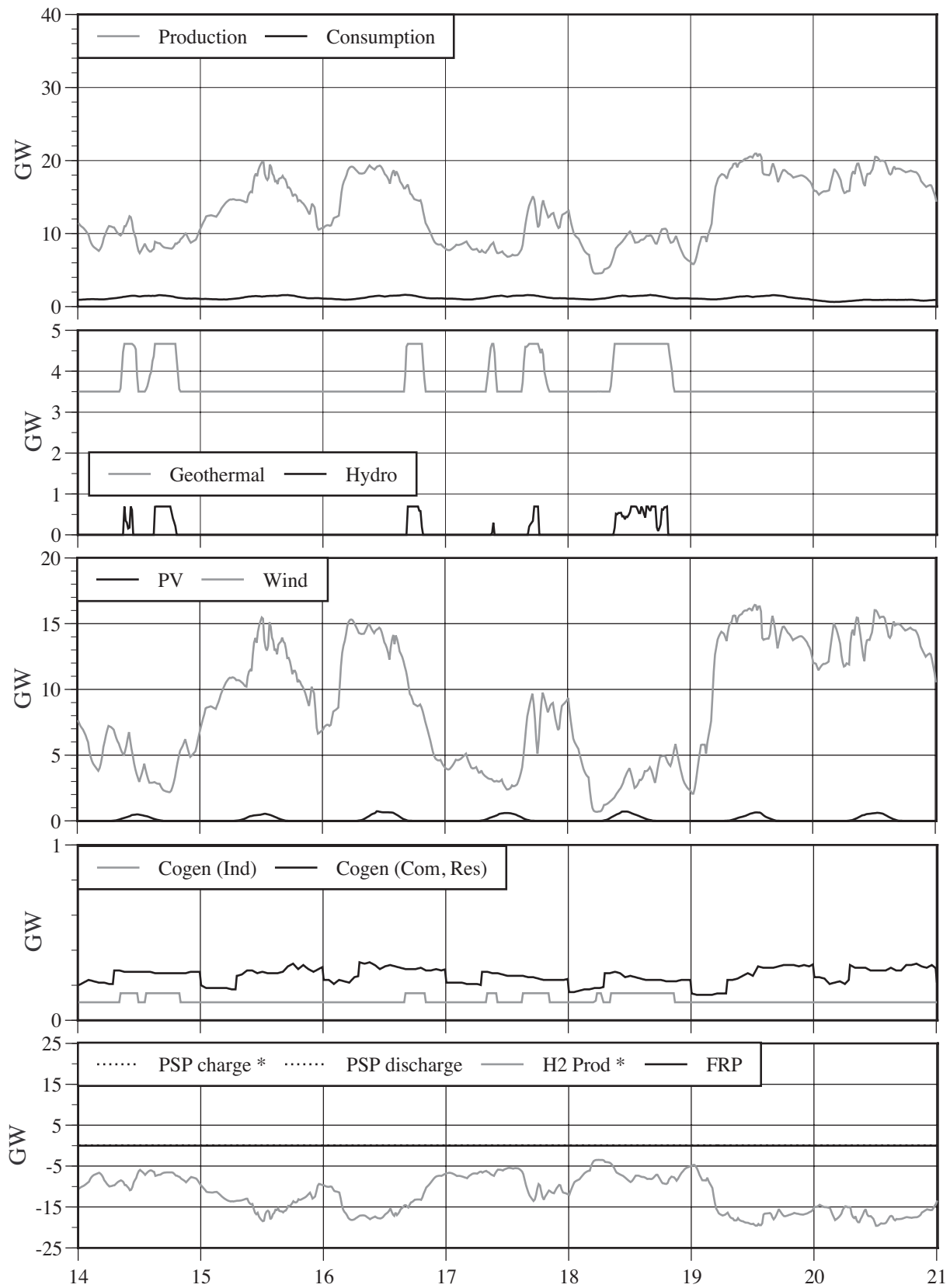


Figure 76 : Energy supply of the Hokkaido West region of the Japanese energy model in the 3rd week of the year. Source: ERJ.

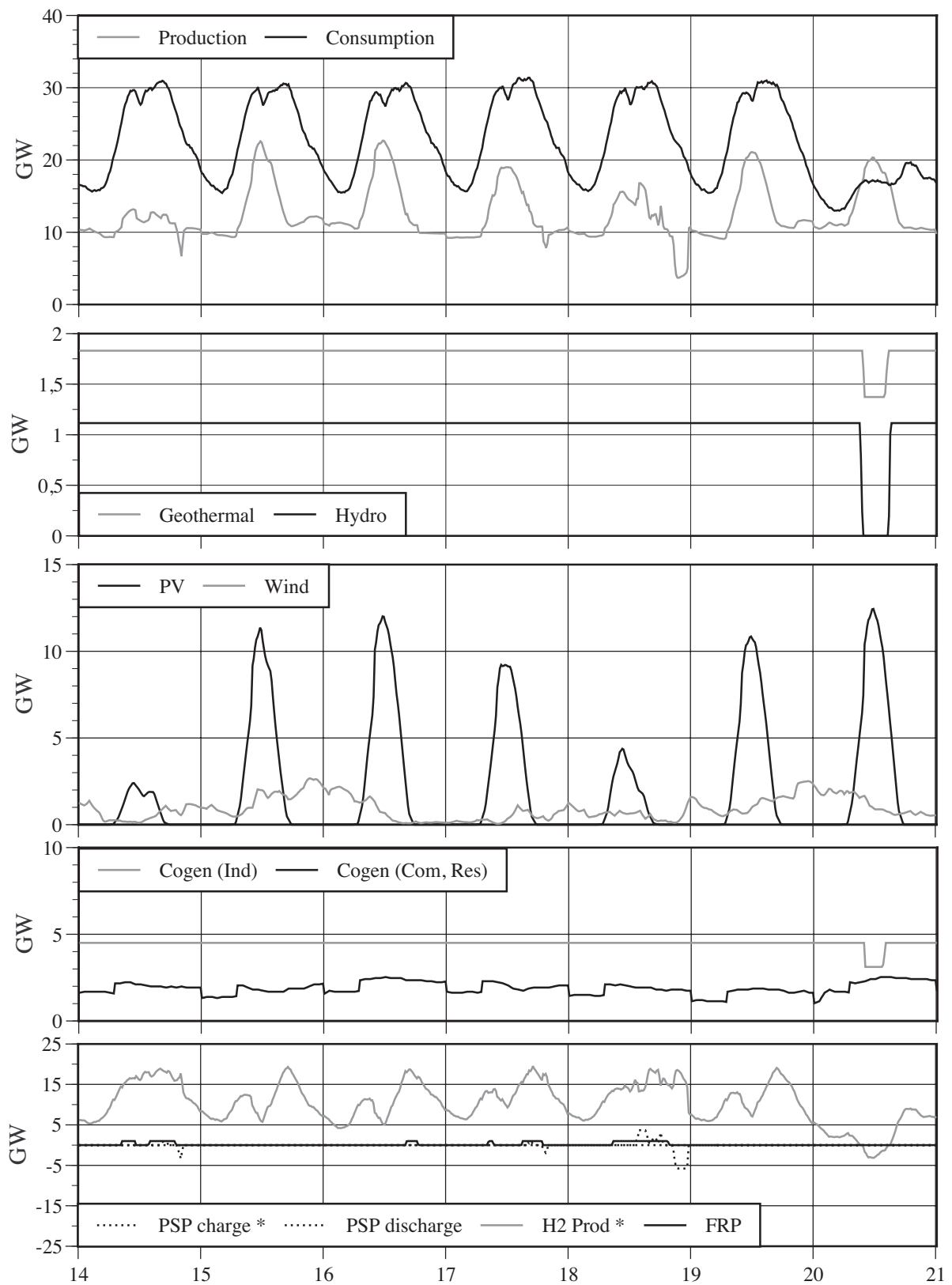


Figure 77 : Energy supply of the Kanto region of the Japanese energy model in the 3rd week of the year. Source: ERJ.

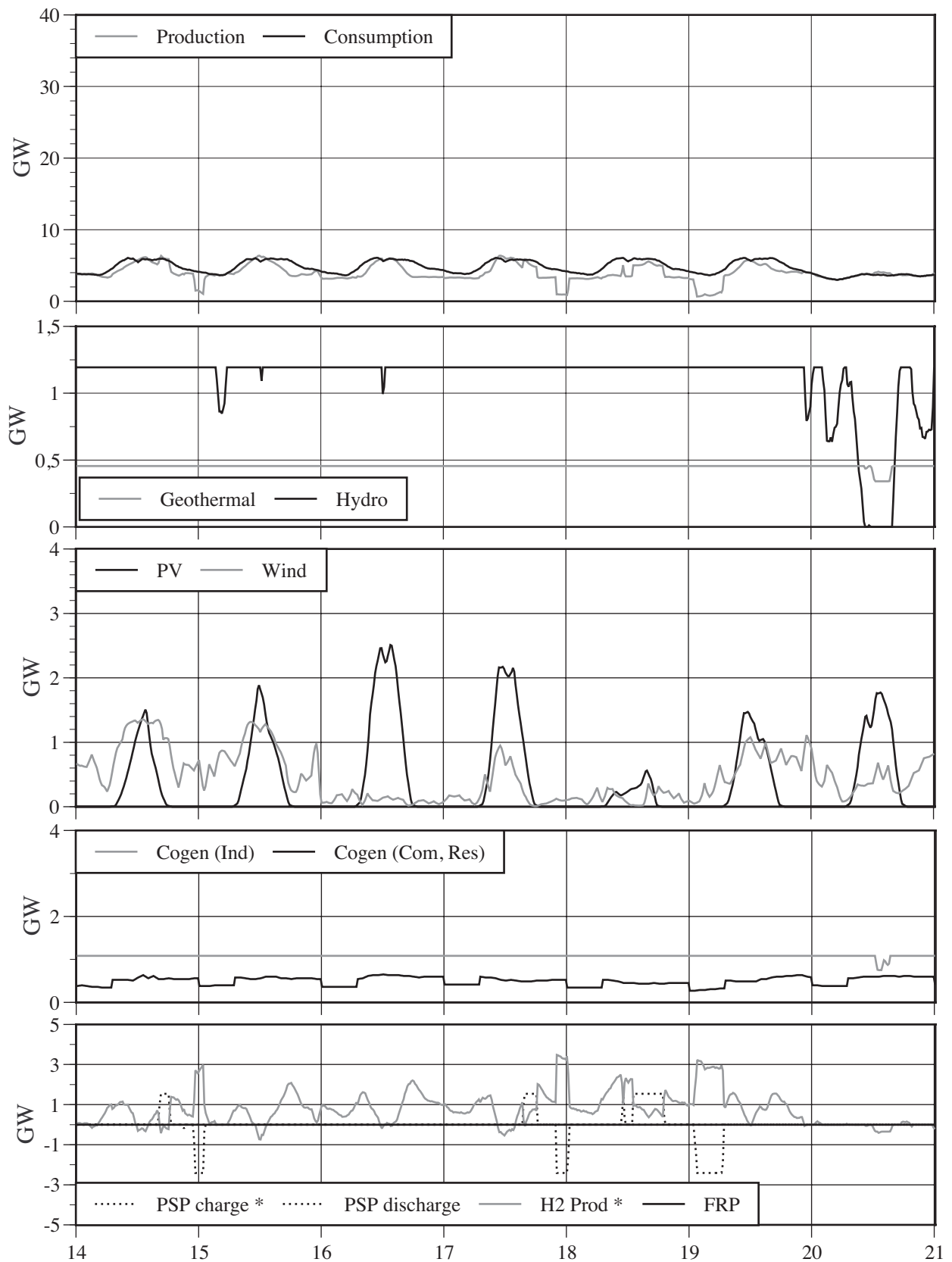


Figure 78 : Energy supply of the Chugoku region of the Japanese energy model in the 3rd week of the year. Source: ERJ.

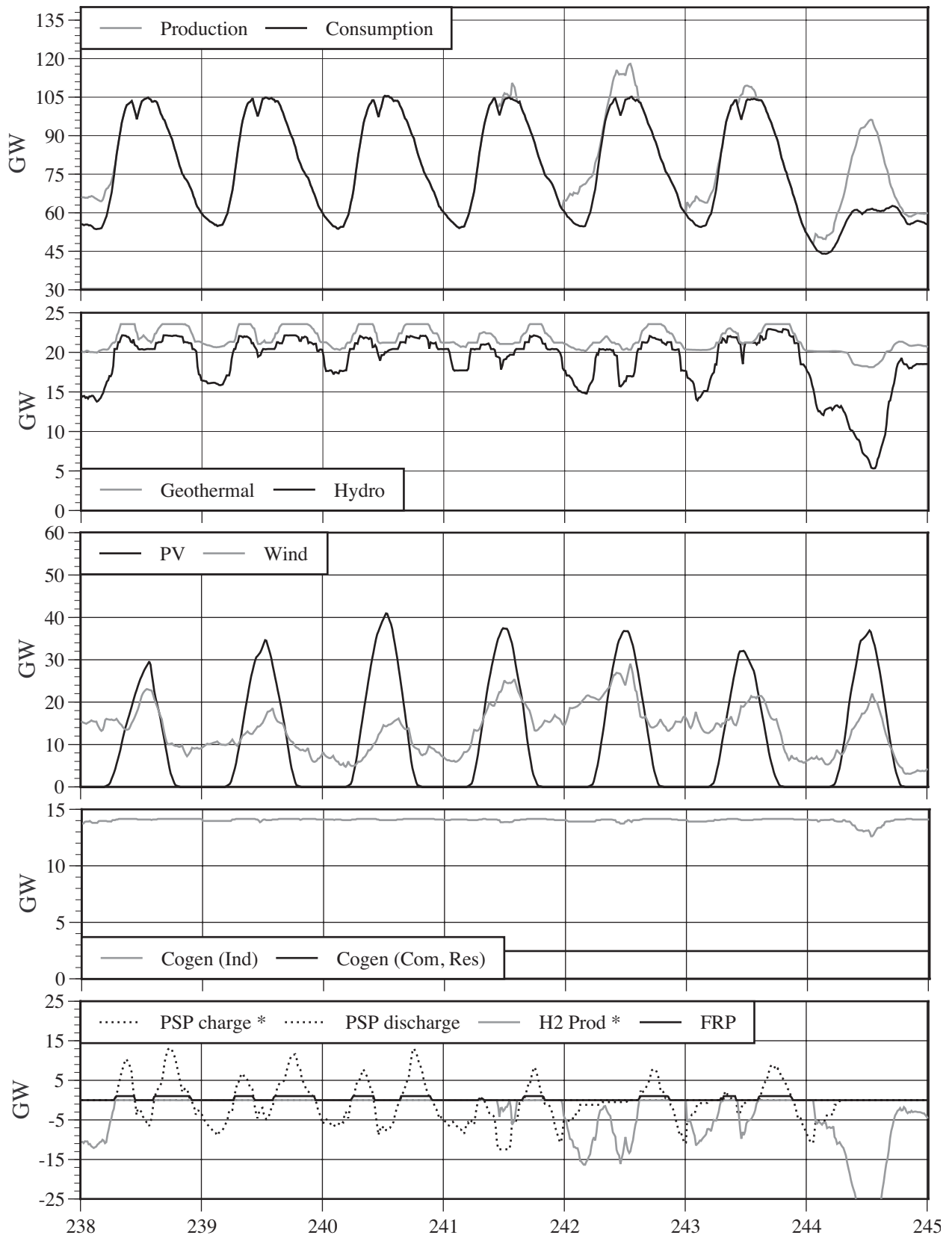


Figure 79 : Energy supply of Japan in the 35th week of the year. Source: ERJ.

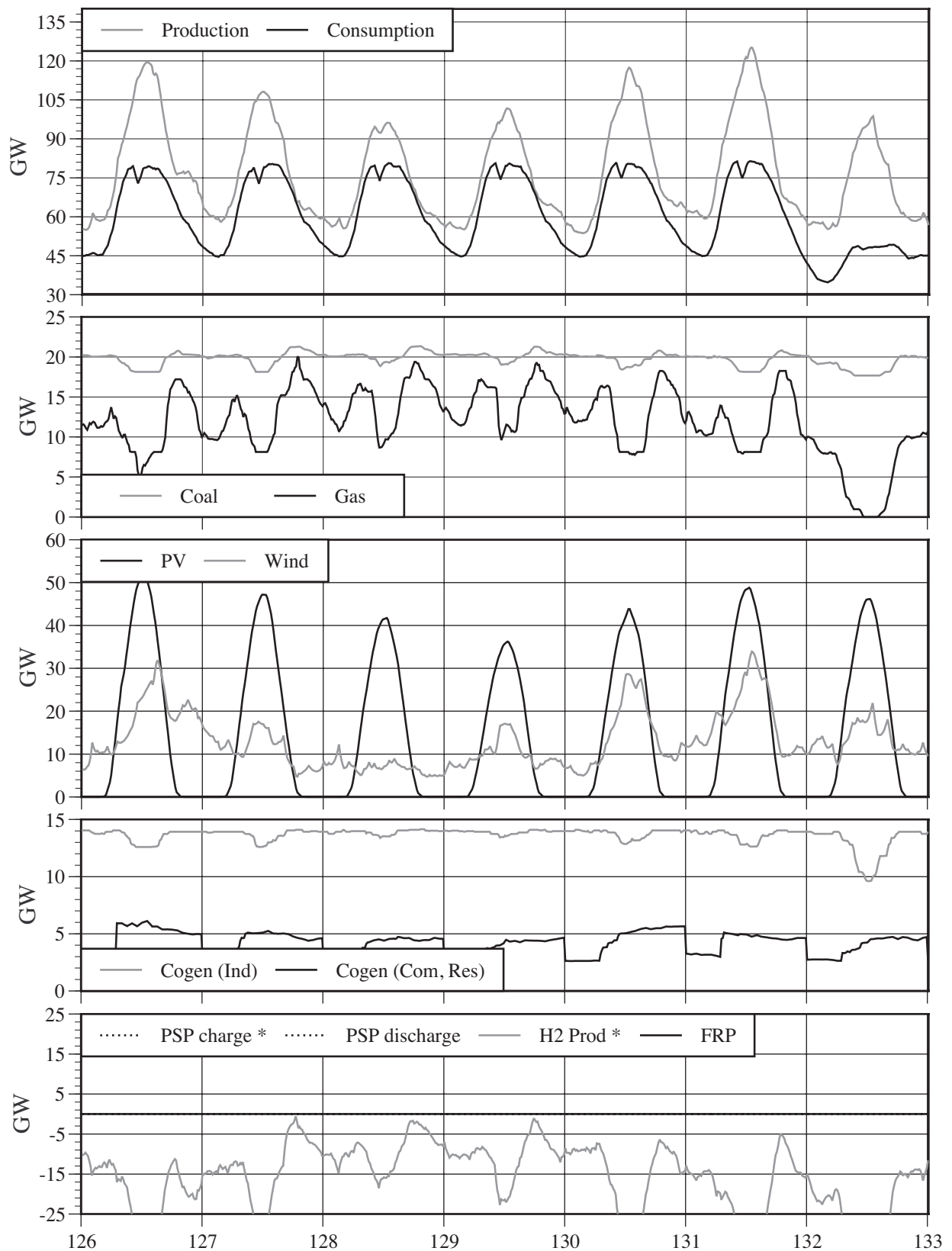


Figure 80 : Energy supply of a model region, including coal-fired and gas-fired power plants. Source: ERJ.

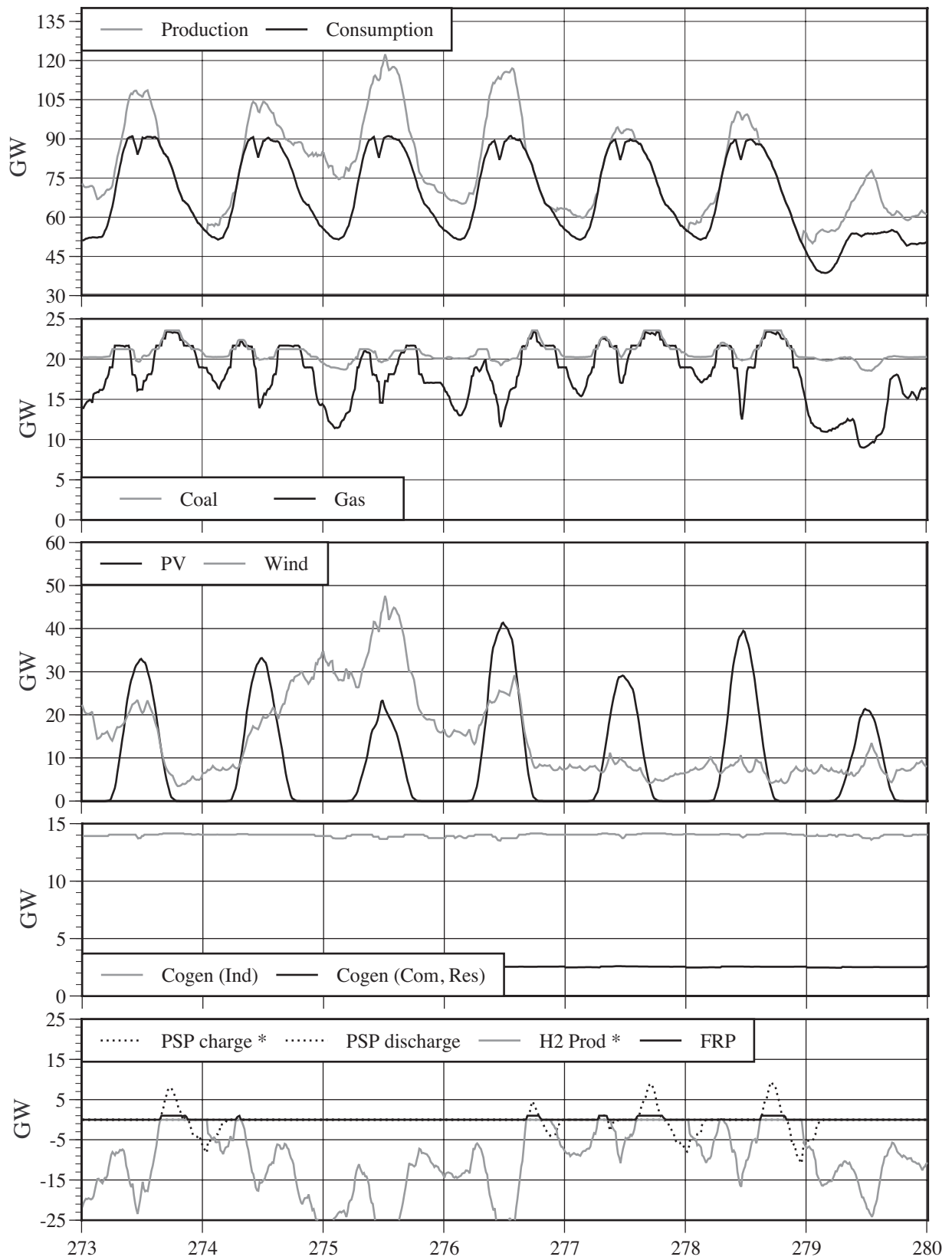


Figure 81 : Energy supply of a model region, including coal and gas power. Source: ERJ.