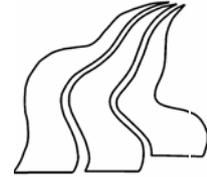
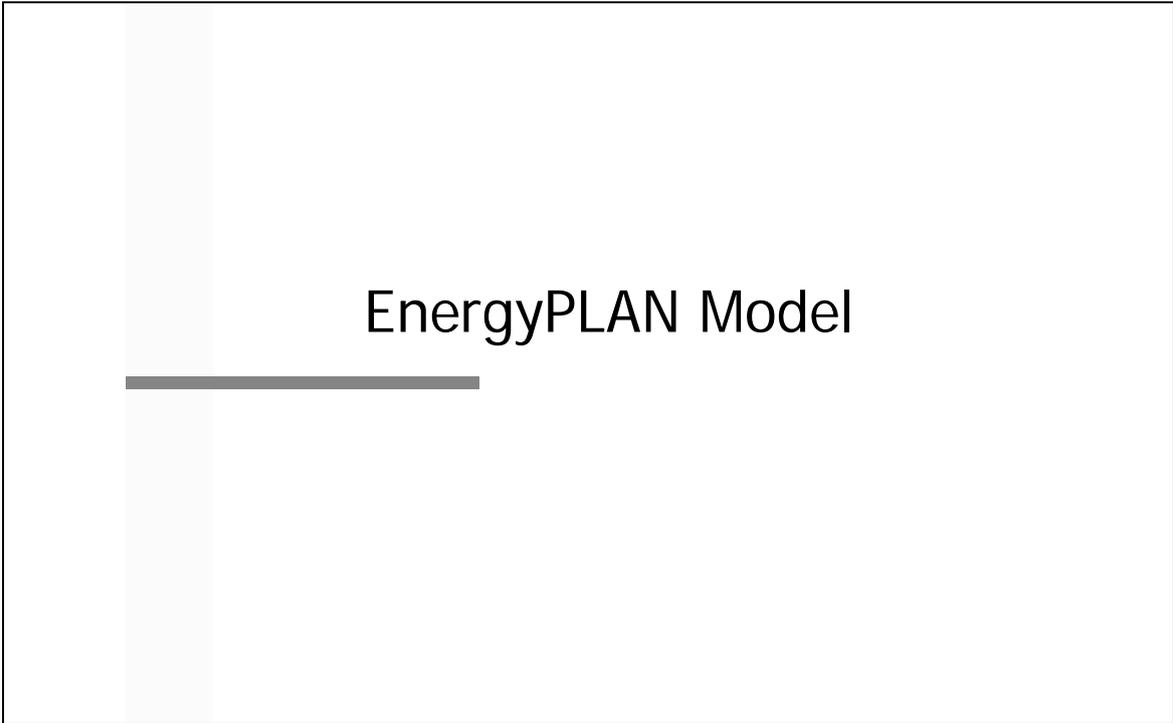


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December 2003



# **EnergyPLAN**

## **Computer Model for Energy System Analysis**

A large rectangular frame containing a light gray vertical bar on the left side. In the center of the frame, the text "EnergyPLAN Model" is displayed. Below the text, there is a thick horizontal gray line.

EnergyPLAN Model

**Version 6.6**

## Preface

The EnergyPLAN model has been developed and expanded to the version 6.6 in the period since year 1999.

Initially, the model was developed by Henrik Lund and implemented in an EXCEL spreadsheet. Very soon, the model grew huge, and consequently in 2001, the primary programming of the model was transformed into visual basic (from version 3.0 to 4.4). At the same time, all the hour by hour distribution data were transformed into external text files. Altogether, this reduced the size of the model by a factor 30. This transformation was done in collaboration with Leif Tambjerg and Ebbe Münster (PlanEnergi consultants).

During 2002, the model was re-programmed in Delphi Pascal into version 5.0. And during 2003, the model has expanded into version 6.0. This transformation was implemented by Henrik Lund with the help and assistance of Anders N. Andersen and Henning Mæng (Energy and Environmental Data). In version 6.0, the model was expanded with a possibility of calculating the influence of CO<sub>2</sub> emissions and the share of RES when the electricity supply is seen as a part of the total energy system of a region. And further possibilities of analysing different trade options on the external electricity market have been added.

During the spring of 2005, the model was expanded into version 6.2 in a comparative study with the H2RES model with a focus on energy system analysis of renewable islands. As part of the work, two new possibilities of storing/converting electricity storage facilities were added to the EnergyPLAN model. The one is an electricity storage unit, which can be used for modelling e.g. hydro storage or battery storage. The other is electrolyzers which are able of producing fuel (e.g. hydrogen) and heat for district heating.

During the autumn of 2005 and the spring of 2006, the model has been expanded further into the present form (version 6.6). The main focus has been to be able to do modelling of the energy system in six European countries as part of the EU project DESIRE. Consequently, the model was added the possibility of more renewable units and nuclear power and hydro power with water storage and reversible pump facilities.

Henrik Lund  
Aalborg University  
March 2006

## Introduction

The main purpose of the model is to design suitable national energy planning strategies from analysing the consequences of different national energy investments. The MODEL emphasises the analysis of different regulation strategies. The analysis is carried out in hour by hour steps for one year. And the consequences are analysed on the basis of both different technical regulation strategies and different market economic optimisation strategies.

The model is an input/output model. General inputs are demands, capacities and a number of optional different regulation strategies emphasising import/export and surplus production of electricity. Outputs are energy balances and resulting annual productions, fuel consumption and import/exports.

The model is designed to make two different types of analyses. The first one being a technical analysis based on demands and capacities. The second one makes an economic optimisation of the behaviour based on further inputs of marginal costs and hour-by-hour price assumptions on the international electricity market. See diagram 1.

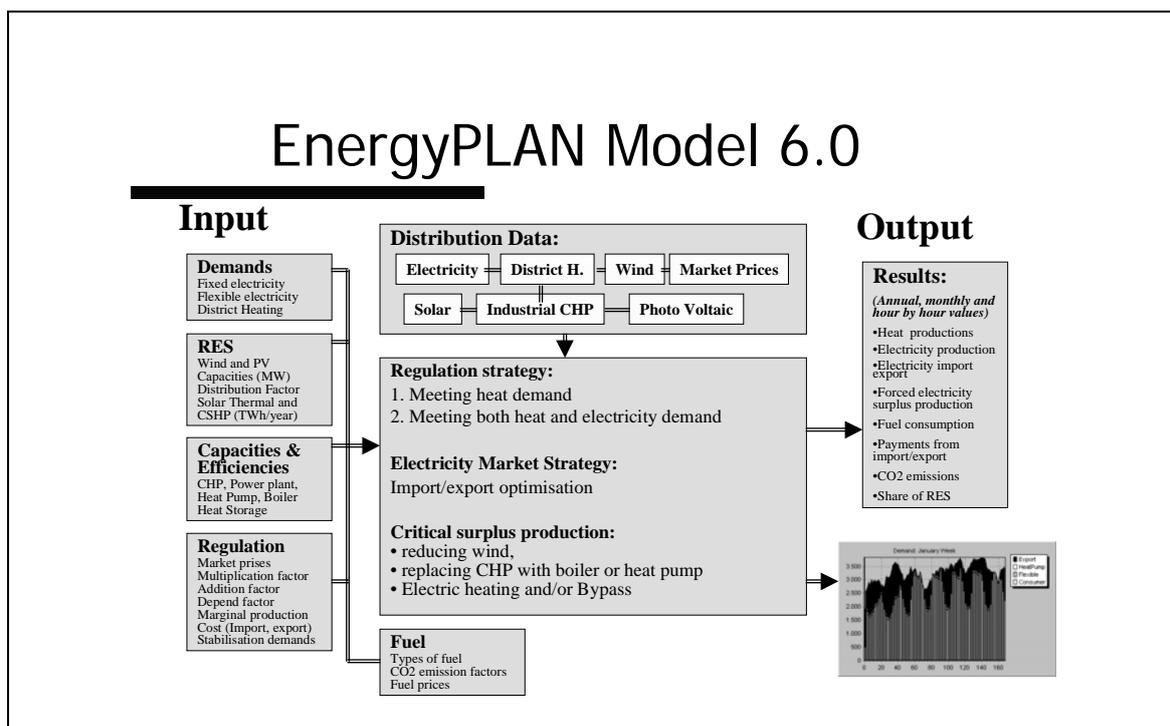


Diagram 1: The EnergyPLAN Energy System Analysis Model

# 1. The EnergyPLAN Energy System

The principle of the energy system in the EnergyPLAN model is shown in diagram 2.

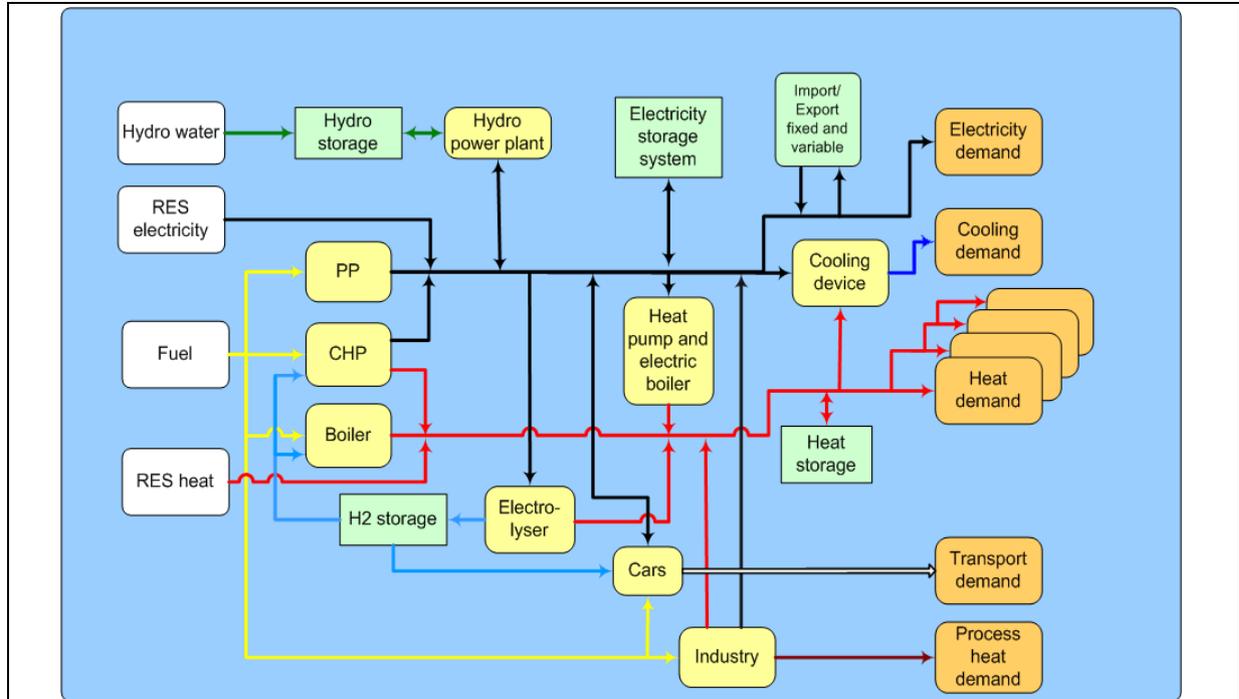


Diagram 2: Principle of the Energy Production System in the EnergyPLAN model.

### The Demand system:

- 1) District heating demand divided into I) group of boiler systems, II) group of decentralised CHP systems and III) group of centralised CHP systems.
- 2) Electricity demand divided into two different types of fixed demands and three types of flexible demands.
- 3) Possibility of adding a fixed external import of export of electricity  
All of the demands are defined by an annual value (TWh per year) and an hour by hour distribution data set (name of data set from the data bank).

### The Production system:

For district heating group I, the production system consists of:

- 1) A solar thermal
- 2) A CSHP unit (Industrial CHP)
- 3) A District Heating Plant (DHP), i.e. a boiler

For district heating group II and III, the energy production system consists of:

- 1) A solar thermal
- 2) A CSHP unit (Industrial CHP)
- 3) A CHP unit
- 4) A heat pump
- 5) A peak load boiler
- 6) A heat storage.

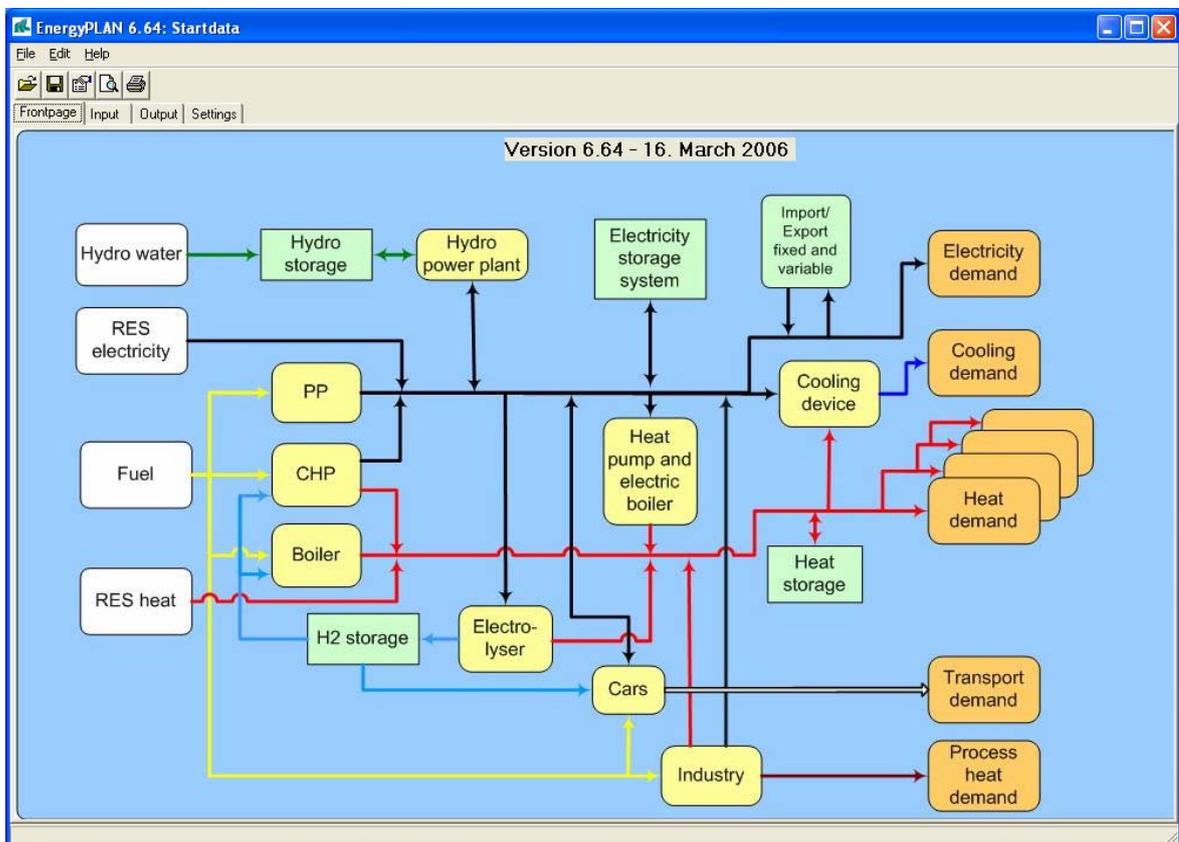
Furthermore, the total production systems include:

- 1) A Wind Power input divided into onshore and offshore
- 2) A Photo voltaic input
- 3) A Power plant (condensed production)

For such an energy system, the model analyses the behaviour in the case of a number of different regulation strategies.

The model is divided into the following overall structure components as illustrated in the diagram:

- front page
- input
- output
- settings



## 2. Input Data

As shown in the diagram below, the input data of the model are divided into seven sets of data: Transport, Demands, Capacities, Renewable Energy, Storage, Fuel and Regulation.

### 2.1 Demands

The screenshot shows the 'EnergyPLAN 6.64: Startdata' window with the 'Demand' tab selected. The interface includes a menu bar (File, Edit, Help), a toolbar with icons for file operations, and a main window with tabs for Transport, Demand, Capacities, RenewableEnergy, Storage, Fuel, and Regulation. The 'Demand' tab is active, showing input fields for District heating (Gr. I, II, III), Electricity demand, Flexible demand (1 day, 1 week, 4 weeks), and Fixed Import/Export. Each field has a numerical input box, a unit (TWh/year or MW), and a 'Change' button. A 'Distribution' button is also present for some fields. A text box at the bottom provides definitions for the District heating groups.

Category	Group	Value (TWh/year)	Unit	Max-effect (MW)	Distribution File
District heating	Gr. I		TWh/year		
	Gr. II	10	TWh/year		Hour_distr-heat.txt
	Gr. III	10	TWh/year		
Electricity demand		20.00	TWh/year		
		20	TWh/year		Hour_electricity.txt
Flexible demand	(1 day)	0	TWh/year	1000	MW
	(1 week)	0	TWh/year	1000	MW
	(4 weeks)	0	TWh/year	1000	MW
Fixed Import/Export		0	TWh/year		Hour_Tysklandsexport.txt
Total electricity demand		20.00	TWh/year		

District heating gr. I is meant to represent DH systems without CHP  
 District heating gr. II is meant to represent DH systems based on small CHP plants  
 District heating gr. III is meant to represent DH systems based on large CHP extraction plants

The annual district heating consumption needs to be stated for each of the three DH groups. And the annual consumption of electricity is stated and divided into flexible and fixed demand, and demand for the transport sector, if any. A maximum capacity value is also stated for potential flexible electricity demand. For the rest of the demands, the input is given by an annual value (TWh per year) and a name of an hour by hour distribution data set.

$Q_{DH}$  = District heating (Divided into the three groups described above)

$E_D$  = Electricity demand (Divided into the fixed and flexible types described above)

## 2.2 Renewable Energy Sources (RES)

	Renewable Energy Capacity: MW	Stabilisation share	Distribution profile	Production TWh/year	Correction factor	Post Correction production
RES1	1000	0	Hour_wind_1.txt	2.07	0	2.07
RES2	500	0	Hour_wind_1.txt	1.04	0	1.04
RES3	0	0	Hour_solar_prod	0.00	0	0.00
RES4	0	0	Hour_solar_prod	0.00	0	0.00

TWh/year	Solar Thermal	Industrial CHP (CSHP):	DH prod	Electricity prod
DH Gr.1:	0		0	0
DH Gr.2:	0		0	0
DH Gr.3:	0		0	0
Total:	0.00		0.00	0.00

Change Hour\_solar\_prod1.txt Change Hour\_cshpel.txt

The input data set defines input from RES and industrial CHP (CHSP) both to the electricity supply and to the district heating supply. The latter is divided into the three district heating groups.

One can choose input of up to four different renewable energy sources. By pressing the button, the following names can be attached to each RES:

- Wind
- Offshore Wind
- Photo Voltaic
- Wave Power
- River Hydro

Input to the electricity production is given by the capacity of each RES and the by the name of the distribution file. In the case that the RES contributed to grid stabilisation, the share can be given between 0 and 1.

The resulting annual production based on the specified input capacity and distribution is shown on the input page.

One can choose to specify a correction factor to change the distribution and increase the annual production. The correction factor influence distribution as described in section 4.1 and the resulting annual production is shown in the input window.

Input to district heating production is given for solar thermal and industrial CHP, the latter including input to electricity production as well.

Additional to either the annual production (TWh per year) or the capacity, the names of the hour by hour distribution data sets are defined for all the inputs.

$C_{pv}$ ,  $C_w$  = Wind power capacity (MW) (Divided into on-shore and off-shore)

$Fac_w$  = Wind distribution factor (Factor to change former wind productions based on historically p.v. or wind turbine configurations into productions from other configurations, i.e. for example from onshore wind turbines to offshore wind turbines).

## 2.3 Capacities (MW electric or MJ/s thermal) and operation efficiencies

The screenshot shows the 'EnergyPLAN 6.64: Startdata' window with the 'Capacities' tab selected. The window is divided into several sections for different energy production groups.

Group II	Capacities		Efficiencies			Heat storage gr. 2 GWh
	MW-e	MJ/s	elec.	Therm.	COP	
CHP	1000	1250	0.4	0.5		10
Heat Pump	0	0			3	
Boiler		5000		0.9		0 Per cent

Group III	Capacities		Efficiencies			Heat storage gr. 3 GWh
	MW-e	MJ/s	elec.	Therm.	COP	
CHP	1500	1875	0.4	0.5		10
Heat Pump	100	300			3	
Boiler		5000		0.9		0 Per cent
Condensing	4000		0.45			

Group I

DHP

0.9

Hydro Power :

Capacity: 0 MW-e      Annual Water supply: 0 TWh/year

Efficiency: 0.33      Distribution of water: Change Hour\_wind\_1.txt

Storage: 0 GWh      Estimated annual production: 0.00 TWh/year

Pump Capacity: 0 MW-e      Storage difference: 0 GWh

Pump Efficiency: 0.9

Nuclear Power:

Capacity: 0 MW-e      Distribution: Change Hour\_wind\_1.txt      Annual production: 0.00 TWh/year

Efficiency: 0

Capacities and operation efficiencies of CHP units, power stations, boilers and heat pumps are defined as part of this input data set. Power stations include nuclear and hydro power, and also the size of heat storage capacities are given here.

$C_{HP}$  = Heat Pump capacity (MW)

$C_{CHP}$  = CHP capacity (MW)

$C_P$  = Power Plant capacity (MW)

$H_B$  = Boiler capacity (MJ/s)

$H_{HP}$  = Heat Pump heat capacity (MJ/s)

$H_{CHP}$  = CHP heat capacity (MJ/s)

$C_{HP}$  = Heat storage capacity (GWh)

$C_P$  is the total sum of power plant capacity and CHP capacity in group III. This is due to the fact that in lack of district heating demand in group 3, the CHP capacity can be turned into purely condensing power plant capacity.

## 2.4 Regulation

EnergyPLAN 6.64: Startdata

File Edit Help

Frontpage Input Output Settings

Transport Demand Capacities RenewableEnergy Storage Fuel Regulation

Regulation Strategy: 1

Market Model: 1

Minimum stabilisation prod. share:   Distribution Hour\_nordpool.txt

Stabilisation share of CHP2:

Addition factor:  DKK/MWh

Multiplication factor:  DKK/MWh

Dependency factor:  DKK/MWh pr. MW

Average price: 227 DKK/MWh

Minimum CHP in gr. 3:

Heat Pump Maximum load:

Marginal import price:  DKK/MWh

Marginal export price (PP):  DKK/MWh

Marginal export price (CHP):  DKK/MWh

Marginal export price (HP):  DKK/MWh

CEEP regulation:

Maximum imp./exp. cap.:  MW

Critical Electricity Excess Production (CEEP) regulation: Write number:

- 1 : Reducing wind production
- 2 : Reducing CHP in gr.2 by replaing with boiler
- 3 : Reducing CHP in gr.3 by replaing with boiler
- 4 : Replacing boiler with electric heating in gr.2
- 5 : Replacing boiler with electric heating in gr.3
- 6 : Reducing photo voltaic production
- 7 : Reducing power plant in combination with wind and photo voltaic production

In case of Market Model 3, the following price is added to the system price in case of import bottlenecks:

DKK/MWh

New Market Heat Storage Regulation :

This input specifies the choice of different regulation strategies, and defines marked prices and marginal production prices. The input also includes some technical limitation.

Four optional technical regulation strategies and three optional market strategies are given. For more detailed information on each strategy, please consult chapters 5 and 12. Also critical surplus production can be removed according to a priority between:

1. Stopping wind turbines (first onshore then offshore)
2. Replacing CHP in group 2 with Heat Pumps or Boilers
3. Replacing CHP in group 3 with Heat Pumps or Boilers
4. Electric heating in group 2
5. Electric heating/or bypass in group 3
6. Reducing Photo Voltaic
7. Reducing power plants in combination with wind and photo voltaic

The five possibilities are activated in a priority. If for instance "CEEP regulation" is stated as 23541, critical surplus production will be removed first by replacing CHP in group 2 and 3, then by electric heating and in the end by stopping the wind turbine. For "CEEP regulation" = 51, surplus production is removed first by electric heating only in group 3 and then by stopping wind turbines.

The prices of electricity on the external market are defined by choosing an hour by hour distribution. These prices can then be changed by a multiplication factor and an addition factor (DKK/MWh). Moreover, the market can be changed by a factor expressing market reactions to trade on the market. This factor is expressed in terms of how much the price (DKK/MWh) change pr. trade (MW).

Short-term marginal production costs can either be stated as input, or in the next section (FUEL input data set), it can be activated for the model to calculate the prices if fuel prices and marginal operation and maintenance cost are given instead. The following marginal costs can be defined:

$MC_{import}$  = Marginal production costs of one MWh electricity less on the Power Plant

$MC_p$  = Marginal production costs of one MWh electricity more on the Power Plant

$MC_{B-CHP}$  = Marginal production cost of one additional MWh by replacing the boiler by the CHP unit

$MC_{HP-CHP}$  = Marginal production cost of one additional MWh by replacing the HP by the CHP unit

If the import costs are zero and the rest is defined with very high numbers (as for instance 9999 as in the example above), then the model will not trade on the market, and the results are then the results of the technical analysis.

Also a number of technical limitations are defined, namely a) the minimum CHP and power plant per cent of the load required in order to remain grid stability, and b) the maximum heat pump per cent of the heat production required in order to achieve the specified COP. Finally, the transmission capacity is stated.

## 2.5 Fuel

EnergyPLAN 6.64: EbbeSPtest2

File Edit Help

Frontpage Input Output Settings

Transport Demand Capacities RenewableEnergy Storage Fuel Regulation

	Coal	Oil	Ngas	Biomass
(TWh/year)	Variable	Variable	Variable	Variable
DHP	0	0	0	1
CHP2	0	0	0	0
CHP3	254.52	25.66	57.95	3.94
Boiler2	0	0	0	0
Boiler3	0	0	0	0
PP	254.52	25.66	57.95	3.94
Households	0	0	0	0
Industry	0	0	0	0
Various	0	0	0	0

Marginal Costs of producing 1 MWh electricity

Incr. CHP2 decr. HP2	41	EUR/MWh
Incr. CHP2 decr. HP3	9999	EUR/MWh
Incr. CHP2 decr. B2	31	EUR/MWh
Incr. CHP2 decr. B3	9999	EUR/MWh
Incr. B2 decr. HP2	54	EUR/MWh
Incr. B2 decr. EB2	18	EUR/MWh
Incr. B3 decr. HP3	53	EUR/MWh
Incr. B3 decr. EB3	18	EUR/MWh

Included in the calculation:

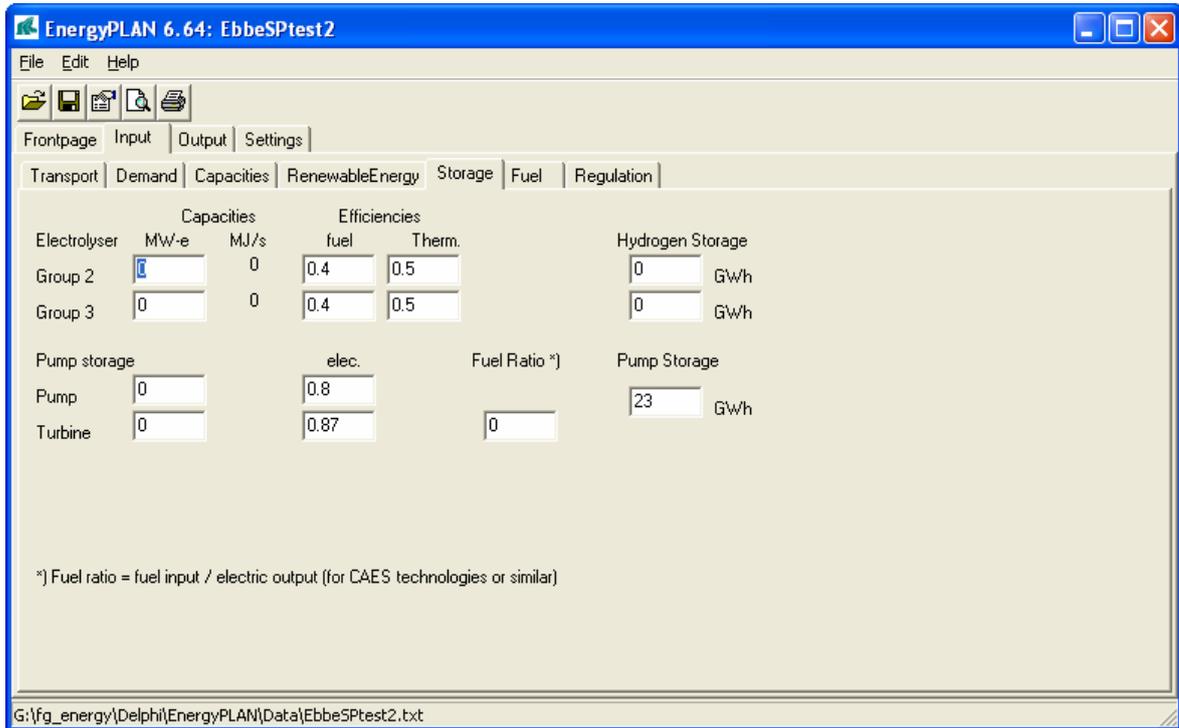
Yes

CO2	76.8	74	56.7	(kg/GJ)
Fuel Price	1.2	6.95	5.36	1.25 (EUR/GJ)
CO2 Price (included in marginal production prices)	13.3	(EUR/t CO2)		
Marginal maintenance costs:	6.6	(EUR/MWh electricity)		

G:\fg\_energy\Delphi\EnergyPLAN\Data\EbbeSPtest2.txt

This input set defines the distribution of fuel types for each energy unit in each district heating group. Also additional fuel consumption for transportation and industry can be added in order to complete the fuel accounts and the accounts of CO<sub>2</sub> emissions. If fuel prices and marginal operation and maintenance costs are stated, then the model can be told to calculate a number of relevant short-term marginal production costs, which will then be used in the strategies of optimising the profits of trade on the external electricity market. If this possibility is activated then the given marginal cost in "REGULATION" will be taken over.

## 1.6 Storage



In the storage input window, one can specify electrolyser and electricity storage systems.

The electrolyser is described in the model as a new component in both group 2 and 3 along with the CHP units, Heat Pumps and boilers.

- Electrolyser (converting electricity to fuel and heat) defined by a capacity and a fuel-efficiency and a thermal efficiency.
- Storage (storing fuel) defined by a capacity. (NOTE: Not included in the calculation)

NOTE: In the present version, the hydrogen storage is NOT included in the calculations.

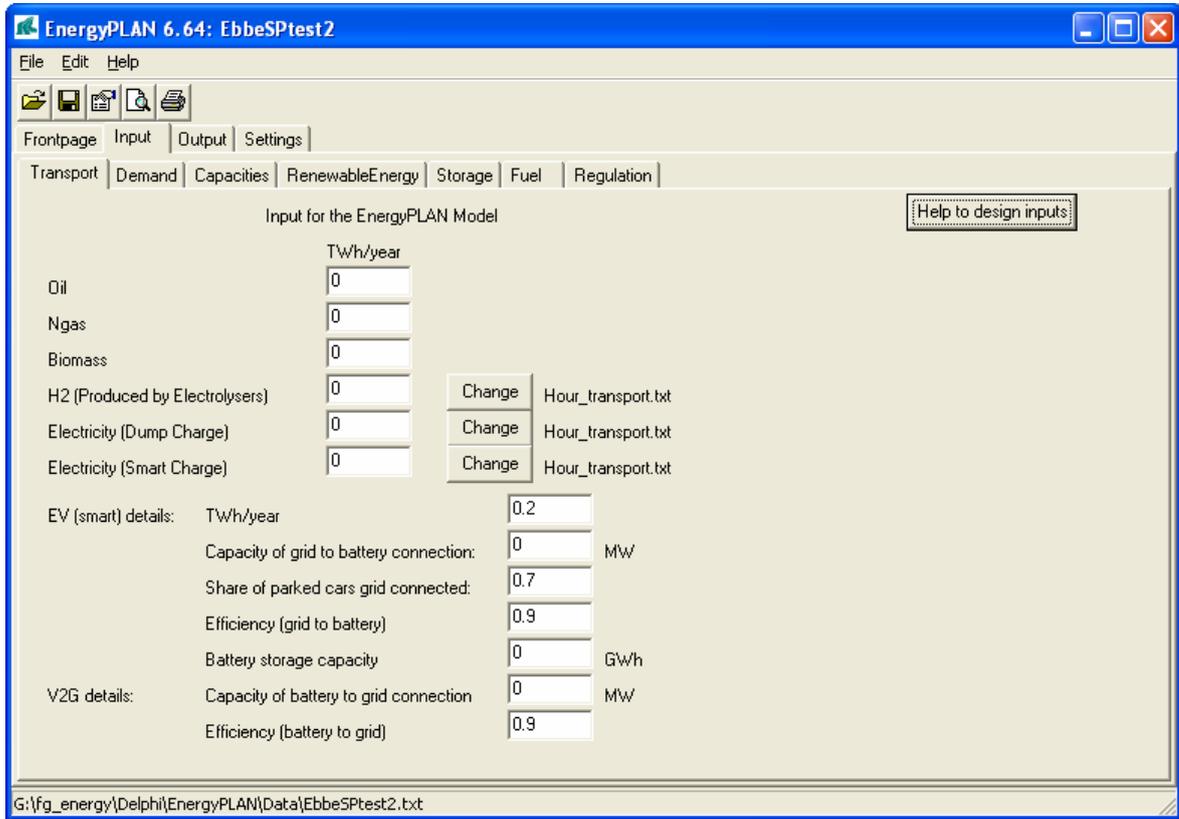
The electricity storage can represent e.g. hydro pump storage or a battery and is given by the following inputs:

- Pump (converting electricity to potential energy) defined by a capacity and an efficiency
- Turbine (converting potential energy to electricity) defined by a capacity and an efficiency
- Storage (storing energy) defined by a capacity.

Also the model can add fuel when the turbine is activated and thereby the systems such as CAES (Compressed Air Energy System) can be modelled. In such case, the following input has to be defined:

- CAES Fuel ratio defined as CAES fuel consumption /  $e_{\text{TURBINE}}$

## 2.7 Transport



The transport input window is designed to describe potential changes in the transport sector.

The fuel inputs in the top state fuel for cars and other transport units divided into oil, natural gas, and biomass. The following inputs describe fuel for cars by electricity. Basically, it is divided into dump cars and smart cars. In the case of dump cars, the input defines an electricity demand for transportation given by an annual demand and a distribution curve. In the case of smart cars, the electricity demand is made a part of the regulations and one has to specify a number of relevant input data.

One can activate a help function by pressing the button in the upper right corner of the window, as illustrated in the following window. By specifying the efficiency of the individual types of cars in terms of km/kWh, one can follow the total numbers of km pr. year during the process of changing the system e.g. by reducing the number of traditional cars and adding new technologies on biomass and/or electric vehicles.

EnergyPLAN 6.64: EbbeSPtest2

File Edit Help

Frontpage Input Output Settings

Transport Demand Capacities RenewableEnergy Storage Fuel Regulation

Input for the EnergyPLAN Model

Help to design inputs

	TWh/year		km/kWh	Billion km/year
Oil	<input type="text" value="0"/>		<input type="text" value="1.5"/>	<input type="text" value="0"/>
Ngas	<input type="text" value="0"/>		<input type="text" value="1.5"/>	<input type="text" value="0"/>
Biomass	<input type="text" value="0"/>		<input type="text" value="1.5"/>	<input type="text" value="0"/>
H2 (Produced by Electrolysers)	<input type="text" value="0"/>	<input type="button" value="Change"/>	<input type="text" value="3"/>	<input type="text" value="0"/>
Electricity (Dump Charge)	<input type="text" value="0"/>	<input type="button" value="Change"/>	<input type="text" value="5"/>	<input type="text" value="0"/>
Electricity (Smart Charge)	<input type="text" value="0"/>	<input type="button" value="Change"/>	<input type="text" value="5"/>	<input type="text" value="0"/>
EV (smart) details:	TWh/year	<input type="text" value="0.2"/>		<input type="text" value="0"/>
	Capacity of grid to battery connection:	<input type="text" value="0"/>	MW	
	Share of parked cars grid connected:	<input type="text" value="0.7"/>		
	Efficiency (grid to battery)	<input type="text" value="0.9"/>		
	Battery storage capacity	<input type="text" value="0"/>	GWh	
V2G details:	Capacity of battery to grid connection	<input type="text" value="0"/>	MW	
	Efficiency (battery to grid)	<input type="text" value="0.9"/>		

G:\fg\_energy\Delphi\EnergyPLAN\Data\EbbeSPtest2.txt

### 3. Distribution Data

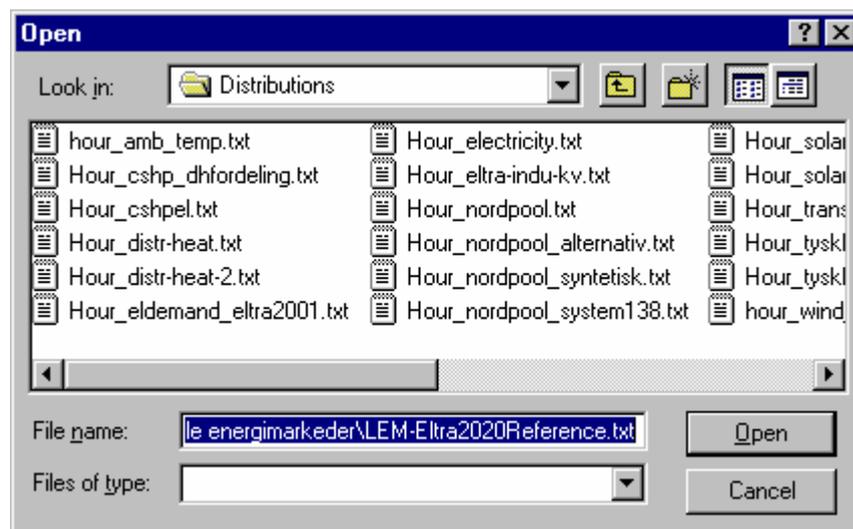
For each demand, each renewable energy source, and for the electricity market, the annual values are distributed into one specific value for each of 8784 hours in one year.

The model has a library including the following distribution data set:

- Hour by hour distribution of a typical Danish electricity demand (Year 2000)
- Hour by hour distribution of a typical Danish district heating demand
- Hour by hour distribution of photo voltaic and solar thermal (Typical Danish distribution based on the Danish Test Reference Year (TRY))
- Hour by hour distribution of industrial CHP.
- Hour by hour distribution of 3 wind years: 1991 (mean), 1994 (high), 1996 (low)
- Hour by hour distribution of NORDPOOL prices in the first year (summer 1999 until summer 2000)

Four of the “hour by hour” distribution data sets are illustrated in diagram 3 (next page).

When starting the model, all inputs have distribution data attached. One can change distribution by activating the bottom "Change". Then the following picture will arise, in which new distribution data can be chosen from the library.



New distribution data can be added to the library, simply by producing a text file with 8784 numbers. All distribution data is calculated relatively to the average value.

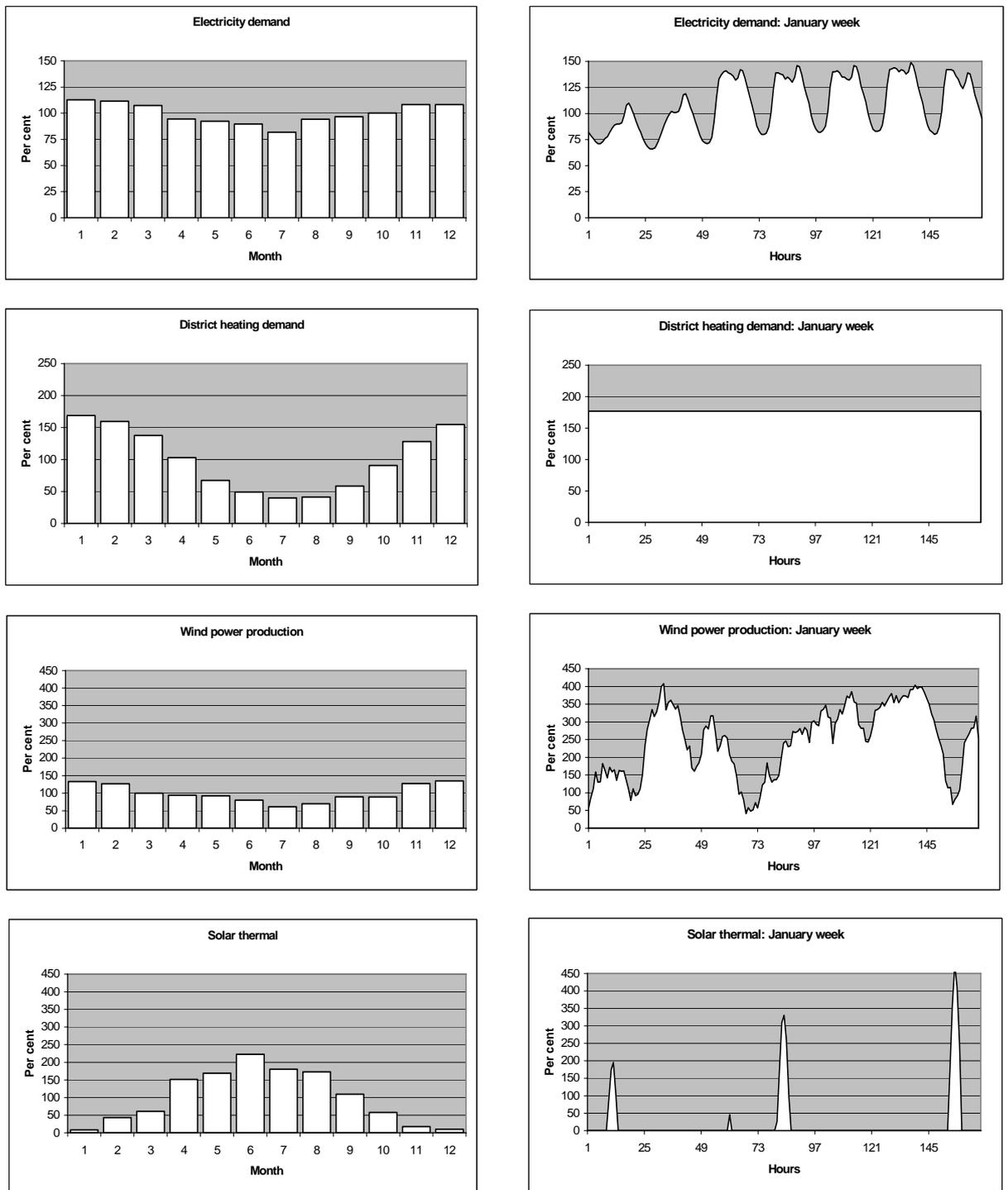


Diagram 3: Four examples of internal model data sets: Electricity demand, district heating demand, wind power production (one out of three possible), and solar heating thermal. To the left is shown the annual distribution on months and to the right is given an example of one week of January.

## 4. Initial Input Data calculations

The model starts by making a number of initial calculations on the input data. First, the model calculates hour by hour values of the following heat demands and productions:

- $q_i$  (MWh/h): district heating demand in 3 dh groups
- $q_{\text{solar}}$  (MWh/h): Solar thermal production in 3 dh groups
- $q_{\text{cshp}}$  (MWh/h): CSHP heat production in 3 dh groups

And the following electricity demands and productions:

- $e_i$  (MWh/h): electricity demand
- $e_f$  (MWh/h): fixed import/export
- $e_w$  (MWh/h): wind power production divided into onshore and offshore
- $e_{\text{pv}}$  (MWh/h): Photo Voltaic production.
- $e_{\text{cshp}}$  (MWh/h): CSHP electricity production

The demands are found simply by distributing the annual demands according to the internal hour by hour distributions. The district heating demand and the heat productions from solar thermal and CSHP are divided into the 3 district heating groups.

### 4.1 Wind Power and Photo Voltaic modifications

The input electricity production from intermittent renewable energy sources such as e.g. wind power is found by multiplication of the capacity by the specified hour by hour distribution. The data library comprises different distributions typically found from historically data. In diagram 4, historical data from Denmark are shown, leading to productions of 2064, 2303 or 1799 kWh/year pr. kW installed capacity.

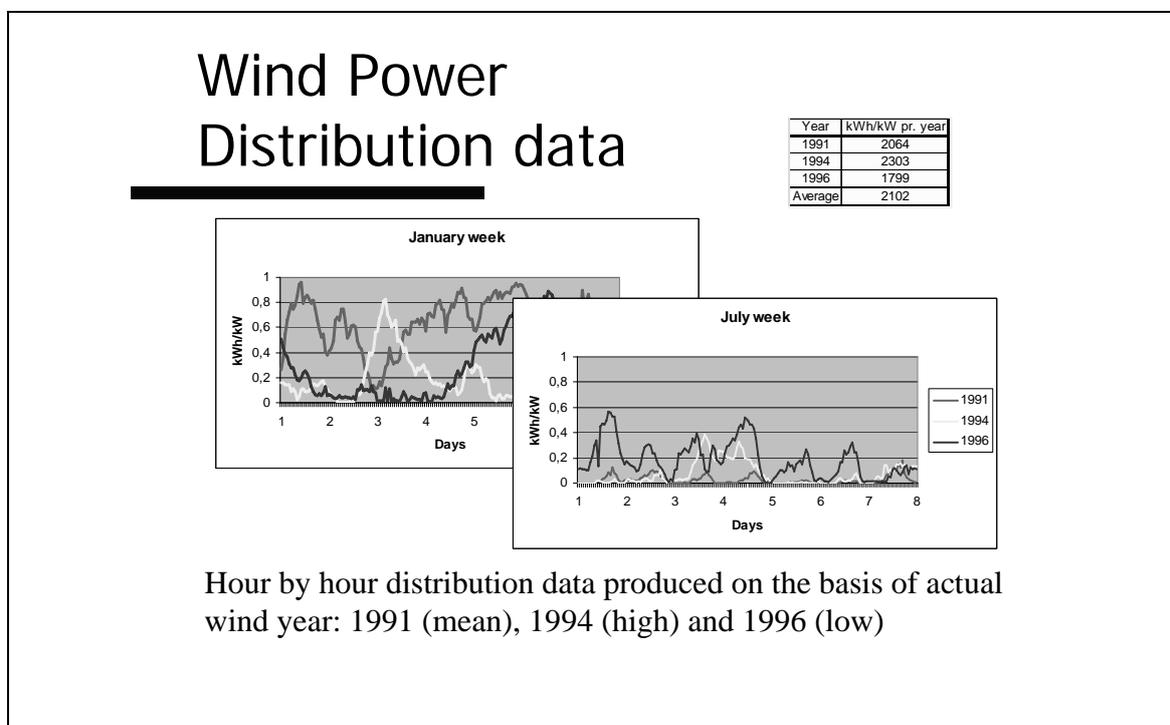


Diagram 4: The model has three different wind production distributions as internal data.

However, different future wind turbine configurations would lead to either lower or higher productions in the same wind years. Therefore, a factor can be added in the input in order to change the productions from the same wind capacities and the same wind year. The factor changes the production in a way that the productions remain the same in hours with either no production or full production while the rest of the values are moderated relatively:

$$e_{W-new} = e_{W-old} * \frac{1}{1 - Fac_W * (1 - e_{W-old})}$$

The same procedure is used for the possible modification of any of the renewable sources.

In the following diagrams, it is illustrated how the factor modifies the input. The examples are based on wind power and photo voltaic distributions in the area of western Denmark year 2001. When defining a capacity of 1000 MW wind power, the annual production becomes 1.96 TWh/year, and when defining 1000 MW of photo voltaic, the annual production becomes 1.00 TWh/year, as shown in row 1 and 3 in the input window below.

The screenshot shows the 'EnergyPLAN: Startdata' window with the following data:

Renewable Energy	Capacity: MW	Stabilisation share	Distribution profile	Production TWh/year	Correction factor	Post Correction production
Wind	1000	0	hour_wind_eltra2	1.96	0	1.96
Offshore Wind	1000	0	hour_wind_eltra2	1.96	0.8	4.10
Photo Voltaic	1000	0	hour_PV_eltra20l	1.00	0	1.00
Photo Voltaic	1000	0	hour_PV_eltra20l	1.00	0.8	2.02

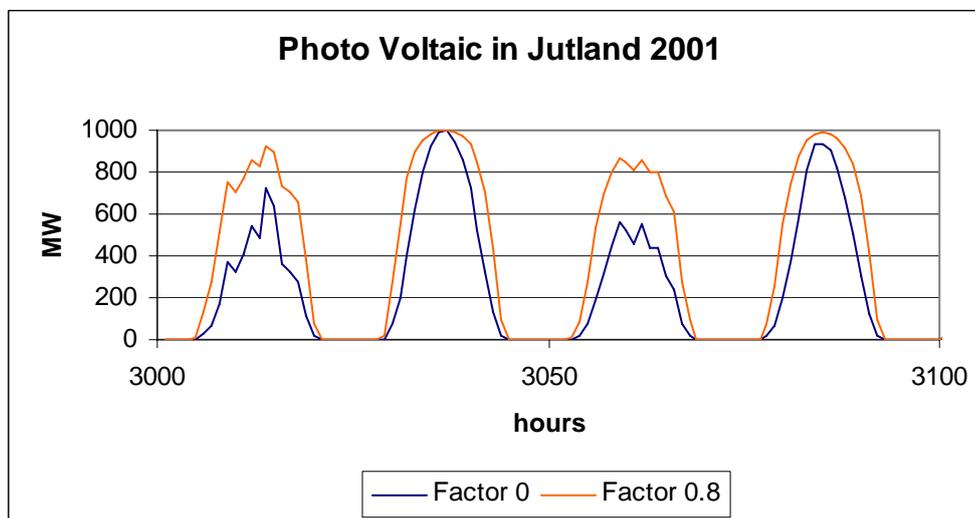
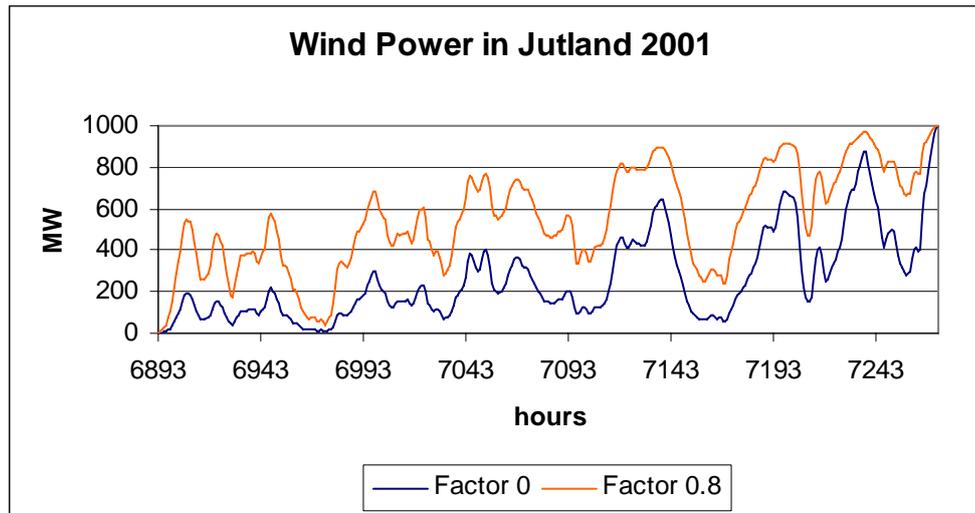
  

TWh/year	Solar Thermal	Industrial CHP (CSHP):	DH prod	Electricity prod
DH Gr.1:	0		0	0
DH Gr.2:	0		0	0
DH Gr.3:	0		0	0
Total:	0.00		0.00	0.00

Buttons: Change Hour\_solar\_prod1.txt, Change Hour\_cshpel.txt

If adding a correction factor of e.g. 0.8, the hour by hour production is modified as illustrated in the two following diagrams. The 0 values and the maximum values of 1000 MW are kept while all the in between values are raised in accordance with the aforementioned formula.

As a result, the annual productions are raised to 4.10 TWh/year for wind power and 2.02 TWh/year for photo voltaic. It should be mentioned that the factor 0.8 is very high especially for photo voltaic. However, such high factor is proper to illustrate the principle of the modifications.



#### 4.2 Electricity demand modifications (Flexible demand)

The model uses an hourly distribution of the electricity demand specified in the input as an external input file. A typical Danish distribution based on statistic information from year 2000 is provided as an option (Shown in diagram 3). Or other external input files can be created. The electricity demand is distributed according to the specified distribution.

Any new demands caused by the use of electricity for transport (batteries and/or hydrogen) or by other purposes can be specified in the inputs. The same goes for fixed import/export, which can be defined in the same way. Meanwhile, electricity for transport can be made flexible. The same routines can be used for defining a certain per cent of the demand as flexible demand. This allows for analysing the consequences of introducing flexible demands for cooling etc. within industries and/or households.

Thus, an additional electricity demand can be made flexible within shorted periods according to the following four categories:

- a. Demand following a specified distribution (typically battery cars being charged during the night).

- 
- b. Demand freely distributed over a 24-hour period according to the actual electricity balance. (Similar to the above, but with the added possibility of concentrating the demand at the actual peak hours for e.g. wind production - requires a method of communicating this knowledge to the consumers).
  - c. Demand which can be distributed freely over a week according to the actual electricity balance (Similar to the above - relevant for consumers with extra battery capacity and for hydrogen-operated vehicles)
  - d. Demand which can be distributed freely over a four-week period (similar to the above - relevant for hydrogen-operated vehicles. Optimal distribution of demand for a period of this length requires a long-term prognosis for the electricity balance to be transmitted to the consumers. As this prognosis is partly based on a weather prognosis, this is hardly possible today, as the prognosis for a four-week period at present is not sufficiently reliable).

For the categories b., c. and d., the distribution of the demand within the given intervals is determined one by one according to an evaluation of the balance between the 'fixed' electricity productions (wind, photo voltaic and CHP) and the following demands:

- The basic demand from consumers and industries:  $e_i$
- The demand fixed import/export:  $e_f$
- The demand from heat pumps:  $e_{HP}$
- The yearly average of demand for transport of the given category.  $E_{Tran} / 8784$  MWh

The distribution of demand within the interval is made in order to follow the variation of this balance with two limitations:

- a. it must be positive at any time
- b. it should be below a given maximum.  $C_{TR,n}$  (defined in the input)

A normalisation of the variation ensures that the average demand for the period equals the yearly average.

Part of the existing demand can be specified to be flexible in the same way as the transport demands of category b, c, and d. Typically, these flexible demands will be connected to either room heating or to cooling processes (air conditioning or cold stores). The flexible demands can be specified for the same three periods as the transport demands. For each period and for each type (cooling, heating), the maximum capacity must be stated. Note that the fixed demand should be decreased in order not to increase the total demand.

The effects on the hourly distribution of the total electricity demand are calculated the same way as for the transport demands.

In diagram 5 and 6, an example of how flexible demand reduces differences in the balance between supply from CHP and Renewable energy and the demand is shown.

The example is given for the following situation:

- Electricity demand = 33 TWh
- District heating = 20 TWh
- Wind Power = 2000 MW
- CHP = 2000+3000 MW-el
- HP = 300 + 500 MW-el

In diagram 5, it is illustrated how this situation in a three-day period in January has a continuous CHP production of app. 3200 MW, and on top of this, a wind production increasing the total production to between app. 3500 and 5000 MW.

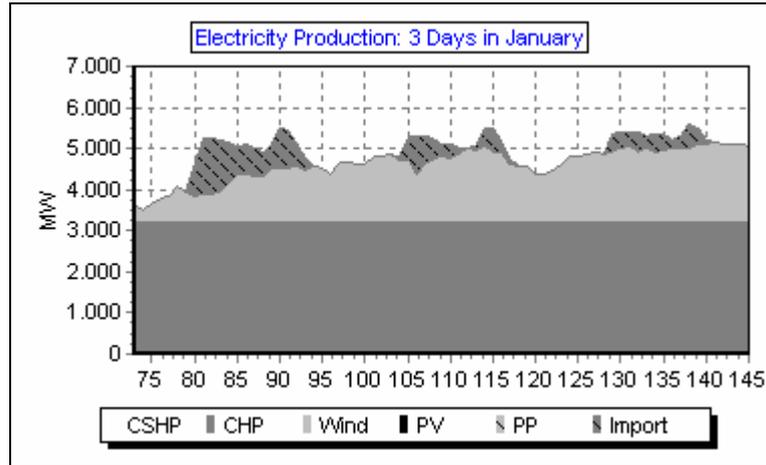


Diagram 5: Electricity Production from CHP, Wind and import 3 Days in January.

In the left top of diagram 6, the demand is shown (in the case of no flexible demand) and to the right, the resulting difference in the balance between supply and demand is shown. The latter diagram is found simply by subtracting the demand and the supply from diagram 5. It can be seen how there is a surplus production during night hours and a lack of supply during day hours, fluctuating along with the variations in the wind production.

At the next three levels of diagram 6, more and more demand has been changed in the input to flexible demand. At the second level, 10 per cent is made flexible within a day. At the next level, an additional 10 per cent is made flexible within a week. And in the last picture, an additional 10 per cent is made flexible within a four-week period. It can be seen how such flexibility is able of continuously improving the balance between supply and demand.

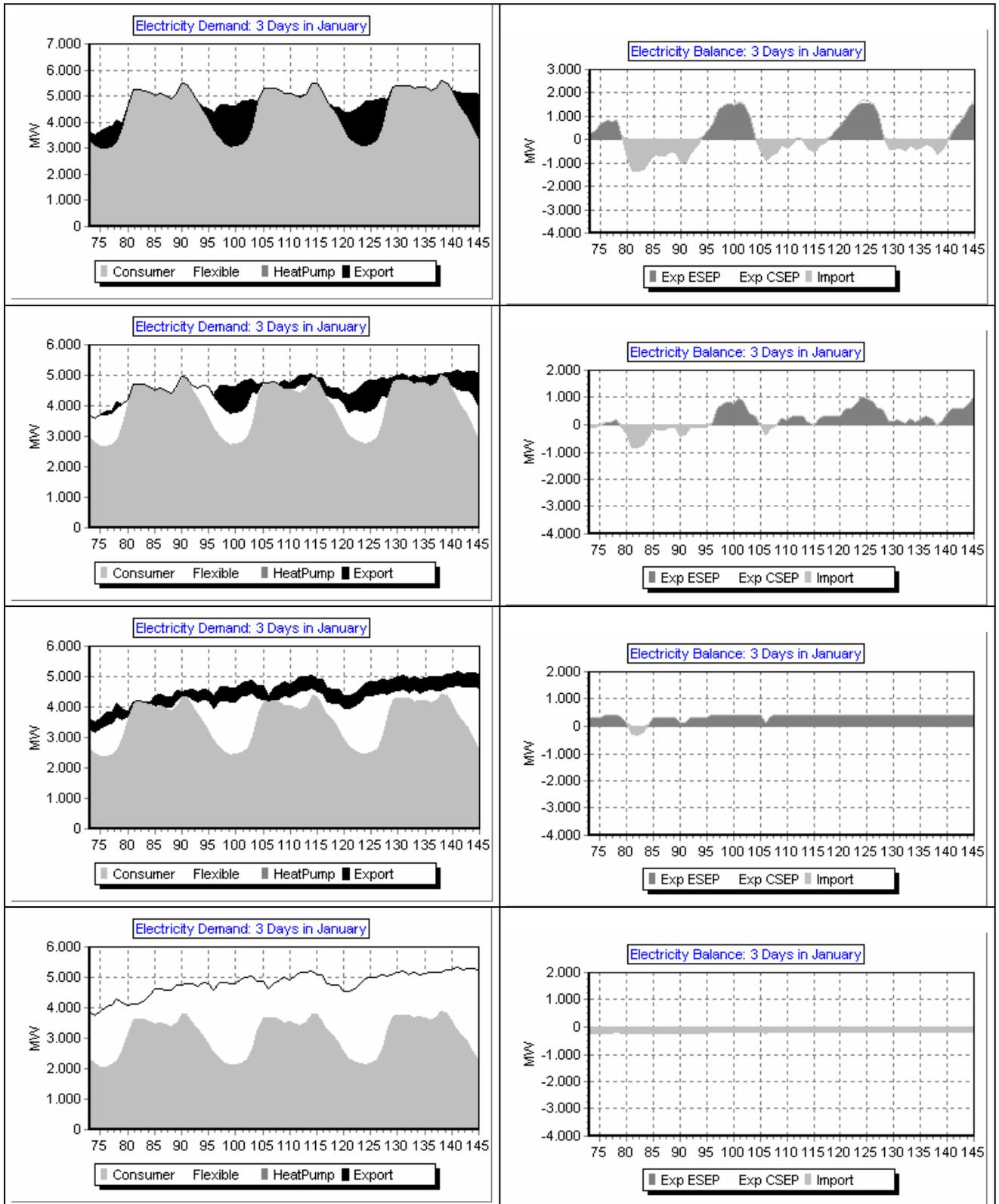


Diagram 6: Example of flexible demand

### 4.3 Electricity market modifications

For the economic optimisation, the market prices are found from the specified hour by hour price distribution ( $NP_i$ ) when modified in the following way:

$$p_i \text{ (DKK/MWh)} = NP_i * \Phi + P_a$$

were  $\Phi$  and  $P_a$  are the multiplication and the addition factors given as input in the regulation window.

In the calculation, the market price is further influenced by the price elasticity, as described in section 5.

### 4.4 District heating production in group I

In group I, heat for district heating is produced by:

1. Solar Thermal:  $q_{\text{solar}}$
2. Industrial CHP (CSHP):  $q_{\text{CSHP}}$
3. District heating plants with boilers:  $q_{\text{DHP}}$

The production from solar thermal and CSHP is given for each hour by the input data and the respective distribution sets. The production from the boiler is found as the difference between demands and solar/CSHP productions:

$$q_{\text{DHP}} = q_i - q_{\text{solar}} - q_{\text{CSHP}}$$

## 5. CHP and power plants

Based on the modified “hour by hour distributions” described above and the rest of the input data, the model calculates electricity and heat productions depending on the regulation strategy chosen.

### 5.1 Regulation strategy I: Meeting heat demand.

In this strategy, all heat producing units are producing solely according to the heat demand.

#### Technical analysis

Heat for district heating is produced by:

- |                           |                    |                 |
|---------------------------|--------------------|-----------------|
| 1. Solar Thermal:         | $Q_{\text{Solar}}$ |                 |
| 2. Industrial CHP:        | $Q_{\text{CSHP}}$  |                 |
| 3. Heat plant CHP:        | $Q_{\text{CHP}}$   |                 |
| 4. Heat pumps:            |                    | $Q_{\text{HP}}$ |
| 5. Boilers at CHP plants: | $Q_{\text{B}}$     |                 |

For district heating group 2 and 3, the units are given priority according to the sequence shown above on an hourly basis. The production from solar thermal and CSHP is given for each hour by the input data and the respective distribution sets. For the heat plant CHPs and the heat pumps, the following limitations are used:

A. Maximum capacity of CHP and HP.

B. Maximum share of heat pumps compared to the total heat demand:  $S_{\text{HP}/\text{tot}}$

(this limitation corresponds to the fact that heat pumps should be used for the production of low temperature heat only).

The electricity production from CHPs,  $e_{\text{CSHP}}$  and  $e_{\text{CHP}}$ , and the consumption from heat pumps,  $e_{\text{HP}}$ , can now be found by using the assumption for efficiencies. The electricity production at the condensation power plants,  $e_{\text{PP}}$ , and the potential export of electricity,  $e_{\text{X}}$ , are determined by the following steps:

#### Step 1:

The electricity consumption is adjusted by the possible use of:

- |  |                 |                 |
|--|-----------------|-----------------|
| - electricity for heat pumps (determined above): | $e_{\text{HP}}$ |                 |
| - electricity for transport:                     |                 | $e_{\text{TR}}$ |
| - influence of flexible elec. demands:           | $e_{\text{F}}$  |                 |

$$e_{\text{ia}} = e_{\text{i}} + e_{\text{HP}} + e_{\text{TR}} + e_{\text{F}}$$

#### Step 2:

The production at the condensation plants is determined as the bigger of the following two values:

A. The difference between the adjusted consumption and the production given by the wind and the heat demand:

$$e_{\text{PP}} = e_{\text{ia}} - e_{\text{W}} - e_{\text{pv}} - e_{\text{CSHP}} - e_{\text{CHP}}$$

B. The minimum production needed to fulfil the requirement of stabilising the grid:

$$e_{pp} = \left( (e_w + e_{pv} + e_{CSHP} + e_{CHP}) * S_{stab/tot} - (e_{CHP} + e_{CSHP}) * S_{stab/CHP} - e_w * S_{stab/wind} \right) / (1 - S_{stab/tot})$$

(the necessary share of power plants with stabilising ability of the total production minus the share of the total CHP production and the wind production, which is assumed to have stabilising ability).

In case  $e_{pp}$  exceeds the specified maximum value  $C_p$ , the necessary electricity production is imported.

*Step 3:*

The export of electricity can now be calculated as:

$$e_x = e_{pp} + e_{CSHP} + e_{CHP} + e_w - e_{ia}$$

The export is divided into two categories: 1) Critical export,  $e_{cx}$  and 2) exportable export,  $e_{ex}$ . Critical export appears when the export increases the maximum capacities of the grid connections abroad.

### **Economic Optimisation**

The production by condensation power plants was calculated above to:

A. Meet the demand (avoid import of electricity)

B. Provide the necessary stabilisation of the grid.

In this section, this production is optimised according to export/import prices on the Nordpool exchange,  $p_i$ .

If this price at a given hour is lower than the marginal production costs for the condensation plants AND the corresponding production exceeds the necessary level of stabilisation, it is possible to replace this surplus by imported electricity,  $e_p$ . By doing this, the maximum transmission capacity of import and the minimum production with stabilising effect are observed.

The costs of import are calculated as:

$$p_{imp} \text{ (DKK/MWh)} = p_i + (p_i / p_o) * Fac_{depend} * D_{trade}$$

where  $p_i$  is the system market price (see section 4.3),  
 $Fac_{depend}$  is the price elasticity (DKK/MWh/MW)  
 $p_o$  is the basic price level for price elasticity (input),  
 $D_{trade}$  is the trade on the market.

Import is calculated as positive and export is negative, resulting in an increase in the market price in case of import and a decrease in case of export.

If, on the other hand, the price on Nordpool at a given hour is higher than the marginal production costs of the condensation plants, the production is increased to the maximum capacity of either the plants or the transmission line.

If the choice of having the model calculate all relevant marginal cost is activated (See section 2.5.) then these numbers are used in the optimisation process. If this choice is not activated then

the input from section 2.4 is used. If these inputs are stated zero for import and high for the rest of the inputs, this means that the market optimisation will have no influence on the result. In such case, the regulation strategy is purely technical.

If the influence of raising the export changes the market price so much that the marginal cost of producing becomes higher than the resulting market price, a balance is found in which the marginal production price of the power plant ( $MP_{pp}$ ) and the market price becomes equal:

$$MP_{pp} \text{ (DKK/MWh)} = p_i + (p_i / p_o) * Fac_{depend} * D_{trade}$$

$$D_{trade} = e_{PP} - e_{IMP}$$

In which  $e_{IMP}$  is the net import of the rest of the system when the electricity production of the power plant is zero. The  $e_{IMP}$  value is found as the sum of all electricity consumptions and productions of the rest of the units in the system. Export is calculated as a negative import.

Hereby, the resulting power plant production (with a balance between marginal productions costs and resulting market prices) is found in the following way in the case of export:

$$e_{PP} = e_{IMP} + [p_i - MP_{PP}] / [(p_i / p_o) * Fac_{depend}]$$

The formula is subject to the following limitations:

- the power plant capacity
- the power plant contribution to grid stability
- the capacity of the transmission line

## 5.2 Regulation strategy II: Meeting both heat and electricity demands

In this section, export of electricity is minimised mainly by the use of heat pumps at combined heat and power plants. This will increase electricity demand and decrease electricity production simultaneously as the CHP units must decrease their heat production.

By the use of extra capacity at the CHP plants combined with heat storages, the production at the condensation plants is minimised by replacing it with CHP production.

The following yearly distributions are the same as for strategy I:

- All demands including transport and flexible demands.
- heat and electricity productions of industrial CHP plants.
- heat production of heat plants with boilers.
- electricity production from wind turbines.

The **electricity production by CHP**,  $e_{CHP}$ , must at any time be lower or equal to the maximum capacity,  $C_{CHP}$ , and to the capacity corresponding to the heat demand left by the industrial CHP and the boiler plants. Within these limits it is determined as the bigger of the results of the following two considerations:

- A. The capacity which can ensure stability of the grid together with a possible stabilising effect of the wind turbines but without relying on any effect from condensation plants:

$$e_{CHP,II,A} = (e_{ia} * S_{stab/tot} - e_w * S_{stab/W}) / S_{stab/CHP} - e_{CSHP}$$

- B. The capacity which will be the result of reducing the CHP production found by strategy I,  $e_{\text{CHP},i}$ , in order to minimise the electricity export found by strategy I,  $e_{x,I}$ . The necessary reduction will depend on whether the heat pumps at the CHP plants are already operating at maximum capacity. (For all hours this is determined as either the technical limit,  $C_{\text{HP}}$ , or by the maximum share of the total heat demand,  $S_{\text{HP,tot}}$ ) If this is not the case, the reduction in heat production caused by the reduction in electricity production can be balanced by an increase in heat production by the heat pumps. This will also reduce the electricity export. As a result, the necessary reduction is reduced by a factor

$$1 + H_{\text{CHP}}/C_{\text{CHP}} * C_{\text{HP}}/H_{\text{HP}}$$

If the heat pumps are already operating at maximum capacity, the CHP production will have to be reduced by the size of the electricity export,  $e_{x,I}$ .

For these reasons the reduction has to be calculated in two steps:

- a. Reduction of CHP plus increase of HP:

$$e_{\text{HPmax}} = \min(C_{\text{HP}} ; q_i * S_{\text{HP,tot}})$$

$$e_{\text{CHP,red,a}} = \min(e_{x,I}/(1 + H_{\text{CHP}}/C_{\text{CHP}} * C_{\text{HP}}/H_{\text{HP}}) ; (e_{\text{HPmax}} - e_{\text{HP}}) * H_{\text{HP}}/C_{\text{HP}} * C_{\text{CHP}}/H_{\text{CHP}})$$

$$e_{\text{HP,inc,a}} = e_{\text{CHP,red,a}} * H_{\text{CHP}}/C_{\text{CHP}} * C_{\text{HP}}/H_{\text{HP}}$$

- b. A possible further reduction of CHP only:

$$e_{\text{CHP,red,b}} = e_{x,I} - e_{\text{CHP,red,a}} - e_{\text{HP,inc,a}}$$

$$e_{\text{CHP,II,B}} = e_{\text{CHP,I}} - e_{\text{CHP,red,a}} - e_{\text{CHP,red,b}}$$

These calculations are performed for group 2 and 3 separately, but with due consideration on total stabilisation demands, etc.

After having determined the production at the CHP plants as maximum, ( $e_{\text{CHP,II,A}}$  ;  $e_{\text{CHP,II,B}}$ ) the production at the heat pumps and the boilers are calculated the same way as in strategy I.

The **electrical production by condensation plants**,  $e_{\text{PP,II}}$ , is determined as the necessary production to meet either the electricity demand or the demand of stabilisation the same way as it was done in strategy I.

The electricity export has now been reduced as much as possible under the given constraints.

### **Economic Optimisation**

The technical operation strategy can be optimised either by raising exports or by raising imports.

If the market price is higher than the marginal cost of replacing the boiler and/or the heat pump by the CHP, exports should be increased if capacities allow it. The potentials are found in the following way:

Potential of raising electricity production from replacing the boiler by the CHP unit (X1):

If  $(MC_{B-CHP} < p_i) * (q_{CHP} < H_{CHP}) * (q_B > 0)$

Then  $X1 = \text{MIN}(H_{CHP} - q_{CHP}, q_B)$

Else  $X1 = 0$

Finally, economic optimisation, regarding the production at condensation plants, is performed as described for strategy I. By doing this as the last step it is also ensured that the criteria of grid stabilisation are fulfilled.

Like in regulation strategy I, if the choice of having the model calculate all relevant marginal cost is activated (See section 2.5.) then these numbers are used in the optimisation process. If this choice is not activated then the input from section 2.4 is used. If these inputs are stated as zero for import and high for the rest of the inputs, this means that the market optimisation will have no influence on the result. In such case the regulation strategy is purely technical.

### **5.3 Regulation strategy III: Meeting both heat and electricity demands and reducing CHP also when it is partly needed for stabilisation reasons (replacing by PP).**

Regulation Strategy III is the same as strategy II apart from one thing.

In strategy II, CHP will not be reduced (and the heat production replaced by heat pumps), if CHP units are needed for stabilisation reasons.

Meanwhile, in some situations (when the CHP stabilisation factor is below 100 per cent) surplus production can be minimised further by reducing CHP and replacing heat production by heat pumps and boilers and stabilisation demands by PP units.

Consequently, in strategy III, CHP units are reduced even when stabilisation demands call for replacement with PP units.

The choice between strategy II and III is a choice between better efficiency in the system and less surplus production.

Economic optimisation is done the same way as in regulation strategy II.

### **5.4 Regulation strategy IV: Meeting the triple tariff**

Regulation strategy IV is the same as strategy I apart from one thing.

In regulation strategy IV, the CHP units in group 2 meet the Danish triple tariff instead of meeting the heat demand.

The electricity production from CHP units in group 2 is located according to a priority of Peak load, high load and low load. And the periods of the triple tariff are defined simply as

Peak load during weekdays between 8.00 and 12.00 (plus 17.00-19.00 in the winter)

High load during weekdays between 6.00 and 21.00, and

Low load the rest of the time.

Regulation strategies I and IV are the same in the sense that in neither cases the CHPs adjust their productions according to the fluctuations in the wind power.

Economic optimisation is done the same way as in regulation strategy I.

## 5.5 Heat Storage Utilisation

To improve the possibilities of minimising the electricity export, the heat storage capacity is included in the model for each of the district heating groups 2 and 3.

In two situations, the storage can be loaded:

A: Increasing the use of HP in situations with electricity export.

B: Moving the electricity production from condensing plants,  $e_{pp}$  to CHP plants

In two situations, the storage can be unloaded:

C: Reducing the CHP production in situations with electricity export

D: Reducing the boiler production.

B is secondary to A, and D is secondary to C. The four loading and unloading cases are used in the following order: C-A-B-D.

These series are then used in the following order:

1: Critical electricity export  $e_{cx}$  and CHP in group 3

2: Critical electricity export  $e_{cx}$  and CHP in group 2

3: Economical electricity export,  $e_{ex}$  and CHP in group 3

4: Economical electricity export,  $e_{ex}$  and CHP in group 2

In order to achieve balance, the calculations are performed over a series of 2-week periods, in which the storage content at the end of the first year is equal to the storage content at the beginning of the second year.

The four loading and unloading situations are calculated as follows:

*A: loading by increasing the use of HP in situations with electricity export.*

First, the smaller of the potential increase in district heating production from HP,  $HP_{pont}$  and the potential increase in storage content,  $St_{pont}$  are determined.

$$HP_{pont} = \min(e_x ; C_{HP} - e_{HP}) * (H_{HP}/C_{HP}) * ((p_i < MC_p) \text{ or } (e_x = e_{cx}))$$

The last parenthesis states that the market price,  $p_i$ , has to be below the marginal production cost of one MWh electricity on the power plant,  $MC_p$ , or the electricity export in question should be critical export; otherwise the  $HP_{pont}$  is set to zero.

$$St_{pont} = H_{STORAGE} - Q_{STORAGE}$$

New values can now be calculated:

$$e_{HP-new} = e_{HP-old} + \min(HP_{pont} ; St_{pont}) * (C_{HP}/H_{HP})$$

$$e_{x-new} = e_{x-old} - \min(HP_{pont} ; St_{pont}) * (C_{HP}/H_{HP})$$

$$q_{HP-new} = q_{HP-old} + \min(HP_{pont} ; St_{pont})$$

$$Q_{STORAGE-new} = Q_{STORAGE-old} + \min(HP_{pont} ; St_{pont})$$

*B: Moving the electricity production from condensing plants,  $e_{pp}$  to CHP plants*

First, the minimum condensing power plant production needed to fulfil the requirement of stabilising the grid is found:

$$e_{PP-\min} = e_{ia} * S_{stab/tot} - (e_{CHP} + e_{CSHP}) * S_{stab/CHP} - e_w * S_{stab/wind}$$

Then the potential increase in district heating production from CHP,  $CHP_{pont}$  and the potential increase in storage content,  $St_{pont}$  are determined

$$CHP_{pont} = \min((C_{CHP} - e_{CHP}) ; (e_{PP} - e_{PP-\min}))$$

$$St_{pont} = H_{STORAGE} * 50\% - Q_{STORAGE}$$

New values can now be calculated:

$$e_{CHP-new} = e_{CHP-old} + \min(CHP_{pont} ; St_{pont}) * (C_{CHP}/H_{CHP})$$

$$e_{PP-new} = e_{PP-old} - \min(CHP_{pont} ; St_{pont}) * (C_{CHP}/H_{CHP})$$

$$q_{CHP-new} = q_{CHP-old} + \min(CHP_{pont} ; St_{pont})$$

$$Q_{STORAGE-new} = Q_{STORAGE-old} + \min(CHP_{pont} ; St_{pont})$$

#### *C: Reducing the CHP production in situations with electricity export*

First, the minimum CHP production needed to fulfil the requirement of stabilising the grid is found:

$$e_{CHP-\min} = (e_{ia} * S_{stab/tot} - e_w * S_{stab/wind} - e_{PP}) / S_{stab/CHP} - e_{CSHP}$$

Secondly, the smallest potential  $e_{CHP}$  reduction,  $CHP_{red}$  and the storage content,  $Q_{STORAGE}$  are found.

$$CHP_{red} = \min(e_x ; e_{CHP} - e_{CHP-\min}) * (H_{CHP}/C_{CHP}) * ((p_i < MC_p) \text{ or } (e_x = e_{cx}))$$

The last parenthesis states that the market price,  $p_i$ , has to be below the marginal production cost of one MWh electricity on the CHP plant,  $MC_{chp}$ , or the electricity export in question should be critical export, otherwise the  $CHP_{red}$  is set to zero.

New values can now be calculated:

$$e_{CHP-new} = e_{CHP-old} - \min(CHP_{red} ; Q_{STORAGE}) * (C_{CHP}/H_{CHP})$$

$$e_{x-new} = e_{x-old} - \min(CHP_{red} ; Q_{STORAGE}) * (C_{HP}/H_{HP})$$

$$q_{CHP-new} = q_{CHP-old} - \min(CHP_{red} ; Q_{STORAGE})$$

$$Q_{STORAGE-new} = Q_{STORAGE-old} - \min(CHP_{red} ; Q_{STORAGE})$$

#### *D: Reducing boiler production.*

First, the smallest potential reduction in boiler production,  $q_{B-red}$ , and potential reduction in storage content,  $St_{red}$ , are determined:

$$q_{B-red} = q_B$$

$$St_{red} = \max(Q_{STORAGE} - H_{STORAGE} * 50\% ; 0)$$

New values can now be calculated:

$$q_{B\text{-new}} = q_{B\text{-old}} - \min(q_{B\text{-red}} ; St_{\text{red}})$$

$$Q_{\text{STORAGE-new}} = Q_{\text{STORAGE-old}} - \min(q_{B\text{-red}} ; St_{\text{red}})$$

## 6. Hydro Power

Hydro Power Units are described by the following inputs:

$C_{\text{HYDRO}}$ :	The capacity of the Hydro Power Electricity Generator in MW
$\mu_{\text{HYDRO}}$ :	The efficiency of the Hydro Power station defined as the conversion factor from energy in the storage to electricity production from the generator.
$C_{\text{HYDRO-STORAGE}}$ :	The capacity of the Hydro Power storage in GWh
$E_{\text{HYDRO-WATER}}$ :	The amount of energy connected to the water supplied to the storage in TWh/year
$d_{\text{HYDRO-WATER}}$ :	The distribution of the energy/water supply in 8784 hour values

Additional inputs options are:

$\mu_{\text{HYDRO-PUMP}}$ :	The efficiency of running the Generator reversible as a Pump defined as the conversion factor from electricity consumption to energy in the storage
$C_{\text{HYDRO-PUMP}}$ :	The capacity of the Hydro Power Pump in MW
$C_{\text{HYDRO-PUMP-STORAGE}}$ :	The capacity of the lower water storage in GWh

The Hydro Power station is subject to the condition that it will always be involved in the task of maintaining grid stability.

### Regulation

The unit is integrated in the regulation of the total system in the following way:

First the average net output is calculated simply by dividing the potential annual production by the number of hours during a year:

$$e_{\text{HYDRO-AVE}} = E_{\text{HYDRO-WATER}} * \mu_{\text{HYDRO}} / 8784$$

Then the programme calculates the hour by hour modelling of the system, including the fluctuations in the storage content, and the input from the hydro plant ( $e_{\text{HYDRO-INPUT}}$ ) is modified in accordance with the generator capacity, the distribution of the water supply, and the storage capacity in the following way:

$$\text{Hydro-storage-content} = \text{Hydro-storage content} + e_{\text{HYDRO-WATER}}$$

$$e_{\text{HYDRO-INPUT}} = \text{MAX} [e_{\text{HYDRO-AVE}}, (\text{Hydro-storage-content} - C_{\text{HYDRO-STORAGE}}) * \mu_{\text{HYDRO}}]$$

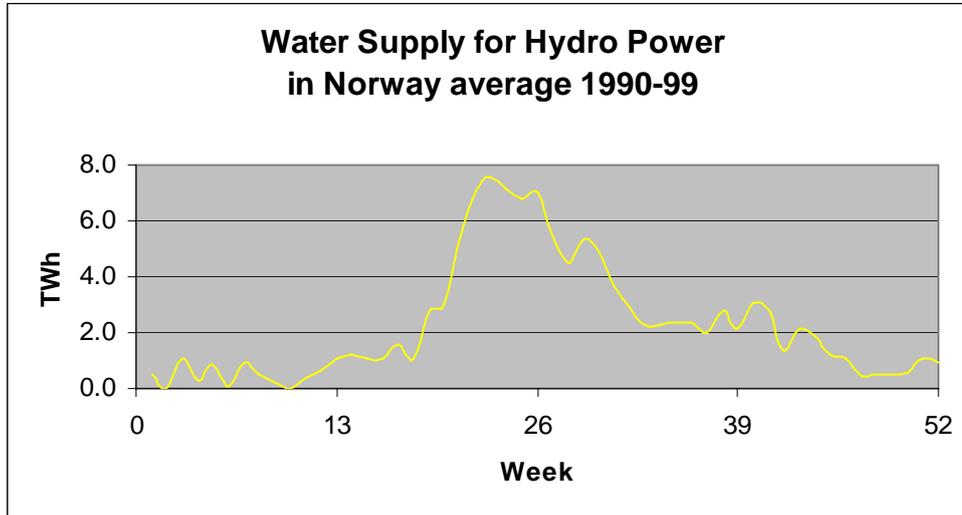
$$e_{\text{HYDRO-INPUT}} \leq C_{\text{HYDRO}}$$

To correct the calculations from errors due to differences in the storage content between the beginning and the end of the calculation period, the above calculation is seeking to identify a solution in which the storage content in the end is the same as in the beginning. Initially, the storage content is defined as 50% of the storage capacity. After the first calculation, a new beginning content is defined as the resulting content in the end of the former calculation.

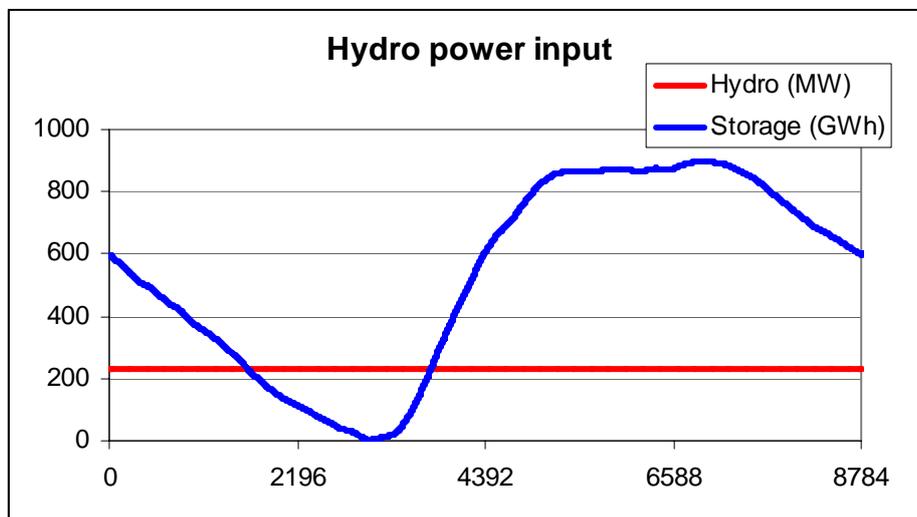
How the input is calculated can be illustrated by the following examples:

Inputs:	
$C_{\text{HYDRO}}$ :	400 MW

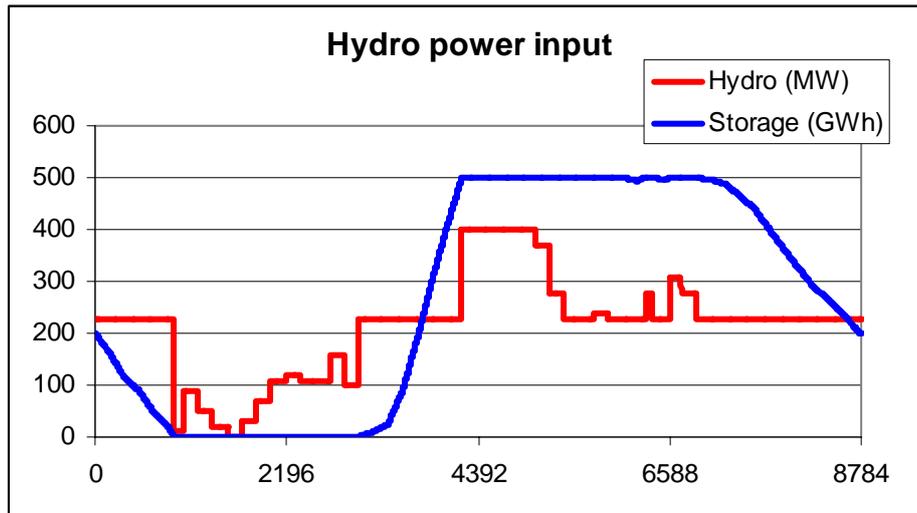
$\mu_{\text{HYDRO}}$ :	0.8.
$C_{\text{HYDRO-STORAGE}}$ :	1000 GWh
$E_{\text{HYDRO-WATER}}$ :	2.5 TWh/year
$d_{\text{HYDRO-WATER}}$ :	Distribution as shown in the diagram



In such case, the storage and the generator capacity set no limits for the system and the resulting hydro input production is equal to the average production of 228 MW, as shown in the following diagram together with the storage content (in GWh). The annual production becomes 2.00 TWh/year (equal to  $2.5 * 0.8$ ). The initial and the final storage content is identified to be 598 GWh.

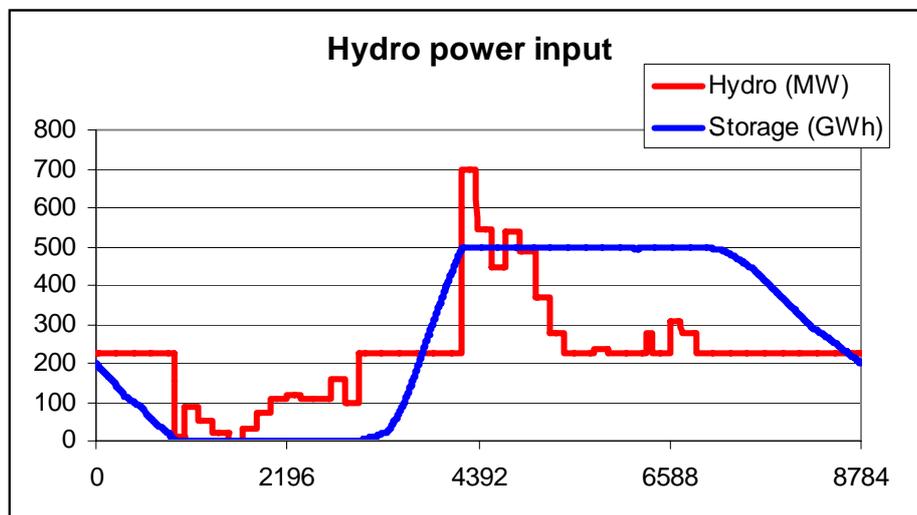


However, if one introduces a limitation to the storage capacity, so that the total water input cannot be utilised during a year (e.g. a storage capacity of 500 GWh), the following solution will be identified:



As one can see, the starting point is the average production of 228 MW. During summer and autumn, when the storage is filled and the water supply is higher than what is needed to produce average, the production of the power plant is increased up to the capacity of the generator. Consequently, the storage is not filled when the water supply is low during spring and the production is decreased accordingly. However, in this case, losses in the storage cannot be avoided and the annual production is limited to 1.88 TWh/year and not the potential 2.00 TWh/year.

If the capacity of the generator is increased to 700 MW, the following solution is found in which the system will produce the fully 2.00 TWh/year. If, on the other hand, the capacity is decreased to 300 MW, the annual production will be only 1.79 TWh/year.



The resulting annual hydro input production is shown simultaneously in the input window in which the input data are specified.

### Flexible demand

In the potential calculation of flexible demand, the baseline hydro power production is subtracted from the various demands (consumers, fixed import/export, heat pumps and transportation) before the distribution of the flexible demand is determined.

### Regulation strategies I, II, III and IV

In regulation strategies I, II, III and IV, the above baseline hydro power production is included when the power production from the rest of the units is determined.

#### Modification

After the determination of productions in accordance with reg. I-IV, the hydropower is used for replacing the condensing units and decrease first CEEP and soundly EEEP in the following way.

First, the potential of replacing the condensing power plant ( $e_{\text{HYDRO-INC}}$ ) is determined as the minimum value of either the production of the condensing unit or the difference between hydro power capacity and hydro power production.

$$e_{\text{HYDRO-INC}} = \text{MIN} (e_{\text{PP}}, (C_{\text{HYDRO}} - e_{\text{HYDRO-INPUT}}))$$

The potential of decreasing hydro power in the case of CEEP ( $e_{\text{HYDRO-DEC-CEEP}}$ ) is determined as the minimum value of either the CEEP or the hydro power production. At the same time, the potential is subject to the limitation of the hydro power plant potentially being part of grid stabilisation:

$$e_{\text{HYDRO-DEC-CEEP}} = \text{MIN} (e_{\text{CEEP}}, e_{\text{HYDRO-INPUT}})$$

$$e_{\text{HYDRO-DEC-CEEP}} \leq e_{\text{HYDRO}} - e_{\text{HYDRO-MIN-GRID-STAB}}$$

In the case of reversal hydro power, i.e. a pump and lower water storage, the potential of decreasing CEEP further ( $e_{\text{HYDRO-PUMP-DEC-CEEP}}$ ) is determined as the minimum value of the CEEP, the pump capacity, or the content of the lower water storage:

$$e_{\text{HYDRO-PUMP-DEC-CEEP}} = \text{MIN} (e_{\text{CEEP}}, C_{\text{HYDRO-PUMP}}, )$$

$$C_{\text{HYDRO-STORAGE}} - \text{Hydro-storage-content} / \mu_{\text{HYDRO-PUMP}},$$

In the same way, the potential of decreasing hydro power in the case of EEEP ( $e_{\text{HYDRO-DEC-EEEP}}$ ) is found.

Knowing the potentials of increasing and decreasing the hydro power production, a balance is found in which the annual hydro power production is maintained. The reduction of CEEP is given priority to the reduction in EEEP.

$$\sum e_{\text{HYDRO-INC}} = \sum e_{\text{HYDRO-DEC-CEEP}} + \sum e_{\text{HYDRO-DEC-EEEP}}$$

Similar to the previous modelling of the hydro power input, the programme again calculates the hour by hour modelling of the system including the fluctuations in the storage content. The hydro power production ( $e_{\text{HYDRO}}$ ) is modified in accordance with the generator capacity, the distribution of the water supply and the storage capacity in the following way:

$$\text{Hydro-storage-content} = \text{Hydro-storage content} + e_{\text{HYDRO-WATER}}$$

$$e_{\text{HYDRO}} = e_{\text{HYDRO}} + e_{\text{HYDRO-INC}} - e_{\text{HYDRO-DEC-CEEP}} - e_{\text{HYDRO-DEC-EEEP}}$$

$$e_{\text{HYDRO-INPUT}} \leq (\text{Hydro-storage-content} - C_{\text{HYDRO-STORAGE}}) * \mu_{\text{HYDRO}}$$

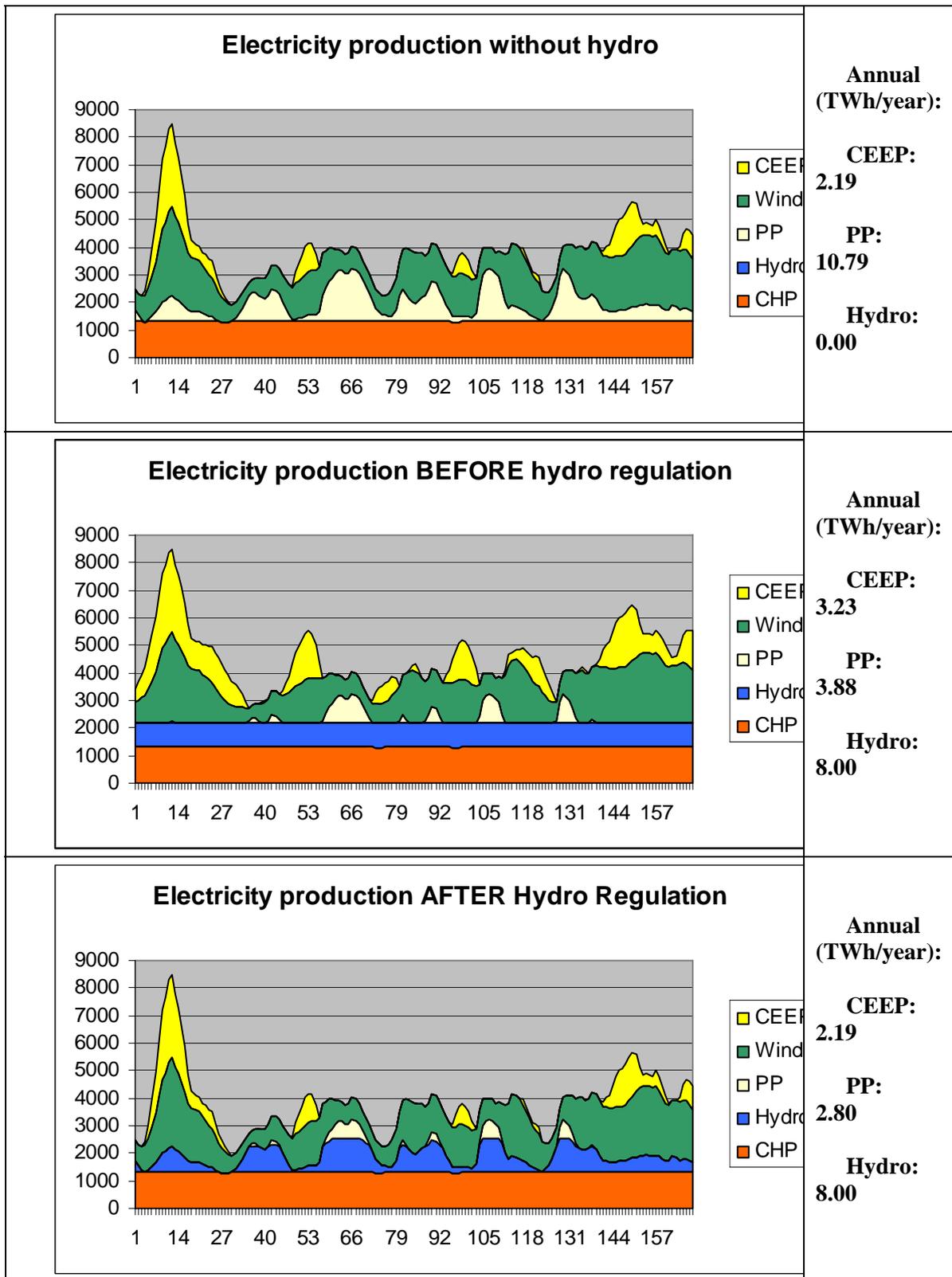
$$e_{\text{HYDRO-INPUT}} \leq C_{\text{HYDRO}}$$

To correct the calculations from errors due to differences in the storage content between the beginning and the end of the calculation period, the above calculation is seeking to identify a solution in which the storage content in the end is the same as in the beginning. Initially, the storage content is defined as 50% of the storage capacity. After the first calculation, a new beginning content is defined as the resulting content in the end of the former calculation.

How the input is calculated can be illustrated by the example in the three diagrams below. The first diagram shows the electricity production for a week in a system with a high share of both CHP and wind power. The system has a high excess electricity production (CEEP).

The next diagram shows the influence of the hydro input (before the hydro regulation). It can be seen how the hydro power automatically replaces the power plant (PP) in the situations in which the PP produces in order to secure grid stability. However, in other situations, the hydro power also adds to the problem of excess production.

In the third diagram, the hydro power is part of the regulation and it can be seen how the hydro power plant is used for replacing the condensing plant and reducing the excess production.



### Reversal Hydro Power

In the case of reversal hydro power, i.e. a pump and a lower storage in combination with hydro power, the system is used in a similar way as in the electric storage system to avoid critical excess electricity production.

The pump and lower water storage facility is regulated in the following way:

The pump is used for filling the storage in the case of the critical excess production,  $e_{CX} > 0$ . In such case, the available space in the upper storage ( $C_{HYDRO-STORAGE} - \text{Hydro-storage-content}$ ) is calculated and the electricity demand of the pump ( $e_{PUMP}$ ) is found as the minimum value of the following three numbers:

- $e_{CX}$ , the critical excess production
- $(C_{HYDRO-STORAGE} - \text{Hydro-storage-content}) / \mu_{HYDRO-PUMP}$  available storage capacity divided by the pump efficiency
- $C_{HYDRO-PUMP}$ , the maximum capacity of the pump.

If  $e_{CX} > 0$  then  $e_{HYDRO-PUMP} := \text{minimum}[e_{CX}, (C_{HYDRO-STORAGE} - \text{Hydro-storage-content}) / \mu_{HYDRO-PUMP}, C_{HYDRO-PUMP}]$

$$E_{STORAGE-new} = E_{STORAGE-old} + e_{PUMP} / \text{Pump}_{EFF}$$

The turbine is used for emptying the storage by replacing the power plant if the production from the power plant,  $e_{PP} > 0$ . In such case, the content of the storage ( $E_{STORAGE}$ ) is identified and the electricity production of the turbine ( $e_{TURBINE}$ ) is found as the minimum value of the following three numbers:

- $e_{PP}$ , the electricity production of the power plant
- $E_{STORAGE} * \text{Turbine}_{EFF}$ , storage content multiplied by the turbine efficiency
- $\text{Turbine}_{CAP}$ , the maximum capacity of the turbine.

If  $e_{PP} > 0$  then  $e_{TURBINE} := \text{minimum}[e_{PP}, E_{STORAGE} * \text{Turbine}_{EFF}, \text{Turbine}_{CAP}]$

$$E_{STORAGE-new} = E_{STORAGE-old} - e_{TURBINE} / \text{Turbine}_{EFF}$$

To correct the calculations from errors due to differences in the storage content between the beginning and the end of the calculation period, the above calculation is repeated until the storage content in the end is the same as in the beginning. Initially, the storage content is defined as 50% of the storage capacity. After the first calculation, a new beginning content is defined as the resulting content in the end of the former calculation. Such procedure is repeated until the difference is insignificant.

## 7. Nuclear Power

Nuclear Power Units are described by the following inputs:

$C_{\text{NUCLEAR}}$ :	The capacity of the Nuclear Power Electricity Generator in MW
$\mu_{\text{NUCLEAR}}$ :	The efficiency of the Nuclear Power station.
$d_{\text{NUCLEAR}}$ :	The distribution of the electricity production in 8784 hour values

The Nuclear Power station is subject to the condition that it will always be involved in the task of maintaining grid stability.

The nuclear unit is considered to be running as base load, and therefore the power plant is not taking part of the active regulation. The electricity production from the nuclear unit ( $e_{\text{NUCLEAR}}$ ) is simply defined by the capacity and the hour by hour distribution.

$$e_{\text{NUCLEAR}} = C_{\text{NUCLEAR}} * d_{\text{NUCLEAR}} / \text{Max}(d_{\text{NUCLEAR}})$$

The efficiency is used only for the calculation of the annual amount of fuel ( $f_{\text{NUCLEAR}}$ ) which is calculated by the following formula:

$$f_{\text{NUCLEAR}} = e_{\text{NUCLEAR}} / \mu_{\text{NUCLEAR}}$$

The fuel consumption is named “Uranium” and is measured in TWh/year in order to be able to compare it to the consumption of the rest of the units.

## 8. Electricity storage

The electricity storage is described in the model as a hydro storage consisting of the following components:

- Pump (converting electricity to potential energy) defined by a capacity and an efficiency
- Turbine (converting potential energy to electricity) defined by a capacity and an efficiency
- Storage (storing energy) defined by a capacity.

Meanwhile, the hydro storage can be used for modelling any kind of electricity storage such as for example batteries.

The regulation of the storage is used solely for avoiding critical excess electricity production (Defined as electricity production which cannot be exported).

If electricity storage capacity is defined in an analysis, the use of the storage is calculated AFTER the calculation of heat and electricity productions from CHP plants and power stations, but BEFORE calculating the reducing of critical excess production by other means.

The storage facility is regulated in the following way:

The pump is used for filling the storage in the case of the critical excess production,  $e_{CX} > 0$ . In such case, the available space in the storage ( $E_{STORAGE-CAP} - E_{STORAGE}$ ) is calculated and the electricity demand of the pump ( $e_{PUMP}$ ) is found as the minimum value of the following three numbers:

- $e_{CX}$ , the critical excess production
- $(E_{STORAGE-CAP} - E_{STORAGE}) / Pump_{EFF}$  available storage capacity divided by the pump efficiency
- $Pump_{CAP}$ , the maximum capacity of the pump.

If  $e_{CX} > 0$  then  $e_{PUMP} := \text{minimum}[e_{CX}, (E_{STORAGE-CAP} - E_{STORAGE}) / Pump_{EFF}, Pump_{CAP}]$

$$E_{STORAGE-new} = E_{STORAGE-old} + e_{PUMP} / Pump_{EFF}$$

The turbine is used for emptying the storage by replacing the power plant if the production from the power plant,  $e_{PP} > 0$ . In such case, the content of the storage ( $E_{STORAGE}$ ) is identified and the electricity production of the turbine ( $e_{TURBINE}$ ) is found as the minimum value of the following three numbers:

- $e_{PP}$ , the electricity production of the power plant
- $E_{STORAGE} * Turbine_{EFF}$ , storage content multiplied by the turbine efficiency
- $Turbine_{CAP}$ , the maximum capacity of the turbine.

If  $e_{PP} > 0$  then  $e_{TURBINE} := \text{minimum}[e_{PP}, E_{STORAGE} * Turbine_{EFF}, Turbine_{CAP}]$

$$E_{STORAGE-new} = E_{STORAGE-old} - e_{TURBINE} / Turbine_{EFF}$$

To correct the calculations from errors due to differences in the storage content between the beginning and the end of the calculation period, the above calculation is repeated until the storage content in the end is the same as in the beginning. Initially, the storage content is defined as 50% of the storage capacity. After the first calculation, a new beginning content is defined as the resulting content in the end of the former calculation. Such procedure is repeated until the difference is insignificant.

## CAES

CAES Fuel ratio defined as CAES fuel consumption /  $e_{\text{TURBINE}}$

The CAES component is modelled in a similar way to the pumped hydro storage, the main difference being the fuel consumption in the electricity production stage. The main capacities and efficiencies defined by the user are:

- Compressor capacity and efficiency
- Storage capacity
- Turbine capacity, compressed air efficiency, and fuel efficiency

Note that in CAES, the main loss in the storage is heat loss, which occurs only during the initial hours after compression. As a certain time usually elapses before the expansion phase begins, the heat loss in the storage is included in the compressor efficiency definition.

The compressor is utilized in the model after calculating the heat and electricity production of the CHP and power plants, but before reducing excess electricity by use of other means. In the case of having pumped hydro storage into the system, it is given a priority over the CAES plant operation.

The turbine is utilized to replace power plant production. Here again, pumped hydro is given priority for production over CAES.

## 9. Electrolyser

The electrolyser is described in the model as a new component in both group 2 and 3 along with the CHP units, Heat Pumps and boilers.

- Electrolyser (converting electricity to fuel and heat) defined by a capacity, a fuel-efficiency and a thermal efficiency.
- Storage (storing fuel) defined by a capacity. (NOTE: Not included in the calculation)

The electrolyser is meant to be a hydrolyser (producing hydrogen) but can be used for modelling any kind of equipment converting electricity into fuel and heat.

The regulation of the storage is used solely in order to avoid critical excess electricity production (Defined as electricity production which cannot be exported).

In the model, the calculation of the electrolyser is carried out AFTER the calculation of the heat and electricity productions of CHP plants and power stations, but BEFORE the calculations of the use of heat storages and the above calculation of electricity storage and the calculating of reducing critical excess production by use of other means.

The electrolyser is regulated in the following way:

The electrolyser is used for producing fuel in the case of the critical excess production,  $e_{CX} > 0$ .

The fuel is used for reducing the fuel consumption in the CHP unit and the boiler of the particular group. NOTE: At the present stage, the storage is not included in the calculation.

If the thermal efficiency is equal to 0, then the use of electrolysers is simply calculated as the minimum value of either the CEEP value or the capacity of the electrolysers.

$$\text{If } \text{Elt}_{\text{EFF-TH}} = 0 \text{ Then } e_{\text{ELT}} = \min(e_{\text{CX}}, \text{Elt}_{\text{CAP}})$$

If the thermal efficiency is more than 0, the heat of the electrolyser is used for reducing heat production of other units subsequent to the following priority:

- reduce boiler production
- reduce CHP production
- reduce Heat pump production
- wasted

### *Reduce boiler production*

First, the potential replacement of the boiler is calculated as the minimum value of either (1) the critical excess production, (2) the capacity of the electrolyser or (3) the responding electricity consumption to the heat production of the boiler. The latter is found as the heat production of the boiler divided by the thermal efficiency of the electrolyser. And the excess production and the production of the boiler and the electrolyser are then adjusted accordingly.

$$\text{Potential} = \min(e_{\text{CX}}, \text{Elt}_{\text{CAP}}, q_{\text{BOILER}} / \text{Elt}_{\text{EFF-TH}})$$

$$e_{\text{CX-NEW}} = e_{\text{CX-OLD}} - \text{Potential}$$

$$e_{\text{ELT-NEW}} = e_{\text{ELT-OLD}} + \text{Potential}$$

$$q_{\text{ELT-NEW}} = q_{\text{ELT-OLD}} + \text{Potential} * \text{Elt}_{\text{EFF-TH}}$$

$$q_{\text{BOILER-NEW}} = q_{\text{BOILER-OLD}} - \text{Potential} * \text{Elt}_{\text{EFF-TH}}$$

#### *Reduce CHP production*

If the excess production is still positive, then the potential decrease in the CHP unit is found first by calculating the factor which will make it possible to remove critical excess without creating import. This factor takes into account the fact that the replacement of the CHP by the electrolyser influences the excess production by decreasing the CHP production as well as increasing the electrolyser consumption. The factor is determined by the following equations:

$$\Delta e_{\text{CX}} = \Delta e_{\text{CHP}} + \Delta e_{\text{ELT}}$$

$$\Delta q_{\text{CHP}} = \Delta q_{\text{ELT}}$$

$$\Delta q_{\text{ELT}} = \Delta e_{\text{ELT}} * \text{Elt}_{\text{EFF-TH}}$$

$$\Delta q_{\text{CHP}} = \Delta e_{\text{CHP}} * \text{CHP}_{\text{EFF-TH}} / \text{CHP}_{\text{EFF-EL}}$$

And the factor then becomes:

$$\text{Faktor} = 1 + \text{CHP}_{\text{EFF-TH}} / (\text{CHP}_{\text{EFF-EL}} * \text{Elt}_{\text{EFF-TH}})$$

The factor is used for identifying the potential replacement of the CHP in which the combination of the CHP decrease and the electrolyser increase outbalance the excess production. Consequently, the potential CHP reduction is found as the critical excess production divided by the factor. Again, the potential replacement of the CHP unit is found as the minimum value of either such reduction or the capacity of the electrolyser or the responding electricity consumption to the heat production of the CHP unit.

$$\text{Potential} = \min (e_{\text{CX}} / \text{Faktor}, (\text{Elt}_{\text{CAP}} - e_{\text{ELT}}), q_{\text{CHP}} / \text{Elt}_{\text{EFF-TH}})$$

In case of identifying the potential of group 3, the potential reduction in the heat production of the CHP unit is found as the difference between the actual production and the minimum production according to the regulation inputs.

$$\text{In group 3: Potential} = \min (e_{\text{CX}} / \text{Faktor}, (\text{Elt}_{\text{CAP}} - e_{\text{ELT}}), (q_{\text{CHP}} - q_{\text{CHP-minimum}}) / \text{Elt}_{\text{EFF-TH}})$$

Again, the excess production and the production of the CHP and the electrolyser are then adjusted accordingly similar to the previous case of the boiler.

#### *Reduce Heat pump production*

If the excess production is still positive then the potential decrease in the heat pump (HP) unit is found first by calculating the factor which will make it possible to remove critical excess without creating import. This factor takes into account the fact that the replacement of the HP by the electrolyser influences the excess production by decreasing the HP production as well as increasing the electrolyser consumption. The factor is determined by the following equations:

$$\Delta e_{\text{CX}} = \Delta e_{\text{HP}} + \Delta e_{\text{ELT}}$$

$$\Delta q_{\text{HP}} = \Delta q_{\text{ELT}}$$

$$\Delta q_{\text{ELT}} = \Delta e_{\text{ELT}} * \text{Elt}_{\text{EFF-TH}}$$

$$\Delta q_{HP} = \Delta e_{HP} * HP_{EFF-COP}$$

And the factor then becomes:

$$\text{Faktor} = HP_{EFF-COP} / \text{Elt}_{EFF-TH} - 1$$

The factor is used for identifying the potential replacement of the HP in which the combination of the HP decrease and the electrolyser increase outbalance the excess production. Consequently, the potential HP reduction is found as the critical excess production divided by the factor. Again, the potential replacement of the HP unit is found as the minimum value of either such reduction or the capacity of the electrolyser or the responding electricity consumption to the heat production on the HP unit.

$$\text{Potential} = \min (e_{CX} / \text{Faktor}, (\text{Elt}_{CAP} - e_{ELT}), q_{HP} / \text{Elt}_{EFF-TH})$$

And again the excess production and the production of the HP and the electrolyser are then adjusted accordingly similar to the previous case of the boiler and the CHP.

#### *Wasted*

If the excess production is still positive then the potential increase in the electrolyser is simply found as the minimum value of either the excess production or the remaining increase up to the capacity of the electrolyser.

$$\text{Potential} = \min [e_{CX}, (\text{Elt}_{CAP} - e_{ELT})]$$

And the excess production and the production of the electrolyser are then adjusted accordingly.

## 10. V2G (Electric Vehicles)

Definition of inputs:

$TD_{V2G}$ :	Transportation Demand of V2G cars in TWh/year (defined as demand from the grid)
$d_{V2G}$ :	The distribution of the transportation demand in 8784 hourly values. (The numbers are relative e.g. each ranging 0 to 1).
$P_{V2G-MAX}$ :	The capacity of the grid connection in MW
$V2G_{MAX-SHARE}$ :	The maximum share of V2G cars which are driving during peak demand hour.
$\eta_{CHARGER}$ :	The efficiency of the grid to battery connection (charger).
$\eta_{INV}$ :	The efficiency of the battery to grid connection (inverter).
$E_{V2G-BATTERY}$ :	The capacity of the battery storage in GWh
$V2G_{CONNECTION-SHARE}$ :	The share of parked V2G cars connected to the grid.

Note: Inputs E and P are annual values. Lower-case e and p are used for hour by hour values. Similarly, TD is the total yearly transportation demand, while lower-case d is the set of 8784 hourly values of transportation demand.

All inputs are expressed for the entire utility system analysed, and for the entire vehicle fleet within the service territory of that utility system. Thus, for example, the maximum system capacity  $P_{V2G-MAX}$  is calculated on the basis of the line maximum power of a single car ( $P_{line}$  from Kempton and Tomic 2005), multiplied by the maximum number of vehicles plugged in at any given time.

One important input is the distribution of the transportation demand ( $d_{V2G}$ ), which is used for two purposes. One is to determine how many V2G cars are driving and consequently not connected to the grid. This, together with the  $V2G_{MAX-SHARE}$  (the maximum share of V2G cars which are driving during peak demand hour) and the  $V2G_{CONNECTION-SHARE}$ , determines the fraction of the V2G fleet that is available to the electrical system at any given hour. The other purpose for  $d_{V2G}$  is to determine the discharging of the battery storage for driving.

### Initial input calculations

The hourly transportation demand and thereby the discharging of the battery ( $td_{V2G}$ ) is calculated as follows:

$$td_{V2G} = [ TD_{V2G} * d_{V2G} / \sum d_{V2G} ] * \eta_{CHARGE}$$

And the grid-connection capacity of the total V2G fleet on an hourly basis ( $p_{V2G}$ ) will be calculated as follows:

$$p_{V2G} = P_{V2G-MAX} * V2G_{CONNECTION-SHARE} * ((1 - V2G_{MAX-SHARE}) + V2G_{MAX-SHARE} * (1 - d_{V2G}/\text{Max}(d_{V2G})))$$

This formula is constituted by three factors. The first factor is  $P_{V2G-MAX}$ , the power capacity of the entire V2G fleet. This is multiplied by  $V2G_{CONNECTION-SHARE}$ , the fraction of the parked vehicles in which we assume to be plugged. The third factor, in parentheses, calculates the fraction of vehicles on the road at each hour. Further decomposing the third parenthesized factor, it consists of the sum of two terms. The first term,  $(1 - V2G_{MAX-SHARE})$ , represents the

minimum fraction of vehicles parked. The second term is the additional fraction of the vehicles parked during non-rush hours. The hourly fraction of vehicles parked is derived from the known input of hourly energy demand for the fleet. This formula yields  $p_{V2G}$ , the power capacity of all connected V2G vehicles, at any given hour. This is a calculation of capacity, not considering whether sufficient battery power is available; the latter is treated in the next section.

The calculation works as described in the following example of 1.9 million cars, each with a grid connection of 10 kW and each with a demand of 2 MWh/year equal to 20,000 km/year. The charge and inverter efficiencies are each defined as 0.9. In total, the demand for transportation becomes  $TD_{V2G} = 3.8$  TWh/year and a maximum capacity of 19,000 MW. The distribution of the power use is a peak demand during rush hours between 7:00 and 9:00 in the morning and between 16:00 and 18:00 in the afternoon, as shown in the diagram for one week. (Recall that this is battery demand, not electric system demand, as the vehicles are necessarily disconnected from the grid while driving.)

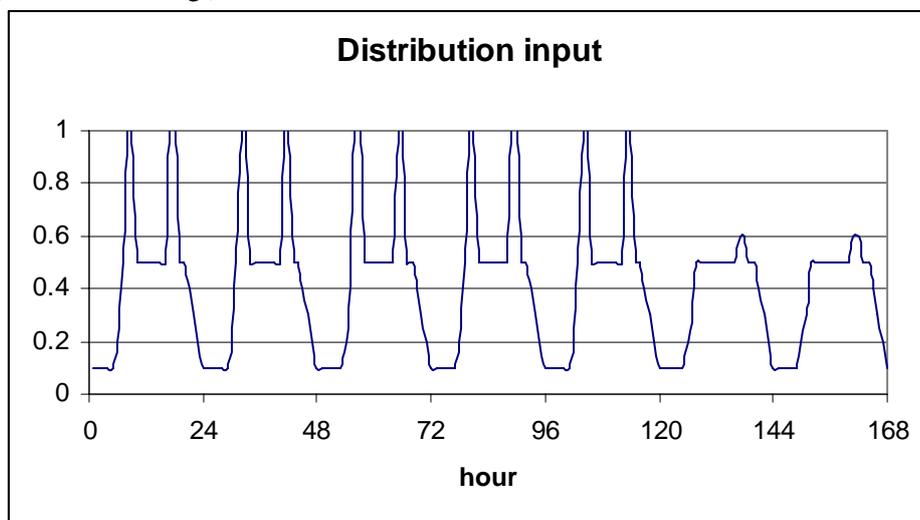


Fig. 1: Input distribution of transportation demand

Based on such information, the model will calculate the distribution of the demand and thereby also the discharging of the battery, as shown in the next diagram. The sum of the diagram within a year becomes 3.42 TWh/year equal to  $0.9 * 3.8$  TWh/year.

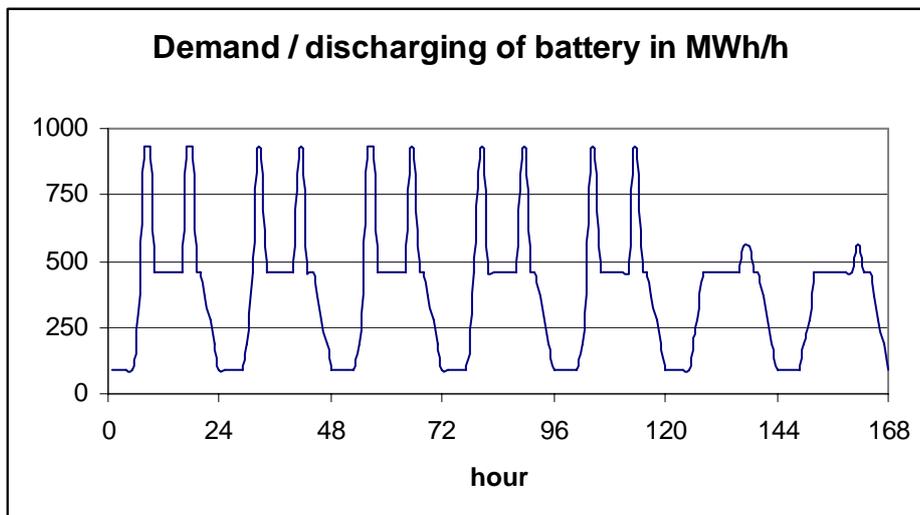
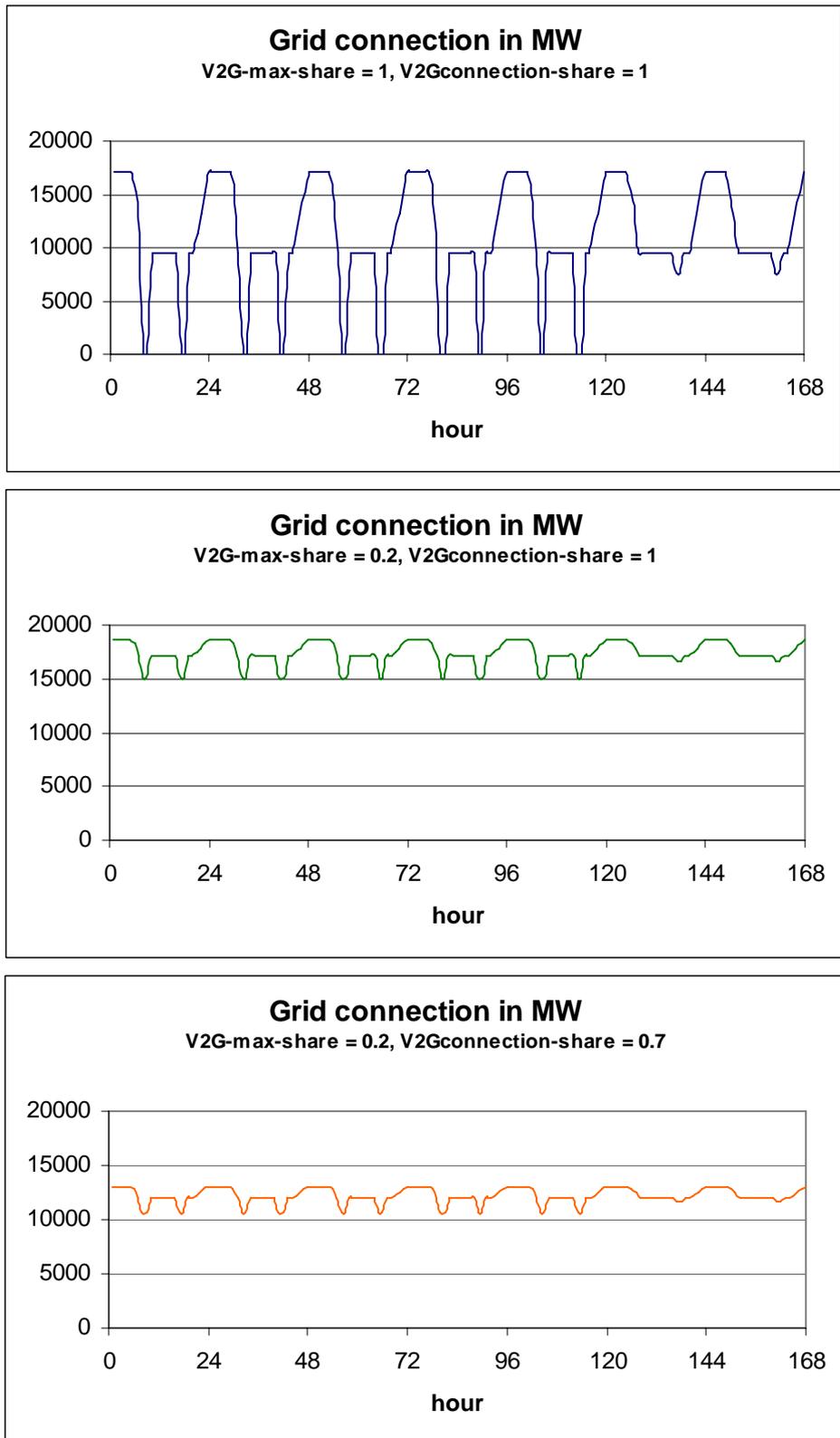


Fig. 2: Transportation demand and thereby discharging of battery.

The calculation of the available grid connection depends on the definition of both the maximum share of V2G cars,  $V2G_{MAX-SHARE}$ , and the share of parked vehicles which are connected,  $V2G_{CONNECTION-SHARE}$ . If both are 100 per cent, the result is as shown in the first diagram of figure 3. In such case, the model assumes that all vehicles are driving during peak demand and, consequently, the grid connection becomes zero. During low demand, the grid connection becomes equal to the maximum grid connection  $P_{V2G-MAX}$ , subtracted by the few vehicles that are driving.

Even during peak demand (rush hour), the model does not assume all vehicles to be driving. One can by setting the  $V2G_{MAX-SHARE}$  value define how many cars are parked and potentially connected to the grid in peak demand. In fig. 3, diagram 2, the  $V2G_{MAX-SHARE}$  has been defined to 20 per cent representing a typical situation in which a minimum of 80 per cent of all cars are parked during rush hours (Kempton et al 2001)

In fig. 3, the input of the share of parked vehicles which are connected,  $V2G_{CONNECTION-SHARE}$ , has been changed from 100 to 70 per cent and, consequently, the grid connection is decreased in general by 30 per cent compared to fig 2.



*Fig. 3: The model calculation of the available grid connection for three different combinations of input definitions.*

### **Considerations on the modelling of the battery and loading before disconnecting**

The batteries of the V2G fleet are modelled as if there were one “big battery” for the entire vehicle fleet. The available battery capacity is equal to the maximum capacity. In reality, the total capacity of the battery is not available all the time, since some of the cars will be driving, and can neither discharge to, nor charge from, the grid; others will need to drive in the next few hours and thus cannot be discharged. However, we assume for simplicity that the batteries for the cars are scheduled to be fully loaded when they disconnect and start driving. Consequently, the model does not gain much from keeping separately account on the share of the battery, which is not connected, since this part would typically within the hour be fully loaded anyway. However, the share representing the cars driving will discharge a bit from one hour to another in the case of cars driving for more than one hour. If one wants to take such issues into consideration, one could simply make a small reduction in the input value for the capacity of the battery,  $E_{V2G-BATTERY}$ .

The model is required to make sure that the individual car is fully loaded before it is planned to disconnect. In general, the batteries are loaded in the case of excess electric power production. However, when there is not excess power production, the model has to make sure that the batteries are loaded prior to driving periods. (In a future refinement of the model, we may assume that the vehicle controller is able to infer how much charge is needed and would not need to always fully charge if there is no excess production and vehicle use is highly regular; e.g. if intercity trips are only taken on Saturdays, the battery may not need to be fully charged at early mornings during weekdays.)

The model assumes that the scheduler on each car is 100% accurate about when the driver will need to drive again. Therefore, the scheduler is assumed to prioritize charging for the cars that will drive again within the next few hours, so if there is only a small amount of excess wind, it is directed to the cars that will be in use next time. That is, during each hour, the model inspects the next e.g. two hours’ driving needs, and if there is not enough in the big battery for this, then the charging is forced even in the case of lack of excess production, specifically, if needed, fossil fuel power plants will be switched on if there is not enough excess wind..

Such procedure simulates that the individual car owner will make priorities on how to optimise between low costs of charging and security of fully loaded batteries when starting to drive. The car owner does this by setting prices and limitations to the computer control of the car. However, the car owner will learn from experience, and will soon know how to optimise, including the setting on how many hours in advance he wants the battery to start charging even in the case of no low prices.

Here the model on its own identifies the necessary number of hours to be able to secure driving and thereby the minimum battery loading. Such necessary number of hours will depend on both the shape and pattern of the distribution of the transportation demand, as well as on the definition of the rest of energy system. For example, a system in which the excess production is severe will call for less “pre-loading” than a system in which the excess production is small.

The necessary hours of “pre-loading” is found by try-and-error. The model starts by assuring that the battery always has a minimum load of being able to supply the next one hour and if this results in lack of battery content the number is raised to two, etc. The number of hours becomes a result of the calculation. In an optimized electric control system, the number of hours prior to driving might also be determined by weather forecasts regarding anticipated wind for the next few hours, but we do not consider such refinements here.

### Modelling of the V2G cars

For each hour, the model calculates as follows. The V2G cars are told to charge in the case of available excess electricity production for that hour ( $e_{CEEP}$ ) and that hour's available battery energy capacity ( $E_{V2G-BATTERY} - e_{V2G-BATTERY}$ ) within the limitations of the power capacity of the grid connection ( $p_{V2G}$ ). Thus, the formula takes the minimum of these three values:

$$e_{CHARGE} = \min [e_{CEEP}, (E_{V2G-BATTERY} - e_{V2G-BATTERY}) / \eta_{CHARGE}, p_{V2G}]$$

Moreover (as mentioned above), the charging is forced in the case in which the transport demands of the present and the next "y" hours cannot be supplied by the battery content. Initially, the "y" value is set to one hour. If this leads to lack of battery content the value is raised in steps of one hour.

The necessary minimum battery content is calculated:

	$x=a$
$e_{V2G-BATTERY-MIN} =$	$\sum td_{V2G}$
	$a+y$

Then the charging of the battery is adjusted accordingly, by requiring that:

$$e_{CHARGE} \geq [e_{V2G-BATTERY} - e_{V2G-BATTERY-MIN}] / \eta_{CHARGE}$$

If  $e_{CHARGE}$  becomes higher than the capacity of the grid connection  $p_{V2G}$  then the number of hours, y, is raised by one, and the calculations starts all over again.

The new battery content is then calculated by adding the above charging and subtracting the discharging caused by driving ( $td_{V2G}$ ):

$$e_{V2G-BATTERY} := e_{V2G-BATTERY} - td_{V2G} + (e_{CHARGE} / \eta_{CHARGE})$$

The V2G cars are told to supply to the grid in the case of potential replacement of production from power plants ( $e_{PP}$ ) and available stored electricity in the battery after supplying the transportation demand:

$$e_{INV} = \min [e_{PP}, ((e_{V2G-BATTERY} - e_{V2G-BATTERY-MIN}) * \eta_{INV}), p_{V2G}]$$

And the resulting new battery content is then calculated as follows

$$e_{V2G-BATTERY} := e_{V2G-BATTERY} - (e_{INV} / \eta_{INV})$$

To correct the calculations from errors due to differences in the battery storage content between the beginning and the end of the calculation period (one year), the above calculation is repeated until the storage content in the end is the same as in the beginning. Initially, the storage content is defined as 50% of the battery storage capacity. After the first calculation, a new beginning content is defined as the resulting content in the end of the former calculation. Such procedure is repeated until the difference is insignificant.

REFERENCES CITED:

Kempton, W., J. Tomic, S. Letendre, A. Brooks & T. Lipman. 2001. Vehicle-to-Grid Power: Battery, Hybrid, and Fuel Cell Vehicles as Resources for Distributed Electric Power in California. UCD-ITS-RR-01-03.

Kempton, Willett and Jasna Tomic, 2005a, "Vehicle to Grid Fundamentals: Calculating Capacity and Net Revenue" *J. Power Sources* Volume 144, Issue 1, 1 June 2005, Pages 268-279. doi:10.1016/j.jpowsour.2004.12.025".

## 11. Reducing Critical Electricity Export

A number of means to reduce Critical Electricity Export,  $e_{cx}$  have been identified:

- 1: Reducing wind power production
- 2: Reducing CHP production in group 2 (Replacing with boiler)
- 3: Reducing CHP production in group 3 (Replacing with boiler)
- 4: Replacing boiler production with electric heating in group 2.
- 5: Replacing boiler production with electric heating in group 3.

It is possible to specify one or more numbers, which will be treated in the specified order.

### Regarding 1: Reducing wind power production

First, wind power production onshore is reduced. The potential is found as follows:

$$\text{Red}_{\text{pont}} = \min(e_{w\text{-onshore}} ; e_{cx})$$

Now new values are calculated:

$$e_{w\text{-onshore-new}} = e_{w\text{-onshore-old}} - \text{Red}_{\text{pont}}$$

$$e_{cx\text{-new}} = e_{cx\text{-old}} - \text{Red}_{\text{pont}}$$

Offshore wind power production is thereafter calculated in the same manner.

### Regarding 2: Reducing CHP production in group 2

First, the minimum CHP production needed in order to fulfil the requirement of stabilising the grid is found:

$$e_{\text{CHP-min-gr2}} = (e_{ia} * S_{\text{stab/tot}} - e_w * S_{\text{stab/wind}} - e_{pp}) / S_{\text{stab/CHP}} - e_{\text{CSHP}} - e_{\text{CHP-gr3}}$$

Then the potential reduction is found:

$$\text{Red}_{\text{pont-gr2}} = \min(e_{\text{chp-gr2}} - e_{\text{CHP-min-gr2}} ; e_{cx})$$

Giving new values:

$$e_{\text{CHP-gr2-new}} = e_{\text{CHP-gr2-old}} - \text{Red}_{\text{pont-gr2}}$$

$$e_{cx\text{-new}} = e_{cx\text{-old}} - \text{Red}_{\text{pont-gr2}}$$

$$q_{\text{CHP-gr2-new}} = e_{\text{CHP-gr2-new}} * H_{\text{CHP-gr2}} / C_{\text{CHP-gr2}}$$

$$q_{\text{B-gr2-new}} = q_{\text{B-gr2-old}} - \text{Red}_{\text{pont-gr2}} * H_{\text{CHP-gr2}} / C_{\text{CHP-gr2}}$$

### Regarding 3: Reducing CHP production in group 3

The same calculations as above, just replacing group 2 with group 3.

### Regarding 4: Replacing boiler production with electric heating in group 2

The potential reduction is calculated as follows:

$$\text{Red}_{\text{pont-gr2}} = \min(q_b ; e_{cx})$$

Then the value for electric heating is calculated

$$E_{\text{electricheating}} = \text{Red}_{\text{pont-gr2}}$$

Subsequently, new values for  $e_{\text{cx}}$  and  $q_{\text{b-gr3}}$  are calculated.

### **Regarding 5: Replacing boiler production with electric heating in group 3**

The same calculations as in situation 4, just replacing group 2 with group 3.

### **New reducing CEE options**

Two new options of reducing CEE critical electricity excess production have been added to the previous 5 possibilities. Again, one can choose freely among the options and make any combination or sequence possible, simple by defining a combination of the different numbers and write it in the “CEE regulation” input in the “Regulation” window.

For example, the combination 315 activates three CEE reductions. First, CEE is reduced as much as possible by option 3, then by option 1 and finally by option 5. All 7 options can be activated in all possible combinations.

The two new options are:

- 6: Reducing Photo Voltaic power production
- 7: Reducing power plant in combination with wind and PV production

### **Regarding 6: Reducing Photo Voltaic power production**

The potential of reducing PV is found:

$$\text{Red}_{\text{pont}} = \min(e_{\text{PV}} ; e_{\text{CX}})$$

And new values of critical export and PV are calculated.

$$e_{\text{PV-new}} = e_{\text{PV-old}} - \text{Red}_{\text{pont}}$$

$$e_{\text{CX-new}} = e_{\text{CX-old}} - \text{Red}_{\text{pont}}$$

### **Regarding 7: Reducing power plant in combination with wind and PV production**

This option has been added because in option 1 and 6 (reduction of wind and PV), the sequence of first increasing the power plant for stabilisation reasons and then decreasing renewable sources in cases of very huge RES shares led to CEE solely from the power station instead. In such cases, one can increase the share of RES and still maintain minimum stabilisation limits by decreasing the power plant and the RES simultaneously.

First, the minimum load of the power plant is calculated in the case of no RES at all:

$$e_{\text{PP-RES}} = ((e_{\text{CSHP}} + e_{\text{CHP}}) * S_{\text{stab/tot}} - e_{\text{CHP2}} * S_{\text{stab/CHP2}} - e_{\text{CHP3}} - e_{\text{TURBINE}}) / (1 - S_{\text{stab/tot}})$$

Then, the reduction potential of the power plant is found as the difference between such number and the previously found electricity production of the power plant:

$$e_{\text{PP-pontial}} = e_{\text{PP}} - e_{\text{PP-RES}}$$

Hereafter, the need for reducing the power plant in combination with reductions in the RES is calculated as the stabilisation share of critical electricity excess production to be reduced:

$$e_{PP-Need} = e_{CX} * S_{stab/tot}$$

Finally, the reduction is found as the minimum value of the two:

$$Red_{pont} = \min(e_{PP-pontial} ; e_{PP-Need})$$

And new values of critical export and power plant production are calculated.

$$e_{PP-new} = e_{PP-old} - Red_{pont}$$

$$e_{CX-new} = e_{CX-old} - Red_{pont}$$

After reducing the power plant as described, the RES are reduced repeating option 1 and 6 in the following sequence: First reducing wind onshore, then wind offshore and finally PV.

## 12. Electricity market modelling and import/export prices

The market price on the external electricity market is defined by the following input (see section 2.4 and 4.3):

- An hour by hour distribution of prices
- A multiplication factor
- An addition factor
- A dependency factor (dependency of import/export)

From these inputs, the system price is calculated as described in section 4.3.

Based on such hour by hour system prices, the model offers the following three different ways of calculating the pricing of import/export.

The three different market models are chosen by activating the "Market model" button under the "Regulation window" (See section 2.4)

### 12.1 Market model 1: System price

In model 1, the payment for import export is simply found by multiplying the import/export by the system price.

### 12.2 Market model 2: Export bottleneck

In model 2, a separation in price areas is introduced, if *export* reaches the limitation of the transmission capacity. In case of critical surplus production, the internal price is set to zero, and in other situations, the internal market price is defined by the short-term marginal costs of the power plant.

### 12.3 Market model 3: Both export and import bottleneck

In model 3, the bottleneck separation in price areas is introduced for both *export* (equal to model 2) and *import*. Critical surplus production is not relevant for import situations, but in the situations of limitations in the transmission capacity, the prices are defined as the system price + 150 DDK/MWh.

---

## 13. Fuel and CO2 accounts

Given a number of inputs, the model will make a fuel account and a CO2 account. Furthermore, the model can be activated to calculate all relevant short-term marginal costs and use them to maximise revenues on the external electricity market.

### 13.1 Fuel account

The fuel account in the model is divided into the following types of fuel:

- Coal
- Oil
- Natural Gas, and
- Biomass

For each energy unit in the model (DHP, CHP2, CHP3, Boiler2, Boiler 3 and PP), the distribution on fuel types are stated as input (See section 2.5). Additional fuel distributions for external components (Transport, Households, Industry and Various) can be described as input as well in order for the model to calculate a complete fuel and CO2 account for the total energy system of the region.

In the calculation, the input fuel consumption for the four external components is simply added to the account. For the rest of the components, the distribution is calculated relatively. The total fuel consumption of each energy unit is the result of the system analyses described in section 5 and 6. Given the total fuel consumption, the distribution on the four fuel types is calculated relatively according to the input values.

If for instance

- the total energy consumption for the DHP unit is found to be 10 TWh, and
  - the input fuel distribution is stated as follows: Coal=1, Oil=1, Ngas=2, Biomass=1
- Then the result will be: Coal=2, Oil=2, Ngas=4, Biomass=2, Total=10.

The model can be told to consider limitations in some of the fuel types by activating the "Variable / Fixed" Button in input.

If for instance

- the total energy consumption for the DHP unit is found to be 10 TWh, and
  - the input fuel distribution is stated as follows: Coal=1, Oil=1, Ngas=2, Biomass=1
  - **and the button for biomass is activated as "Fixed"**
- Then the result will be: Coal=2.25, Oil=2.25, Ngas=4.5, Biomass=1, Total=10.

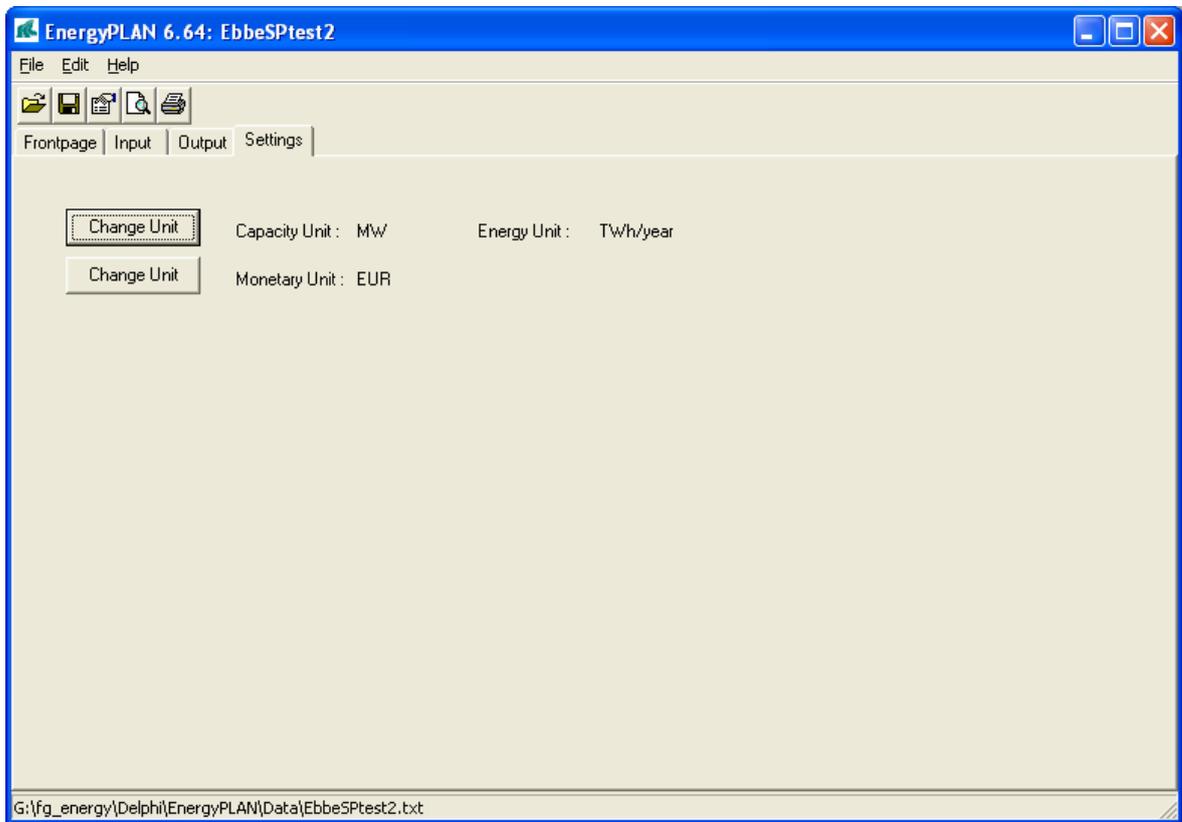
If **all** buttons are activated on "fixed", then the model is told to consider them all as "variable". The model also makes an import/export corrected fuel account: This is done simply by using the input data for the PP unit to adjust the import/export. In the final account, wind power, photo voltaic and solar thermal are added to the account as a fifth type of fuel named "Renewable"

### 13.2 CO2 Account

Given the CO2 emission (kg/GJ) for each of the four fuel types as an input, the model calculates the CO2 emission simply by multiplying the fuel consumption by the emission data.

The model also calculates an import/export-corrected CO2 emission by using the import/export-corrected fuel account.

## 14. Settings



In the settings window, one can define the energy units and monetary units.

The unit is changed by activating one of the buttons “Change Unit”.

Note: No input or output numbers will be changed by activating the bottom. Only the writing of units in the windows and on the printed pages are changed.

The energy/capacity units can be changed between the following combinations:

- kW and GWh/year
- MW and TWh/year
- GW and PWh/year

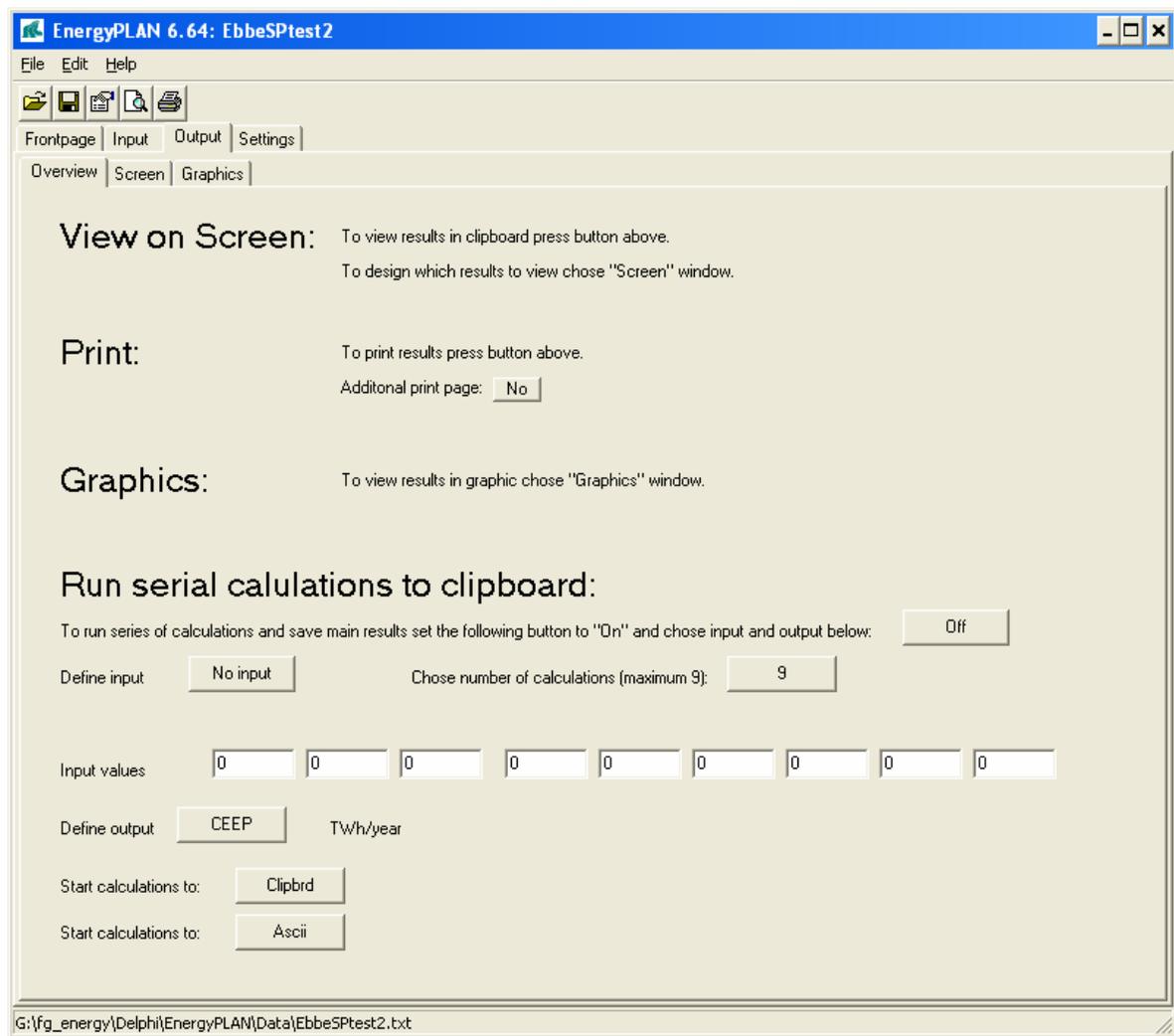
## 15. Output

The output can be shown and/or exported from the model in the following ways:

Results can be viewed on the screen. All calculated results of each unit in the system can be shown both on an annual and a monthly basis. Moreover, one can see each hour by hour value. In the “Screen” window, one can design exactly what to see.

Results can be printed in an A4 version defined by the model. One can choose to add an additional page of specifications.

Results can be shown graphically and exported by the clipboard function



Moreover, the output window allows for running series of up to 9 calculations by activating the “Run series calculations”. The calculations are started by activating either the “Clipbrd” or the “Ascii” buttons. In the first case, the results are put into the clipboard and can be loaded into any windows program such as Word or Excel by the Ctrl+V function.

Before starting the series calculations, one has to

- define which input parameters are to be changed by activating the “Define input” button

- define how many calculations are to be carried out by activating the “series number” bottom
- define a value of each input by writing inputs in the “input values” column, and
- define which output parameter one wants to save in the Clipbrd/Ascii function by activating the “define output” bottom.

The programme provides information on the number of calculations made.

### 15.1 The screen function

The function can be activated in the upper line of the main display of the programme in the picture called "view clipboard". When activating this facility, the programme will start calculating and then open a text file, in which the results are shown. By using the general cut and paste function in windows, the figures can be exported to other programs.

The screenshot shows a window titled "EnergyPLAN 6.64: EbbeSPtest2" with a menu bar (File, Edit, Help) and a toolbar. The main area displays a text file with the following content:

```

Fuel Consumption (excl. H2) = 489.87
Fuel Consumption (incl. H2) = 530.86
Fuel Consumption (corrected) = 456.65
Coal Consumption = 231.11
Oil Consumption = 23.30
Ngas Consumption = 52.62
V2G Pre Load Hour = 0

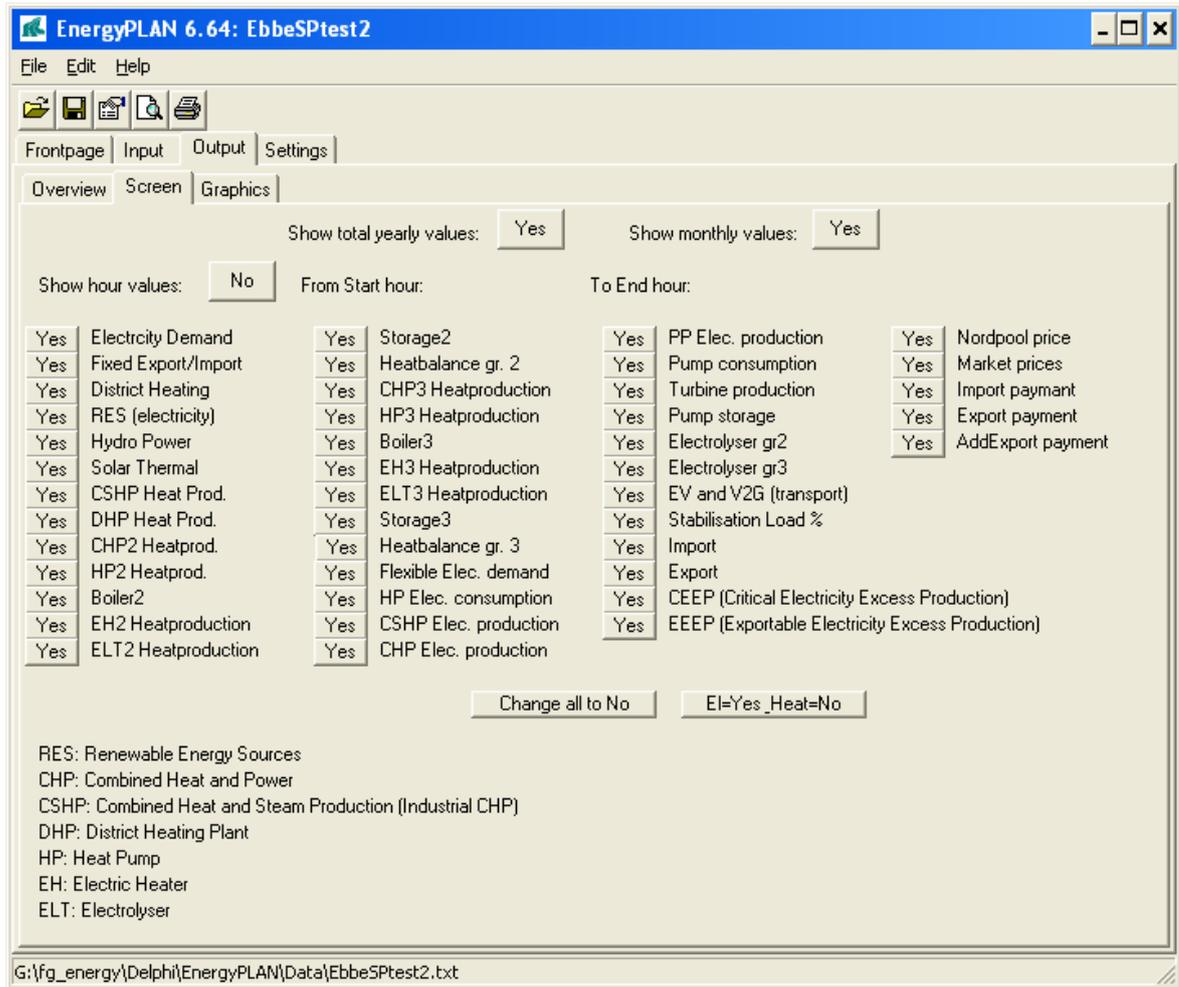
elec. demand    Fixed Exp/Imp    district heating    wind power    Offshore wind    PV    River hydro    Hydro power    Hydro pump
TOTAL FOR ONE YEAR (TWh/year):
Annual:         235.41         0.00         0.05         15.60         0.00         0.02         26.59         18.99         0.00

MONTHLY AVERAGE VALUES (MW):
January         27156         0         11         2359         0         1         3826         2040         0
February       27965         0         11         1571         0         1         2952         2266         0
March          27741         0         8         1973         0         2         2848         2237         0
April          24992         0         8         2101         0         2         3167         2125         0
May            24915         0         3         1411         0         2         4111         2048         0
June           27039         0         3         1487         0         3         3108         2224         0
July           27871         0         2         1304         0         3         2418         2286         0
August         25691         0         2         1538         0         3         2223         2149         0
September     26858         0         2         1691         0         2         2194         2232         0
October       25117         0         2         1969         0         1         2254         2103         0
November     27677         0         8         1855         0         1         3015         2140         0
December     28632         0         8         2037         0         1         4181         2101         0

Average        26800         0         6         1776         0         2         3027         2162         0
Maximum        38105         0         11        4550         0         10        4181         4438         0
Minimum        15466         0         2         80          0         0         2194         0          0
    
```

The status bar at the bottom shows the file path: G:\fg\_energy\Delphi\EnergyPLAN\Data\EbbeSPtest2.txt

The user can define the results to be shown in the "Setup" window in the EnergyPLAN model. All hour by hour data for all the calculations are available.



### 15.2 The print

The function can be activated in the upper line of the main display of the programme in the picture called "printer". When activating this facility, the programme will start calculating and then send a print to the printer. An example is shown below.

Input										The EnergyPLAN model 6.64																													
Wind	4550 MW	15.60 TWh/year	0.00	Grid	Capacities					Efficiencies					Regulation Strategy					Market Model:																			
Offshore Wind	0 MW	0 TWh/year	0.00	stabilisation	Group 2:	MW-e	MJ/s	elec.	Ther	COP	KEOL regulation	24100	Minimum Stabliisation share					0.00	Hydro Pump:					0	0.50														
Photo Voltaic	10 MW	0.02 TWh/year	0.00	share	CHP	1	2	0.25	0.54	3.00	Stabilisation share of CHP	0.00	Stabilisation share of wind					0.00	Hydro Turbine:					0	0.57														
River Hydro	4181 MW	26.59 TWh/year	0.00		Heat Pump	0	0				Stabilisation share of wind	0.00	Heat Pump maximum share					0.50	Electrolyser Gr.2:					0	0.40	0.50													
Electricity demand, fixed	235.41	TWh/year			Boiler	0	0				Heat Pump maximum share	0.50	Minimum CHP gr 3 load					2000 MW	Hydrostorage:					23	GWh														
Electricity for transportation	0.00	TWh/year			Group 3:	CHP	2000	0	0.35	0.87	Maximum import/export	17000 MW	Addition factor					0.00 EUR/MWh	H2storage Gr.2:					0	GWh														
Flexible demand (day)	0.00	TWh/year	1000 MW		Heat Pump	0	0				3.00	Multiplication factor					3.00	H2storage Gr.3:					0	GWh															
Flexible demand (week)	0.00	TWh/year	1000 MW		Boiler	0	0				3.00	Dependency factor					0.00 EUR/GWh																						
Flexible demand (4 weeks)	0.00	TWh/year	1000 MW		Condensing	26754					0.35	Non predictability value					0.00 EUR/MWh																						
Total electricity demand)	235.41	TWh/year			Electricity production	Gr.1: 0.00	TWh/year					Import regulation price					41 EUR/MWh																						
District heating (TWh/year)			Gr.1	Gr.2	Gr.3	Sum	Heatsstorage:	gr.2: 0 GWh	gr.3: 0 GWh	Fixed Boiler:	gr.2: 0.0	Per cent	gr.3: 0.0	Per cent	PP export reg. price	41 EUR/MWh																							
District heating demand	0.05	0.00	0.00	0.05			from CSHP	Gr.2: 27.88	TWh/year			CHP export reg. price					9999 EUR/MWh																						
Solar Thermal	0.00	0.00	0.00	0.00				Gr.3: 0.00	TWh/year			HP export reg. price					9999 EUR/MWh																						
Industrial CHP (CSHP)	0.00	0.00	0.00	0.00																																			
Demand after solar and CSHP	0.05	0.00	0.00	0.05																																			
Output																																							
District Heating										Consumption										Electricity										Exchange									
Demand										Production										Production										Balance					Payment				
Dist. heating MW										Solar CSHP DHP CHP HP ELT Boiler EH										Elec. demand MW Flexible MW HP MW Electrolyser MW EH MW Hydro Pump MW Turbine MW RES MW Hydro clear MW CSHP MW PP MW										Stab-Load % Imp MW Exp MW CEEP MW EEP MW					Imp Exp Million EUR				
January	11	0	0	11	0	0	0	0	0	0	0	27156	0	0	0	0	0	0	6186	2010	7902	3174	0	10939	100	105	3060	0	3060	2	92								
February	11	0	0	11	0	0	0	0	0	0	0	27965	0	0	0	0	0	0	4525	2295	6947	3174	0	13859	100	173	3008	0	3008	4	85								
March	8	0	0	8	0	0	0	0	0	0	0	27741	0	0	0	0	0	0	4823	2242	6688	3174	0	14093	100	131	3407	0	3407	3	103								
April	8	0	0	8	0	0	0	0	0	0	0	24992	0	0	0	0	0	0	5270	2105	6427	3174	0	10571	100	171	2827	0	2827	5	82								
May	3	0	0	3	0	0	0	0	0	0	0	24915	0	0	0	0	0	0	5524	2063	7207	3174	0	9461	100	193	2707	0	2707	5	82								
June	3	0	0	3	0	0	0	0	0	0	0	27039	0	0	0	0	0	0	4598	2247	7208	3174	0	12246	100	415	2850	0	2850	10	83								
July	2	0	0	2	0	0	0	0	0	0	0	27871	0	0	0	0	0	0	3725	2321	7642	3174	0	13622	100	359	2982	0	2982	10	98								
August	2	0	0	2	0	0	0	0	0	0	0	25691	0	0	0	0	0	0	3764	2145	7722	3174	0	12080	100	65	3260	0	3260	2	98								
September	2	0	0	2	0	0	0	0	0	0	0	26658	0	0	0	0	0	0	3887	2232	6513	3174	0	14486	100	66	3500	0	3500	2	102								
October	2	0	0	2	0	0	0	0	0	0	0	25117	0	0	0	0	0	0	4225	2082	6947	3174	0	11894	100	84	3260	0	3260	2	98								
November	8	0	0	8	0	0	0	0	0	0	0	27677	0	0	0	0	0	0	4871	2126	7642	3174	0	13337	100	106	3279	0	3279	2	96								
December	8	0	0	8	0	0	0	0	0	0	0	25632	0	0	0	0	0	0	6219	2085	7989	3174	0	12341	100	101	3276	0	3276	2	99								
Average	6	0	0	6	0	0	0	0	0	0	0	26800	0	0	0	0	0	0	4804	2162	7241	3174	0	12374	100	163	3118	0	3118	Average price (EUR/MWh)									
Maximum	11	0	0	11	0	0	0	0	0	0	0	39105	0	0	0	0	0	0	8024	4549	7989	3174	0	26285	100	9971	6065	0	6066	34	41								
Minimum	2	0	0	2	0	0	0	0	0	0	0	15466	0	0	0	0	0	0	2515	0	6428	3174	0	0	0	0	0	0	0	0	0								
Total for the whole year																																							
TWh/year	0.05	0.00	0.00	0.05	0.00	0.00	0.00	0.00	0.00	0.00	0.00	235.41	0.00	0.00	0.00	0.00	0.00	0.00	42.20	18.99	63.60	27.88	0.00	108.70	1.43	27.39	0.00	27.39	48	1110									
FUEL BALANCE (TWh/year):																																							
	DHP	CHP2	CHP3	Boiler2	Boiler3	PP	Nuclear	Hydro	Ele.ly.2	Ele.ly.3	CAES	Wind	Offsh.	PV	Hydro	Solar.Th	Transp.	househ.	Industry	Various	Total	Imp/Exp	Corrected	CO2 emission (Mt):	Total	Netto													
Coal	-	-	-	-	-	-	231.08	-	-	-	-	-	-	-	-	-	-	-	-	-	-	231.08	-55.19	175.89	63.89	48.63													
Oil	-	-	-	-	-	-	23.30	-	-	-	-	-	-	-	-	-	-	-	-	-	-	23.30	-5.56	17.73	6.21	4.72													
N.Gas	-	-	-	-	-	-	52.61	-	-	-	-	-	-	-	-	-	-	-	-	-	-	52.61	-12.57	40.05	10.74	8.17													
Biomass	0.06	-	-	-	-	-	3.58	-	-	-	-	-	-	-	-	-	-	-	-	-	-	3.64	-0.85	2.79	0.00	0.00													
Renewable	-	-	-	-	-	-	-	18.99	-	-	-	15.60	-	0.02	26.59	-	-	-	-	-	-	61.19	0.00	61.19	0.00	0.00													
H2 etc.	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0.00	0.00	0.00	0.00	0.00													
Nuclear	-	-	-	-	-	-	159.01	-	-	-	-	-	-	-	-	-	-	-	-	-	-	159.01	0.00	159.01	0.00	0.00													
Total	0.06	-	-	-	-	-	310.56	159.01	18.99	-	-	15.60	-	0.02	26.59	-	-	-	-	-	-	530.82	-74.18	456.65	80.83	61.53													

Diagram 5: Example of output data

### 15.3 Graphics

By activating the "Graphics" window, the results can be illustrated graphically using the hour by hour values.

- Three choices are offered by activating the buttons in the lower left corner:
- The model is able to show the electricity balance, the district heating balance, or the flexible electricity demand. Three diagrams are shown for each of the items.
- The length of the diagrams can be shown either for one day, three days, one week or one month.
- The diagrams can be shown either in colour or in monochrome (black and white).

The results can be shown for all periods of the year by activating the two buttons "Forward" and "Back".

Also, the diagrams can be exported by activating the "clipboard" button located in the upper right corner of each diagram.

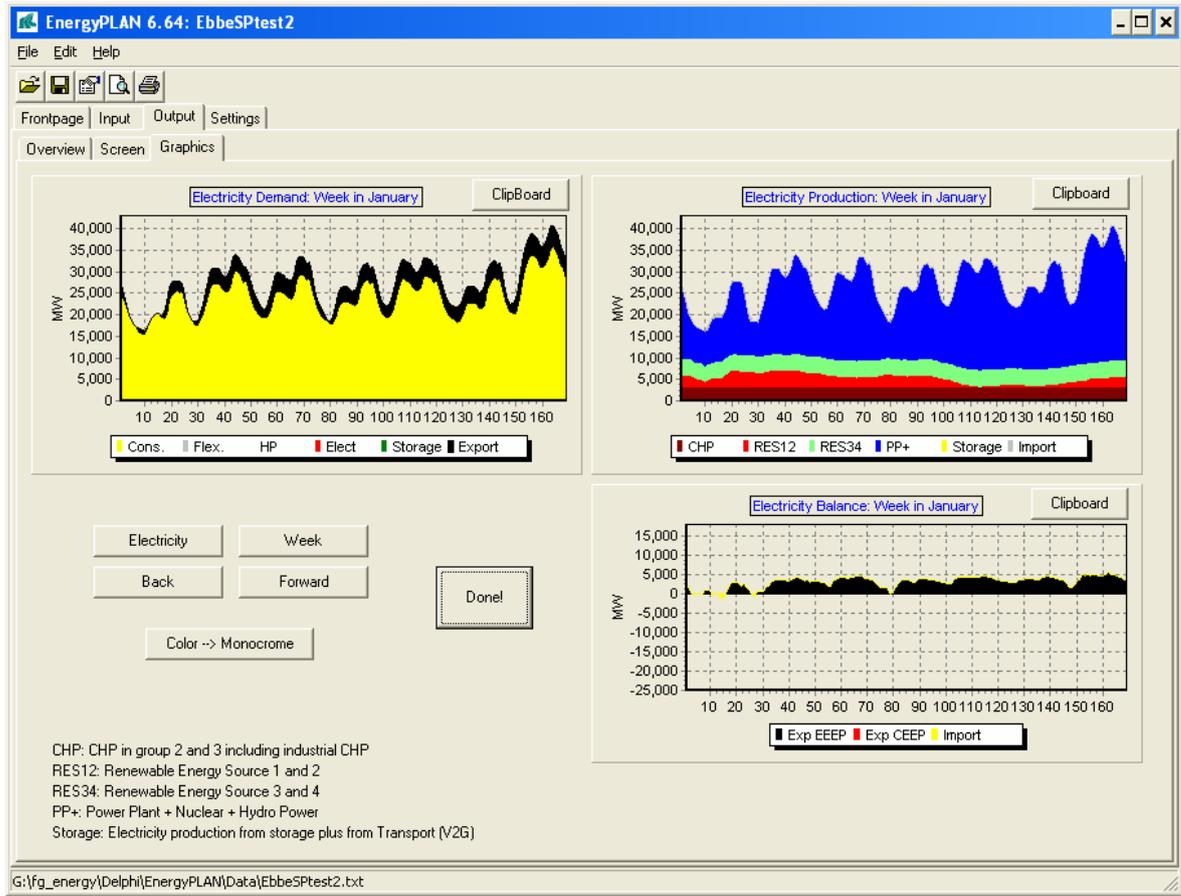


Diagram 6: Example of graphical illustrations of results