Interactive simulation of electricity demand and production
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PowerPlan: the supply model

PowerPlan is an interactive simulation model about the planning of electricity supply. Starting from a reference year, the electric power system is simulated. At each planning interval (which can be one or more years), decisions must be made to build new electric power plants and/or to invest in energy conservation (‘Negawatts’) and/or decentralized capacity. At the end of each simulation step the results (costs, reliability, fuel use, emissions) can be examined and used as an aid for the input of the next planning round. In this chapter the technical background of the model is presented.

5.1 Introduction

In most countries, nowadays the electricity generation is coordinated by a central (public or private) electricity board. Such a board is held responsible for the reliable and cost-effective generation of the electricity required. Decentral capacity is seen in most countries as an option with a minor contribution compared to that of the total electricity production. Electricity conservation and decentralized generation of electricity are carried out (by distribution utilities or end-users) largely out of sight of the central producers. There are various interactions between the central board and private producers of electricity. For example, in the management of commonly occurring win-win situations an industry can be asked to deliver electricity in peak hours to the public grid with a cogeneration plant or be asked to stop a production process.

PowerPlan is based on the perspective of a central electricity board, in control of the central demand/supply balance in a country or region, in contrast to the decentral part served by distribution utilities or end-users. Investments in decentral capacity and conservation measures are possible; these investments are kept separated from central made investments. The central demand is the total electricity demand from which the decentral electricity generated and the conservation measures are subtracted. This chapter describes the way central and decentral electricity generation and conservation are modelled in PowerPlan.

5.2 PowerPlan, the structure

The core of the PowerPlan model simulates the electric power generation in a given year. A complete one year calculation cycle is as follows. The annual demand for electricity is calculated from the Load Duration Curve (LDC) and
Chapter 5

The Simultaneous Maximum Demand (SMD). The means of production are the electricity generating equipment installed. Using the merit-order approach, annual fuel inputs are calculated from the electricity generated per plant. In combination with exogenous fuel-price time-series, investment costs and interest rate, kWhe-generating costs are calculated. The emissions are calculated from the fuel use, fuel and power plant characteristics. Then, in turn, the growth of the electricity demand for the next period is calculated. Therefore exogenously given economic growth and the price elasticity time-series, or directly available SMD-growth time-series are used.

The PowerPlan model consists of four modules:
1. a macro-economic forecasting module from which the growth in electricity demand is determined by:
   - the growth rate of the electricity demand which is assumed to be linear with the growth rate of the population, and
   - the economic growth (GDP growth per Caput) coupled by an elasticity (GDP elas.).
2. the production simulation module in which the electricity production (El. production) is calculated from the LDC and the SMD, and in which the supply reliability of the generating system (Gen. System) is calculated. The SMD and LDC can be influenced by the installation of decentral capacity and by conservation measures (Dec. Cons.).
3. a costs module in which the kWhe cost-price is calculated using fixed (investments, Gen. System characteristics), variable (fuel costs = Fuel use * Fuel Price) and Transmission & Distribution (T&D) costs data. Changes in the kWhe cost-price influence the SMD for the next planning round.
4. the fuel and environment module in which the fuel use and their associated emissions as well as other solid waste products are calculated, depending on the electricity generated, Gen. System characteristics and Fuel quality.

Figure 5.1 shows a diagram containing the structure of PowerPlan with its basic feedback relations and the main exogenous information flows.

The data set used in the model can be divided into three subsets:
1. "Strong"**1** input data, i.e. facts which need no further discussion: e.g. CO₂ emission factors, technical specifications of power plants already present and those under construction (efficiency, capacity, fuel, first and last year of operation, SO₂-emission reduction and NOₓ-emission, fixed and O&M costs,

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1 "Strong" = the potential for empirical falsification in repeated, controlled experiments [De Vries, 1989 and Groenewold, 1981].
planned and unplanned outage) and the LDC.

2. "Weak" input data, i.e. scenario variables: the user must make assumptions or explicit expectations about future developments of crucial time-series (e.g. oil price paths, growth of the GDP per capita), other variables (e.g. price-elasticities) and specifications of future power plants. These exogenous variables define the context of the simulation.

3. Decision variables, i.e. input data during a simulation: e.g. the type of power plants and decentralized capacity that should be installed, which conservation measures should be taken, which pollution abatement measures should be implemented.

The system simulation results in scenarios concerning capacity installed, electricity generated, reliability, emissions, solid waste, fuel use and costs. Most of the output can be made available in tables as well as in graphs.
In the next section the relations used and the model assumptions made are discussed in more detail.

5.3 Electricity demand

Planning models often use as input an annual chronological demand pattern consisting of hourly averaged electricity demand values. The calculations are necessarily time-consuming. An interactive simulation model requires a different approach. PowerPlan uses only the integral of the Load Duration Curve (LDC, represented by 10-250 points) to calculate the electricity demand. This LDC is normalized, so the electricity demand is calculated from the SMD and the integral under the LDC. The shape of the LDC is kept constant over (parts of) the planning period, so the growth of the electricity demand is determined by the increase of the annual peak demand or SMD (MWe). The SMD-growth can be specified as an exogenous time-series or determined on the basis of the Population growth rate (ΔPop/Pop), the growth rate of the Gross Domestic Product per Capita (ΔGDPC/GDPC), the GDP-Electricity-Elasticity (GEE) and the Short Run and Long Run Price Elasticities (SRPE, LRPE). In formula:

\[ SMD_{t+1} = SMD_t \times \left( \frac{\Delta \text{Pop}_t}{\text{Pop}_t} + 1 \right) \times \left( \frac{\Delta \text{GDPC}_t}{\text{GDPC}_t} \times \text{GEE} + 1 \right) \times f(EP) \quad \text{(MWe)} \]  

(5.1)

with \( t \) the time subscript and \( f(EP) \) a function which depends on the Electricity Price as discussed below.

The GDP-Electricity-Elasticity is defined as:

\[ GEE_t = \frac{\Delta SMD_t}{SMD_t} \times \frac{\text{GDP}_t}{\Delta \text{GDPC}_t} \]  

(5.2)

In the model this is a time-series which can be adjusted by the user for the whole planning period\(^2\), this elasticity is often used in scenario studies. Figure 5.2 shows an example of the GDP-Electricity-Elasticity together with the GDP and the Electricity demand for the Netherlands (1960-1990).

Changes in this elasticity can result from several developments:
- structural change: engagement of electricity in- or extensive industries. In the

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\(^2\) One assumes that population increase within a year is small so:
\[ \Delta \text{GDPC}/\text{GDPC} = \Delta \text{GDP}/\text{GDP}. \]
Netherlands, for example electricity-intensive industries grew rapidly around 1970 [Molag, 1979] (+/-);

- electrification c.q. substitution of fossil fuels by electricity: electric car, electric heat pump for space heating, etc. (+);
- autonomous electricity conservation (-);
- introduction of new technologies: PC, fax etc. (+/-).

A + sign indicate an increase and the - sign indicate a decrease of the elasticity. A positive sign means an increase of the electricity use per unit GDP and thus a positive value for the elasticity.

The function \( f(E) \) represents the time-lag of the reaction of electricity demand to changes in the electricity price (EP):

\[
f(E) = \left[ \frac{E_{t}}{E_{t-1}} \right]^{SRPE} \ast \left[ a_{1} \ast \frac{E_{t-1}}{E_{t-2}} + a_{2} \ast \frac{E_{t-2}}{E_{t-3}} + a_{3} \ast \frac{E_{t-3}}{E_{t-4}} \right]^{LRPE}
\]  

(5.3)

in which \( a_{1}, a_{2} \) and \( a_{3} \) are constants (which add up to 1) representing the distribution of the price effect over time. \( SRPE \) and \( LRPE \) denote the short-run and the long-run price elasticity, respectively. The short-run price elasticity represents actions a consumer can take immediately, like switching off lights in places where no lighting is needed. The long-run price elasticity represents the
longer-term strategic and investment-response behaviour like buying more energy-efficient appliances if old ones have to be replaced. Fair values for both SRPE and LRPE range from 0 to -2 [Ford, 1983, Van Helden, 1987, Mount, 1974 and Taylor, 1975]. This relation should be seen as a "weak" variable and it should be used carefully if at all, in scenario studies.

If the growth rate of the SMD is defined as a time-series and is used instead of the growth rate of the GDP and the elasticities, the SMD is defined as follows:

$$SMD_{t+1} = SMD_t \times (1 + \frac{SMD_{t}}{SMD_t}) \text{ (MWe)}$$  \hspace{1cm} (5.4)

Thus far the growth of the electricity peak demand is calculated when only central demand and production of electricity are taken into account. If one also wants to simulate the decentral electricity demand and production, the calculations and the input data will be influenced:

- the SMD growth obtained from a time-series or calculated represents the total (central and decentral) SMD growth
- the central SMD equals the total SMD minus the Decentral SMD
- the shape of the LDC, as seen by the central producers, is influenced by the decentral electricity demand/production.

From the viewpoint of the central producers, the production with decentral units and the contribution of conservation efforts can be handled as a negative demand referred to as "Negawatts".

In formula:

$$SMD_{centr,t+1} = SMD_{centr,t} \times (1 + SMD\text{growth}_{t+1}) - SMD_{decentr,t} \text{ (MWe)}$$  \hspace{1cm} (5.5)

The decentral peak demand is defined as the cumulative peak demand of all separate decentral and conservation options installed in year t.

The influence of electricity conservation and decentral electricity production on the LDC is described in section 5.4.2.

For planning purposes the user can inspect the forecasted SMD for a 12-year planning period ahead. For this purpose, Formula (5.1) is used without the function f(EP). Here the electricity demand met by the central utility system (i.e. what remains after the contribution of end-use conservation and private generation) is taken into account.

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3 Central demand/production denotes demand/production as perceived by the central electricity generating organisation, in contrast to the decentral part served by distribution utilities or end-users.
5.4 Electricity generation

As described in section 5.1, PowerPlan is based on the perspective of the central demand/production system. The decentral demand/production and conservation measures have their own way to be calculated since they are considered to be beyond the influence of the central utilities.

5.4.1 Central electricity generation

PowerPlan uses the LDC as the representation of the electricity demand in the calculation of the amount of electricity to be generated in order to meet the demand. This LDC is filled with the electricity production data of existing power plants according to a certain merit order. For these calculations the so-called Cumulant Method\(^4\) is used [Stremel, 1980]. This method is based on a probabilistic approach of unit outage. Each unit has an (unplanned) outage probability: \(p\), which designates the time fraction the unit is not available and probability: \(1-p\), designating the time that a plant is fully available (fair values of \(p\) range from 0.01 for Hydro to 0.12 for nuclear power plants [IEEE, 1979]).

The LDC is parameterized by a number of cumulants. These cumulants are used to calculate the load of each separate unit. A detailed description of this method as it is implemented in PowerPlan is given elsewhere [Dijk, 1989]. Revision planning (or planned outage) as illustrated in Figure 5.3 is not taken into account in PowerPlan. Instead, the capacity of each power plant is derated with an average fixed percentage throughout the year (cf. Figure 5.4). This percentage of the derated capacity equals the percentage of a year a certain unit is taken out of operation for revision. For illustration purposes only a part of the surface of the curves are filled (5 power plants in the example) in Figure 5.3 and Figure 5.4. The surfaces of the 5 (hatched) power plants match each other. So, the year average of available capacity and thus the maximum amount of electricity generated per power plant per year match each other.

With the Cumulant Method one calculates both electricity generated and two system reliability parameters: the so-called Loss Of Load Probability (LOLP) and the amount of Unserved Electricity (EUE). The LOLP is a widely-used measure of the aggregate match between generating capacity and load on a

\(^4\) The Cumulant Method is essentially a method to approximate the probabilistic representation of the load curve plus unit outages [Baleriaux, 1967 and Booth, 1972]. The advantage of this representation is that it yields one conceptual framework for both electricity generation estimates and system reliability. The cumulant method [Schenk, 1981 and Stremel, 1980], is a reasonably accurate and fast approximation method and so suitable for interactive modelling.
single electric utility grid. The LOLP is usually expressed as the number of
hours per year (or the number of days in a 10 year period) during which
installed generating capacity cannot meet instantaneous electricity demand. The
EUE gives the amount of energy in GWhe per year that is expected to remain
unserved as a result of loss-of-load incidents. Typical values for the LOLP and
for the EUE in Western Europe are in the order of 1 day per 10 year period or
one kWhe per GWhe of end-use respectively. It should be noted that reliability
estimates in PowerPlan refer to those generating units that are designated as

Figure 5.3: Schematic real time one year curve with revision
planning (each pattern corresponds with a specific power plant),
see also Figure 5.4.

Figure 5.4: One year Load Duration Curve (re-arranged time)
with derating of capacity (surfaces of the 5 derated power plants
equal those in Figure 5.3.)
centrally planned capacity only.

Another important approximation concerns the way individual power plant operation is simulated. Most utilities use some optimisation routine for unit-dispatch. This leads to a certain order in which existing plants are put into operation as load increases [IAEA, 1984 and Kahn, 1988]. This order is called the merit-order and reflects variations in production costs. Thus, a nuclear or hydro plant with relatively low or zero fuel costs will always be used for base-load purposes i.e. run as many hours a year as is technically feasible.

This is also the approach taken in PowerPlan. However, the merit-order in PowerPlan is not the result of an endogenous optimisation (for example based on cost) but is determined exogenously by predetermining the order of the various power plant types on the input file (e.g. hydro, nuclear, coal-fired, combined-cycle, gas turbine)\(^5\). This initial ranking is refined in two further steps. First, the individual generating units within each category are sorted according to the year of plant-commissioning. Second, all plants are labelled as a base-load, a middle-load or a peak-load unit. In the ranking example given above, the result is that initially the group of coal-fired plants is dispatched before combined-cycle plants. Within each group, the members are individually ranked according to age. Old or otherwise exceptional plants, e.g. coal-fired plants without flue-gas desulphurisation, may be labelled as peak-load units. The reverse may also take place, e.g. highly efficient (gas-fired) combined-cycle units may get higher priority than coal-fired plants. This initial ranking with its refinements gives the user of PowerPlan ample flexibility to specify the merit-order according to his own judgment.

Users are allowed to define up to 10 types of units which refer to this merit-order approach; within each type up to 4 specifications are possible. These specifications give the user the possibility to choose between e.g. a cheap coal-fired plant without Flue Gas Desulphurisation (FGD) or a more expensive one with FGD equipment installed.

\section*{5.4.2 Decentral electricity generation}

As mentioned before decentrally generated electricity and conservation measures are treated differently from centrally generated electricity.

Installed decentral capacity operates on a fixed and predefined load. For each

\footnote{\textit{In PowerPlan the user can define up to 10 different types of power plants. Within a type 4 power plants with their specific characteristics can be defined. These maximal 40 different power plants form the order book for the central utilities. This order book can be adjusted during the simulation, representing technology improvements.}}
type of decentral capacity a simplified load curve is defined. The hours in the LDC are divided in three parts, e.g.: 0-2000 (peak load), 2000-6000 (mid load) and 6000-8760 (base load) hours (cf. Figure 5.5). For each type of decentral capacity or conservation option\(^6\) the fraction for each of these three parts is specified. This fraction represents the part of the capacity which is used during the chosen part of the LDC. The three dotted rectangles are determined by the definition of Peak, Middle and Base load hours and by the accompanying decentral capacity or conservation fractions (PFr, MFr and BFr). The surface of these rectangles equals the electricity generated or saved ("Negawatts") by the chosen decentral capacity and conservation options. In order to smooth the rectangular shaped surface to be subtracted from the LDC as seen by the central utilities, a curve is calculated from the three fractions (PFr, MFr and BFr), that connects the points PP, PM, MB and BB, see Figure 5.5. Finally all the decentral capacity and conservation options are subtracted, the LDC is resorted and normalized.

The three load fractions for each option can be obtained from chronological data. Figure 5.6 shows the load for Photo-Voltaic cells. In determining the LDC for Solar PV, first the chronological load data for Solar PV should be coupled to those of the total electricity demand. Second, the demand curve is sorted to

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\(^6\) In PowerPlan the user can define up to 10 different types of decentral capacity and/or conservation measures options. Within a type 4 sub-types with their specific characteristics can be defined. These maximal 40 different options form the order book for the distribution utilities and end-users. The characteristics can be adjusted during the simulation, representing technology improvements.
an LDC and thus the load of PV cells is sorted with it, so for each hour in the
LDC the load of solar PV is known. Third, the load in the first 2000 hours is
averaged and becomes the first fraction. The same is done for the two other
parts of the LDC. The so determined fractions are decreased with the unplanned
outage of the conservation or decentral capacity type. It is assumed that the
fractions remain constant if the LDC changes by increasing use of decentral
capacity or conservation and the load hours have to be resorted.

For each type of decentral capacity or conservation 4 different specifications are
possible in the model. With these 4 specifications it is possible to simulate the
decreasing load for e.g. solar PV as the result of reaching the technical
potential. In Table 5.1 an example for solar PV is given. The first row
(# PV = 1) specifies those PV units which are installed on locations with the
highest yield, in this example 100 MWe (see also Figure 5.6). In the peak hours
(0-2000), each unit generates 0.21 MWh per MWe installed, etc..
Table 5.1: Load fractions for 4 Solar PV cells.

<table>
<thead>
<tr>
<th>#PV</th>
<th>Peak Fraction 0-2000 (hrs)</th>
<th>Middle Fraction 2000-6000 (hrs)</th>
<th>Base Fraction 6000-8760 (hrs)</th>
<th>Capacity (MWe)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.21</td>
<td>0.11</td>
<td>0.05</td>
<td>0.100</td>
</tr>
<tr>
<td>2</td>
<td>0.19</td>
<td>0.09</td>
<td>0.04</td>
<td>0.500</td>
</tr>
<tr>
<td>3</td>
<td>0.17</td>
<td>0.08</td>
<td>0.03</td>
<td>0.500-1.000</td>
</tr>
<tr>
<td>4</td>
<td>0.15</td>
<td>0.07</td>
<td>0.02</td>
<td>1.000+</td>
</tr>
</tbody>
</table>

Three other differences compared with centrally planned capacity must be mentioned:

- Retrofitting is not possible for decentral capacity.
- Once installed, the decentral capacity or a conservation measure will be automatically reinstalled after the technical lifetime has passed and thus remain operational till the end of the planning period. At the moment of reinstallation PowerPlan checks if the specifications (e.g. better efficiency) are changed. If so these new characteristics will be allocated to this renewed capacity.
- Decentral capacity and conservation are seen as a set of small 'units' which do not become operational all at once but spread out over time, called the penetration. The first year of operation is thus: year of decision + year(s) for construction + year(s) for penetration. In Figure 5.7 two examples illustrate the penetration of 5 and 6 years respectively (construction time of 2 years).
  For large decentral industrial units, this penetration can be set at value 1 (which means no spread over time) if these units represent a separate large unit.

5.5 Generation costs

The costs calculated in PowerPlan are based on exploitation and investment costs; tariffs are not included. PowerPlan contains a price-demand feedback as
described in section 5.3. Following the approach taken in modelling the electricity generation a distinction is made between central and decentral costs.

5.5.1 Costs of centrally generated electricity

The total costs reflected in the kWh e cost price in Monetary Units (MU) is the summation of the fixed (capital) costs, the variable (fuel+operation and maintenance) costs and the Transmission and Distribution (T&D) Costs.

![Figure 5.8: Relations among PowerPlan variables and the kWh e cost-price. Abbreviations used: PE = Price Elasticity, RF = Reserve Factor and ELT = Economic Life Time.](image)

In Figure 5.8 the main relations which determine the kWh e cost-price are presented. In Formula (5.6), the calculation for the costs per kWh e exclusive of the T&D costs for unit i is given:

\[
C_i = \frac{a \times IC_i + PC \times FU_i + \sum_{j=1}^{n} (F_f_j + F_P_j)}{EG_i} + OM_i \quad (MU/kWh) \quad (5.6)
\]

Where:
- \( C_i \) = Costs of electricity for unit i (MU/kWh)
- \( a \) = the annuity factor: \( r/[1 - (1+r)^{-t}] \)
- \( IC_i \) = Investment Costs for unit i (MU/kWe)
- \( PC \) = Plant Capacity (kWe)
- \( FU_i \) = Fuel Used per year for unit i (ton or 1000m³)
Fr\textsubscript{j} = Fraction of a fuel quality j
FP\textsubscript{j} = Fuel Price of a fuel quality j (MU/ton or MU/1000m\textsuperscript{3})
EG\textsubscript{i} = Electricity Generated per year for unit i (kWhe)
O&M\textsubscript{i} = annual operation and maintenance cost for unit i (MU/kWhe)
r = interest rate
L = economic Life-time of unit i

In PowerPlan the T&D Costs (TC) are a function of the Simultaneous Maximum Demand and the T&D Capital Costs (TCC in MU per MW). In Formula (5.7) TC is expressed per kWhe:

\[
TC = \frac{TCC \times a \times SMD}{TEG} \quad (MU/kWhe) \quad (5.7)
\]

Where:
a = the annuity factor: \( r/[1 - (1+r)^{-L}] \)
r = interest rate
L = economic Life-time of the T&D equipment
TEG = Total Electricity Generated

In the model the investments for a power plant are distributed normally over the years of its construction.

The interest rate (r) in Formula (5.6) is a function of the Available Capital (AC) and the Total Investments (TI) for the electricity production. In formula:

\[
r = ACM \times TI \quad (5.8)
\]

\[
ACM = (0.8 + 0.2 \times \exp(-\frac{TI}{AC} - 1)) \quad (5.9)
\]

Where:
II = Initial Interest
0.8, 0.2 = Default values which determine the range of fluctuation

So the Available Capital Multiplier (ACM) fluctuates around 1. If TI and AC are equal, there is a balance on the money market and the ACM = 1. This relation should be seen as a "weak" variable and is added for educational purposes. It should be used carefully if at all, in scenario studies, therefore it can be set optional to the value: ACM = 1, which assumes a money market in balance.
5.5.2 COSTS OF DECENTRALLY GENERATED ELECTRICITY

Costs for decentral units and conservation measures are calculated in the same way as those for central units. There is one essential difference: the investment costs for a unit which include the marginal costs. To implement the change in marginal costs, a supply cost curve is defined for each decentral and conservation type. This supply cost curve produces a multiplier which is a function of the total installed capacity of the decentral and conservation type considered. In formula:

\[ TDIC_i = DIC_i \cdot f(CI) \quad (MU/kWe) \]  \hspace{1cm} (5.10)

Where:  
- \( TDIC \) = Total Decentral Investment Costs for unit i (MU/kWe)  
- \( DIC \) = Decentral Investment Costs for unit i (MU/kWe)  
- \( f(CI) \) = multiplier obtained from the supply cost curve for decentral/conservation type n, which is a function of the Capacity Installed

For example: the multiplier for wind turbines decreases with increasing installed capacity as a result of cheaper production technologies (learning curve effect). In a following stage of expansion it may increase again due to extra investments required to place the turbines in regions with higher investment costs. An example in the Netherlands is an offshore wind turbine island in the North Sea.

5.6 Fuel input

In the version of PowerPlan described in this thesis several types of fuel can be used by power plants: traditional fuels (Coal, Lignite, Peat, Natural Gas, Oil, Uranium) and also: MSW (Municipal Solid Waste), biofuel and hydrogen or blast furnace gas. For each fuel type 4 qualities can be defined with their own characteristics (heat rate, sulphur content etc.). Each power plant has its own fuel which cannot be changed within a given year. Changes in dual or triple firing are thus limited in PowerPlan to changes on an annual basis. A dual firing power plant with a fuel switch within a given year can be modelled by splitting this power plant in 2 separate units, with the ratio in capacity representing the ratio between the 2 different fuels used in that unit and in that year.

The fuel used per power plant can be calculated directly from the electricity generated per unit as described in the previous section, the efficiency and the average combustion enthalpy.
In formula:

\[
FU_i = \frac{EG_i \times 3.6}{Eff_i \times \sum_{j=1}^{n} (Fr_j \times CE_j)} \quad \text{(ton)}
\]  

Where:  
- \(FU_i\) = Fuel Used for unit i (ton, kg or 1000 m³) 
- \(EG_i\) = Electricity Generated for unit i (MWhe) 
- 3.6 = conversion factor from MWhe to GJ 
- \(Eff_i\) = Efficiency for unit i 
- \(Fr_j\) = Fraction of a fuel quality j 
- \(CE_j\) = Combustion Enthalpy (GJ/ton for liquid and solid fuels; GJ/1000 m³ for gas; GJ/kg for uranium).

The efficiency data used in PowerPlan should include a correction for the decrease in efficiency due to flue gas desulphurization and denitrification. The efficiency should also be averaged over the load because in PowerPlan the efficiency is independent of the load of a power plant. Fuel used for the spinning reserve and for pre-heating is not taken into account. This simplification causes a structural underestimation of the fuel used.

5.7 Environmental emissions and solid waste

On the basis of data concerning the fuel used per unit as described in section 5.6, the average fuel quality and the plants specific characteristics the pollution per power plant can be calculated. The summation of these individual pollution data leads to the total gaseous emissions and total solid waste flows. PowerPlan keeps track of SO₂-, NOₓ- and CO₂-emissions, solid waste and particle emissions from solid fuel power plants and nuclear waste.

5.7.1 Gaseous emissions

The most complex of the three possible gaseous emissions is that of SO₂. The components of the supply system which influence the SO₂-emission level as well as the kind of data/input (see also section 5.2) are shown schematically in Figure 5.9.

An input entry can belong to one of three classes distinguished: "strong" variable, "weak" variable or "decision" variable. For example: the efficiency presented here as "strong" input for a given installation can also be seen as a
"weak" variable if it concerns a specification for a future power plant. The $\text{SO}_2$ reduction e.g. is "strong" if it concerns an existing plant but can become a decision variable if a user decides to retrofit an existing plant with a FGD installation.

In formula:

$$SO_2_i = FU_i \times \sum_{j=1}^{4} (Fr_j \times SC_j) \times 2 \times (1-SA) \times (1-FGD_i) \quad \text{(ton)}$$ (5.12)

Where:
- $SO_2_i$ = emission of $\text{SO}_2$ per year for unit i (ton)
- $FU_i$ = Fuel Use per year for unit i (ton or 1000m³) cf. section 5.6
- $Fr_j$ = Fraction of a fuel quality j
- $SC_j$ = Sulphur Content of a fuel quality j (fraction)
- 2 = conversion from S to $\text{SO}_2$
- $SA$ = Sulphur retained in Ash (fraction)
- $FGD_i$ = Flue Gas Desulphurization for unit i (fraction)

![Figure 5.9: Factors influencing $SO_2$-emission.](image)

For each fuel type 4 qualities can be defined with their own characteristics (e.g. heat rate, sulphur content). An example (the coal quality used in the Dutch
power plants in 1990), is given in Table 5.2.

**Table 5.2:** Coal characteristics; the Netherlands 1990.

<table>
<thead>
<tr>
<th>Origin</th>
<th>Fraction used</th>
<th>Combustion Enthalpy (GJ/ton)</th>
<th>Weight % S</th>
<th>Weight % Ash</th>
</tr>
</thead>
<tbody>
<tr>
<td>Poland</td>
<td>0.35</td>
<td>29.0</td>
<td>1.0</td>
<td>10.0</td>
</tr>
<tr>
<td>USA</td>
<td>0.25</td>
<td>26.9</td>
<td>0.7</td>
<td>12.0</td>
</tr>
<tr>
<td>Columbia</td>
<td>0.25</td>
<td>26.0</td>
<td>0.6</td>
<td>9.0</td>
</tr>
<tr>
<td>Australia</td>
<td>0.15</td>
<td>29.0</td>
<td>0.85</td>
<td>10.0</td>
</tr>
</tbody>
</table>

[Source: N.V. KEMA, 1990]

Using the coal described here, a power plant with an efficiency of 40%, with 90% sulphur removal and a SA value of 0.05 emits 495g SO$_2$/MWh. The user of the model has thus the option to set up fuel contracts for the future making use of the 4 qualities per fuel type.

Regarding NO$_x$-emissions PowerPlan uses plant specific emission values (g/GJ). The influence of the fuel-bound nitrogen component cannot be specified separately. Reduction of NO$_x$-emission by Selective Catalytic Reduction (SCR) or other techniques should be introduced as a lower plant-specific emission. The NO$_x$-emission per unit per year can thus be calculated from the Electricity Generated, the Efficiency and the plant Specific NO$_x$-Emission.

In formula:

$$NO_x_i = \frac{EG_i \cdot 3.6}{Eff_i} \cdot SNE_i \text{ (ton)}$$

(5.13)

Where: $NO_x_i = NO_x$-emission per unit $i$ (ton)

$EG_i = Electricity$ Generated per unit $i$ (TWh)

$SNE_i = Specific$ NO$_x$-Emission (ton/PJ)

The calculation of the CO$_2$-emission per unit (CO2 in ton) is implemented similarly. Instead of a plant specific emission a fuel Specific CO$_2$-Emission (SCE in ton/PJ) is used:

$$CO_2_i = \frac{EG_i \cdot 3.6}{Eff_i} \cdot SCE \text{ (ton)}$$

(5.14)
5.7.2 Solid Waste and Particle Emissions

Solid waste disposal from solid fuel fired power plants is calculated as cumulated amounts. There are three different sources for solid waste:

- waste as slag, cf. Formula (5.15);
- waste from electro-static filters, cf. Formula (5.16);
- FGD waste, cf. Formula (5.17).

Part of the coal ash remains as bottom-ash in the form of slag. The main part of the ash is emitted as aerosols with the combustion gases. Nowadays nearly 100% of this fly-ash can be removed from the combustion gases by means of electrostatic filters cf. Formula (5.15).

The amount of solid waste is calculated according to Formula (5.15):

\[
SW_i = FU_i \times \sum_{j=1}^{j=4} (Fr_j \times AC_j) \times (FAR + FPR \times (1-FAR)) \quad \text{(ton)} \tag{5.15}
\]

Where:
- \(SW_i\) = Solid Waste per year for unit i (ton)
- \(FU_i\) = Fuel Use per year for unit i (ton)
- \(Fr_j\) = Fraction of a fuel quality j
- \(AC_j\) = Ash Content of a fuel quality j (fraction)
- \(FAR\) = Fraction of Ash which is Retained as slag
- \(FPR\) = Fraction of Particles which is Retained in the electro-static filter

The resulting Particle Emissions (PE) are calculated according to Formula (5.16):

\[
PE_i = FU_i \times \sum_{j=1}^{j=4} (Fr_j \times AC_j) \times (1-FAR) \times (1-FPR) \quad \text{(ton)} \tag{5.16}
\]

The third source of solid waste is not a result of burning coal. It results from the optional cleaning of the combustion gases from \(SO_2\), caused by the oxidation of the present (organic) sulphur. Desulphurization of the Flue Gases (cf. section 5.7.1) results in waste or in usable products like gypsum or pure sulphur.
\[ FGW_i = FU_i \times \sum_{j=1}^{I} (Fr_j \times SC_j) \times SA \times 2 \times FGD_i \times FW \] (ton)  

(5.17)

Where:  
\( FGW_i \) = Waste from Flue Gas desulphurization per year for unit i (ton)  
\( FW \) = Waste from Flue-gas desulphurization multiplier (ton FGD waste/ton Sulphur)  
\( FGD_i \) = Flue Gas Desulphurization for unit i (fraction)

The amount of radio-active waste from nuclear power plants is also calculated. A distinction is made between high level and intermediate+low level radio-active nuclear waste. Not only the amount of waste produced during the lifetime of a nuclear plant is calculated, but the decommissioning waste produced is also taken into account. In Formula (5.18) the Total High level Nuclear waste (\( THN \) in \( m^3 \)) per unit per year is calculated from Electricity Generated (\( EG \)). The High Level Nuclear waste (\( HLN \) in \( m^3/MWhe \)) and the decommissioning waste are calculated from the High level Decommissioning Nuclear waste produced (\( HDN \) in \( m^3/MWhe \)) and the Nuclear Capacity (\( NC \) in MWc). The intermediate+low level radio-active waste produced is calculated in a comparable way.

\[ THN_i = EG_i \times HLN + \frac{(NC_i \times HDN_i)}{TLT_i} \] (m\(^3\))  

(5.18)

With:  
\( TLT \) = Technical Life-Time (yr)

5.8 Summary

The three main design principles for PowerPlan which determined the model structure are:
• the need to be interactive;
• the method of approach, was a combination of the central electricity board, in control of the central supply and the distribution utilities which deal with decentral capacity and conservation measures;
• the multi purpose use of the model as an educational tool and as a tool for scenario studies.

The choice for interactivity implies a simplification in the modelling of the electricity supply system in order to reduce calculation time. The choice for an approach with a distinction between central and distribution utilities implies a division in a central and a decentral (inclusive conservation) section, which are
modelled differently.
The third principle implies a reduction in the data to be gathered and to be allowed to be changed during a simulation run. The use in a educational context asks for an easy to understand (i.e. transparent) model. The first and the third set of model simplifications are a compromise between accurate simulation results and reduction of data and calculation time (i.e. relevancy).

The most relevant simplifications made in PowerPlan to achieve the necessary time reduction, transparency and relevancy are summarized below:

- electricity demand is determined from the LDC and the peak demand instead from chronological data, which effects:
  - revision planning in the form of derating of capacity;
  - demand-constrained options like district heating and industrial cogeneration;
  - supply-constrained options like solar, wind and hydro;

The most relevant choices to simplify and reduce input data are:

- no minimal load;
- no standby option, pre-heating time and cooling down period;
- use of averaged values for plant characteristics (efficiency and NO\textsubscript{x}-emission factor);
- merit order is fixed per run;
- pumped storage and other storage options are not explicitly present.

Chapter 7 presents the results of the analysis of PowerPlan according to simplifications and data reduction as described above.