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SUPWIND Deliverable D 2.1

Report on Findings of Working Package 2

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Preface

This deliverable is part of a series of working documents within the project *Decision Support for Large Scale Integration of Wind Power SUPWIND*, supported by European Commission within the 6th FP under Contract No. TREN/05/FP6EN/S07.61830/020158 SUPWIND. It describes the outcomes of Working Package 2 and is structured as follows.

Chapter 1 describes in short the usefulness of stochastic planning tools for TSOs in order to cope with large amounts of wind power. Chapter 3 depicts the overall set of tools developed within SUPWIND and to be applied to several case studies. The key equations of the strategic planning tool E2M2s, as extended within the SUPWIND project, are described in Chapter 4. In the subsequent Chapter 5, the databases and their corresponding functions which are associated to E2M2s are described briefly. This deliverable ends with some conclusions which highlight the findings of this work package and give an outlook on the planned applications of the tools for strategic decision making.

1 Definition of requirements for strategic planning tool

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This chapter summarizes the discussions within the SUPWIND consortium aiming at definig what the SUPWIND Planning tools can be used for in the context of strategic planning by TSOs.

When planning grids, TSOs have to face many uncertainties, which have to be considered carefully in order to avoid future crises in the supply of electricity. Traditionally, TSOs use load flow based approaches for estimating the needs for grid enforcements or extensions. The input for well functioning load flow models has to cover a detailed technical description of the grid topology with all technical parameters, as well as the patterns, structure and magnitude of load and generation. With the help of this kind of information, TSOs are able to calculate the necessity of grid adaptations, reserve needs and security issues. So far the assessment of load and generation patterns has been undertaken with the help of historical extrapolations or the application of deterministic market models. In the past these approaches were sufficient, because electricity was traditionally generated in large thermal power plants and load patterns were well known. But nowadays two ongoing trends make it more complicated for TSOs to estimate load and generation patterns.

On the one hand, the liberalization of electricity markets led to a situation, where electricity trading has increased rapidly, and as a consequence generation patterns changed significantly. On the other hand, the existing efforts to mitigate climate change have led to a situation with growing amounts or electricity stemming from renewable energy sources, which are mostly operated at a smaller scale. One of the most widespread technologies applied is the wind turbine. Due to the stochasticity of wind, the operation and planning of the grid has become more difficult for TSOs to handle. The European Union and its member states have planned to increase the wind power capacities rapidly in the years to come. In order to cope with this new situation, the TSOs are confronted with unfamiliar situations, which make it necessary to introduce new methodologies for planning their capacities and for maintaining the technical security within the grid. Within the SUPWIND project, a set of tools is developed which help TSOs to estimate the changes in market behaviour and in generation and load patterns due to increasing amounts of wind power. The developed market models apply stochastic programming approaches which are suited to address the stochasticity of wind properly.

Within this note the strategic planning tool for the aid of investment decisions is described. With such a tool the changes in market operation and especially in investment decisions for power plants can be considered. With given scenario parameters it is possible to calculate prices, economic decisions and load and generation within a future electricity market with a high penetration of wind power. The results of the strategic decision tool can be fed into a more sophisticated unit commitment model and can be used to show load and generation patterns which can be used for load flow models. At the same time, the calculation results support the TSOs with information on trends and scenarios describing the future Electricity generation mix. This kind of information is also very helpful when planning grid extensions and enforcements.

2 Full-size planning using a connected set of models

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In order to make the SUPWIND Tools compatible amongst each other, the different parts of the tools have to be interlinked with each other. Although the tools can be used independently of each other, they also might be used in conjunction. This section gives an overview on the different approaches to link databases and models and on the rationale why the different models are interlinked. The following figure reveals the overall structure of the SUPWIND tools:

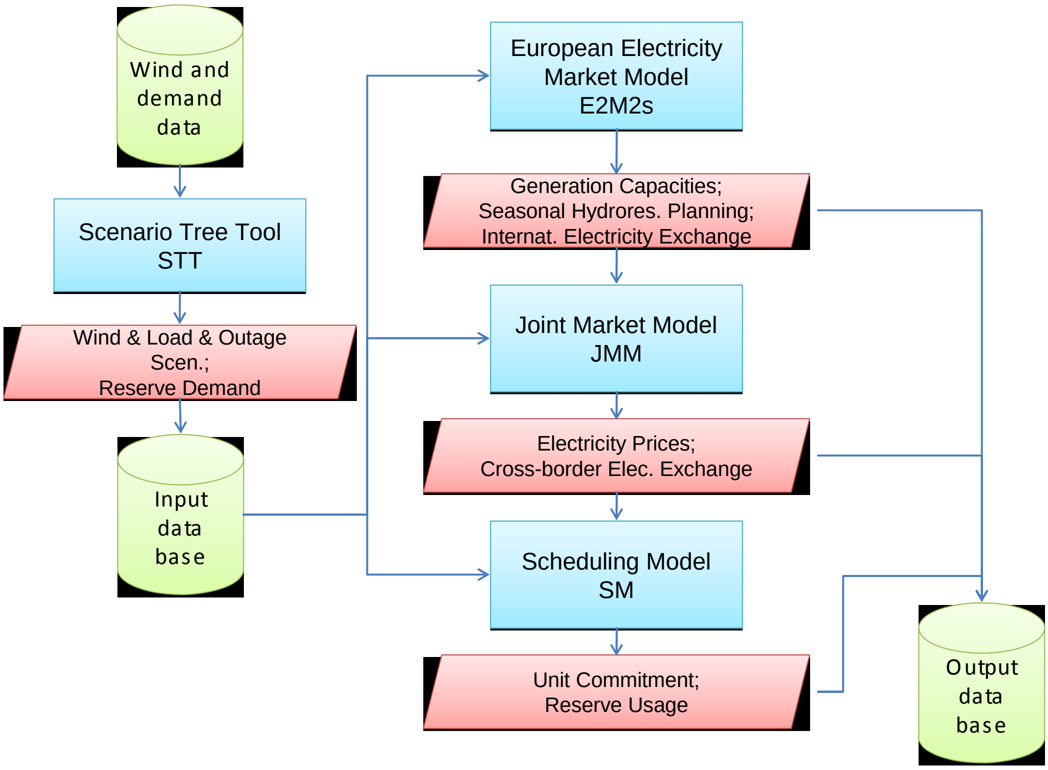

Figure 1: Overview of SUPWIND Planning Environment.

The green cylinders are databases, the red parallelograms indicate exchange of information between sub models or databases, the blue rectangles are models.

The generation of the necessary stochastic parameters, for the stochastic optimization Tools, is undertaken within the Scenario tree tool (STT). Through the use of so called scenario reduction algorithms some dominant scenarios can be created which consider the range of uncertainties best. These scenarios parameters are put into the input database where all raw data describing the European electricity system is stored. This database can create ASCI files with a proper aggregation which are suited to the needs of the three SUPWIND market models. Due to different aggregation levels and time resolutions, the input files have to be created by different queries. Consistency is created through the use of the same raw data. The long term market model is E2M2s is described in detail within this note (see section 2). E2M2s models whole years and investment decisions into generation possibilities. The results of E2M2s can be past to the Joint market model (JMM) and the so called scheduling model (SM). All information which has to be determined on a yearly basis, e.g. storage levels of seasonal hydro storages, newly built power plant capacities or CO_2- prices has to be calculated when starting model runs of the operational modelling tools which are taking place in the future.

The two operational tools JMM and SM are quite similarly designed. The most important difference is the treatment of unit commitment: Within the JMM unit commitment is depicted with the help of a linear approximation approach, within the SM a more detailed mixed integer programming approach is implemented. The distinction is necessary, because depending on the needs of the model user detailed information on the unit commitment or alternatively a large geographic scope for the model run is necessary. A combination of detailed unit commitment and a large scope is due to size and complexity of the problem not solvable at the same time – even with a well equipped Computer. If these kinds of calculations become necessary, a combination of the JMM and the SM can be undertaken. In a first step the power flows between nodes and the unit commitment of neighbouring countries are approximated with the help of the JMM, afterwards the results are fed into the scheduling model. The scheduling model can be used to calculate the Unit commitment in more detail for one single country or a smaller group of countries.

The results of such a unit commitment calculation are quite helpful for a TSO when planning and operating his grid. Nowadays a TSO applies mostly electro-technical load flow models for grid planning, which represent the topology of the grid in a very detailed way. In order to consider the underlying laws of physics correctly, these models are mostly alternate current load flow models, which implies that they are strictly non-linear. This non-linearity limits the size of the model due to calculation time and feasibility. Therefore, the TSOs can not represent market and generation issues in their models in detail. They have to put the raw information on generation and load patterns into their load flow calculations. In order to get high quality results of load flow models, the quality of the market representation is of increasing importance. Due to the fact that market operation is becoming more and more complex and that grid and generation planning provide potential benefits of scope, it is not sufficient to estimate future market conditions and operations with high amounts of stochastic wind generation with simplistic approaches. Here the SUPWIND Tools can be applied, because they consider in the detail the technical and economic properties of generation and load in the electricity market. With better estimations on future market patterns it is possible for a TSO to calculate the benefits and costs of grid extensions and enforcements in more detail. The knowledge of future power generation scenarios can give insights on security issues and reserve needs as well, because the different generation technologies are associated with different generation characteristics which might become more challenging in future constellations. Another potential field of application is the calculation of NTC values. Net transmission capacities (in short NTC) are published by the TSOs on regulary basis, they give the market participants, who are interested in cross border trade of electricity an impression on the magnitude of available transfer capacities which can be used for market activities, namely trade. Due to security issues and reserve needs not the total thermal transmission capacities are open for trade. With the help of load flow models the NTC values can be estimated by the TSOs. For these load flow calculations also data on market operation is necessary. The better the data is, the better the TSOs can calculate security margins, reserve needs and capacities free for trade. Therefore, the market tools might be helpful when deciding which amount of electricity can be traded in between countries.

A small example can illustrate this interdependency of the models: If a TSO wants to check the value added from potential grid extensions in the year 2010 induced by a certain amount of wind power, he firstly has to specify some scenario conditions (e.g. fuel prices and CO_2 bounds) which are fed into E2M2s. Using stochastic parameters from the scenario tree tool, technical characteristics and market conditions from the Input database one can specify all necessary parameters automatically with the help of the frontend databases. Afterwards the user makes E2M2s model runs which give him information on the future Electricity generation mix, CO_2 prices etc. This information he feeds into the Joint market model which can be used for the calculation of short term unit commitment and optimal dispatch of all thermal power plants within Europe. Thereby, load, wind and outages are derived from the stochastic scenario tree tool. Now taking exchange schedules and some other parameters as given, he can apply the scheduling model with the most detailed representation of power plants in his country, to get information on plant operation in the future power system. The generation pattern provided by the model is the final result of the SUPWIND Tools. The generation pattern is fed into a load flow model of the TSO who now is better able to calculate the need and the potential value of grid extensions within his grid.

3 E2M2s: a strategic investment planning tool

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3.1 Introduction

With the liberalisation of European electricity markets, the formerly well-defined environment of electricity producers has become subject to increasing uncertainty. With the political will to increase the share of renewables in electricity generation, a further source of uncertainty is getting increasingly important. This is the fluctuating and intermittent production of many renewables, especially of wind and solar generation. This will influence the performance of the whole system and the increase in uncertainty tends also to add costs to the overall system operation.

In this context, appropriate models are needed to estimate the impact of increased uncertainty on system operation and system operation costs, notably to respond to the strong public and scientific interest in the costs of wind integration in electricity systems.

Debates on large-scale wind integration mainly focus on (i) how to estimate the costs of wind's intermittency and (ii) how to apportion the costs between wind generators and system operators. These aspects are subject to current research as may be seen with some recently published reviews [1]–[3]. Within this paper a stochastic approach to determine the changing system operation costs of wind's intermittency is presented.

Examples of past studies on the integration costs for wind include the studies by Grubb [4], Strbac [5], Hirst and Hild [6] as well as DeCarolis and Keith [7]. All of these studies are based on simulating an electricity system bottom-up. Such models can be expected to be a good choice in order to estimate changing system operation costs due to large-scale wind integration. However they are less suited to analyse the optimal adaptation of the electricity system to increased wind penetration. Conventional electricity system models, such as [8] – [13], determine the optimal system configuration including optimal investment strategies depending on the political and fuel market context. However most of these models are purely deterministic and are thus hardly adequate to cope with the fluctuations of wind energy. Hence, so far no adequate models exist to describe the impact of increased wind energy production on the overall electricity system, including adaptation of generation capacities. Also the German dena study [14] has not used an integrated modelling approach to determine the impact of increased fluctuating generation on conventional power plant investments and operation.

In order to get an integral approach, a stochastic electricity market model is needed, which describes the fluctuations of wind energy while at the same time allowing for endogenous investment. This paper describes such a model based on a stochastic recombining tree and an optimization of the cost minimal system operation. Thereby the system is allowed to adapt on increasing wind integration, fuel price changes, CO_2 restrictions etc. by not only modifying the operation of the system but also by adapting endogenously investments in conventional thermal power plants. Additionally the changing system operation costs due to large-scale wind integration in this system can be estimated.

3.2 Model Description

Fundamental models basically aim to analyze power markets based on a description of generation, transmission and demand, combining technical and economical aspects. Thus electricity prices are derived from the marginal generation costs plus the impact of other system restrictions such as limited transmission capacities, start up costs etc. Basically thereby two types of models may be distinguished. On the one hand short term unit commitment and load dispatch models, which aim at modelling the details of plant and grid operation for single power plant operators or entire grids (for an overview on such models cf. e.g. [15]). These have high time resolution and encompass a detailed modelling of plant and grid operation restrictions. Capacity investments are usually not treated in these models given that they cover only short time horizons of one day, one week or at most one year. On the other hand long term energy system or electricity system models aim at analysing the evolution of the electricity system under prespecified scenarios, e.g. on demand growth or emission constraints (cf. e.g. [16]). In such models typically investment decisions are modelled endogenously and the modelling of operational constraints is simplified.

The major innovative contribution of this paper is to provide a system model with endogenous investment while at the same time having a high enough temporal resolution to model fluctuations in wind energy. More over not only the variability of wind energy is taken into account but also its unpredictability is modelled using a stochastic recombining tree. Hence in fact the proposed model combines many features of generation scheduling models (unit commitment and load dispatch) with endogenous investment as found typically in energy system models.

In the following first the general approach and then the deterministic version of the model is discussed. This is followed by a discussion of the stochastic extension of the model. Table 1 gives an overview of the symbols used.

Table. 1. Symbols used in the model

Variables				
E	Transmission flow	*OC*	Operating costs	
FC	Fixed costs	*Q*	Production	
H	Storage level	*S*	Stochastic stages	
L	Capacity	*SC*	Start-up costs	
N	Nodes	*TC*	Total costs	
Indices				
0	Minimal	*R*	Region	
Cyc	Cycling	*Pum*	Pumping	
Inv	investment	*res*	Power reserve	
M	Marginal	*S*	Stochastic Stage	
N	Node	*stu*	Start-up	
New	New	*T*	Time step	
Old	Old	*T*	Final time step	
Onl	Online	*U*	Unit type	
Oth	other	*V*	Voltage magnitude	
Parameters				
A	Annuity factor	*Lt*	Lifetime	
C	Transmission constraint	*oc*	Other variable costs	
D	Duration	*sc*	Specific start-up costs	
D	Energy demand	*W*	Water inflow	
FC	Frequency	*H*	Efficiency	
Fc	Specific fixed costs		*ψ*	Occurring probability
Fp	Fuel price	*P*	Availability	
I	Interest rate	*T*	Transition probability	

Lf	Load factor	*Ω*	Susceptance

3.2.1 Deterministic Model

Under the assumption of power markets with efficient information treatment and without market power, the market results will be equivalent to the outcomes of an optimization undertaken by a fully informed central planner. If electricity demand is treated as price inelastic, welfare maximization is then equivalent to cost minimization in the considered power network. Thus the model minimizes the costs for satisfying a given demand as a function of available generation and transmission capacities, primary energy prices, plant characteristics and possible investments. Thereby also the impact of hydro-storage and start-up costs as well as endogenous investment decisions are taken into account. In the deterministic case, the objective function can be written as:

$$TC = \sum_{r} \sum_{u} \sum_{t} d_t f_t (OC_{r,u,t} + SC_{r,u,t} + FC_{r,u,t}) \qquad (1)$$

The total costs TC to be minimized are hence determined as the sum of operating costs $OC_{r,u,t}$, startup costs $SC_{r,u,t}$ and fix costs $FC_{r,u,t}$ summed over regions r, unit types u and time segments t. The summands are weighted by the duration d_t and frequency f_t of the corresponding time segment. In the following it is assumed that a whole year is represented by a number n_D of typical days, composed each of n_H time segments.

For the operating costs $OC_{r,u,t}$ an affine function of the plant output $Q_{r,u,t}$ is assumed. Additionally, the decision variable "capacity currently online" $L^{onl}_{r,u,t}$ is introduced [17]. The capacity online generally forms an upper bound to the actual output. Multiplied with the minimum load factor, it provides also a lower bound to the output for each power plant (for details see [17]). Hence operating costs can be decomposed in fuel costs for operation at minimum load, fuel costs for incremental output and other variable costs:

$$OC_{r,u,t} = \frac{fp_{r,u,t}}{\eta^m_u}(Q_{r,u,t} - lf_u L^{onl}_{r,u,t}) + \frac{fp_{r,u,t}}{\eta^0_u} lf_u L^{onl}_{r,u,t} + oc_u Q_{r,u,t} \qquad (2)$$

In this equation, $fp_{r,u,t}$ is the fuel price, η^m_u the marginal efficiency for an operating plant and η^0_u the efficiency at the minimum load factor lf_u. With $\eta^m_u > \eta^0_u$ it is less costly to increase the output of an already running plant than to increase the capacity only. Thus the operators have an incentive to reduce the capacity online. Furthermore other variable costs oc_u are included.

Besides operation costs, start-up costs may influence the unit-commitment decisions considerably. Again the capacity currently online $L^{onl}_{r,u,t}$ is used, in order to avoid binary variables. Then specific start-up costs sc_u arise, if the capacity online is increased, i. e. if the start-up capacity $L^{stu}_{r,u,t}$ gets positive. This start-up capacity is constrained by

$$\begin{aligned} L^{stu}_{r,u,t} &\geq L^{onl}_{r,u,t} - L^{onl}_{r,u,t-1} \\ L^{stu}_{r,u,t} &\geq 0 \end{aligned} \qquad (3)$$

and will as low as possible, given the costs associated with starts. Thus at least one of these inequalities will be fulfilled with equality. The total start-up costs $SC_{u,t}$ are then described by:

$$SC_{r,u,t} = sc_u L^{stu}_{r,u,t} \qquad (4)$$

In order to take into account the longer term development of the power system, investments in new conventional thermal power plants are treated endogenously in this model. This reflects that the system will adapt over time to varying exogenous circumstances, e.g. an increased share of wind generation in total production. Hence not only the generation scheduling has to be dealt with, but also the fixed costs $FC_{r,u,t}$ enter into the optimization. Thereby the choice among different available investment alternatives with specific investment costs fc^{inv}_u is modelled using the decision variable of newly build capacity $L^{new}_{r,u,t}$:

$$FC_{r,u,t} = a(i, lt_u) fc^{inv}_u L^{new}_{r,u,t} + fc^{oth}_u L_{r,u,t} \qquad (5)$$

To limit the size of the optimization problem, the optimization problem is formulated for single years under the assumption of myopic expectations. Then the investments are valued using the annuity factor $a(i, lt_u)$ depending on the interest rate i and the lifetime lt_u. Additionally, also other specific fixed costs fc^{oth}_u for the total installed power plant capacity $L_{r,u,t}$ are taken into account.

The key constraint to optimization is that supply and demand have to be identical in every region r and at every time step t:

$$\sum_u Q_{r,u,t} + \sum_{r'} (E_{r'\to r,t} - E_{r\to r',t}) \geq D_{r,t} + \sum_u Q^{pum}_{r,u,t} \qquad (6)$$

Thereby total demand equals the sum of exogenously given domestic demand $D_{r,t}$ and variable export flows $E_{r'\to r,t}$, while supply is given by the power production $Q_{r,u,t}$ and import flows $E_{r\to r',t}$.

Due to the fact that power flows depend on the laws of physics, the economic planning of electricity exchange in between different regions is constrained. Power flows can be described best by an alternate current load flow model, which is strictly non linear and therefore not usable in a large economic system model of the electricity market. In order to approximate real power flows and physical constraints a direct current load flow implementation is appropriate. The following equation describes the restrictions with a DC power flow consideration:

$$(E_{r\to r',t} - E_{r'\to r,t}) - \Omega_{r',r}(V_{r,t} - V_{r',t}) = 0$$

Hereby $V_{r,t}$ stands for the voltage magnitude in a certain region of the electricity grid. The product of the voltage angle between two nodes of the grid with the susceptance of the corresponding transmission line has always to be equal with the net exchange of electricity between the two regions under consideration. The susceptance is defined as the imaginary part of the complex electrical conductance.

By reason that this condition itself has multiple solutions, an additional restriction has to be introduced, which defines one of the regions in the model (r_0) as a reference angle. This ensures that one unique solution for optimal power flows can be calculated:

$$V_{t,r_0} = 0$$

Additionally, the voltage angles in between the nodes of the electricity grid can be limited; e.g.with 30°, due to electro technical constraints which ensure that system stability is assured in all periods. In addition the power flows are also limited by the given transmission capacities in between the modelled regions:

$$E_{r\to r',t} \leq C_{r\to r'}$$

Moreover, pumping energy $Q^{pum}_{r,u,t}$ has to be added in order to model also pumped hydro storage. The production $Q_{r,u,t}$ is constrained by the total installed capacity $L_{r,u,t}$ multiplied by an availability factor $\rho_{u,t}$.

$$Q_{r,u,t} \leq L_{r,u,t}\rho_{u,t} \qquad (7)$$

The availability factor depends on the time of the year and accounts for planned and unplanned outages. Similar capacity constraints are formulated for the pumping energy $Q^{pum}_{r,u,t}$ and for the import and export flows $E_{r'\rightarrow r,t}$.

For hydro storage plants, storage constraints need to be considered and the filling and discharging has to be described. This leads to a storage level equation linking the storage level $H_{r,u,t}$, expressed in energy units, to the storage level $H_{r,u,t-1}$ at time step $t-1$, the production $Q_{r,u,t}$ and the inflow $W_{r,u,t}$ for all hydro storage plants.

$$H_{r,u,t} \leq H_{r,u,t-1} - Q_{r,u,t} + W_{r,u,t} \qquad (8)$$

For the pumped storage plants moreover the already introduced pumping energy $Q^{pum}_{r,u,t}$ has to be included, taking into account the so called cycling efficiency η^{cyc}_{u}.

$$H_{r,u,t} \leq H_{r,u,t-1} - Q_{r,u,t} + W_{r,u,t} + \eta^{cyc}_{u} Q^{pum}_{r,u,t} \qquad (9)$$

Additionally, an adequate terminal condition for the water reservoirs has to be included. One attractive formulation is to require that the final and the initial reservoir level are identical, which can be expressed through the following initial cyclical condition for the hydro plants (thereby the first time step is indicated by $t-1$ and the final time step by $t = T$):

$$H_{r,u,1} \leq H_{r,u,T} - Q_{r,u,1} + W_{r,u,1} \qquad (10)$$

and for the pumped storage plants:

$$H_{r,u,1} \leq H_{r,u,T} - Q_{r,u,1} + W_{r,u,1} + \eta^{cyc}_{u} Q^{pum}_{r,u,1} \qquad (11)$$

Environmental restrictions may be modelled by setting an upper bound E^{MAX} on the emissions of Greenhouse Gases or other pollutants. With the fuel-based emission coefficient ε_f we have:

$$\sum_t d_t f_t \sum_r \sum_u \varepsilon_{f(u)} \left(\frac{1}{\eta_u^m} (Q_{r,u,t} - lf_u L_{r,u,t}^{onl}) + \frac{1}{\eta_u^0} lf_u L_{r,u,t}^{onl} \right) - p_{Em}^{MAX} E^{EXC} \leq E^{MAX} \quad (12)$$

Here an upper price limit p_{Em}^{MAX} for the emission price has been introduced and a corresponding excess emission quantity E^{EXC}. This can be used to model policy processes which effectively limit the prices.

The reserves required in the system to cope with unforeseen variations in load, plant outages and wind fluctuations are described by the requirement that the capacity online has to exceed the actual demand by a certain reserve capacity, depending on the maximum demand, the installed wind power and the size of the largest unit:

$$\sum_u L_{r,u,t}^{onl} \geq D_{r,t} + L_r^{res} \left(D_r^{\max}, \max_u \{L_{u,r}\}, L_r^{wind} \right) \quad (13)$$

3.2.2 Stochastic model

In order to cope with the stochastics of intermittent wind generation, the aforementioned equations need to be extended. In fact for one typical hour in time, not only one operation mode of the system has to be considered, but different alternative stochastic states depending on the actual wind generation which is far from being predictable. Time segments are thereby grouped into S stochastic stages $s \in \{1,2,..., S\}$, that may comprise one or several time segments. For each stage N stochastic states or nodes $n \in \{1,2,..., N\}$ are distinguished. In this setting, the number of decision variables increases with the power of N, if the decisions are assumed to be path-dependent. This is the curse of dimensionality of conventional stochastic optimization models.

A way out of this curse of dimensionality is the use of a recombining tree as depicted in Figure 1. All variables are assumed to be node and not path-dependent, thus leading to a computational burden proportional to $S \cdot N$. . Nevertheless, the stages are required to reduce the resolution of the stochastic representation and thus to limit the computational burden.

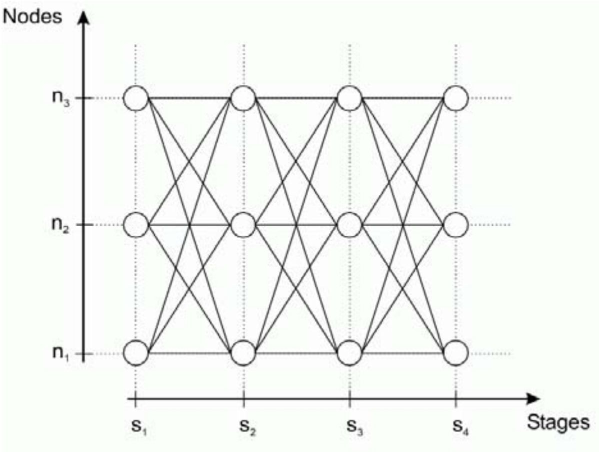

Figure 2: Stochastic representation by a recombining tree

Each node in the recombining tree is characterized by the respective value of the stochastic variable and its probability $\psi_{r,s(t),n}$ (here $s(t)$ indicates that to each time segment t a unique stochastic stage s is associated). Each node n' at stage s is considered to be coupled with each node n' at stage $s+1$. Thereby transition probabilities $\tau_{r,s \to s+1, n \to n'}$ need to be taken into account. They give the probability that a specific stochastic state is expected to follow a specific state on the preceeding stage. To be more specific: In this paper the nodes represent different stochastic states, e. g. low, medium and high wind generation, at a given stochastic stage, i. e. the wind power generation is assumed to be constant in the hours comprised by the stochastic stage.

Given that typical days are considered, the transitions at the end of each day should take into account the possibility to switch to a day of the same type and the possibility of a shift from weekend to weekday and vice versa.

The stochastic objective function is here a straightforward extension of the deterministic approach in Eq. (1). The key point is that all decision variables are simultaneously indexed over time *t* and node *n* and that the different nodes enter the objective function with their probability $\psi_{r,s(t),n}$:

$$
\begin{aligned}
TC = & \sum_{n} \sum_{u} \sum_{t} \sum_{n} d_t f_t \psi_{r,s(t),n} \\
& \times (OC_{r,u,t,n} + SC_{r,u,t,n} + FC_{r,u,t,n})
\end{aligned}
\qquad (14)
$$

Deterministic "static" equations may easily be transformed into theiri stochastic counterpart by simply adding the index *n* for the nodes. The capacity, reserve and transmission constraints are examples of such static equations, cf. Eq. (6). They have to be fulfilled in each node at each time step.

However, for dynamic equations, which link different time steps, the approach to be followed is somewhat more complicated. Here the transition probabilities have to be taken into account. E. g. start-up capacity is defined as the weighted average over the different transitions

$$L^{stu}_{r,u,t,n} \geq \frac{1}{\sum_{n'} \psi_{r,u,s(t-1)\to s(t),n'\to n}} \sum_{n'} \psi_{r,u,s(t-1)\to s(t),n'\to n} \left(L^{onl}_{r,u,t,n} - L^{onl}_{r,u,t-1,n'} \right) \qquad (15)$$

$$L^{stu}_{r,u,t} \geq 0$$

The weighting is done in order to reflect as exactly as possible the start-up-costs during the operation.

Similarly the reservoir fillings at the end of a time segment *t* will be determined by the probability weighted average of the filling levels at all nodes of the prior time segment *t-1*.

$$H_{r,u,t} \leq \frac{1}{\sum_{n'} \psi_{r,u,s(t-1)\to s(t),n'\to n}} \sum_{n'} \left(\psi_{r,u,s(t-1)\to s(t),n'\to n} H_{r,u,t-1} \right) - Q_{r,u,t} + W_{r,u,t} + \eta^{cyc}_{u} Q^{pum}_{r,u,t} \qquad (16)$$

This is of course only an approximate treatment of the evolvement of reservoir fillings over the day and the year. Actually, the reservoir level will be a function of exactly the stochastic realisations which occurred in the past and not a function of probability weighted possible occurrences. Yet a precise modelling of this effect would require the use of a non-recombining tree, leading to the aforementioned curse of dimensionality of stochastic optimisation.

4 Connecting E2M2s to the database

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A short overview of the databases involved in the total model environment is given in Section 4.1, Section 4.2 focuses on the E2M2s model and input to this model (sets and parameters).

4.1 The SUPWIND Databases

The data and queries for the SUPWIND project are split into several smaller databases, which ease the handling of very complex and large data amounts and the multitude of different application needs. Therefore, a system consisting of several interdependent Microsoft Access databases was developed:

- Input database (Data container)
- Scenario database (Stochastic Data Container)
- JMM front end
- JMM output database
- E2M2s front end
- E2M2s output database

The databases are briefly described in the following

4.1.1 Input database

This is the main data container with all data needed for the JMM and E2M2s models. Tables for stochastic data are linked to the Scenario database. Within this database, all parameters and sets, describing the economics and the technical features of the European electricity system are stored. The database only stores all kind of data, therefore it has no queries.

4.1.2 Scenario database

All stochastic data generated by the "Scenario Tree Tool" are placed in this database. These data are hourly wind power and hydro power production as well as data on forced outages and load variations. This database has no queries.

4.1.3 JMM front end

Most tables are linked tables linking to either the Input or Scenario databases. The only tables that are not linked are a few tables that hold temporary data generated by update queries that are executed in connection with export of JMM input files. The purpose of this database is the generation of input files which are put into the operational decision tools. It aggregates data into a form which is suitable for model runs. Data files for the JMM model are generated by queries "O Set Xxxx" and "O Parameter Yyyy".

4.1.4 JMM output database

The JMM model writes output text files that are imported to the JMM output database. Within the database the results of JMM model runs can be analysed in a flexible way.

4.1.5 E2M2s front end

Most tables are linked tables linking to either the Input or Scenario databases. There are a few not-linked tables that hold temporary data generated by update queries that are executed in connection with export of E2M2s input files. Also some E2M2s-specific tables, e.g. tables defining the typical times used by E2M2s, are not linked. Within this database the queries for generating the input files from the input database are stored. Data files for the E2M2s model are generated by queries “Set Xxxx” and “Par Yyyy” depending on subqueries “Sub Zzzz”. The function of this database is not only the formatting and setting of given data into a correct form, but also the aggregation and calculation of model input. Within E2M2s power plant classes are modelled instead of single power plants. The front end database allocates a very large number of plants into a much smaller number of power plant vintage classes. At the same time, it calculates the decay rate of all power plant classes under consideration, which is necessary for long term investment planning. Within this database also scenarios for model runs can be specified.

4.1.6 E2M2s output database

After E2M2s is run the optimisation results are written into an Access database with the help of the Access to GDX facility provided by the used modelling software GAMS. Within this database the specific results of E2M2s are transformed into a format which is easier to read and understand. E.g. electricity exchanges between nodes which are calculated for typical hours and days and stochastic nodes can be transformed into a resolution which is fitting to the JMM model runs. All results of E2M2s which are relevant and necessary for the operational planning tool can be transformed into a format which is suited for the short term unit commitment models.

4.2 The E2M2s model representation

E2M2s is written in GAMS (General Algebraic Modelling System) which is a high-level modelling system for mathematical programming and optimization. The GAMS language is based on Sets and Parameters (and other elements that are not dealt with here). A Set is a list of items, e.g. all power plants or all fuels, and Parameters hold the actual data, input or calculated within the model. For instance fuel prices and power production are Parameters.

E2M2s reads its input (model structure and data) from include files generated by executing some queries in the E2M2s front end (cf. section 4.1.5). There are two groups of include files:

Files with file names ”Set Xxxx.inc” describe Sets. These files are generated by queries “Set Xxxx”. Files with file names ”Par Yyyy. inc” hold Parameters. These files are generated by queries “Par Yyyy”. The following tables list all sets that are input to E2M2s.

Geography:

Set	Description
Set bRegio	Zones and Heat regions.
Set Zone	Zones = Country groups.
Set HeatRegio	Heat regions.
Set HeatRegio_in_Zone	Connects Heat regions with Zones.

Fuels and Plants:

Set	Description
Set PrimaryEnergy	Fuel types.
Set Plant Exist	Plant classes: Existing power plants.
Set Plant New	Investment technologies: Power plants that can be used for investments.
Set Plant_Fuel Exist	Connects Plant classes with Fuel types.
Set Plant_Fuel New	Connects Investment technologies with Fuel types.
Set Plant_Zone Exist	Connects Plant classes with Zones.
Set Plant_Zone New	Connects Investment technologies with Zones.
Set PlantType	A list of available plant types.
Set Power_Plant_Type	Connects plants with plant types.

Power Transmission:

Set	Description
Set Line Exist	Existing power transmission lines and the connected Zones.
Set TransType	Power transmission line types (AC line, DC line).

Time:

Set	Description
Set SimYears	Simulated years.
Set Hour	Typical hours of the day, e.g. 05 meaning 04:00 to 06:00.
Set Day_Segment	Segments of the day, e.g. P2 meaning 00:06 to 12:00.
Set Day_Type	Day types. We=Werktag=workday, Wo=Wochenende=weekend.
Set PerYear	Periods of the year, e.g. Jan meaning January and February.
Set Time	Time steps, e.g. We07Jul meaning Workday, 06:00-08:00, July+August
Set Time_Succ	Connects time steps with successors.
Set PerYear_Time	Connects time steps with period of year.
Set Type_Time	Connects time steps with type of day.
Set Hour_Time	Connects typical hours with time steps.
Set Hour_Segment	Connects typical hours with time segments of day.

Stochastic Modelling:

Set	Description
Set Node	The nodes of the stochastic model.
Set Node_Succ_nt	Connects nodes with successors.
Set PerYear_Node	Connects nodes with period of year.
Set Type_Node	Connects type of weekday with nodes.
Set Segment_Node	Connects time segments with nodes.
Set Wat_Node	Connects water scenario with node.
Set Win_Node	Connects wind scenario with node.
Set Water_Scen	Water scenario.
Set Wind_Scen	Wind Scenario.
Set Scene	Scenarios (combinations of water and wind scenarios).

Others:

Set	Description
Set Options	A list of options (not values) used to control E2M2s, e.g. 'IncludeCHP'.

Parameter	Defined on	Description	Unit	Data source
Par Availability Exist	PlantClass, PeriodOfYear	Availability of power plant class during period of year.	Factor	[Data PlantClass Availability].Avail
Par Cap_CHP_Y Exist	Year, PlantClass, HeatRegio	The capacity in “Par Cap_Ref Exist” split between heat regions.	Factor	[Default tech data to units].MaxPower [Data AAA YYY Heat Demand].AnnualHeatDemand
Par Cap_Ref Exist	PlantClass, Zone, Year	Installed capacity of power plant class.	MW	[Default tech data to units].MaxPower
Par CapSp Exist	PlantClass, Zone	Potential for provision of spinning reserves for power plant class.	Factor	[Default tech data to units].SpinResCapab
Par Cost_Fix Exist	PlantClass	Yearly fixed costs (excl. investment) of power plant class.	€/kW per year	[Default tech data to units].AnnualOaMcosts [Default tech data to units].MaxPower
Par Cost_Misc Exist	PlantClass	Variable costs of operation (excl. fuel) of power plant class.	€/MWh	[Default tech data to units].VarOaMcosts [Default tech data to units].MaxPower
Par Cost_Startup_Abr Exist	PlantClass	Variable start up costs (excl. fuel costs) for power plant class.	€/MW	[Default tech data to units].StartUpVarCosts [Default tech data to units].MaxPower
Par Cost_Startup_Fuel Exist	PlantClass	Variable start up fuel costs for power plant class.	MWh fuel/MW	[Default tech data to units].StartUpFuelCons [Default tech data to units].MaxPower
Par Eff_Plant Exist	PlantClass, Zone	Marginal efficiency of power plant class.	Factor	[Default tech data to units].MaxEff [Default tech data to units].MaxPower
Par Eff_Plant_Min Exist	PlantClass, Zone	Efficiency at minimum production of power plant class.	Factor	[Default tech data to units].MinEffFactor [Default tech data to units].PartEff [Default tech data to units].MinPower
Par Fct_PQ_BP Exist	PlantClass	Backpressure constant (Cb-value) for CHP power plant class.	Factor	[Default tech data to units].CHP_CB2

				[Default tech data to units].MaxPower
Par Fct_PQ_Extr Exist	PlantClass	Extraction coefficient (Cv-value) for extraction power plant class.	Factor	[Default tech data to units].Ext_CV
				[Default tech data to units].MaxPower
Par Fill_Level_Max Exist	PlantClass, Zone	Maximum fill level for storages (power plant class).	MWh	[Default tech data to units].Sto_MaxContent
				[Default tech data to units].Sto_MinContent
Par Min_Load_Fct Exist	PlantClass, Zone	Minimum load factor of power plant class.	Factor	[Default tech data to units].MinPower
				[Default tech data to units].MaxPower
Par Pump_Cap Exist	PlantClass, Zone	Capacity of pumping storages (power plant class).	MW	[Default tech data to units].Sto_MaxCharging
Par Pump_Cap_Fct Exist	PlantClass, Zone	Capacity factor of pumping storages (power plant class).	Factor	[Data PlantClass Availability].Avail
				[Sub NumberOfDays in PeriodOfYear].NumberOfDays
Par Pump_Eff Exist	PlantClass, Zone	Pumping (charging) efficiency of hydro storages (power plant class).	Factor	[Default tech data to units].LoadLoss
				[Default tech data to units].MaxPower
Par Reliab Exist	PlantClass, Zone	Reliability of power plant class for reserve calculation.	Factor	[Default tech data to units].Reliab
				[Default tech data to units].MaxPower
Par SpdTurb Exist	PlantClass, Zone	Maximum time of turbine use of hydro storage plants (power plant class).	Hours per year	[Data PlantClass Availability].Avail
				[Sub NumberOfDays in PeriodOfYear].NumberOfDays

5 Conclusions

The analyses carried out have shown that strategic decision support for Transmission System Operators require a careful balancing of different objectives. An endogenous treatment of investments of conventional power producers clearly is advantageous when it comes to analyzing the impacts of new transmission assets. On the other side a detailed modeling of day-to-day planning is required in order to fully understand the implications of increased amounts of wind energy for the electricity system. This has led the consortium to develop a set of planning tools as basis for strategic analysis, comprising the European Electricity Market Model (E2M2s) model based on typical days and endogenous investments, the Joint Market Model (JMM) model with linear programming and day-to-day planning and the Scheduling Model (SM) for detailed analysis of unit commitment using mixed integer. Those models are complemented by a set of data bases and data handling tools, notably the scenario tree tool, which allows to determine adequately the stochastics of wind power, load and plant outages. An important part of the research carried out so far and not initially foreseen has been an improved representation of the grid in the models. Here a DC load flow representation has been implemented in the E2M2s model, which improves consistency with physical grid operation and allows also to model future load-flow based market systems. Another major step forward has been the consideration of CHP, as this influences also the integration of wind energy.

Besides the development of this improved representation another focus of the model development has been the coupling to a common input database. This allows the use of a consistent dataset for the different models and a possibility of storing and using transparently the different information relevant for regional and European market and wind integration models. The database has been implemented using Microsoft Access and allows generating automatically the input datasets for the model runs to be carried out using GAMS.

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