ASSESSMENT OPPORTUNITIES AND CHALLENGES TO INCREASED REGIONAL ENERGY COOPERATION IN SOUTH ASIA

WORKING DOCUMENT – OPTIMIZATION MODEL DESCRIPTION

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# Assessment Opportunities and Challenges to Increased Regional Energy Cooperation in South Asia

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LIST OF ACRONYMS

ATC: Available Transfer Capacity
CAES: Compressed Air Energy Storage
CAPEX: Capital Expenditures
CCS: Carbon Capture and Storage
CO₂: Carbon Dioxide
CSV (files): Comma-Separated Values files (also noted as .csv)
DC: Direct Current
ETS: Emission Trading System
EU: European Union
FCR: Frequency Containment Reserves
FRR: Frequency Restoration Reserves
HV: High Voltage
IADC: Interests Accumulated During Construction
LDC: Load Duration Curve
MILP: Mixed Integer Linear Programming
NPV: Net Present Value
OPEX: Operational Expenditures
O&M: Operation and Maintenance
RR: Replacement reserves
UI: User Interface
VOLL: Value of Lost Load
1. INTRODUCTION

1.1. PROJECT BACKGROUND AND OBJECTIVES

The South Asia region is confronting several challenges affecting national electricity systems in the region: rapidly growing demand; electricity supplies that have not kept pace with demand and are frequently interrupted; large but unevenly distributed electricity generation potential (across space and seasons); many electricity suppliers in moderate to severe financial distress; strong incentives for use of often-inefficient captive generation sources; and substantial environmental challenges associated with electricity production. Responding effectively to these challenges will require concerted national-level efforts to increase generation capacity, improve its operating reliability and environmental performance, and strengthen transmission systems – including the achievement of fully national-scale grid inter-connections.

Beyond these critical steps, however, overcoming current electricity challenges in SAR would be facilitated considerably by increased cooperation across national electricity systems in the region. Increased regional level cooperation could lower costs and increase reliability of power supplies by:

- better utilizing complementarities and comparative advantages in primary energy endowments and thus more efficient utilization of existing generating resources (especially the region’s huge hydro resources), increasing access to lower-cost supplies
- making possible economies of scale for new generation capacity through larger projects to serve more integrated systems
- reducing supply risks and reliability costs through the provision of multiple links between system loads and cross-country generating resources, and through shared generation reserve margins
- reducing environmental costs by increasing availability of and access to cleaner affordable sources of supply (hydro, natural gas) and reducing system balancing challenges with increased use of intermittent renewables (wind, solar).

This project includes quantitative technical and economic modelling of the power sector to construct and analyze specific scenarios for addressing the potential benefits of differing degrees of regional cooperation in the power sector. A complementary effort will be undertaken separately through qualitative analysis to take stock of institutional, regulatory, and political economy issues that would have an impact on the realization of increased regional power sector cooperation.

The modelling analysis needs to assess several measures of potential economic benefits from improved power system cooperation. At the micro level, these include potential reductions in marginal generation costs, and benefits from improved supply quality and lower cost of its delivery (e.g., reduced reserve margins, improved hydro-thermal balance, enhanced access to a broader variety of technologies including renewable energy resources), as well as reduced economic waste from tariff distortions. At the macro level, additional measures to be assessed include reductions in the total cost of electricity consumption and revenues gained from increased electricity exchange, as well as costs of increased outlays for extra-regional gas imports.

To carry out the analysis, the consultant has collected:

a. Detailed information on existing generation and transmission capacities (plant/transmission lines) including operational characteristics, vintage, heat rate, capacity utilization factors, emissions, fuel and other operation and
maintenance costs, plant availability and utilization factors, line losses, location etc.

b. Information as stated in item “a” above plus investment costs ($/kW for generation and $/km for transmission lines) for committed and identified generation and transmission investments within individual countries.

c. Annual data on load forecasts by jurisdiction (States and Union Territorial level in India and national level in other countries).

d. Details of cross-border generation and transmission projects currently underway, planned, or under discussion within the region, with their characteristics, separating those able to be realized within 5 years and those with longer time lines.

e. Details of electricity and natural gas import projects currently underway, planned, or under discussion within the region, with their characteristics, separating those able to be realized within 5 years and those with longer time lines.

All these inputs collected will be used to feed the simulation tool described in the next sections.

1.2. In This Document

The reader will find in this document a transparent description of the model used to perform the analysis previously outlined (ORDENA model\(^1\)), including its structure, mathematical equations and real life examples of its use.

It is important to note that the description provided is tailored to this specific project, being ORDENA model able to model a relevant amount of features that were not used for this project due to data availability time constraints and computational complexity.

This report is structured as follows, section 2 will present high level features of the modelling task and the model itself while section 3 will detail all the components of the model on a modular approach as detailed in the following box.

**Box 1 – Structure of Section 3**

Each sub-section of section 3 will be devoted to the description of a particular set of equations that, all together (including the objective function), form the optimization problem to be solved (and that in fact constitute the core of the ORDENA model). The section will begin with the description of the temporal and regional characterisation of the model and after that it will described the maths of the objective function, followed by different sub-sections that group similar type of constraints (e.g. demand/supply balance, thermal generation modelling, network modelling, etc). For the sake of clarity, the following lines outline the structure that will be followed throughout the section.

Firstly, a qualitative description of the purpose of the each module will be given. Secondly, The equation or equations forming the module will be shown. After that all the necessary notation will be univocally defined as follows:

<table>
<thead>
<tr>
<th>Item</th>
<th>Description</th>
<th>Units</th>
<th>Type</th>
</tr>
</thead>
</table>

\(^1\) ORDENA is an optimization model developed to identify the optimal expansion and dispatch of electricity systems.
Assessment Opportunities and Challenges to Increased Regional Energy Cooperation in South Asia

Being:

- **Item**: the item to be described.
- **Description**: a short note describing the nature and meaning of the item.
- **Units**: If the item can be measured, its units, if not, empty.
- **Type**: The letter I will indicate an Index (i.e., pertaining to a set), the letter P indicates a Parameter (i.e., a value input by the model user) and the letter V indicates a Variable (i.e., an unknown that will take a certain value as a result of the optimisation process).

To end, if applicable, a summary of the data needed and a small application example to this study will be shown.
2. DESCRIPTION OF HIGH LEVEL FEATURES

The planning and operation of power systems are complex activities. The high number of variables and alternatives requires the use of mathematical optimisation models to select the “best” option of a large number of alternatives.

Optimisation models are typically very computationally intensive, and thus special care has to be taken when modelling complex systems such as power systems and electricity markets.

Figure 1 shows the typical information flow of power economics models:

![Figure 1 - Introduction to Power System Modelling](image)

The mathematical model represents the economic operation of the system. Usually the mathematical formulation requires a very large number (hundreds of thousands to millions) of variables and constraints. State-of-the-art solvers allow finding a good solution to complex mathematical optimisation problems with millions of variables in a matter of minutes.

The mathematical problem to be solved is a challenging one due to the size of the problem and the use of integer variables for the representation of non-convex relationships.

The solution is obtained using Mixed Integer Linear Programming (MILP), which allows an efficient representation of discrete decisions and non-linear relations. Modern solver algorithms are able to deal with large problems by direct optimisation and provide robust solutions in manageable times. In the event that the solution time for a certain problem becomes an issue approximations of the MILP solution can be made, which still provide good solutions.

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2 A problem defined by convex functions describes a “smooth” region of feasible outcomes. A problem defined by non-convex functions has possible outcomes that are not “smooth”. Non-convexity is the “worst enemy” of linear optimisation problems as it complicates the search for the optimal solution of the problem, therefore mathematical modellers use all sort of techniques to accommodate these curves while still providing an optimal solution. Whenever “non-convex” in this report is read, reader can assume it means “very difficult”.
2.1. The Modelling Approach

The model contains three modules (long-, mid- and short-term). These can be used separately or in combination with each other. This document will be centred on the long-term module as this has been the tool used in order to calculate the capacity development and interconnection opportunities of the region.

The long-term planning module is a mathematical optimisation model that determines the least cost generation and transmission investment schedule required to supply the forecasted load in a multi-zone or multi-country system.

Simply put, the planning objective is to find the optimal trade-off between capacity expansion (investment) and operational costs of the system (including the cost of non-serving the load). All costs are discounted to the first year of the optimisation horizon to reflect its net present value. Main drivers for the expansion of the system are demand growth, already existing assets (generation and transmission) and resource and policy constraints (e.g., fuel supply limitations or emissions reduction targets).

The objective of the model is to minimise the net present value (NPV) of total system costs over the entire planning horizon subject to a number of constraints. These “total system costs” are:

1) the cost of new investment in transmission and generation plants;
2) plus expected dispatch costs - fuel costs and variable operation and maintenance (O&M)-;
3) plus the cost of supply reliability standards (the value of lost load (VOLL)\(^3\) or an implicit target capacity planning margin or capacity mechanism) and other constraints\(^4\); and
4) plus or minus the effects of externalities, like the cost of CO\(_2\) emissions or non-competitive behaviour in the case of electricity markets.

The model is able to compute a single-optimal (least cost) generation and transmission expansion solution that hedges the outcomes represented by the stochastic samples weighted by each sample’s probability. This means that “robust strategies” can be determined where the model produces an appropriate result under different possible futures. It is important to identify and analyse a manageable number of scenarios for the evolution on external variables in order to provide a plausible estimate of the future evolution of key outputs. The external variables include, although are not limited to, fuel prices and availability, renewable resource availability, demand growth, transmission system development, timing of new technology entry (e.g. CCS or wave energy) and construction and planning delays. The next sub-sections briefly detail the modelling of some specific features.

2.1.1. Generation

Generation options include conventional thermal generation (nuclear, coal, gas, etc.), renewable generation (wind, wave, tidal), hydro (run-of-river, pumped storage) generation and interconnections with other regions or countries.

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\(^3\) In the event that there is inadequate generation to satisfy demand, to avoid involuntary load shedding the market price must rise to a level that demand voluntarily curtails to the point it matches supply. This price can be thought of as the opportunity cost of a consumer that has decided to reduce its demand. Within ORDENA model this is called the “cost of non-supplied energy”.

\(^4\) Model constraints include, for example, reliability requirements, technology investment limits, emissions restrictions, renewable electricity targets, plant availability (year-round and at peak demand), variable generation and unpredicted contingencies.
The model allows the representation of hydro plants and renewable resource availability, typically based on historic meteorological conditions.

The operation of thermal plants is normally modelled in this module assuming linear variable operating costs (constant marginal cost across the unit’s operating range) however the model allows representing piece-wise fuel consumption curves as-well.

2.1.2. TRANSMISSION

The transmission network can be represented within the model using a DC load flow approach that fulfils both Kirchhoff’s Laws or using he available transfer capacity (ATC) approach. Maximum capacity per line, area protection contingencies (e.g., N-2 security) and must run generation can all be represented. Losses can be represented as a percentage to energy flows in each regional interlink or power line or they can be represented using a piecewise linear approximation (in case the both Kirchhoff’s law were to be used).

2.1.3. DEMAND

The time series of demand is transformed to a load-duration curve that can be defined at weekly, monthly, quarterly, seasonally or yearly level. A load duration curve and detailed representation of peak load for each of the transmission system regions/nodes will be constructed at the pre-processing stage based on historical data.

2.1.4. ORDENA MODEL STRUCTURE

ORDENA’s model workflow can be seen in the next figure:

Figure 2 – ORDENA Model Structure

The input data can be introduced manually in the model using the User Interface (UI), or read from a database in .csv (Comma Separated) format. Once all the data has been introduced the mathematical model (written in the Mosel language and core of the model and described in this document), the model determines the
optimisation problem to be solved by the commercial solver Xpress which uses cutting-edge MILP techniques to compute the least cost solution. After the optimisation problem is computed the results are saved as .csv files. The visual module will be specifically tailored for the client; it is MS Excel based and presents the results in a graphical and a tabular way.
3. DESCRIPTION OF DETAILED FEATURES

This section provides a qualitative description of the approach used in the ORDENA model to meet the client’s requirements. The description under this section is project specific and will not reflect the full range of capabilities of the model but just the ones in use for the study. Each sub-section will provide the details outlined in Box 1 previously presented.

3.1. TEMPORAL CHARACTERISATION

Prior to the description of each module of the optimization problems that forms ORDENA, this sub-section will describe the temporal structure used for these simulation and the underlying assumptions behind them.

One of the main problems when building a power system model is how to structure the mathematical problem in a way that is solved in acceptable computing times, but that at the same time provides results that are representative of the underlying system to be modelled. In this sense, a critical variable are the time steps (time slices that define the problem to be solved, e.g. hours, weeks, years) to be used. The ORDENA model is fully flexible in this sense and allows an almost unlimited range of temporal representation options, depending on the requirements of particular scenarios.

The temporal characterisation is modelled in ORDENA using a three-tier approach:

1. Periods, that can represent years or groups of years;
2. Stages are subgroups inside a period and are used to represent seasons, months, weeks, or even days; and
3. Load blocks which can be basically seen as time subgroups within each stage.

**Box 2 – Temporal Characterisation Indices**

The following three indices will define and allocate each variable and parameter in time, they are defined as follows, and this definition will apply to all the following equations, variables and parameters unless otherwise noted.

<table>
<thead>
<tr>
<th> </th>
<th>Index of periods ( p = { p_1, ..., P } )</th>
<th>I</th>
</tr>
</thead>
<tbody>
<tr>
<td> </td>
<td>Index of stages ( e = { e_1, ..., E } )</td>
<td>I</td>
</tr>
<tr>
<td> </td>
<td>Index of load-blocks ( b = { b_1, ..., B } )</td>
<td>I</td>
</tr>
</tbody>
</table>

For long term studies the most common method of describing each demand is a load-duration curve (LDC). For these problems a low temporal granularity is not required as the computational requirements would otherwise be too high while the uncertainty posed by a very distant horizon can be excessive.

The LDC is equivalent to the load-over-time curve sorted in order of decreasing power. The duration of the LDC ranges from one day or week to a whole year and it is constructed using historical demand hourly records. The following figure shows and example of the use of these records on different application, being the bottom-right figure the one corresponding to this study.
It is important to note that the LDC approach changes the data from a chronological order to a decreasing monotone\(^5\) shaped curve. This lack of chronological information is particularly important in the presence of large amounts of hydro and pumped hydro generation and demand-side response where a chronological representation may be preferred to load duration curve methods.

In order to overcome this problem and to ensure a realistic representation of the interchanges between countries, the approach will be the following:

- Each hour of the year needs to be unambiguously assigned to one load block and it needs to be the same block for all zones considered, i.e. the load blocks need to be simultaneous to all zones, so that, for example, the hourly consumption at 6pm will fall under the same load block for all countries.
- In order to calculate the optimal load blocks that allows the best representation of the demand and interchanges a simple optimization program was developed with the objective of minimizing the difference between the real LDC and the block-wise representation.
- Departing from the historic hourly demand profiles over one year for each of the model zones represented, the load blocks are calculated.

The following figure shows an example of the real (red) and modelled (blue) load duration curves obtained and used in ORDENA. The model will be using eight load blocks for each of the four seasons to characterize demand. So, as a summary, the model will working with annual periods, divided into four stages (seasons), subdivided into eight load-blocks each.

\(^5\) In order of the level of demand, with highest level of demand first and lowest level of demand last. You can think of this as asking a class of children to line up either based on their date of birth (chronological) or with the tallest first in order of height (decreasing monotone).
At the end of the day, and for the sake of simplicity using only three load-blocks, the demand representation for the aggregated demand (if all the zonal demands were to be added into a single one) will look similar to the following figure.

### Figure 5 - Temporal Characterisation of Demand Using Load Blocks

#### 3.2. Regional Characterisation

After the temporal characterisation of the problem, it is important to define the way each country (and internal country sub-division) will be represented. The regional characterisation and the transmission network representation are linked, the more complex the regional characterisation is, the more complex the transmission network model will be.

On one side, if the power system was modelled on a nodal basis (representing each high voltage (HV) substation bars), the transmission network should include all HV lines and their physical relationships (both first and second Kirchhoff’s laws). On the opposite side, if the modeller assumes a single-node approach, no transmission network is needed as all generation and demand would virtually coincide in the same physical point, thus assuming no congestion in the network. The intermediate approach is to balance the mathematical complexity and result accuracy by using a zonal approximation (as shown in Figure 6 and described hereafter) applied under this project.

The ORDENA model has three levels of spatial differentiation:
1. The first level is called area, and coincides typically with the different control areas of the TSOs and/or with political boundaries.

2. The second level is called free flow zone and is used to define zones inside a control area with limited transmission capacity between them due to transmission line ratings or security of supply constraints.

3. To end, the third level allows for the representation of individual nodes of the transmission network within each free flow zone defined.

**Box 3 – Regional Characterisation Indices**

The following three indices will define and allocate each variable and parameter in space, they are defined as follows, and this definition will apply to all the following equations, variables and parameters unless otherwise noted.

<table>
<thead>
<tr>
<th>Index</th>
<th>Description</th>
<th>I</th>
</tr>
</thead>
<tbody>
<tr>
<td>a</td>
<td>Index of areas (a = {a_1, \ldots, A})</td>
<td></td>
</tr>
<tr>
<td>z</td>
<td>Index of free flow zones (z = {z_1, \ldots, Z})</td>
<td></td>
</tr>
<tr>
<td>i</td>
<td>Index of load-blocks (i = {i_1, \ldots, I})</td>
<td></td>
</tr>
</tbody>
</table>

Differently to what happens with the temporal characterisation, which will remain the same throughout the whole study, regional characterisation will be changed depending on the goal of the simulation, for example, when modelling the capacity development of each country isolated (this is, not allowed to interconnect—or further interconnect if already linked- to its neighbours), the areas will correspond to each of the different colours shown on the next figure. In the case of a full regional integration, only one area will be used.

**Figure 6 - Regional Characterisation**
The reason of this change is that security of supply (as seen later on in this document) is defined as a constraint in the model for each area, meaning that, in the former case (isolation), each country will define its own security requirements which won’t be shared while in the later (integration) the security of supply will be shared among all participants.

### 3.2.1 Transmission Network

The electricity transmission network can be modelled using both Kirchhoff’s Laws within ORDENA. These two laws represent the real physical conditions electricity has to fulfil to be carried from its sources (generators) to its consumption (demand).

Given the scope of the project, data availability and computational requirements, for this study, a zonal modelling approach will be applied, meaning that (as seen in the figure above) each region subject to congestion will be considered an electric node, interconnected to others via flowgates representing the available transfer capacity between this two regions (ATC modelling approach). The model allows considering transmission losses as proportional to power flows using a loss factor.

### 3.3. Objective Function

The objective function represents the operating costs of the power system, which consist on those of power generation, demand side management and those related to energy not supplied plus the capital expenditures of both generation and transmission assets that will enter the system in the future.

The ORDENA model is able to consider different stochastic scenarios (see Box 4 below) regarding demand, renewable power generation or fuel costs, thus uncertainty is included in the objective function. A simplified representation of the objective function is shown below; each of its different terms will be described thoroughly in the next sections:

\[
\min \sum_{w=1}^{W} \sum_{p=1}^{P} \frac{1}{(1+r)^{p-1}} \cdot \left( \sum_{g} (p_{r}^{w} \cdot CV_{p,g}^{w} + CF_{p,g} + IC_{p,g}) \right) \\
+ \sum_{d} (p_{r}^{w} \cdot CV_{p,d}^{w} + CF_{p,d} + IC_{p,d}) + \sum_{l} (p_{r}^{w} \cdot CV_{p,l}^{w} + CF_{p,l} + IC_{p,l})
\]

Where:

<table>
<thead>
<tr>
<th>w</th>
<th>Index of scenarios (w = {w_1, ..., W})</th>
<th>I</th>
</tr>
</thead>
<tbody>
<tr>
<td>g</td>
<td>Index of generators (g = {g_1, ..., G})</td>
<td>I</td>
</tr>
<tr>
<td>d</td>
<td>Index of demands (d = {d_1, ..., D})</td>
<td>I</td>
</tr>
<tr>
<td>l</td>
<td>Index of power lines (l = {l_1, ..., L})</td>
<td>I</td>
</tr>
<tr>
<td>r</td>
<td>Discount Rate</td>
<td>p.u.</td>
</tr>
<tr>
<td>(p_{r}^{w})</td>
<td>Probability of occurrence of scenario (w)</td>
<td>p.u.</td>
</tr>
</tbody>
</table>

* For the sake of simplicity, the scenario notation will only be used in the objective function definition and omitted in the rest of constraints. Note that the fixed costs are unique for all scenarios as the system expansion calculated is the same for all the defined scenarios (i.e., not a stochastic variable).
The variable cost function is composed by:

- Fuel Costs;
- Operation and maintenance variable costs;
- Emission costs;
- Demand-side management costs; and
- Penalties associated to slack variables (i.e. non-supplied energy)

While the fixed cost function will include the operation and maintenance fixed costs together with the investment cost used in the long-term model. Investment costs include the capital expenditures (including interests accumulated during construction) and decommissioning costs (if applicable).

Note that in order to consider the time value of money and investment risk, the objective function will be discounted yearly at the given discount rate. This is the value denoted by \( r \) above.

**Box 4 – Dealing with Uncertainty**

The operation and planning of power systems is dominated by uncertainty in some key variables. The main sources of uncertainty in the planning of power system are:

- Fossil fuels price forecast,
- Demand forecast and,
- Renewable source availability.

There are several ways to address these issues, via scenarios, using Monte Carlo simulation and applying stochastic optimization.

Under this study, both the scenario approach and the stochastic optimization will be used. Scenario approach will be applied by running different simulations with changes to a key parameter on a *ceteris paribus*\(^7\) manner, and then calculating the

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\(^7\) When using *ceteris paribus* in economics, assume all other variables except those under immediate consideration are held constant.
difference in welfare provoked by the applied changes. Stochastic optimization will be in use when running all the simulations, as the uncertainty of the renewable sources availability will be computed* as a stochastic input.

### 3.4. Energy Balance

The electric power system represented in the ORDENA model is subject to energy balance constraints, derived from first Kirchhoff’s law, these are defined as follows:

\[
\sum_{t \in l} g_{t,b} + \sum_{h \in l} g_{h,b} + \sum_{r \in l} g_{r,b} + \sum_{i} \sum_{j} f_{i,j,b} = \sum_{i} f_{i,j,b} + \sum_{d} \left( d_{d,b} - e_{s,b} \right) + \sum_{h} g_{h,b} + \sum_{r} g_{r,b} + \frac{1}{2} \sum_{i} \left( f_{i,j,b} + \sum_{j} 0.5 f_{i,j,b} \right) + s_{b} \quad \forall i, b \in e \in p
\]

Where:

| \( t \) | Index of thermal generators \( t=\{t_1, \ldots, T\} \) | \( I \)
| \( h \) | Index of hydro generators \( h=\{h_1, \ldots, H\} \) | \( I \)
| \( r \) | Index of renewable generators \( r=\{r_1, \ldots, R\} \) | \( I \)
| \( i,j \) | Index of nodes \( i=\{i_1, \ldots, I\} \) | \( I \)
| \( g_{t,b} \) | Thermal generation of group \( t \) in load block \( b \). | MW \( V \)
| \( g_{h,b} \) | Hydro power generation of group \( h \) in load block \( b \). | MW \( V \)
| \( g_{r,b} \) | Renewable power generation of group \( r \) in load block \( b \). | MW \( V \)
| \( g_{p,h,b} \) | Pump consumption of group \( h \) in load block \( b \). | MW \( V \)
| \( g_{p,r,b} \) | Pump consumption of group \( r \) in load block \( b \). | MW \( V \)
| \( s_{b} \) | Power generation surplus in node \( i \), in load block \( b \). | MW \( V \)
| \( e_{s,b} \) | Non-supplied energy in node \( i \), in load block \( b \). | MW \( V \)
| \( f_{i,j,b} \) | Power flow through line \( i,j \) in load block \( b \). | MW \( V \)
| \( l_{i,j,b} \) | Losses in line \( i,j \) in load block \( b \). | MW \( V \)

This equation will assure that energy is balanced on a nodal basis, being the non-supplied energy and power surplus variables slack unknowns used to assure a feasible solution to the optimization problem. The non-supplied energy variable

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* Depending on the data collected, the renewable sources to be computed as stochastic will include hydro, and if available, also wind and solar.
plays a key role as it is directly linked to the security of supply (electricity rationing).

3.5. **Modelling Generation and Transmission Assets**

3.5.1. **Thermal Plants**

The operation of thermal plants is limited by certain constraints, such as:

- **Capacity limits:**

These are used to limit generation to the installed capacity and to consider must-run constraints.

\[
\begin{align*}
g_{t,b} & \geq G_{\text{min},t,e} \cdot \text{Avail}_{t,e} \cdot \text{sched}_{t,e} \cdot (1 + F_{\text{max},t,b}) \\
g_{t,b} & \leq G_{\text{max},t,e} \cdot \text{Avail}_{t,e} \cdot \text{sched}_{t,e} \cdot (1 + F_{\text{max},t,b})
\end{align*}
\]

Where:

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$G_{\text{max},t,e}$</td>
<td>Maximum available generation of group $t$ in stage $e$</td>
</tr>
<tr>
<td>$G_{\text{min},t,e}$</td>
<td>Minimum available generation of group $t$ in stage $e$</td>
</tr>
<tr>
<td>$\text{Avail}_{t,e}$</td>
<td>Availability (excluding considered scheduled stops) of group $t$</td>
</tr>
<tr>
<td>$g_{t,b}$</td>
<td>Net power generation of group $t$ in period $p$ in stage $e$ in block $b$</td>
</tr>
<tr>
<td>$\text{sched}_{t,b}$</td>
<td>Availability due to scheduled stops of group $t$</td>
</tr>
<tr>
<td>$F_{\text{max},t,b}$</td>
<td>Impact of external factors and cooling on the maximum output</td>
</tr>
</tbody>
</table>

- **Maintenance constraints**

ORDENA allows optimising scheduled stops for existing, planned and for candidate plants with discrete expansion. Depending on the problem this might significantly increase computing requirements.

\[
\begin{align*}
1 - \text{sched}_{t,e} & \leq \text{sched}_{t,e} \\
\sum_e((1 - \text{sched}_{t,e}) \cdot \sum_b \text{Dur}_b) & \geq SOR_t \\
1 & \geq \text{sched}_{t,p,e}
\end{align*}
\]

Where:

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\text{sched}_{t,e}$</td>
<td>Binary. Is 1 in case the unit $t$ performs a full or partial stop in the stage $e$</td>
</tr>
</tbody>
</table>

- **Provision of operating reserves:**

It considers one type of operating reserve.

\[
\begin{align*}
opres_{T,t,b} & = G_{\text{max},t,e} \cdot \text{Avail}_{t,e} \cdot \text{sched}_{t,e} - g_{t,b} \\
opres_{T,t,b} & \leq G_{\text{max},t,e} \cdot \text{OpRes}_{T_t}
\end{align*}
\]

Where:
The provision of operating reserves of unit $t$ in block $b$ is given by $\text{opres}T_{t,b}$. The amount of operating reserves of unit $t$ is able to provide related to the installed capacity is $\text{OpResT}_t$.

- **Allocation constraints:**

In order to represent the limited start-up/down flexibility, the minimum time online and/or must run constraints:

$$g_{t,b} \cdot D_{wr_b} \leq AF_{t,b} \cdot \sum_{b \in e} (g_{t,b,b} \cdot D_{wr_{bb}})$$

$$g_{t,b} \cdot D_{wr_b} \geq AF_{\min t,b} \cdot \sum_{b \in e} (g_{t,b,b} \cdot D_{wr_{bb}})$$

Where:

| $AF_{t,b}$ | Maximum allocation factor of group $t$ in $p$, stage $e$, block $b$ | p.u. | P |
| $AF_{\min t,b}$ | Minimum allocation factor of group $t$ in $p$, stage $e$, block $b$ | p.u. | P |

- **Variable cost calculation:**

$$CV_{t,p} = \sum_{b \in e} (D_{wr_b} \cdot g_{t,b} \cdot (VarO&M_t - EnPay_{t,p}) + \sum_{f} f_{uel_{t,f,b}} \cdot FuelCost_{t,f,e}$$

$$+ \sum_{p_0} \sum_{t \in a} E_{mit_{t,p_0,b}} \cdot E_{miCost_{a,p_0,e}})$$

Where:

| $E_{miCost_{a,p_0,e}}$ | Emission costs in area $a$, for pollutant $p_0$, for stage $e$ | currency / pollutant unit | P |
| $FuelCost_{t,f,e}$ | Provision cost of fuel $f$, at unit $t$, for stage $e$ | currency / fuel unit | P |
| $OM_{var_t}$ | Variable operation and maintenance costs of unit $t$ | currency/MWh | P |

- **Fixed cost calculation**

$$CF_{t,p} = \frac{\sum_{b \in e} (G_{max_{t,e}} \cdot D_{wr_b})}{\sum_b D_{wr_b}} \cdot OM_{fix_t}$$

Where:

| $OM_{fix_t}$ | Fix operation and maintenance costs of unit $t$ | currency/MW | P |

- **Calculation of fuel consumption**
The model allows additionally a more detailed representation of fuel consumption using different operating points.

\[ \sum_f fuel_{t,f,b} \geq Dur_f \cdot Const_t \cdot g_{t,b} \quad \forall \ t, b \]

- **Calculation of emissions**

\[ emi_{t,po,p} = \sum_f fuel_{t,f,b} \cdot FEmi_{t,f,po} \quad \forall \ t,po,p \]

Where:

<table>
<thead>
<tr>
<th>Item</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Thermal Power Plant Name</td>
</tr>
<tr>
<td>2</td>
<td>Number of Units</td>
</tr>
<tr>
<td>3</td>
<td>Installed Capacity (MW)</td>
</tr>
<tr>
<td>4</td>
<td>Minimum Generation (MW)</td>
</tr>
<tr>
<td>5</td>
<td>Maximum Generation (MW)</td>
</tr>
<tr>
<td>6</td>
<td>Average availability [time available / total time] (%)</td>
</tr>
<tr>
<td>7</td>
<td>O&amp;M variable costs (USD/MWh)</td>
</tr>
<tr>
<td>8</td>
<td>O&amp;M fixed costs (USD/KW)</td>
</tr>
<tr>
<td>9</td>
<td>Fuel Used</td>
</tr>
<tr>
<td>10</td>
<td>Average fuel consumption (MCal/MWh)</td>
</tr>
<tr>
<td>11</td>
<td>Fuel cost (USD/unit) [Units = ton, MBTU, MWh...]</td>
</tr>
<tr>
<td>12</td>
<td>Number and type of alternative fuels that can be used</td>
</tr>
<tr>
<td>13</td>
<td>Type of Power Plant (CCGT, Steam Turbine,...)</td>
</tr>
<tr>
<td>14</td>
<td>Capable of providing Spinning Reserves (Yes/No)</td>
</tr>
<tr>
<td>15</td>
<td>Plant Status: Existing or future (date of commissioning)</td>
</tr>
</tbody>
</table>

With this information, the consultant is able to represent the real function of power plants. The model will create an internal merit order in order to supply demand at
the least possible cost while fulfilling all the technical and economic constraints present.

### 3.5.2. **RENEWABLE POWER GENERATION AND STORAGE**

This module allows the user to represent any power generation technology with a controllable output and defined store, this can include:

- Hydroelectric plants with reservoir;
- Concentrated solar power with storage capability;
- Storage technologies such as pumped storage, compressed air energy storage (CAES), chemical storage based on electrolysis (hydrogen) or other reactions; or
- Demand shifting.

**Figure 7 - Structure of the Storage Model**

The model allows representation of both controllable (hydropower and solar thermal) as well as non-controllable renewable generation, such as wind or solar. These share several constraints with thermal units. In order to reproduce their behaviour additional constraints need to be added. Under this section, the constraints that are similar to the already presented for thermal plants won’t be repeated, this stands for:

- Capacity Limits
- Ramp constraints
- Provision of spinning reserves
- Allocation constraints
- Availability
- Variable cost calculation
- Fixed cost calculation
Renewable power generation is represented using allocation constraints. In this case the total available generation is determined by the availability of wind, water and sunlight.

- **Resource availability**

\[ gr_r \cdot Dw_b \leq AF_{r,b} \cdot G_{max_{r,e}} \cdot Util_{r,e} \]
\[ gr_r \cdot Dw_b \geq AF_{min_{r,b}} \cdot G_{max_{r,e}} \cdot Util_{r,e} \]

\( \forall r, b \in e \)

Where:

<table>
<thead>
<tr>
<th>AF_{r,b}</th>
<th>Maximum allocation factor of group r in block b</th>
<th>p.u.</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td>AF_{min_{r,b}}</td>
<td>Minimum allocation factor of group r in block b</td>
<td>p.u.</td>
<td>P</td>
</tr>
<tr>
<td>Util_{r,e}</td>
<td>Utilisation of group r in stage e</td>
<td>h</td>
<td>P</td>
</tr>
</tbody>
</table>

- **Energy balance**

This equation is very similar to that of the energy balance equation of the short term model. In this case the inflows are substituted by the utilisation of the unit, which represents not only the natural inflows but also water stored during or for other stages. The storage loading and discharge data thus exclude reservoir management during periods of longer than one stage.

\[ \frac{storange_{r,b}}{StorEff_r} - stordis_{r,b} = \frac{Util_{r,p}}{\sum_b Dw_b} \cdot Dw_b \cdot G_{max_{r,e}} + Dw_b \cdot (PumpEff_r \cdot g_{r,b} - g_{r,b}) \]

\( \forall r, b \)

Where:

| Util_{r,e} | Utilisation of unit h in stage e (excluding pump) | h | V |

- **Storage level**

In order to represent the real behaviour of power plants with storage capabilities, the medium and long term modules allows two possible representations of these plants. The first representation is using the regulation factor \((RegFact_r)\), which defines the share of water which can be “moved” from one block to another of the same stage, this is implemented using \(AF_{min_{r,b}}\). Another option used for pumped storage is to define the minimum cycling period of the reservoir in order to calculate the amount of water that can be loaded during a stage.

\[ \sum_{b \in e} storange_{r,b} \leq S_{max_{r}} \cdot \frac{\sum_{b \in e} Dw_{b}}{StorPer_r} \]
\[ \sum_{b \in e} storange_{r,b} = \sum_{b \in e} stordis_{r,b} \]

\( \forall r, e \)

Where:

| RegFact_r | Regulation factor of unit r | p.u.  | P |
Summary of data needed

As it happened for thermal plants, the following table shows the data to be collected in order to model the different type renewable energy assets.

**Table 2 – Renewable Generation Data Needs (Hydro)**

<table>
<thead>
<tr>
<th>Item</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Name / Location of plant</td>
</tr>
<tr>
<td>2</td>
<td>Downstream plant for turbine discharges</td>
</tr>
<tr>
<td>3</td>
<td>Number of generation units</td>
</tr>
<tr>
<td>4</td>
<td>Installed Capacity (MW)</td>
</tr>
<tr>
<td>5</td>
<td>Net Head (masl)</td>
</tr>
<tr>
<td>6</td>
<td>Mean production factor (MW/m3/s)</td>
</tr>
<tr>
<td>7</td>
<td>Minimum turbine outflow (m3/s)</td>
</tr>
<tr>
<td>8</td>
<td>Minimum storage (Hm3)</td>
</tr>
<tr>
<td>9</td>
<td>Maximum storage (Hm3)</td>
</tr>
<tr>
<td>10</td>
<td>Initial storage level (typically it is the reservoir level at January 1st given as a fraction of the maximum storable capacity, it can also be in meters in case we have the height of the dam)</td>
</tr>
<tr>
<td>11</td>
<td>Ability to regulate: None, hourly, daily, weekly...</td>
</tr>
<tr>
<td>12</td>
<td>Minimum total outflow = Minimum turbining + spilling in m3/s</td>
</tr>
<tr>
<td>13</td>
<td>Average availability [time available / total time] (%)</td>
</tr>
<tr>
<td>14</td>
<td>O&amp;M variable costs (USD/MWh)</td>
</tr>
<tr>
<td>15</td>
<td>O&amp;M fixed costs (USD/KW)</td>
</tr>
<tr>
<td>16</td>
<td>Plant Status: Existent or future (commissioning date)</td>
</tr>
</tbody>
</table>

**Table 3 – Renewable Generation Data Needs (Others)**

<table>
<thead>
<tr>
<th>Item</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Name / Location of plant</td>
</tr>
<tr>
<td>2</td>
<td>Number of generation units</td>
</tr>
<tr>
<td>3</td>
<td>Installed Capacity (MW)</td>
</tr>
<tr>
<td>4</td>
<td>Type of Plant/Resource Used</td>
</tr>
<tr>
<td>5</td>
<td>Ability to store: None, hourly, daily, weekly...</td>
</tr>
<tr>
<td>6</td>
<td>Average availability [time available / total time] (%)</td>
</tr>
<tr>
<td>7</td>
<td>O&amp;M variable costs (USD/MWh)</td>
</tr>
<tr>
<td>8</td>
<td>O&amp;M fixed costs (USD/KW)</td>
</tr>
</tbody>
</table>
Regarding the resource availability, the following figure shows an example of the data set that is intended for use.

**Figure 8 – Example of Historical Monthly Resource Availability**

The figure shows historical records of water inflows into a certain reservoir. The smaller the granularity of the records and the longer the horizon the better for modelling purposes. As the power generation from weather dependant renewable sources behaves in a different way to those of thermal plant. The approach to representing them in the model is different (as seen in the equations above).

The representation of weather dependant renewable sources is based on allocation factors of power generation of each stage (thus the need to collect historical records, also used to build stochastic scenarios for modelling). These factors represent the maximum and minimum share of power generation that can be produced in each block.

**Figure 9 – Wind Power Allocation Factors among Load Blocks (Example)**
To combine the demand variations and the intermittence of renewable power generation, in the following example, twelve load blocks are defined for each stage (four levels of demand and three levels of wind).

The allocation factors are computed from historical records and associated to the temporal characterisation of demand. This means that if b1 represents peak demand, the corresponding allocation factor is the historical capacity factor of the renewable source at peak hours (medium, high and low).

**Figure 10 - Load Duration Curve for Example Season (spring, 2208 hours)**

Under this study and due to the very limited resource availability information available, only hydro assets will be modelled as uncertain (with scenarios) being wind and sun resources considered as average for all cases.

**3.5.3. Transmission Lines**

The following constraints stand for the modelling transmission lines considering only the Kirchhoff’s First Law, which states that at any node (junction) of an electrical circuit, the sum of currents flowing into that node is equal to the sum of currents flowing out of that node.

- **Capacity limits:**

  \[ f_{i,j,k,b} \leq f_{max_{i,j,k}} \quad \forall k, b \]

  Where:

<table>
<thead>
<tr>
<th>K</th>
<th>Index for circuits</th>
</tr>
</thead>
<tbody>
<tr>
<td>f_{max_{i,j,k}}</td>
<td>Maximum flow for circuit k</td>
</tr>
</tbody>
</table>

  **Losses:**

  \[ l_{i,j,k,p,e,b} = \gamma_{i,j,k} \cdot f_{i,j,k,b} \quad \forall k, b \]

  Where:
- **Available Transfer Capacities**

The power flows between defined zones of the transmission system are also limited so that power supply can be ensured after the trip of the largest generator or of a transmission line.

\[-ATC_{neg} g,e \leq \sum_{k \in G} f_{i,j,k,b} \leq ATC_{pos} g,e\]  \( \forall g,e \)

Where:

| ATCpos g,e | Available Transfer Capacity from zone z1 to zone z2 of flow-gate g | MW | P |
| ATCneg g,e | Available Transfer Capacity from zone z2 to zone z1 of flow-gate g | MW | P |

- **Summary of data needed**

In order to come to a model that satisfies the previous constraints, which under this work will mean a regional representation as seen in Figure 6, the following data is needed.

**Table 4 – Transmission Grid Data Needs**

| Region FROM | Region To | Capacity (MVA) | FROM => TO Transfer limit (MW) | TO => FROM Transfer limit (MW) | Loss Factor (%) |

As this information is not readily available at most sources, the consultant usually departs from the following sources so as to derive this info,

a. Existing grid and its problems, in particular system plans and required expansions. Transmission constrains. Stability problems (permanent and transitory). Stability problems are related to frequency problems in the system, voltage/reactive power problems, etc.

b. Corridor constraints. Due to stability or voltage problems, some groups of lines may be constrained to a maximum flow.

c. Existing interconnection with other countries, maximum capacity (NTC => Net Transfer Capacity and/or ATC => Available Transfer Capacity). It is the maximum exchange capacity between two areas compatible with security standards applicable in both areas and taking into account the technical uncertainties on future network conditions. These constraints should be provided for international and for intra-national links if applicable.

d. Studies and objectives related to the future development of the system, as well as interconnections with systems of other countries.

e. Technical characteristics of existing lines and transformers. Line serie resistance and reactance, line length, Transformer reactance. Maximum transmission
capacity [MW] (normal situation). Transformer capacity [MVA]. A table view of the information could be the following:

### 3.5.4. Candidate Assets and Retirements

This section will explain how candidate projects and retirements are taken into account in ORDENA model, as the procedure is very similar for all kind of power plants, the explanation will be done over a generic plant. There are two ways of including candidate projects in ORDENA, as continuous or as discrete values. First, the method to account for the capital costs of power plants is discussed.

The long term planning model optimises the future expansion of the power system based on a set of candidate assets defined by the user. These assets can be generation units (of any kind) or transmission lines. In simple terms, the model will arbitrate between building new power plants, strengthening the transmission network to interconnect existing resources or decreasing energy consumption at a certain cost (alternatives are not mutually exclusive, a feasible output can be a combination of all the elements).

Generation options can include conventional thermal generation (nuclear, coal, gas, etc.), renewable generation (wind, wave, tidal, hydro) generation or forms of storage.

Candidates for new generation and transmission can be considered as discrete or continuous decision within the optimisation module. That means they are available in “lumps” of investment, or as any value of investment. For example, wind generators are relatively small, so its expansion can be considered as a continuous investment decision, on the other side, big hydro projects are so project-specific that are usually analysed as discrete decision. Having said this, the model solves faster with continuous than with discrete variables.

In modelling terms, the optimisation algorithm minimises the NPV of the total system costs. This means that lifetime operating expenditures are discounted to the first year of the analysis to reflect the real cost of a project. Capital costs are discounted assuming constant expenditures during construction (a uniform per year capital expenditure across the construction period. In the event that the lifetime of the asset exceeds the optimisation horizon, capital expenditures are scaled down to take into account the residual value of the investment.

Capacity payments, subsidies or policies impacting on investment risk are implemented as a modification of the capital expenditure, as these measures do not impact short term dispatch, but do affect investment decisions.

Next figure summarises how expenditure is modelled in ORDENA as capital and operation expenditures (shown in red arrows above the line), the benefits (capacity payments, subsidies, etc.) are computed by the model causing a reduction in the overall costs of the asset (shown in orange arrows beneath the line).

**Figure 11 - Expenditure and Benefits/Revenue Associated with Candidate Projects**

The long model also allows for inclusion of planned generation. The units are given an entry year (although entry in a specific month can be represented by adjusting unit availability in the entry year data sheet) and a retirement year, after which the
unit is no longer available for production and adds no costs to the system. The same principle is applied to assets that exist at the start of the simulation.

Additionally refurbishment, retrofitting and upgrade can be modelled within ORDENA as a new asset that can replace an existing one: the capital expenditure of the “new” asset would only consist of the costs associated with refurbishment.

ORDENA allows power plant retirements which take place before the end of the lifetime. The model represents the trade-off between an earlier retirement and one at the end of the lifetime by taking into account the potential O&M savings as well as the revenue loss.

The mathematical structure of this module is the following:

- **Capital costs:**

\[
IC_{g,p} = \text{Int}_g \cdot \frac{\text{AnnLife}_g}{\text{AnnRem}_{g,p}} \cdot (\text{CAPEX}_g + \text{AdCAPEX}_g - \text{CapPay}_{g,p} - \text{AvaPay}_{g,p}) \cdot \text{inv}_{g,p} \quad \forall \ g, p
\]

\[
\text{Int}_g = \frac{1}{\text{Const}_g} \cdot \sum_{i=0}^{\text{Const}_g-1} (1+r)^{\text{Const}_g-i} \quad \forall \ g
\]

\[
\text{AnnLife}_g = \frac{r \cdot (1+r)^{\text{Amort}_g-1}}{(1+r)^{\text{Amort}_g}-1} \quad \forall \ g
\]

\[
\text{AnnRem}_{g,p} = \frac{r \cdot (1+r)^{\text{Rem}_{g,p}-1}}{(1+r)^{\text{Rem}_{g,p}}-1} \quad \forall \ g, p
\]

Where:

<table>
<thead>
<tr>
<th>$IC_{g,p}$</th>
<th>Annualized capital cost to be included in the objective function.</th>
<th>currency/MW</th>
<th>p</th>
</tr>
</thead>
<tbody>
<tr>
<td>$CAPEX_g$</td>
<td>CAPEX of the power plant g</td>
<td>currency/MW</td>
<td>p</td>
</tr>
<tr>
<td>$AdCAPEX_g$</td>
<td>Additional CAPEX of the power plant g used to represent investors’ risk</td>
<td>currency/MW</td>
<td>p</td>
</tr>
<tr>
<td>$\text{Int}_g$</td>
<td>Accumulation of interests during construction</td>
<td>p.u.</td>
<td>p</td>
</tr>
<tr>
<td>$\text{AnnLife}_g$</td>
<td>Annuity factor considering the whole lifetime of the asset</td>
<td>p.u.</td>
<td>p</td>
</tr>
<tr>
<td>$\text{AnnRem}_{g,p}$</td>
<td>Annuity factor considering the remaining period of the simulation horizon of the asset</td>
<td>p.u.</td>
<td>p</td>
</tr>
<tr>
<td>$\text{inv}_{g,p}$</td>
<td>Variable representing investments</td>
<td>[0,1]/MW</td>
<td>V</td>
</tr>
<tr>
<td>$\text{Dism}_g$</td>
<td>Dismantling costs of generator g</td>
<td>currency/MW</td>
<td>p</td>
</tr>
<tr>
<td>$\text{ret}_{g,p}$</td>
<td>Variable representing retirements</td>
<td>[0,1]/MW</td>
<td>V</td>
</tr>
</tbody>
</table>
Assessment Opportunities and Challenges to Increased Regional Energy Cooperation in South Asia

<table>
<thead>
<tr>
<th></th>
<th>Description</th>
<th>Unit</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\text{CapPay}_g)</td>
<td>Capacity payments discounted to construction time</td>
<td>currency</td>
<td>P</td>
</tr>
<tr>
<td>(\text{Rem}_{g,p})</td>
<td>Remaining period of simulation considered for generator g in period p</td>
<td>years</td>
<td>P</td>
</tr>
<tr>
<td>(\text{Amort}_g)</td>
<td>Amortization time of plant g</td>
<td>years</td>
<td>P</td>
</tr>
<tr>
<td>(\text{Const}_g)</td>
<td>Construction time of plant g</td>
<td>years</td>
<td>P</td>
</tr>
<tr>
<td>(r)</td>
<td>Discount rate</td>
<td>p.u</td>
<td>P</td>
</tr>
<tr>
<td>(\text{AvaPay}_{g,p})</td>
<td>Availability payment of generator g in period p discounted to construction time</td>
<td>currency/MWh</td>
<td>P</td>
</tr>
</tbody>
</table>

The interest accumulated during construction (IADC) for discount rate \(r\) is given by:

\[
\text{IADC}_{g,r} = \text{CAPEX}_g \left(1 - \frac{1}{\text{Const}_g} \frac{(1 + r)^{\text{Amort}_g} - 1}{(1 - u)}\right).
\]

where \(u\) is the discount factor: \(u = 1/(1+r)\). The additional capex is the difference between the IADC values for the variant of \(r\). Additional capex figures for the generator candidate assets are derived in the accompanying spreadsheet, worksheet “candidate generation”.

Once the capital costs are known, the model has to follow the next constraints:

- **Continuous decision:**

\[
\sum_p \text{inv}_{g,p} \leq \text{gmax}_g \quad \forall \ g
\]

\[
\text{inv}_{g,p} \leq \sum_{p=p+1}^{p+\text{Amort}_g} (\text{ret}_{g,p} + \text{rfb}_{g,p}) \quad \forall \ g, p
\]

\[
\text{exist}_{g,p} = \text{exist}_{g,p-1} + \text{inv}_{g,p} - \text{ret}_{g,p} - \text{rfb}_{g,p} \quad \forall \ g, p
\]

\[
\text{gen}_{g,b} \leq \text{exist}_{g,p} \quad \forall \ g, b \in e \in p
\]

Where:

<table>
<thead>
<tr>
<th></th>
<th>Description</th>
<th>Unit</th>
<th>V</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\text{inv}_{g,p})</td>
<td>Investment in generator g in year p</td>
<td>MW</td>
<td>V</td>
</tr>
<tr>
<td>(\text{exist}_{g,p})</td>
<td>Existence of generator g in year p</td>
<td>MW</td>
<td>V</td>
</tr>
<tr>
<td>(\text{ret}_{g,p})</td>
<td>Retirement of generator g in year p</td>
<td>MW</td>
<td>V</td>
</tr>
<tr>
<td>(\text{rfb}_{g,p})</td>
<td>Refurbishment of generator g in year p</td>
<td>MW</td>
<td>V</td>
</tr>
</tbody>
</table>

- **Discrete decision:**

\[
\sum_p \text{inv}_{g,p} \leq 1 \quad \forall \ g
\]
Assessment Opportunities and Challenges to Increased Regional Energy Cooperation in South Asia

Where:

\[ \text{inv}_{g,p} \leq \sum_{p=p+1}^{p+\text{Amort}_g} (\text{ret}_{g,p} + \text{rfb}_{g,p}) \quad \forall \ g, p \]

\[ \text{exist}_{g,p} = \text{exist}_{g,p-1} + \text{inv}_{g,p} - \text{ret}_{g,p} - \text{rfb}_{g,p} \quad \forall \ g, p \]

\[ \text{gen}_{g,b} \leq \text{exist}_{g,p} \cdot g_{\text{max},p} \quad \forall \ g, b \in e \in p \]

- **Candidate transmission lines**

The previous explanation also holds for transmission lines, so it won’t be repeated, the only important consideration to be made clear is that only discrete decisions are allowed for transmission lines expansion due to the unrealistic results that may come up when allowing continuous expansion on transmission assets.

- **Summary of data needed**

In order to model the candidate assets the following information is to be added to the already seen in Table 1, Table 2, Table 3 and Table 4 for generation and transmission facilities,

- Type of investment (planned or candidate)
- Investment Costs
- First year of possible commissioning
- Asset’s life-time
- Construction time
- If the candidate asset is a refurbishment or upgrade, the plant/line to be substituted has to be identified.

3.6. **Additional Features**

Additional constraints are included in order to model aspects such as, the security of supply, fuel and emission constraints, renewable energy incentives, targets or subsidies, carbon (or other pollutants) limitations, etc.

3.6.1. **Reliability Constraints**

The most severe sudden frequency disturbances are typically caused by large generators or transmission lines unexpectedly going offline, or by a network fault disconnecting a large portion of demand. In short term models a three tier representation (frequency containment reserves (FCR), frequency restoration reserves (FRR) and replacement reserves (RR)) of the reserves is usually applied, due to the temporal characteristics of the long term models three level of reserves are summarised into a single type.

- **Operating reserves’ requirements**

The provision of operating reserves in each area has to be greater than the requirements.
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3.6.2. **FUEL AND ENVIRONMENTAL CONSTRAINTS**

The ORDENA model is capable of internalising investment decisions in response to policies promoting low carbon investment. These can be modelled explicitly (limits on total, regional or individual technology emissions), or implicitly (a cost for each unit of emissions).

- **Explicit emission constraints**

ORDENA allows constraints for each zone for the annual emissions of the defined pollutants, such as CO₂. Limits can be set by modelled time step such that they steadily lower over time according to a set schedule. This is very useful for policy makers, as the model also provides the abatement costs through the dual variable of this constraint.

- **Implicit emission constraints**

There are also options for carbon pricing. This can be an external input from a cap and trade system such as the EU ETS carbon prices (units polluting will end up having higher operating cost based on CO₂ intensity). Furthermore, the shadow price associated with plant operating constraints can be used to determine the system opportunity cost of reducing output from specific emissions intensive plant in accordance with these policies.

- **Maximum fuel constraints**

The annual fuel consumption in a particular area can be constrained, to represent a scenario where import capacity is limited, e.g. a pipeline which only allows limited natural gas imports. For power plants the model allows limiting the available fuel in each stage due to issues related to the procurement contracts or of other nature.

The mathematical formulation is as follows:
• **Emission limits:**

In order to limit the negative effects of emissions the model allows setting a maximum value to the annual emissions for each area. The shadow costs of the constraint reflect the emissions abatement costs.

\[
\sum_{g\in z, b\in p} emi_{g,p,v} \leq EmiLimit_{z,p,v} \quad \forall z, p
\]

Where:

<table>
<thead>
<tr>
<th>EmiLimit_{z,p,v}</th>
<th>Maximum emissions po in zone z per year p and scenario variant v.</th>
<th>unit of emissions</th>
<th>P</th>
</tr>
</thead>
</table>

• **Fuel quota:**

In order to limit the consumption of fuel the model allows setting a maximum value to the consumption for each stage.

\[
\sum_{g\in a, b\in e} fuel_{g,f,v} \leq FuelQuota_{a,f,e,v} \quad \forall a, f, e, s
\]

Where:

<table>
<thead>
<tr>
<th>FuelQuota_{a,f,e,v}</th>
<th>Maximum fuel consumption in area a per stage e</th>
<th>unit of emissions</th>
<th>P</th>
</tr>
</thead>
</table>

• **Fuel limits per area:**

To limit the consumption of fuel per area a maximum value for each stage can be set; the limit can be modified for each scenario:

\[
\sum_{g\in a, b\in e} fuel_{g,f,v} \leq FuelLimit_{a,f,v} \quad \forall a, f, e, s
\]

Where:

<table>
<thead>
<tr>
<th>FuelLimit_{a,f,v}</th>
<th>Maximum fuel consumption in area a per stage e and scenario variant v</th>
<th>unit of emissions</th>
<th>P</th>
</tr>
</thead>
</table>

• **Green share**

In order to represent policy goals concerning the share of demand covered by green technologies, the model allows setting a green target. In case the target isn’t achieved certain penalty can be introduced. Alternatively, the model can also provide the dual costs associated to the constraint which reflects the price which green certificates would require so that the given green share is reached.

\[
\sum_{g,p,e} g_{g,p,e} \cdot GreenG_g \leq \sum_{d,p,e} (Dem_{d,p,e} \cdot Green_{d,p}) \quad \forall pt, fuel, p, e
\]

Where:
### Summary of data needed

These different parameters are obtained from very different sources:

a. Security of supply and reserve coefficients are calculated from technical regulations, codes, or real operation of the system

b. Green related limitations (constraints, penalties, capacity shares) are also obtained from regulatory sources or governmental information.

c. Fuel limitation are usually known from plant-by-plant operation, countries importation facilities, or governmental regulations.

#### 3.6.3. Investment Limitations

Both the annual generation capacity expansion and investments can be limited in the long term model to a certain value.

\[
\sum_g inv_{g,p} \leq MaxExp_{a,p} \\
\sum_g inv_{g,p} \cdot CAPEX_g \leq MaxInv_{a,p}
\]

Where:

<table>
<thead>
<tr>
<th>MaxExp_{a,p}</th>
<th>Maximum expansion allowed in area a year p</th>
<th>MW</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td>MaxInv_{a,p}</td>
<td>Maximum investment allowed in area a year p</td>
<td>currency</td>
<td>P</td>
</tr>
</tbody>
</table>

The investment limitations are usually an unknown to the modeller and are used during the calibration process in order to avoid solutions that being mathematically and economically optimal are unrealistic to occur in real life, such as massive substitution of an existing technology for a new one in a single year, or severe investment in one (or various technologies) up to levels of expenditure not addressable by a certain economy.

#### 3.7. Generation and Capacity Limits

The installed capacity and annual generation of each technology in the long term model can be limited by a minimum and maximum value.
\[ \sum_{g \in \text{tech}} g_{g,b} \cdot \text{Dur}_b / \text{AggYears}_p \leq E\text{Max}_{\text{tech},p} \quad \forall \text{tech}, p \]

\[ \sum_{g \in \text{tech}} g_{g,b} \cdot \text{Dur}_b / \text{AggYears}_p \geq E\text{Min}_{\text{tech},p} \quad \forall \text{tech}, p \]

\[ \text{exists}_{g,e} \leq G\text{Max}_{\text{tech},p} \quad \forall \text{tech}, e \in p \]

\[ \text{exists}_{g,e} \geq G\text{Min}_{\text{tech},p} \quad \forall \text{tech}, e \in p \]

Where:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
<th>Unit</th>
<th>Stage</th>
</tr>
</thead>
<tbody>
<tr>
<td>( E\text{Max}_{\text{tech},p} )</td>
<td>Maximum annual power generation of technology tech year p</td>
<td>GWh</td>
<td>P</td>
</tr>
<tr>
<td>( E\text{Min}_{\text{tech},p} )</td>
<td>Minimum annual power generation of technology tech year p</td>
<td>GWh</td>
<td>P</td>
</tr>
<tr>
<td>( G\text{Max}_{\text{tech},p} )</td>
<td>Maximum installed capacity of technology tech year p</td>
<td>MW</td>
<td>P</td>
</tr>
<tr>
<td>( G\text{Min}_{\text{tech},p} )</td>
<td>Minimum installed capacity of technology tech year p</td>
<td>MW</td>
<td>P</td>
</tr>
<tr>
<td>( \text{exists}_{g,e} )</td>
<td>Installed capacity of generator g in period p in stage e</td>
<td>MW</td>
<td>V</td>
</tr>
</tbody>
</table>

These constraints are usually employed to limit the investment on certain limited resources; the most common cases are renewable. For this, the use of resource availability maps and previous studies on economic and technical availability of RES are used.