ANALYTIC MODEL OF ENERGY SOURCES COMBINATION TO REDUCE POWER GENERATION VARIABILITY

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ABSTRACT
The increasing amount of renewables generation feeding to the grids is a new challenge to system operators who have to deal with higher unpredictability of net load variability and balance fluctuations. This work focuses on how to stabilize power generation through energy combination of fossil and renewable sources.

To avoid an excessive combinatorial analysis, the first part of the work explores current technology options to find out what energy sources are the most suitable for the purpose. The second part of the work identifies the most important “factors” that characterize an energy source and its combination. The third part of the work shows the proposed combination model that explains how to combine, evaluate and find the best combination. The application of the model with a specific case study is in the fourth part of the work. The last part analyzes the interdependencies among all the variables of the model to give better understanding of the dynamics of the model and its results.

KEY WORDS
Combination Model, Energy Sources Combination Variability Control, Interdependencies Model, Variability Reduction

1. Introduction
Electricity cannot be stored on a massive scale in an economic way. Thus, system operators must always try to balance the power supply and demand to maintain the system stability and power quality. Major mismatches or interruptions could lead to breakdown of a power system and blackout of a power area.

Conventional power generation fired by coal, oil and gas provides steady and predictable feed-in to the grids. Their output can be scheduled. Variable renewables refer to those energy sources such as wind and solar, for which power output is intermittent and cannot be accurately and completely predicted or scheduled. An increasing amount of renewables generation feeding to the grids is a challenge to system operators who have to deal with higher unpredictability of net load variability and balance fluctuations.

The non-programmable nature of an energy source refers to the possibility of controlling (in an profitable way) energy generation to the grid rather than to the unpredictable nature of its production.

Possible solutions are:
- Energy Storage (Pumped Hydroelectric Storage, Compress Air Energy Storage; Chemical Battery);
- Geographic diversification of installation site;
- Energy sources combination.

While energy storage still presents limits of efficiency and economics, diversification can reduce a part of source variability, however intrinsic variability (e.g. wind and sun) remains. For this reason, the scope of this work is to create a model that aims at the best energy combination and at those “factors” that influence most the choice between different sources.

2. Energy Sources Combination

Energy Sources Combination (ESC) is the integration of two or more power plants that use different sources. In details, ESC is the integration of a new power plant with a non-programmable power generation at or near the point of transmission interconnect for a new or existing programmable power plant (fossil fuel, biomass, hydroelectric). Transmission capacity is shared between two or more integrated plants. Some amount of programmable power generation is sacrificed to control and transmit variable power plant generation.

The aim of combination is to stabilize the resultant power generation.

2.1 Single Source Analysis & Selection
The first part of the work deals with the identification of the most suitable energy sources through a screening level analysis of the economic competitiveness and technical feasibility.

The paper will not take into account energy sources with a high cost and performance dependency from the installation site (geothermic, hydroelectric) because they are too specific. Biomass generation evaluation needs a
fuel cost analysis that goes beyond this work that wants to have a general application. However, the model presented in this paper is able to study biomass combination. The Energy Information Administration Annual Energy Outlook (Fig.1) gives a good snapshot of the state of the art in energy conversion technology in a mid-term perspective.

Looking at the Levelized Cost and Capacity factor, Natural Gas Combined Cycle and Natural Gas Combined Cycle Flexible are the most interesting fossil-based technologies from a combination point of view. On-shore Wind is the most interesting renewable energy source. Solar-based technologies fill out the form with Photovoltaic and Concentrated Solar Plant. While PV technology will be taken “as is”, CSP will be studied in their integrated variants: Integrated Solar Combined Cycle and Solar Gas Hybrid Turbine. There are a variety of benefits to integrating variable and non-variable generation, including less fuel consumption and high overall efficiency relative to a stand-alone plant, the creation of a combined system with a more stable cost profile (due to a lower fuel cost) and the ability to unlock new variable power generation without adding new transmission capacity.

2.2 Factors for Integration Analysis

Factors Analysis is aimed to identify for characteristics that assume relevance from an integration point of view.

The first step is the evaluation of source variability. Model needs the investigation of energy source min-to-min variability and its capacity factor. In case of fossil fuel technology, the evaluation of plant flexibility is more important. Flexibility depends mostly on partial efficiency and ramp rate of the power plant. Partial efficiency is evaluated with the efficiencies curves of the plant. Ramp rate is the power maximum variability that a plant can offer in a minute. The net capacity factor of a power plant is the ratio of the actual output of a power plant over a period of time and its potential output, had it operated at full nameplate capacity for the entire time.

2.3 Energy Sources Combination Model

Combination model takes in different energy sources and integration factors to generate a set of combinations that will be later evaluated and optimized.

2.3.1 Combinatory Energy Model

In the first step, the model takes a set of combinations. Combinatory Energy Model checks some factors of combined sources and makes a first selection. Then the model analyzes the variability and flexibility factors. In case of a programmable plant with a low ramp rate the model excludes those combinations with more than an integrated source.
In case of combination with more than two sources with a low capacity factor the model advises to exclude them due to economic and production limits (CSP integrated plant is an exception).
In case of programmable power plant with a low capacity factor the model suggests to exclude combination with more than a variable source.
Combinations with technologies using the same source will be automatically excluded (e.g. CSP and PV).

2.3.2 Sizing Model and Operating Scenarios choice

Sizing model takes in every combination that successfully passes the energy model and generates the maximum integration size.
Sizing model compares min-to-min variability of the non-programmable energy sources in order to find the maximum value that constrains integration size.
The next step is calculating the “Combination Coefficient” in case of 100% load following scenario. Combination Coefficient is equal to maximum variability (expressed as percentage change in terms of total plant capacity) divided by the ramp rate of the programmable power plant (expressed as the ramp rate per minute divided by the plant capacity). This can be written as an equation (Ihle, 2003):

\[ CC = \frac{\text{max}[\text{Var. min to min}] \cdot \text{ramp rate}}{1 \ldots N} \]

The inverse of this coefficient provides the maximum integration in terms of percentage of programmable power plant size. Model chooses the operating scenario looking at the integration ratio as shown in tab.1:

<table>
<thead>
<tr>
<th>Operating Scenario</th>
<th>IR</th>
</tr>
</thead>
<tbody>
<tr>
<td>100% following</td>
<td>39%</td>
</tr>
<tr>
<td>Imperfect following</td>
<td>19%</td>
</tr>
<tr>
<td>Variable Throttle Back</td>
<td>10%</td>
</tr>
<tr>
<td>Fixed Throttle Back</td>
<td>&lt;9%</td>
</tr>
</tbody>
</table>

Once chosen the strategy the model calculates the integration ratio in different scenarios. In case of real-time scenario (100% following and imperfect following) we have already seen how to calculate integration ratio. In case of non-real-time scenario, the max. integration ratio will depend on the programmable power plant operating characteristics, including efficiency curves and the value of the turndown point (expressed in terms of percentage of the plant size).

\[ CC = \frac{1}{(1 - \tau\%)} \]

2.3.3 Combinatory Evaluating Model

This part of the model takes in the combinations and their max. integration ratio to evaluate some technical, economic and financial indicators.
The simulation model, in this case, creates different configurations for each combination to optimize each combination through model indicators.
First of all it is important to fix the overall size of the combination.

\[ P_{\text{tot}} = P_f + \sum_{i=1}^{N} f_i \cdot P_{ti} \cdot i \quad \text{con} \sum_i f_i \leq 1 \]

Then, we have to define the programmable power plant average efficiency taking into account the integration with a variable production. In case of real-time operating scenario, the average efficiency is calculated as:

\[ \eta_{\text{avg}} = \eta_{\text{parz}} \cdot f_c \cdot \text{int} + (1 - f_c \cdot \text{int}) \cdot \eta_{\text{nom}} \]

In case of non-real-time operating scenario, the average efficiency is calculated as the partial efficiency that the programmable power plant efficiency curves gives at the programmable power plant size less the integrated power size level. In the next step model evaluates the different power generation contributions from each plant:

\[ E_{\text{tot}} = Ef = P_f \cdot 8760 \cdot fc \cdot f \quad [\text{MWh}] \]
\[ E_{i} = P_{ti} \cdot i \cdot f_i \cdot fc \cdot 8760 \quad [\text{MWh}] \]

Now we are able to evaluate the capacity factor of the programmable power plant after the integration:

\[ fc,f = \frac{E_{\text{tot}} - \sum_{i=1}^{N} E_{i}}{P_f \cdot 8760} \]

Modified capacity factor is important to evaluate the fuel cost of the fossil power plant.

\[ CC = \frac{E_{\text{fuc}}}{\eta_{\text{el,avg}}} = \frac{P_f \cdot 8760 \cdot fc \cdot f_{\text{uc}}}{\eta_{\text{el,avg}}} \quad [\text{€}] \]

The overall capital cost of the configuration can be evaluated as follow:

\[ C_{\text{inv}} = Pf \cdot c_{\text{inv},f} + \sum_{i=1}^{N} f_i \cdot P_{ti} \cdot c_{\text{inv},i} \]

While the revenue from energy sales can be calculated from the annual energy production:
In case of incentives for renewable source generation, these revenues could be evaluated as follow:

\[ R_{ee} = p_{ue} \cdot E_{tot} \ [\text{€}] \]

The process of selection of the best configuration needs the introduction of some indicators that are reported below.

Fuel Cost variation is the difference between the combination annual fuel cost and the equivalent stand-alone case. In case of a negative indicator, the alternative one will be excluded.

Efficiency Variation is the second energy indicator. It is evaluated as the difference between the Overall Efficiency of the combination and the efficiency of the equivalent stand-alone case. A negative variation will exclude the alternative from the process of selection.

In the last step of the model, the financial analysis selects the best configuration.

### Table 2: Financial assumptions and indicators

<table>
<thead>
<tr>
<th>Financial Assumptions</th>
<th>Financial Indicators</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inflation Rate</td>
<td>Return On Equity</td>
</tr>
<tr>
<td>Project Lifecycle</td>
<td>Net Present Value</td>
</tr>
<tr>
<td>Tasso di sconto</td>
<td>Redditività</td>
</tr>
<tr>
<td>Debt Ratio</td>
<td>Payback Period</td>
</tr>
<tr>
<td>Debt Interest Rate</td>
<td>Internal Rate of Return</td>
</tr>
</tbody>
</table>

### 2.4 Application on a basic scenario

This section demonstrates the application of the integrated model in a case study.

#### 2.4.1 Model set up

Technical (fig.2) and economical (fig.3) data used to set up the model are shown in the tables below:

#### 2.4.2 Sizing Model and Evaluating Model

In this paragraph, there is an application of the sizing model to a NGCC+Wind combination case.

First part of the model requires an investigation in min-to-min wind resource variability (fig.4) and plant ramp rate that in case of NGCC power plant is 5%/min.

![Fig.4 Example of Minute-to-minute wind system output change](image)

Maximum min-to-min variability is equal to 24%, so the Combination Coefficient is equal to 4.8 and technical power integration is 21%.

### Table 3: Wind contribution to NGCC+Wind combination

<table>
<thead>
<tr>
<th>Wind Farm Size (MW)</th>
<th>Percentage Wind Capacity</th>
</tr>
</thead>
<tbody>
<tr>
<td>40</td>
<td>20%</td>
</tr>
<tr>
<td>30</td>
<td>15%</td>
</tr>
<tr>
<td>20</td>
<td>10%</td>
</tr>
<tr>
<td>10</td>
<td>5%</td>
</tr>
<tr>
<td>5</td>
<td>3%</td>
</tr>
</tbody>
</table>

### Table 4: Evaluating model for NGCC+Wind combination

<table>
<thead>
<tr>
<th>Plant #1</th>
<th>Plant #2</th>
<th>Wind Energy Share</th>
</tr>
</thead>
<tbody>
<tr>
<td>NGCC</td>
<td>Wind</td>
<td></td>
</tr>
<tr>
<td>300</td>
<td>4%</td>
<td>55%</td>
</tr>
<tr>
<td>210</td>
<td>5%</td>
<td>55%</td>
</tr>
<tr>
<td>150</td>
<td>6%</td>
<td>55%</td>
</tr>
</tbody>
</table>

Note: NGCC size= 200 MW

### 2.4.3 Results Figures

Fig.4 shows the combinations that pass the process of selection.
Coal based technology and photovoltaic combination have not passed the selection due to their high capital cost (PV) or their low flexibility (Coal) combined with low capacity factors.

Renewable Energy Share (RES) depends on sizing model capacity factors and the process of configurations optimization.

OCGT plants can reach higher RES than NGCC because of their higher ramp rate and a lower capacity factor. Energy Source Combination (red), besides, reduces in low percentages the capacity factor in comparison with the stand-alone (yellow) case (fig.6).

Financial analysis results are shown below; OCGT combinations that have high RES are not a safe investment (fig.8). NGCC combination are more profitable when they are combined with CSP and Wind farm.

As regards industrial production costs (€/MWh), simulation has verified that in some cases energy source combination leads to a reduction. Furthermore, combination reduces the high influence of variable fuel costs.
2.5.1 Interdependencies Map (fig.10)

This map shows the interactions between factors (white and blue circles), which are the input of the model, energy and economic indicators (white and red circles) that are mainly used to select the best combination. Blue circles are the two most important indicators, as we can see from fig.9, nearly every indicator depends on energy share, so, once fixed blue circles (factors), is easy to optimize the combination that influences the value of this factor and find out the maximum profitability for the combination (second blue circle).

2.5.2 RES and Technical Factors Interdependencies

RES can be written as follow:

\[
\%E = \frac{E_{\text{int}}}{E_{\text{int}} + Ef}
\]

Using sizing model formulas for real-time scenario we can see how RES depends on technical factors:

\[
\%E = \frac{1}{1 + \left(\frac{\max(\text{var}) \cdot fc \cdot f}{\%r \cdot fc_{\text{int}}}\right)}
\]

This formula confirms simulation results. Fig.10 shows that with an equal ramp rate OCGT combinations has an higher RES than NGCC due to its lower capacity factor.
2.5.3 Economic Factor and Energy Share Interdependencies

Annual Plant Cost is the sum of annual plant capital cost, O&M costs and fuel cost. All these costs can be written in function of RES:

$$ C_{\text{titu}} = \frac{\%E}{1 - \%E} \left( \frac{1}{N} \cdot \text{cinv}_{\text{int}} \cdot f_{c,f} f_{c,f} - c_{\text{rec}} \right) + C_{\text{O&M}} + \frac{\text{CUC}}{\eta_{\text{nom}}} + \frac{1}{N} \cdot \text{cinv}_{\text{f}} $$

Annual Plant Cost variation depends on the comparison between the annual capital cost of the integrated plant and an energy indicator that represents the “Reduction Fuel Cost” per MWh generated by renewable sources (rfc). If the capital cost is higher than rfc, then annual cost will increase with the energy share, otherwise annual cost will decrease. This means that with the increasing of the annual cost of the combination the model will choose the configuration with lowest possible RES (NGCC combinations), while in case of decreasing annual cost the model will choose that configuration with the higher integration (OCGT combinations).

Total costs will influence combination cash flow and its profitability. Combination cash flow ($F_{\text{C}}$) for a generic period can be written in function of RES as follows:

$$ F_{\text{C}} = \left[ p_{\text{net}} + \%E \cdot p_{\text{int}} \cdot \left( 1 - \Delta f_{r} \right) \right] \cdot \left( 1 + \frac{\%E}{1 - \%E} \right) \cdot f_{c,f} \cdot f_{T} $$

Financial costs are a function of energy share:

$$ \frac{GF}{pf} = \frac{\text{cinv}_{\text{f}} \cdot r \cdot \left[ 1 + \frac{1}{N} \cdot (1 - n) \right]}{pf} $$

In case of NGCC+Wind combination with the model set-up values, the cash flow for the first year depends on energy share in this way:

![Fig.12 Cash Flow for NGCC+Wind combination](image-url)

3. Conclusion

This paper presents the model created to identify a set of optimal energy sources combinations that smooth out the variability of energy generation from renewable sources. Furthermore, the interdependency map shows the dynamics of the model and the main variables. Results show that combinations are technically feasible and that are interesting from an energetic point of view. Results do not correspond to specific case because of the generic application. However, this model is able to evaluate combinations performance in a specific case. Transmission capacity is assumed to be adequate to carry the maximum power output of programmable power plant. In case of real-time operating scenario, combination is able to deliver a non-intermittent bundled power product to the electric market. Responsibilities traditionally associated with integrating an intermittent resource into power system would be transferred from system operator to power suppliers [2]. Italian energy market is already following this path introducing generation cuts and costs related to non-programmable generation from renewable energy sources. This would enhance the value proposition of energy combination to reduce variability moving the duties to sort this problem out from the electricity transmission to the generation.

**List of Symbols**

- **CC** Combination Coefficient
- **Ptot** Total size of the combination (MW)
- **Pf** Fossil based plant size (MW)
- **Pti** Technical integrated size (MW)
- **\( \eta_{\text{avg}} \)** Fossil power plant annual average efficiency
- **\( \eta_{\text{parz}} \)** Partial efficiency at Ptot-Pf size
- **\( f_{\text{c,int}} \)** Capacity factor of integrated energy source
- **\( \eta_{\text{nom}} \)** Fossil based plant nominal efficiency
- **\( E_{\text{f}} \)** Energy generated by fossil based plant
- **\( f_{c,f} \)** Fossil based plant capacity factor after integration
- **\( E_{\text{int}} \) or \( E_{\text{i}} \)** Energy generated by renewable plants
- **CUC** Fuel Cost (€/MWh)
- **cinv_{i}** Capital cost integrated power plant (€/kW)
- **cinv_{f}** Capital cost fossil based power plant (€/kW)
- **Ree** Energy Sale Revenues
- **pue** Average price of electricity (€/MWh)
- **Ifrr** Governatives subsidies for renewable generation (€/MWh)
- **%E** Renewable Energy Share
- **Max(var%)** Maximum Variability min-to-min for the renewable energy source
- **%r** Ramp rate as percentage of fossil based size plant (%/min)
- **C_{\text{titu}}** Combination overall annual cost
\( N \)  
Project lifecycle (years)

\( crc \)  
Fuel cost saving to renewable generation ratio (€/MWh)

\( i \)  
Inflation rate

\( OF \)  
Financial costs

\( r \)  
Debt interest rate

References


