AAEE PhD-Day

Fourth International AAEE Student Chapter PhD-Day
March 30th, 2014

The fourth PhD-Day took place at the Vienna University of Technology on March 30th. The aim of the event is to give PhDs the opportunity to present their current scientific work. As in previous years, participation was free.

The event was initiated by a speech in which the dean of the faculty of economics and management, Professor Dr. Brunner, represented the senate of the university and gave some introductory words.

The feedback of all participants was overwhelmingly positive, and we are already looking forward to the PhD-Day 2015.

Last name: [Enter]
First name: [Enter]
Institution: [Enter]
Department: [Enter]
Present Paper: [Enter]
Cost/Benefit analysis of further expansion of the Austrian transmission grid to enable further integration of renewable electricity generation (RES-E)

Bettina Burgholzer*, Hans Auer*

*Energy Economics Group (EEG)
Vienna University of Technology
Gusshausstrasse 25-29/E370-3, Vienna

Abstract

This paper elaborates on the costs and benefits of further expansion of the Austrian transmission system and the implementation of grid-impacting technologies (e.g. flexible AC transmission systems (FACTS), dynamic line rating (DLR)) to support further integration of RES-E. Therefore, a fundamental market model has been developed - respecting DC load flows - and applied for analysing different scenarios in the future, especially for the time horizon 2020, 2030 and 2050. Up to 2020 and 2030 special focus is put on the finalisation of the 380 kV-level transmission ring in Austria to enable further RES-E integration. The results confirm that the transmission power line expansions in Salzburg and Carinthia are important to connect imports from Germany with pumped hydro storage (PHS) capacities, on the one hand, and the wind systems in the east with the PHS in the western part of Austria, on the other hand. For 2050 the results indicate that the implementation of innovative technologies like FACTS and DLR can reduce RES-E curtailment significantly.

Keywords: cost/benefit analysis, Linear Optimization Problem, electricity market, fundamental market model, RES-E integration, transmission grid expansion

*Corresponding author. Phone: +43-(0)1-58801-370366
Email address: burgholzer@eeg.tuwien.ac.at (Bettina Burgholzer)

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1. Nomenclature

All sets with the corresponding indices, the parameters and the decision variables of the market model are listed below.

- **$H$ (index $h$)**: set of time steps (hours)
- **$I$ (index $i$)**: set of nodes
- **$L \subset L_{AC} \cup L_{DC}$ (index $l, l_{AC}, l_{DC}$)**: set of transmission power lines
- **$TH_i$ (index $th_i$)**: set of thermal units in node $i$

- **$C^{CO_2}$**: CO$_2$ certificate price
- **$C^{WindPV}$**: generation costs of wind and PV systems
- **$C^{Hydro}$**: generation costs of Run-of-River (RoR)
- **$CapLines_l$**: Net Transfer Capacity (NTC) values
- **$DLR_h$**: Dynamic Line Rating
- **$\alpha^{max}$**: maximum phase shifter angle
- **$Demand_{h,i}$**: demand in step $h$ and node $i$
- **$VoLL$**: Value of Lost Load
- **$SRMC_{h,i,th_i}$**: short run marginal costs of thermal power plants
- **$ThEm_{i,th_i}$**: CO$_2$ emissions of thermal power plants
- **$\eta_{i,th_i}^T$**: efficiency of thermal power plants
- **$\eta_{i,th_i}^P$**: ramping limit of thermal power plants
- **$ThCap_{i,th_i}^{max}$**: max capacity of thermal power plants
- **$HyCap_{i}^{max}$**: max capacity of RoR
- **$\eta_{i}^{Hy}$**: efficiency of RoR
- **$Inflow_{h,i}$**: natural inflow RoR
- **$PHSTuCap_{i}^{max}$**: max turbine capacity
- **$PHSPuCap_{i}^{max}$**: max pump capacity
- **$\eta_{i}^{Tu}, \eta_{i}^{Pu}$**: efficiency of turbine and pump
- **$PHSStor_{h}$**: relative value of storage level
- **$PHSEN_{i}^{max}$**: max storage level PHS
- **$PHSEN_{i}^{min}$**: min storage level PHS
- **$Inflow_{PHS_{h,i}}$**: natural inflow PHS
2. Introduction

The target of the European Commission is to achieve a harmonized European electricity market with an almost single price for wholesale electricity across all EU Member States. This objective is based on at least the following reasons: significant social welfare increase due to optimal utilization of electricity generation and transmission assets in Europe, increasing security of supply and renewable electricity generation as well as limitation of price fluctuations due to variable renewable electricity generation as a result of improved market coupling.

The work presented in this paper is part of a European project in the Intelligent Energy Europe (IEE) program (called GridTech\[^1\]), where a fully integrated

\[^1\]Impact Assessment of New Technologies to Foster RES-Electricity Integration into the European Transmission System” (IEE/11/017/SI2.616364); Available: www.gridtech.eu.
impact assessment of the implementation of new technologies (e.g. RES-E generation, bulk storage, transmission network technologies) into the European electricity system is conducted, to study the optimal exploitation of the full potential of future RES-E generation across Europe with lowest possible total electricity system costs. In the GridTech project two approaches are applied: top-down modelling covering the EU30+ region and bottom-up modelling of selected European target countries. The analyses in GridTech are fully in line with actual EU policies and legislation (Directive 2009/28/EC, National Renewable Energy Action Plans (NREAPs), Regulation 347/2013, Regulation 713/714/715/2009/EC, Communication COM (2010) 677/4, “Energy Roadmap 2050” (Communication COM (2011) 885/2)). Also the “Ten-Year Network Development Plans (TYNDPs)”, the “Projects of Common Interest (PCIs)” as well as the ENTSO-E Cost Benefit Analyses Methodology (having been adopted by the European commission recently) of the European Network Transmission System Operators for Electricity (ENTSO-E) are taken into account accordingly.

For the top-down modelling of the EU30+ region the simulation tool MT-SIM\textsuperscript{2} is used. To guarantee consistency of the two GridTech approaches some of the results of the top-down analysis, notably those concerning electricity exchanges between countries and the associated wholesale prices serve as inputs for the regional case study analysis in selected target countries. They are setting the boundary conditions of the regional analysis. This paper examines the bottom-up modelling approach for Austria (one of the target countries) of the above mentioned project and comprises several selected scenarios of different time horizons (e.g. 2020, 2030 and 2050). The main focus is put on the following specific measures and technology developments:

- Completing 2 major 380 kV High-Voltage AC Overhead Lines (HVAC OHLs) projects to close the so-called ”380 kV HVAC transmission ring” in Austria.

\textsuperscript{2}MATLAB tool developed from Ricerca sul Sistema Energetico - RSE S.p.A., Milano.
• Increasing/upgrading (pumped)-hydro storages (PHS) capacities to support balancing of electricity systems of neighbouring countries.

• Studying the impact of further increase of wind (eastern part of the country) and notably PV (across the country) penetration.

• Studying the growing load flows from north to south, also including the possibility of a future east-west HVDC link from Austria to Slovakia.

• Implementing Flexible AC Transmission Systems (FACTS) and Dynamic Line Rating (DLR) based OHLs via diverse simulations.

• Furthermore, the impact of high/low Run-of-River (RoR) electricity generation on the transmission grid is conducted for the time horizon 2050.

In the next section the methodology of the bottom-up approach is explained, especially in more detail the used market model, the underlying target function and all respected constraints. Section 4 comprises the results of several selected scenarios of the Austrian case study analyses. In general, special focus in result interpretation is put on the transmission system operators (TSOs) point-of-view. Finally, the paper is closed by the conclusions.

3. Methodology

For the Austrian bottom-up approach a fundamental market model called EDisOn (Electricity Dispatch Optimization) has been developed in MATLAB (for more information see [1] and [2]), to analyse in detail the further development of the Austrian electricity market and transmission grid qualified to enable the further integration of RES-E generation. EDisOn is designed as a linear programming problem and is deterministic in nature, assumes a perfect competitive market with perfect foresight, and uses an hourly resolution of a full year. Generation capacities are given exogenously. (Pumped)-hydro storage and Run-of-River (RoR) are following an annual pattern. Electricity generation
of Wind and PV are considered based on historical data, but it is also possible to implement a time series based on a stochastic process. EDisOn covers the whole transmission system of Austria (220 and 380 kV-level) as well as its interconnections to neighbouring countries.

Austria is divided into 17 load and generation nodes, which correlate with the main substations within Austria, and 7 nodes in the neighbouring countries. Generation is allocated to the closest node and the load allocation is based on population figures and large industrial sites. All parallel transmission power lines (TPL) between the nodes are merged to one representative TPL, which leads to a total of 35 TPLs (see Figure 1 below).

![Figure 1: Austrian transmission grid supposed for the year 2020.](image)

The objective of the Linear Optimization Problem (LOP) model is to obtain the schedule that minimizes the total operational costs of the electricity system by considering various costs such as variable costs (e.g., fuel, O&M and CO₂ costs). There are also several technical constraints implemented, e.g., generation capacity constraints, maximum ramp rates, reservoir balance, spillage of hydro, RES-E generation technologies etc., having to be fulfilled in the whole simulation horizon. The power flows between nodes are simulated via power transfer
distribution factor (PTDF) matrix. FACTS is considered as phase shifters by
phase shifter distribution factors (PSDF) and also HVDC lines with DC dis-
100 trIBUTIO n factors (DCDF) (see [3] and [4]).

3.1. Target function

The minimisation of total generation costs is the target function of the mar-
ket model. Not only thermal generation is considered with its short run marginal
costs (SRMC), but also some small amounts of RoR, PV and wind generation
are taken into account. The last term in (1) is for demand, which cannot be
covered. In some literature, e.g. [9], the average value of lost load (VoLL)
is between 10,000 and 20,000 USD/MWh. In this analysis a VoLL of 10,000
EUR/MWh is assumed.

\[
\min Total Cs = \sum_{i,h} \sum_{th_i} \text{thP}_{h,i,th_i} \cdot SRMC_{h,i,th_i} + \text{hyP}_{h,i} \cdot C^{Hydro}
\]

\[
+ \ (PV_{h,i} + Wind_{h,i} - Spill_{h,i}) \cdot C^{WindPV}
\]

\[
+ \ NSE_{h,i} \cdot VoLL
\]

(1)

with \( SRMC_{h,i,th_i} = C^{OKM} + C^{fuel}_{th_i} \cdot \eta_{th_i} + C^{CO_2} \cdot \eta_{th_i} \cdot ThEm_{th_i} \cdot \eta_{th_i} \), where the
indices \( h \) describe time (hour), \( i \) the node and \( th_i \) the kind of thermal unit in
node \( i \).

3.2. Constraints

The following constraint is one of the most important ones. Demand in every
node has to be covered by supply in every simulated hour.

\[
\forall h \in H, \forall i \in I : Demand_{h,i} - NSE_{h,i} = \sum_{th_i} \text{thP}_{h,i,th_i} + \text{hyP}_{h,i} + Wind_{h,i} + PV_{h,i}
\]

\[
- Spill_{h,i}^{WindPV} + tuP_{h,i} - puP_{h,i} - Exch_{h,i}
\]

(2)

For thermal power plants there are some technical constraints, which have
to be considered in market models. Thermal units are able to produce less than
the maximum capacity only, which is defined in equation (3) and generation can be increased or decreased stepwise (see inequalities (4)).

\[
0 \leq \text{th}P_{h,i,th} \leq \text{ThCap}_{h,i,th}^{max}, \quad \forall(h, i, th) \quad (3)
\]

\[
\forall h \geq 2, \forall(i, th) : \\
\text{th}P_{h,i,th} - \text{th}P_{h-1,i,th} \leq \text{rampLimit} \cdot \text{ThCap}_{h-1,i,th}^{max} \\
-\text{th}P_{h,i,th} + \text{th}P_{h-1,i,th} \leq \text{rampLimit} \cdot \text{ThCap}_{h-1,i,th}^{max} \quad (4)
\]

The RoR plants can generate less than the maximum capacity only and should be equal to the natural inflow, which is calculated by using the annual average production. In this context the variable means, that the lock of a RoR plant is open. Therefore, a certain amount of MWh is not used for electricity generation.

\[
\forall(h, i) : \\
0 \leq \text{hy}P_{h,i} \leq \text{HyCap}_{i}^{max} \\
\text{hy}P_{h,i} + \text{Spill}^{Hy}_{h,i} = \text{Inflow}_{h,i} \cdot \eta^{Hy} \quad (5)
\]

The pumps and the turbines of the PHS plants are limited to their technical maximum.

\[
\forall(h, i) : \\
0 \leq \text{pu}P_{h,i} \leq \text{PHSPuCap}_{i}^{max} \\
0 \leq \text{tu}P_{h,i} \leq \text{PHSTuCap}_{i}^{max} \quad (6)
\]

In Austria, the reservoir content of storage of PHS plants follows a certain annual pattern based on data of E-Control (Austrian Regulator) from 1997 to 2011 and is limited to its maximum and minimum storage level. In addition, the equations describing the storage level balance are very important (see equation (7) and (8)).

\[
\text{storLev}_{1,i} = \text{PHSstor1} \cdot \text{PHSEn}_{i}^{max} - \frac{\text{tu}P_{1,i}}{\eta^{u}} + \text{pu}P_{1,i} \cdot \eta^{p} \\
+ \text{Inflow}_{PHS_{1,i}}, \quad \forall i \in I \quad (7)
\]
for $h \geq 2$ and $\forall i \in I$ :
\[
\text{storLev}_{h,i} = \text{storLev}_{h-1,i} - \frac{\text{tuP}_{h,i}}{\eta_{\text{Tu}}} + \text{puP}_{h,i} \cdot \eta_{\text{Pu}} + \text{Inflow}_{PHS_{h,i}}
\] (8)

\[
PHSE_{n_i}^{\min} \leq \text{storLev}_{h,i} \leq PHSE_{n_i}^{\max} \quad \forall (h,i)
\] (9)

The exchanges - or more precisely the injections - have to be equal the sum of the flows, which are going out and coming in, compare [4]. Therefore, negative injection in a node means that demand is higher than supply and vice versa. The power flow on each TPL has to be between the lower and the upper capacity limit of each TPL and the same applies for the phase angles of the phase shifters and their maximum value, variables and (see equation and inequalities (10)-(12)). The power flows also have to satisfy equation (13), where the variables PTDF, PSDF and DCDF are respected.

\[
\text{Exch}_{i,h} = \sum_{l \in L} A_{l,i} \cdot \text{Flow}_{l,h} \quad \forall h \in H, \forall i \in I
\] (10)

\[
\forall l \in L \subset L_{AC} \cup L_{DC}, \forall h \in H :
- CapLines_{sl} \cdot DLR_h \leq \text{Flow}_{l,h} \leq CapLines_{sl} \cdot DLR_h
\] (11)

\[
\forall l_{pst} \in L_{pst} \subset L_{AC}, \forall h \in H :
- \alpha_{\text{max}} \leq \alpha_{l_{pst},h} \leq \alpha_{\text{max}}
\] (12)

\[
\forall l_{AC} \in L_{AC}, \forall h \in H :
\text{Flow}_{l_{AC},h} = \sum_{i \in I} \text{PTDF}_{l_{AC},i} \cdot \text{Exch}_{i,h}
\quad + \sum_{l_{pst} \in L_{pst} \subset L_{AC}} \text{PSDF}_{l_{AC},l_{pst}} \cdot \alpha_{l_{pst},h}
\quad + \sum_{l_{DC} \in L_{DC}} \text{DCDF}_{l_{AC},l_{DC}} \cdot \text{Flow}_{l_{DC},h}
\] (13)

The remaining constraints are for considering RES-E curtailment of wind
and PV and for limiting the occurrence of NSE.

\[
\forall h \in H, \forall i \in I :
\]

\[
0 \leq \text{Spill}^{\text{WindPV}}_{h,i} \leq \text{Wind}_{h,i} + \text{PV}_{h,i}
\]

\[
0 \leq \text{NSE}_{h,i} \leq \text{Demand}_{h,i}
\]

\[(14)\]

3.3. Calculation of the PTDF, PSDF and DCDF matrices

The matrix \(B_d\) is a symmetric \(L_{\text{AC}}\)-dimensional matrix with the susceptances of the TPLs in the diagonal entries and the remaining entries are zero. The matrix \(A\) comprises the incidence matrix; it describes which nodes are connected with each other. The PTDF, PSDF and DCDF matrices are calculated as follows (for details see [3]):

\[
\text{PTDF}^{L_{\text{AC}} \times I} = (B_d \cdot A) \cdot (A^T \cdot B_d \cdot A)^{-1}
\]

\[(15)\]

\[
\text{PSDF}^{L_{\text{AC}} \times L_{\text{pst}}} = B_d - (B_d \cdot A) \cdot (A^T \cdot B_d \cdot A)^{-1} \cdot (B_d \cdot A)^T
\]

\[(16)\]

\[
\text{DCDF}^{L_{\text{AC}} \times L_{\text{DC}}} = -\text{PTDF} \cdot A_{\text{DC}}^T
\]

\[(17)\]

The hourly based results of the different scenarios provide the basis for the calculation of the electricity system benefits (welfare, congestion rent, fossil fuel, \(\text{CO}_2\) emissions and others). For the evaluation of the benefits the key indicators as shown in Table [1] are applicable (see [8]).

<table>
<thead>
<tr>
<th>Benefit/Aspect</th>
<th>Key indicators</th>
</tr>
</thead>
<tbody>
<tr>
<td>Social Welfare increase</td>
<td>ability of a power system to reduce congestion as a basis for an efficient market</td>
</tr>
<tr>
<td>Reliability increase</td>
<td>adequate and secure supply of electricity</td>
</tr>
<tr>
<td>Resilience improvement</td>
<td>ability of the system to withstand increasingly extreme system conditions</td>
</tr>
<tr>
<td>(\text{CO}_2) emissions reduction</td>
<td>(\text{CO}_2) emissions in the power system</td>
</tr>
<tr>
<td>RES-E spillage reduction</td>
<td>reduce the RES-E curtailed energy</td>
</tr>
<tr>
<td>Controllability &amp; Flexibility increase</td>
<td>possibility to control power flows and different possible future development paths or scenarios</td>
</tr>
<tr>
<td>Socio-environmental impact</td>
<td>public acceptance and environmental impact</td>
</tr>
</tbody>
</table>

Table 1: Key indicators
4. Results

A detailed description of additional scenarios and the corresponding results of the Austrian case study analysis can be found in [7].

4.1. Selected scenarios for the time horizon 2020

For the time horizon 2020 in Austria it is important to extend the interconnection to Germany, mainly due to high import expectations from Germany. Therefore, the expansion of the TPL in Salzburg is necessary to connect the imports with the high PHS capacities in the Alps. Furthermore, the extension in Salzburg is of high interest for closing the 380 kV circle in Austria, which is necessary for guaranteeing sufficient security and reliability of supply. In addition, the interconnection to Italy will also be extended. In Table 2 the selected scenarios for 2020 are defined.

Due to the TPL expansion in Salzburg electricity generation of renewables can be slightly increased, especially the activities of PHS plants can be increased. Also thermal generation has slightly increased and in this case a fraction of electricity generation by gas power plants has been replaced by the much more polluting coal technology. This occurrence can be explained by two reasons: firstly, the CO$_2$ certificate price is low; therefore electricity generation of coal-fired power plants is cheaper than of gas-fired power plants. Secondly, the transition to a more flexible grid allows transferring excess generation of coal power plants to the load centres.

The cumulative number of hours of TPLs with load factors higher than 70 % is reduced in the (2020B) scenario compared to scenario (2020A). In particular, for the expanded TPL in Salzburg no load factor exceeds 70 % in scenario
The average number of hours for the 23 TPLs within Austria can be reduced by around 15 %, from 976 to 832 hours per line.

Other important parameters determining security and reliability of supply are Not Supplied Energy (NSE) and RES-E curtailment. For the time horizon 2020 for both scenarios there exists no hour where NSE occurs, but RES-E curtailment occurs in a few hours. Spillages of RoR emerge in scenario A and B in 8 hours; wind is curtailed in scenario A in 4 hours and in B 6 hours. However, RES-E curtailment can be reduced by 41 MWh due to the expansion of the TPLs.

The implication of all above mentioned facts is that the total generation costs for electricity in Austria can be reduced by 0.64 % compared to the base case, which is in absolute numbers 2.1 M EUR. In addition, the wholesale electricity prices are slightly lower in scenario (2020B) in a few hours.

An additional important variable in terms of TPL expansion is the achievable annual congestion rent (CR), which is exemplarily calculated for two markets A and B as follows:

\[ CR = |p_A - p_B| \cdot \text{Flow}_{A-B} \]

The variables \( p_A, p_B \) are the price vectors of the two markets and \( \text{Flow}_{A-B} \) is the vector of the power flows on the considered TPL between these two markets.

Assuming a nodal pricing system in Austria an annual congestion rent of 234 735 EUR is generated on the TPL in Salzburg for scenario (2020A). In this case the annual average price levels of the two considered nodes are slightly different; the mean price in node "SBG_n" is 0.28 EUR/MWh higher than in "SBG_s". After the expansion of the TPL the prices of the nodes converge and reach on average the same level. However, due to the converging prices the congestion rent is reduced in scenario (2020B). Only 11 758 EUR can be earned, which are just 5 % of the (2020A) scenario.

An implication of the above mentioned changes is that a nodal pricing approach within a control zone would not provide enough incentives to invest in extending the TPL in Salzburg. Therefore, regulated grid tariffs are still neces-
sary to guarantee sustainable transmission grid investments in the future.

Table 3 gives an overview of the key indicators for the cases of the time horizon 2020, summarizing the results of the previous paragraphs. It becomes clear, that the expansion of the 220 kV-level TPL in Salzburg and the extension of the German interconnection via Bavaria have positive effects on the Austrian transmission grid, except the socio-environmental impact (reflecting public acceptance) is negative. In addition, the upgrade to a 380 kV-level TPL in Salzburg is necessary to achieve a closed 380 kV circuit in Austria in the near future guaranteeing sufficient security of supply.

<table>
<thead>
<tr>
<th>Benefit/Aspect</th>
<th>Social Welfare increase</th>
<th>Reliability increase</th>
<th>Resilience improvement</th>
<th>CO₂ emissions reduction</th>
<th>RES-E spillage reduction</th>
<th>Controllability &amp; Flexibility increase</th>
<th>Socio-environmental impact</th>
</tr>
</thead>
<tbody>
<tr>
<td>(2020 A) Base</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>(2020 B) Expansion</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>0</td>
<td>+</td>
<td>+</td>
<td>-</td>
</tr>
</tbody>
</table>

Table 3: Key indicators for 2020 cases.

4.2. Selected scenarios for the time horizon 2050

In 2050 a RES-E share of 64 % is assumed for Austria, especially the increase of Wind and PV capacity is significant. Therefore, in order to provide more flexibility in the transmission system one focus will be the analysis of the impact of DLR and FACTS. The second emphasis is put on the extension of PHS capacities (turbine as well as pumping capacity). This could provide to neighbouring countries, e.g. Germany, more flexible generation and additional storage potentials. Furthermore, the impact of high/low annual production of RoR is analysed. Finally, the focus of analysis is put on the first possible interconnection to Slovakia, a 2 GW HVDC line. An overview of the selected scenarios is provided in Table 4.
For the first scenarios the differences in electricity generation show that the transition to a flexible transmission grid leads to an increase of RES-E generation and otherwise electricity generation of thermal power plants is reduced. Additionally, the activities of PHS plants are diminished except for scenario (2050r), due to less annual electricity generation of RoR plants. For the other scenarios the need for PHS is slightly reduced, which is a result of the more flexible transmission system or because of additional imports from Slovakia as for the case (2050 SK). The differences in the generation structure of RES-E, RoR and PHS generation for the year 2050 are shown in Figure 2.

![Figure 2: Differences in the generation structure for the 2050 cases compared to (2050 A).](image)

As mentioned above, electricity generation of thermal power plants is reduced in all 2050 scenarios compared to the base case. The fossil fuel savings
are shown in Figure 3 in GWh as well as their monetary values. As a result of the additional imports from Slovakia thermal generation is reduced by 12% in scenario (2050 SK).

![Image](image1.png)

Figure 3: Fossil fuel savings (in GWh) for the 2050 cases and the resulting monetary values.

The respected generation costs of the analytical target function (see (1)) can be split into costs of thermal generation, RoR, Wind and PV generation costs and costs for NSE. These values are shown in Figure 4 in relation to the base case. The costs of NSE for the cases (2050 r) and (2050 SK) are higher than for the reference scenario. From this result it can be concluded that for 2050 it is necessary to achieve a more flexible transmission grid in Austria to guarantee electricity transmission without congestion and to avoid redispach measures.

![Image](image2.png)

Figure 4: Generation costs in relation to (2050 A).
An annual congestion rent of 86 M EUR could be earned on the new 2 GW HVDC interconnection with the assumptions made. In Figure 5 the hourly congestion rent, nodal prices of Austria and Slovakia and the hourly load factors of the TPL are shown for the week, where the maximum of CR occurs.

Figure 5: Selected week indicating the CR of the 2 GW HVDC connection to Slovakia.

The major results are summarized, as for the 2020 analysis, in Table 5.

<table>
<thead>
<tr>
<th>Benefit/Aspect</th>
<th>Social Welfare increase</th>
<th>Reliability increase</th>
<th>Resilience Improvement</th>
<th>CO\textsubscript{2} emissions reduction</th>
<th>RES-E spillage reduction</th>
<th>Controllability &amp; Flexibility increase</th>
<th>Socio-environmental impact</th>
</tr>
</thead>
<tbody>
<tr>
<td>(2050 A) Base</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>(2050 D) FACTS &amp; DLR</td>
<td>++</td>
<td>+</td>
<td>+</td>
<td>++</td>
<td>++</td>
<td>++</td>
<td>0</td>
</tr>
<tr>
<td>(2050 F) High PHS, FACTS &amp; DLR</td>
<td>++</td>
<td>+</td>
<td>+</td>
<td>++</td>
<td>++</td>
<td>++</td>
<td>-</td>
</tr>
<tr>
<td>(2050 r) -33.3 % RoR</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>(2050 SK) HVDC SK-AT</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>++</td>
<td>+</td>
<td>+</td>
<td>-</td>
</tr>
</tbody>
</table>

Table 5: Key indicators for 2050 cases.
Particularly the application of DLR is very encouraging and cost effective. In the analysed cases there is, on the one hand, a strong positive correlation between large amounts of wind generation and cooling of the overhead lines by wind (therefore, curtailment of wind can be significantly reduced). But, on the other hand, it must be kept in mind that in case large amounts of power (non-wind related RES-E or conventional generation) have to be transported during periods with low wind speeds, DLR is less effective and the upgrade of lines will be the preferable solution to increase the grid transfer capacity.

5. Conclusions

The major conclusions of the Austrian case study analyses for the time horizons 2020 and 2030 (see [7] for more details) are that TPL expansions (from 220 kV to 380 kV-level) in Salzburg and Carinthia are quite important for closing the Austrian 380 kV circle and, therefore, to guarantee transmission adequacy in Austria up to 2030. The future Austrian 380 kV circuit also provides a significant contribution for enhanced national and European RES-E integration; especially for Austria it is important to foster the connection of wind farms in the eastern part and PHS in the west.

For the time horizon 2050 the analyses of the different scenarios indicate that the implementation of innovative transmission technologies like FACTS and DLR can reduce RES-E curtailment significantly. Thus, more flexibility in the transmission grid will be necessary to support the perfect integration of all electricity produced by renewable technologies. The major implication from the Cost/Benefit Analysis in terms of Congestion Rent (CR) is that the revenues earned mainly contribute to cover the cost of expansions of cross-border interconnections, due to the prevailing differences in zonal prices in Europe. As a consequence, regulated grid tariffs are still necessary in the future to finance transmission expansion, especially within control zones.

Last but not least, the GridTech regional analyses of Austria confirm the time line of the Masterplan 2030 [8], having been published by the Austrian
TSO Austrian Power Grid (APG). In addition, the implementation of DLR and/or FACTS could achieve further supplementary flexibility in the Austrian transmission grid.

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