Improved Representation of the European Power Grid in Long Term Energy System Models: Case Study of JRC-EU-TIMES

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11 authors, including:

Wouter Nijs
European Commission

Sofia G Simões
Universidade NOVA de Lisboa

Alessandra Sgobbi
European Commission

Pablo Ruiz
European Commission

Improved Representation of the European Power Grid in Long Term Energy System Models: Case Study of JRC-EU-TIMES

Wouter Nijs, Sofia Simoes, Alessandra Sgobbi, Pablo Ruiz-Castello, Christian Thiel, George Giannakidis, John Mantzaris, Kostas Tigas, Dionisios Dimitroulas, Pavlos Georgilakis and Costas Vournas

Abstract This chapter describes a methodology to integrate DC power flow modeling and N − 1 security into JRC-EU-TIMES, a multiregional TIMES energy system model. It improves the accuracy of modeling cross-border transmission expansion especially for energy systems with higher penetration of renewable energy sources (RES). We describe three grid representations with increasing accuracy of modeling power flow constraints: (1) basic trade flow without DC power flow, (2) DC power flow with fixed line characteristics and (3) DC power flow with a discretization algorithm, endogenous grid characteristics and N − 1 contingency analysis. The last approach uses the newly developed Integrated

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W. Nijs (✉) · S. Simoes · A. Sgobbi · P. Ruiz-Castello · C. Thiel
European Commission—Joint Research Centre—Institute for Energy and Transport, Petten, The Netherlands
e-mail: wouter.nijs@ec.europa.eu

S. Simoes
e-mail: sofia.simoes@ec.europa.eu

A. Sgobbi
e-mail: alessandra.sgobbi@ec.europa.eu

P. Ruiz-Castello
e-mail: pablo.ruiz-castello@ec.europa.eu

C. Thiel
e-mail: christian.thiel@ec.europa.eu

G. Giannakidis · J. Mantzaris · K. Tigas
Centre for Renewable Energy Sources and Saving (CRES), Athens, Greece
e-mail: ggian@cres.gr

J. Mantzaris
e-mail: jmantzaris@cres.gr

K. Tigas
e-mail: ktigas@cres.gr

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TIMES–NEPLAN Software (ITNS) that couples JRC-EU-TIMES energy system modeling with NEPLAN-based electricity grid modeling. To evaluate the improvement of the JRC-EU-TIMES modeling mechanisms, the three grid representations are compared. We conclude that cross border transmission expansion is cost efficient regardless of the grid representation. The impact of power flow constraints is limited for the analyzed case study under the assumption of perfect markets. However, integrating these constraints is leading to slightly higher cross-border capacities for most countries mainly in periods with limited availability of variable renewable electricity. This occurs when grid extensions and peaking power in some strategic countries are more competitive than local peaking power for each country. This is possible without a substantial increase in model running time.

1 Introduction

The combined generation and transmission expansion planning (CGTEP), also called composite or coordinated, or integrated resource planning, is a very complex non-linear and non-convex optimization problem (El-Debeiky and Hasanien 2000; Alvarez Lopez et al. 2007; Roh et al. 2007; Tor et al. 2008; Sepasian et al. 2009; Bent et al. 2011; Hemmati et al. 2013b). The large integration of renewable energy sources (RES) into modern power systems has made the CGTEP problem even more challenging, because the greatly increased uncertainties introduced often require new transmission lines in order to maintain a satisfactory level of power system security and adequacy (Contaxi et al. 2012; Orfanos et al. 2013). CGTEP is typically split into generation expansion planning (GEP) (Kabouris and Contaxis 1991; Zhu and Chow 1997; International Atomic Energy Agency 2001; Chuang et al. 2001) and transmission expansion planning (TEP) (Romero et al. 2002; Georgilakis 2010; Hemmati et al. 2013a) to improve computational tractability. Comprehensive reviews on CGTEP, GEP, and TEP can be found in Zhu and Chow (1997), Hemmati et al. (2013a, b), respectively. However, in planning for RES, the complete decoupling of the two problems is not necessarily the best approach. The potential to generate energy is highly dependent on where the generators are built and the distances to connect RES to existing systems bring the relative costs of transmission and generation closer in scale.

D. Dimitroulas · P. Georgilakis · C. Vournas
National Technical University of Athens (NTUA), Athens, Greece
e-mail: ddimitr@power.ece.ntua.gr

P. Georgilakis
e-mail: pgeorg@power.ece.ntua.gr

C. Vournas
e-mail: vournas@power.ece.ntua.gr

Examples of a coupling between energy model and electrical network model can be found in UKERC (2009), REALISEGRID (2010), Sakellaridis et al. (2011), Deane et al. (2012), Hamasaki (2014). More specifically, the MARKAL-MED energy model is combined with the WASP GEP (International Atomic Energy Agency 2001) model and a combined gas and electricity network model in UKERC (2009) in order to assess how the UK system can move to a secure and low-carbon energy system over the period to 2050. The combined use of MARKAL, WASP and Cost (Stochastic modeling tool) for the analysis of the electricity system under high RES penetration is presented in Sakellaridis et al. (2011). The use of TIMES and Stochastic Analysis for the analysis of the electricity system under high RES penetration is also presented in Sakellaridis et al. (2011). TIMES is used to model the energy system and a tool is developed for planning cross-border transmission capacity expansion in REALISEGRID (2010). Geographical information system (GIS) gathered renewable energy potential data are coupled with a multiregional TIMES energy system model to study the effect of feed-in tariff (FIT) in the development of wind turbines for the Japanese electricity system (Hamasaki 2014). A soft-linking methodology that employs detailed simulation outputs from a dedicated power systems model to gain insights and understanding of the generation electricity plant portfolio results for the electricity sector from a separate energy systems model is presented in Deane et al. (2012).

The previous analysis has shown that there is an open challenge to establish a link between an energy system model and an electricity network model. This challenge is even bigger, if the objective is to create a link between a well-established energy model and a widely used network analysis model. The work presented in this chapter is designed so as to fill the above mentioned gap, because the objective is to provide interfaces for the integration of TIMES-based energy system modeling with NEPLAN electricity grid modeling.

The TIMES energy system model is a long-term energy planning model that finds the least-cost solution of the evolution of a specific energy system in terms of time resolution and of a Reference Energy System simulating the real energy system (Loulou et al. 2005). TIMES is a bottom-up, partial equilibrium energy model based on maximizing total societal surplus. Main inputs in TIMES are the evolution of the economy resulting in scenarios of useful energy demand, a forecast of international fuel prices and technology roadmaps including specific costs and efficiencies for a time period of several decades.

The TIMES model does not consider in detail the analysis of the electrical power system. It includes a rather elementary approach for dispatching generation, use of transmission and integration of non-dispatchable renewable generation. As a result, the optimal technology mix computed by TIMES may not be optimal when considering the geographically specific transmission grid investments resulting from that technology mix. In addition, renewable investments economic analysis should normally include costs related to transmission grid expansions necessary for penetration in geographical areas with a high potential of renewables, and costs related to balancing measures required due to variations of renewable generation, such as pumped storage plants, gas turbines.

NEPLAN is a well-established software tool to analyze, plan, optimize and simulate electrical, water, gas and district heating networks (BCP Busarello+Cott +Partner Inc. 2014). The NEPLAN Programming Library (NPL) allows to access NEPLAN data and calculation algorithms through a C/C++ written program (BCP Busarello+Cott+Partner Inc. 2014). NPL allows developing user defined algorithms.

This chapter proposes a methodology for the integration of DC power flow modeling into a multiregional TIMES energy model. More specifically, the chapter proposes an Integrated TIMES–NEPLAN Software (ITNS) that provides interfaces for the integration of TIMES-based energy system modeling with NEPLAN-based electricity grid modeling. Among others, the ITNS allows more accurate estimation of maximum permissible penetration of RES in a system.

The ITNS incorporates economical and technical parameters of transmission grid expansion planning to the solution of TIMES and modifies its solution in order to include transmission line investment costs. These parameters are either incorporated in the TIMES solver directly or are incorporated through available loading coefficients of the transmission lines. In this sense, constraints and costs imposed by transmission system operators when determining an expansion plan of the transmission grid are taken into account and affect the generation expansion planning proposed by TIMES. Thus, the solution calculated through ITNS is more realistic than the basic TIMES solution as it incorporates costs of transmission investments, which cannot be evaluated otherwise, since network reinforcements depend on the generation expansion plan. Reversely, cost of these reinforcements should be weighed against a more expensive dispatching that demands fewer investments in transmission network. This interaction may be modeled only with an integrated approach.

The ITNS software incorporates the $N - 1$ security criterion[1] to the expansion planning determined by TIMES. Although the optimality of the solution is not guaranteed, the solution exported by ITNS can be considered at least near-optimal, thanks to an iterative optimization algorithm, which is the core innovation of ITNS. Major constraints are incorporated in the objective function, while other constraints can be accounted for by a fine tuning and do not affect significantly the TIMES solution. The ITNS and its optimization algorithm have been fully adopted by EU-JRC within the JRC-EU-TIMES model. Application results of JRC-EU-TIMES indicate the value and the usefulness of the proposed approach.

To evaluate the improvement of the JRC-EU-TIMES modeling mechanisms, three grid representations are compared in scenarios with free and fixed transmission expansion.

[1] The $N - 1$ criterion for system operation requires that the system is able to tolerate the outage of any one component (line, generator, transformer) without disruption of the operation of the electrical system.

2 Methodology

2.1 General Description of the JRC-EU-TIMES Model

The JRC-EU-TIMES model represents the EU28 energy system plus Switzerland, Iceland and Norway (hereafter EU28+) from 2005 to 2050, where each country is modeled as a single region. Each year is divided into twelve (12) time-slices that represent an average of day, night and peak demand for every one of the four seasons of the year.

The materials and energy demand projections used in JRC-EU-TIMES for each country are differentiated by economic sector and end-use energy service, using as a starting point historical data of 2005 and macroeconomic projections from the GEM-E3 model and in line with the values considered in the EU Energy Roadmap 2050 reference scenario. From 2005 till 2050 the exogenous useful energy services demand grows by 32 % in agriculture, 56 % in commercial buildings, 28 % in other industry, 24 % in passenger mobility and almost doubles (97 %) in freight mobility. On the other hand, the exogenous useful energy services demand for residential buildings is 12 % lower in 2050 than in 2005 due to the assumptions on energy efficiency improvements in buildings.

Energy consumption data from Eurostat is used to derive country and sector-specific energy balances, which determine the characterization of energy technology profiles for supply and demand technologies in the base year. Beyond the base year, new energy supply and demand technologies are compiled in an extensive database with detailed technical and economic characteristics. The model considers power plants in operation and under construction as well as plants to be decommissioned and built, allocating a specific vintage to each electricity generation technology. Cumulative CO_2 storage capacity is derived from the GEOCAPACITY research project,[2] and does not include national policy decisions restricting storage possibilities, such as only storing in offshore sites, or no storage. We consider country-specific wind and solar annual availability profiles for an average year for the 12 modeled time-slices.

Regarding electricity grids, in its basic configuration, JRC-EU-TIMES considers both import/export processes regarding the existing infrastructures (capacity and flows) and possible new investments both within EU28+ and with the rest of the world. In the basic JRC-EU-TIMES configuration there are three levels of electricity voltage and conversion between levels, while no DC power flow is considered. Transmission grids have an associated cost of in euros/kW based on the electricity transport tariff for 2011 for each country from Eurostat.

In this section as well as in Sect. 2.2 certain procedures of the methodology will be presented. The overall methodology will be presented in Sect. 2.3.

[2] http://www.geology.cz/geocapacity.

2.2 *Incorporating DC Power Flow Equations and Power Flow Scenarios Formulation*

2.2.1 DC Power Flow Equations into TIMES and Regional Interconnection Costs

A special version of the TIMES model generator developed by CRES, VTT, NTUA and JRC incorporates Power Flow Analysis into the calculations of TIMES. This version is applicable to all TIMES models and was also implemented in JRC-EU-TIMES. In particular, a linear (DC) power flow algorithm, which is a linearized approach of the Power Flow problem and calculates power flows of a rather aggregated transmission grid of the studied system, was incorporated into TIMES. The grid used for the power flow analysis is not necessarily identical to the region split used in a multiregional TIMES model. For example, Fig. 1 presents a simplified network where R1–R4 represent the regions in which the energy system is split in the TIMES model. As it can be seen, each region of TIMES may include several network nodes.

Trade (transactions between regions) and internal flows within a region should comply with the restrictions imposed by network capacity. The equations to calculate the power flow in each power line of the network are Eqs. 1 and 2 (Seifi and Sepasian 2011).

For every bus (node) i:

$$\mathrm{P_{G,i} - P_{L,i} = P_{T,i} \quad i = 1, \ldots, N} \tag{1}$$

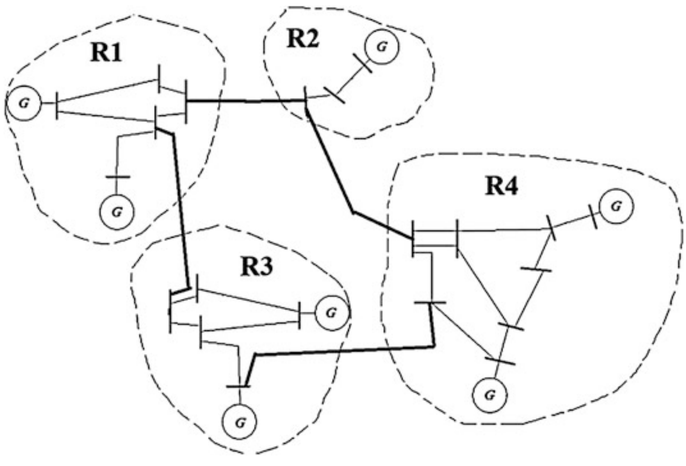

Fig. 1 Representation of regions R1–R4 of an energy system in regional TIMES

and

$$P_{T,i} = \sum_{j=1}^{M} P_{flow,ij} = \sum_{j=1}^{M} B_{ij} \cdot \left(\delta_i - \delta_j\right) \quad i = 1, \ldots, N \tag{2}$$

where

N	the total number of nodes
M	the number of branches that are connected with node i,
$P_{G,i}$	active power injected into node i by generators
$P_{L,i}$	active power withdrawn in node i by loads
$P_{T,i}$	total active power injected into node i
P_{flowij}	branch active power flow between nodes i and j
B_{ij}	susceptance of the branch connecting nodes i and j
δ_i	voltage phase angle of node i with respect to a reference angle

Rewriting the nodal active power balance equations, in matrix notation:

$$[B_r] \cdot [\delta] = [P_T] \tag{3}$$

where

B_r is the reduced admittance matrix by the line and column corresponding to the slack bus—(N − 1) × (N − 1),

δ is the nodal voltage angle vector (except for slack bus)—1 × (N − 1)

In addition, the branch power flow equation is

$$\left[\tilde{B}\right] \cdot [\delta] = [P_{flow}] \tag{4}$$

where

P_{flow} is the matrix of power flows in every power line,

$\tilde{B}$ being the flow admittance matrix—M × N

$$[P_{flow}] = \left[\tilde{B}\right] \cdot [B_r]^{-1} [P_T] \tag{5}$$

where

P_{flow} is the power flow in every power line,

P_T is the power injection in every bus except for the slack bus—(N − 1) × 1.

Regional interconnection costs are given as exogenous input by the user, in terms of cost per unit of power transmission capacity (euros/MW). It should be noted that investments calculated by TIMES are indicative as they do not correspond to actual line types, as it will be explained in detail in the next sections.

2.2.2 Allocation of Additional Capacity, Generation and Demand

The solution of TIMES results in the total quantity (in terms of energy) of generation and demand of electricity for each type of generation technology (CCNG, wind, PV, etc.) or demand category (industry, households, etc.) for each time slice modelled. In addition TIMES results define the capacity of electricity production plants in every region for every generation technology. Based on these information, power flow scenarios are formed for each time slice.

First of all energy quantities (generation and demand) are translated into power, based on the duration of each time slice. The following step is the allocation of these quantities to the grid nodes. As it is referred in Sect. 2.2.1 multiple nodes may be included in a single region. Thus, the aggregated quantities (generation, demand and capacity of power plants) should be allocated to the existing nodes for every region. The allocation of generation and demand can be performed based on a set of criteria:

- The first is to use a predefined distribution scheme based on statistical data, for the nodes of each region. For example, if the solution of TIMES show industrial load to increase in a region, there should be a predefined distribution of industrial load among the region's nodes. Therefore, certain nodes near industrial areas will undertake the additional loads, while others in urban or mountainous areas will not. This approach is used in order to allocate electricity demand.
  The same criterion is also used in allocating the capacity of distributed generation plants. This procedure is also based on statistical data derived from suitable sites for expansion of distributed plants ensuring that development of new distributed power plants (e.g. wind, solar or CHP) will take place in sites with high RES or CHP potential.
- The second criterion is applied for (non-distributed) generation expansion allocation and is to mark predetermined sites for new plants. This applies mostly to conventional plants, for which sites for a new power plant of a certain type (e.g. coal, nuclear) inside a region can easily be determined in advance.

2.2.3 Synchronous and Asynchronous Connections

Before analyzing synchronous and asynchronous connections, it is necessary to define the notion of a corridor. In a transmission network, multiple circuits may link the same network nodes. In the current analysis, every group of such circuits is merged and substituted by one equivalent line, which is called "a corridor". In case that the circuits of a corridor operate at different voltage levels, transformers at both ends of the circuit together with the circuit are substituted with an equivalent admittance.

Depending on the type, a connection may be synchronous (AC connections) or asynchronous (DC connections). Asynchronous connections are capable of controlling power flow due to the converter stations that exist at both ends of the line. DC connections are usually used in interconnections between countries or isolated areas. Since power flow is controlled, the flows in asynchronous connections are considered in TIMES as normal trade processes. In the power flow problem, asynchronous lines are omitted from the network and substituted with a positive power injection in one end and an equal negative power injection in the other end of the line.

Power injection at synchronous connections is not controlled. Power flow in these lines is calculated through DC power flow equations, based on the network admittance matrix. However, in the realization of the algorithm a third category of lines arises, which are radial connections. Radial connection is a connection between two nodes, that if it is opened, one node becomes isolated from the rest of the power grid. In such connections, the flow depends only on positive or negative injections of power from generation and load demand. Thus, the excess of production or load of a radially connected node equals the power flow in the connection line. These circuits are considered as DC connections (predefined power flow).

In Fig. 2, a simplified network of Western Europe is shown as an example of the method that has been used with the JRC-EU-TIMES model. United Kingdom (UK) and Ireland (IR) are connected through DC lines, while Spain (ES) and Portugal (PT) are radially connected through AC lines.

The corridor PT-ES is radial and therefore flow in this corridor is determined by the excess or the shortage of power generation comparing to the demand in nodes of PT and ES. Asynchronous and radial connections have been modeled with the traditional trade approach and synchronous with the flow based methodology developed.

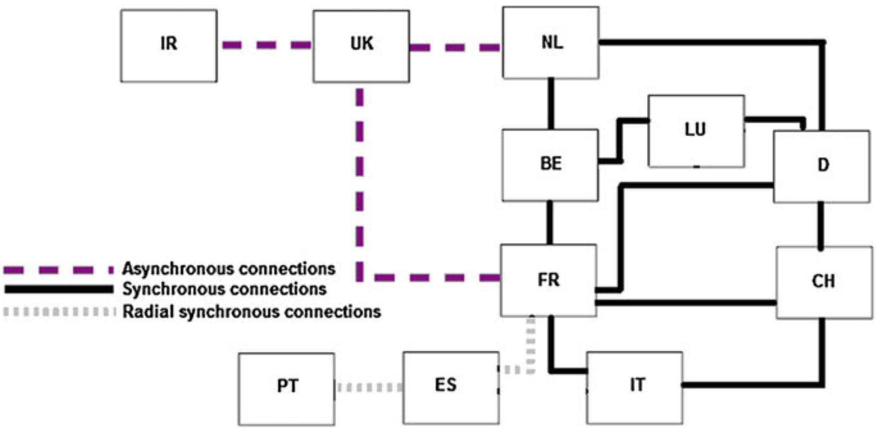

Fig. 2 Simplified network

2.3 Incorporating N − 1 Security Constraints Integrating TIMES with NEPLAN

Incorporating N − 1 security constraints in TIMES directly is not possible as this would make the problem non-linear. Therefore, N − 1 security analysis is performed indirectly using a usability coefficient (ε) which determines the acceptable loading of a corridor. The basic concept is that through this coefficient it is possible to limit the loading of a corridor in N (normal) state—which is modeled in TIMES through DC power flow—so as to avoid overloading in N − 1 (emergency) conditions. In particular, incorporation of the N − 1 security constraint is being performed using an iterative method through which the value of the usability coefficient (ε) is determined. This coefficient expresses the percentage of acceptable loading for a certain corridor in N state in order to fulfill N − 1 criterion. This acceptable loading depends on the characteristics of the corridor, as well as on the surrounding network. The initial value of the usability coefficient is determined by Eq. 6:

$$\varepsilon_{ij} = \begin{cases} \dfrac{\min\left\{\sum_{n_{ij}-1} \mathrm{P}_{\mathrm{k}}^{\max}\right\}}{\sum_{n_{ij}} \mathrm{P}_{\mathrm{k}}^{\max}}, & \text{if} \quad n_{ij} > 1 \\ 0.9, & \text{if} \quad n_{ij} = 1 \end{cases} \tag{6}$$

where $\mathrm{P}_{\mathrm{k}}^{\max}$ is the transfer capacity of circuit k of corridor *ij* and n_{ij} is the number of circuits constituting corridor ij.

Equation 6 expresses the acceptable loading of a corridor so that after a trip of the circuit with the maximum transfer capacity, the corridor will not be overloaded. In other words, by applying this criterion we assure that if power flows do not change after a circuit trip, the loading of corridor ij will be within predefined limits. As it is well known, a modification of a network, such as a circuit trip, modifies all power flows in the network. Yet, this is an approximate way of determining the initial value of the usability coefficient ε. For corridors that consist of only one circuit, the initial value of usability coefficient ε is taken equal to 0.9.

2.3.1 N − 1 Contingency Analysis

The N − 1 contingency analysis is performed through an iterative procedure that uses NEPLAN and eventually calculates usability coefficients (ε). As it is described in Sect. 2.2 for every time slice a corresponding power flow scenario is formulated and used as an input in NEPLAN with a more detailed network model, which includes individual circuits. This procedure uses network data imported into NEPLAN, along with power flow data calculated through the procedures described in Sect. 2.2.2 and performs N − 1 security check using NEPLAN functions.

The overloading of a circuit computed through NEPLAN has to be translated into a restriction for the loading of the corresponding corridor, in order to be used by TIMES (usability coefficient). Through this procedure a correction factor of the initial value of usability coefficient is calculated.

Suppose that for the m contingency (i.e., the contingency of circuit m), circuit k gets overloaded. The overload indicator L_{km} is then computed as follows (Eq. 7):

$$L_{km} = \begin{cases} \frac{P_{km}}{P_k^{\max}}, & \text{if} \quad P_{km} \geq P_k^{\max} \\ 0, & \text{if} \quad P_{km} < P_{km}^{\max} \end{cases} \tag{7}$$

where

L_{km} overloading indicator of circuit k under the contingency of circuit m
P_{km} loading of circuit k under the contingency of circuit m
P_k^{max} upper limit of loading (capacity) of circuit k

For each overloaded circuit and for each contingency, we compute the indicators I_m and J_k as follows (Eqs. 8 and 9):

$$I_m = \sum_{k=1}^{n_{lines}} L_{km} \tag{8}$$

$$J_k = \sum_{m=1}^{n_{cont}} L_{km} \tag{9}$$

where

n_{lines}, n_{cont} total number of circuits and total number of contingencies, respectively.

In practice, indicator I_m is the total overloading that appears in all circuits under contingency m. Similarly, indicator J_k is the total overloading of circuit k under all contingencies.

The overloading of circuit j is computed by selecting the maximum value of J and the value of the maximum J as follows (Eq. 10):

$$J_j = \max_k \{J_k\} \tag{10}$$

We compute the contingency i with the maximum I and the value of the maximum I as follows (Eq. 11):

$$I_i = \max_m \{I_m\} \tag{11}$$

Using these two parameters, we calculate the value of the correction factor K_c for each corridor. The correction factor K_c for each corridor indicates the required reduction of the value of usability coefficient ε according to the N − 1 security analysis results. In other words, the correction factor K_c reduces the acceptable loading of a corridor in case it is overloaded when a contingency occurs.

There are two cases of correction requirements:

Case 1: $J_j \geq I_i$, which means that circuit j (belonging to corridor c) has to be reinforced. In this case, the value of K_c for the corridor c is computed as follows (Eq. 12):

$$\mathrm{K_c} = \frac{1}{\mathrm{L_{ji}}} = \frac{1}{\max\limits_{\mathrm{m}} \{\mathrm{L_{jm}}\}} \tag{12}$$

$$L_{ji} = \max_{m}\{L_{jm}\} = \max\{L_{j1}, L_{j2}, \ldots, L_{ji}, \ldots, L_{jn_{cont}}\} \tag{13}$$

where L_{ji} denotes the overloading of circuit j during the contingency i.

Case 2: $J_j < I_i$, which means that in this case we have to avoid contingency i, i.e., we have to reinforce the corridor c in which the circuit i belongs, the outage of which results in the contingency i. In this case, in order to force TIMES to add a new circuit in the corridor c, the value of K for corridor c is defined as (Eq. 14):

$$\mathrm{K_c} = 0.5 \tag{14}$$

The new value of the usability coefficient is calculated through Eq. 15:

$$\varepsilon_{ij}^{new} = K_{ij}\varepsilon_{ij}^{old} \tag{15}$$

2.3.2 Discretization of Line Investments

Corridor reinforcements indicated by the TIMES model solution is a continuous variable (since TIMES gives a linear programming solution). A mixed integer programming solution with discrete investments can be calculated, however this will considerably increase the computational time. Since investment costs depend on the types of circuits constructed or upgraded, there is a need for a discretization algorithm, which rationalizes the reinforcements and associated investments indicated by the TIMES solution.

As mentioned in Sect. 2.2.3, every corridor consists of several circuits of different capacities. In the methodology used it is assumed that each corridor may be reinforced by a predefined type of circuit, based on certain criteria (e.g. topological features of transmission grid). In other words, the characteristics of each corridor indicate acceptable reinforcements and investments. If the additional capacity requirement calculated from the TIMES solution exceeds a predefined percentage of the capacity of the predefined reinforcement, the investment is approved by the algorithm. Otherwise the investment is not approved, and the network is not reinforced.

2.4 *Iterative Process Coupling JRC-EU-TIMES with Neplan (ITNS)*

The individual procedures analysed in Sects. 2.2 and 2.3 are assembled in a process that constitutes ITNS, the overall methodology of coupling between JRC-EU-TIMES and NEPLAN and is analysed in the current section. This coupling is performed through an iterative process, which allows both models to approach a minimum cost solution, taking into account the transmission expansion costs. A simplified flow chart of the algorithm is shown in Fig. 3 and the steps that should be followed are:

First step: This step includes three elements. First of all it includes an external procedure that imports the initial values of all parameters and variables into the JRC-EU-TIMES model (e.g. circuit admittance, cost, network parameters). The second element is the execution of JRC-EU-TIMES and the third is an external function that extracts the results of JRC-EU-TIMES into ASCII files. The extracted results are the generation and demand of electricity for every region, the generation and load type as well as the generation capacity expansion.

Second step: This is performed in an external function that formulates power flow scenarios. Demand, generation and generation expansion are allocated at the nodes of each region of JRC-EU-TIMES for every time slice. Thus, for every year, a load flow scenario is formulated, for each time slice (instances of grid operation). In addition, new circuit investments are calculated in JRC-EU-TIMES and then they are discretized according to method presented in Sect. 2.3.2.

Third step: This step is similar to the first step. Updated data from the second step are imported into JRC-EU-TIMES through an external procedure. These data are the adjusted allocation factors for generation and demand and the line investments calculated through the discretization process presented in Sect. 2.3.2. These grid reinforcements are imported as fixed line investments.

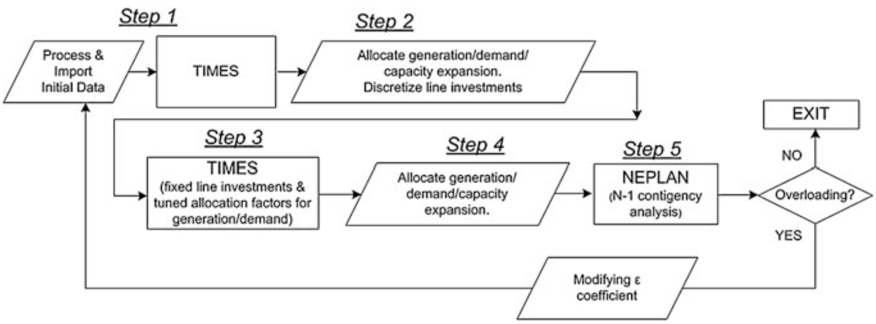

Fig. 3 Flow chart of the coupling between JRC-EU-TIMES and NEPLAN software (ITNS)

JRC-EU-TIMES is re-executed with the updated values calculated in the second step and the new results are extracted in ASCII files.

Fourth step: This step is similar to the second step. It is an external procedure that uses the JRC-EU-TIMES results produced in step three and reallocates demand, generation and generation expansion to the nodes of every region of TIMES for every time slice and for every year studied.

Fifth step: This step consists of three procedures. The first procedure imports data into the NEPLAN software (circuit investments which is the discretization output, injections of generation and demand). The second procedure is the N − 1 security analysis, which is performed using NEPLAN, and the calculation of the overloading of circuits under all contingencies. The third procedure is the calculation of the correction factor of usability coefficients (K_c) through an external procedure (see Sect. 2.3.1).

Sixth step: This is an external procedure that is a logic check for the termination of the iteration. If the solution of NEPLAN does not indicate overloading calculated through the N − 1 contingency analysis, the iterations are terminated. In the opposite case, the iteration starts again from step 1. The execution of JRC-EU-TIMES is performed with new epsilon coefficients calculated by multiplication of the initial ε with the K_c coefficients using Eq. 15.

In Fig. 3, the flow chart of the overall methodology is presented. Every iteration presupposes that NEPLAN detects overloading of circuits under N − 1 conditions. Usability coefficients are then reduced (through K coefficient). Thus, in every iteration the JRC-EU-TIMES solution reduces the loading of corridors. This may be accomplished by modifying the dispatch of electricity (allocation of generation to the different nodes), or by reinforcing the electricity network. The reduction of circuit/corridor loading after each iteration, leads to the convergence of the algorithm.

2.5 Power flow representation in JRC-EU-TIMES

The simplified grid of the European electricity system for the base year of study is presented in Fig. 4. The asynchronous and radial connections are simulated like a trade process in TIMES. The synchronous connections are modeled using the DC Load Flow algorithm in TIMES. The synchronous grid is represented with 13 nodes and 23 synchronous connections. Each node represents a country of the former UCTE 1st synchronous zone of the West and Central Europe.

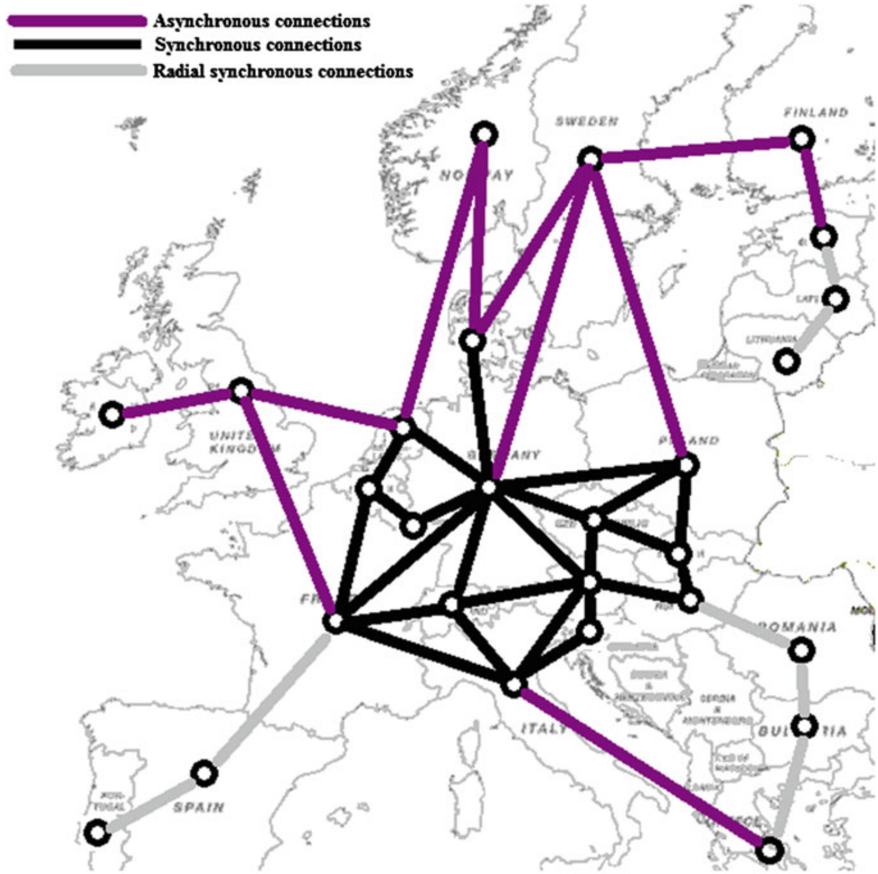

Fig. 4 Simplified model of European grid at the base year of study

3 Scenarios to Assess Integrating Grid Constraints in JRC-EU-TIMES

To assess both the impact of DC Power flow modeling and ITNS in JRC-EU-TIMES results, we developed four scenarios as shown in Table 1. To determine the effect of the different grid representations we compare the optimal solutions of the basic TIMES code with the more advanced approaches. Asynchronous and radial connections are always modeled with the traditional trade approach. However, synchronous connections have been modeled with both the traditional trade approach as well as with the new flow based methodologies. The three grid representations are compared in the scenarios TRADE, DC and DC_Neplan where the transmission expansion is free after 2025. The last scenario, DC_FixGrid, has a fixed transmission expansion up to 2050.

Table 1 Scenario description

Scenario	Grid representation of synchronous connections	Grid expansion
TRADE	Trade based (basic TIMES)	Endogenous grid expansion (after 2025)
DC	TIMES DC power flow with fixed grid characteristics	
DC_Neplan	TIMES DC power flow with discretization algorithm, endogenous grid characteristics and N − 1 contingency analysis via the ITNS	
DC_FixGrid	TIMES DC power flow with fixed grid characteristics (as DC scenario)	Fixed grid expansion (fixed up to 2050)

In an optimization model scheduled electricity flows are equal to the physical flows as optimal price signals exist so that the market solutions fully represent the physics. However, this can only be implemented if the physical flows are represented properly. More details for each scenario are provided as follows:

- The TRADE scenario corresponds to the solution of JRC-EU-TIMES without incorporating the DC Power flow algorithm (i.e. it is the basic TIMES model). Energy transactions between regions in the European system are calculated like normal trade functions in TIMES.
- The DC and DC_FixGrid scenarios refer to using the JRC-EU-TIMES model in the versions with the incorporation of DC power flow, where power flows between regions are more accurately estimated. However, ITNS loops are deactivated, and thus corridor reactances and allocation factors are not updated after the definition of the initial investment plan.
- The DC_Neplan scenario refers to the execution of the complete TIMES-NEPLAN integrator software (ITNS), including discretization algorithm, endogenous grid characteristics and N − 1 contingency analysis.

In all scenarios an 80 % CO_2 emission cap was considered compared to 1990 values. Moreover, all scenarios have in common the following assumptions: (i) No consideration of specific policy incentives to RES (e.g. feed-in tariffs, green certificates); (ii) three additional constraints to ensure: (1) sufficient reserve capacity, (2) realistic representation of variable RES generation and (3) sufficient storage charging capacity. Variable RES (wind, solar, PV and ocean) cannot operate during the winter peak time slice to account for reserve capacity considerations; and (iii) countries without nuclear power plants (NPPs) will not have these in the future (Austria, Portugal, Greece, Cyprus, Malta, Italy, Denmark and Croatia). NPPs in Germany are not operating after 2020 and Belgium NPPs are not operating after 2025.

The main objective of the case study is to evaluate the improvement of the JRC-EU-TIMES modeling mechanisms by including grid related constraints. Note that when looking into the results of our case study regarding the impact on the power system there are several limitations, such as that the insights that are gained from the current configuration are most useful when the consumption and production of electricity are similar to the assumed averages of the 12 time slices. Ideally, one would include a higher number of time slices, regions as well as the national grids to represent different conditions for power plant availability, weather conditions and volatility of fuel prices. This allows including in JRC-EU-TIMES representative day patterns with much more combinations of normal and more extreme events as well as regional differences in renewable availability. Moreover, more differences will be visible when more disruptive situations are modeled based on less perfect circumstances.

4 Results

In the JRC-EU-TIMES model, cross border transmission expansion is cost efficient regardless of the grid representation. The most important factors determining cross border electricity flows as well as the cost efficiency of transmission expansion are (1) the electricity price difference between the countries strongly driven by technology specificity, (2) the transfer capacity limits active in the model and (3) storage possibilities in JRC-EU-TIMES. The results show that a more accurate representation of the grid is possible and worthwhile in a large energy system model. However, we observe that the impact of DC Power Flow is limited for the analyzed case study. Figure 5 shows the net electricity export in 2035 for the four scenarios. The large export from Norway is notable as well as the export from France in the scenario with limited grid expansion (DC_FixGrid). At this level of detail, there are very limited differences between the three grid representations TRADE, DC and DC_Neplan.

Remarkably, unscheduled flows do not appear in the DC scenario because the physical grid limitations are fully internalized in JRC-EU-TIMES. The TRADE scenario does not have grid constraints so unscheduled flows, deviations between scheduled flows and physical flows, take place. Including DC Power Flow triggers

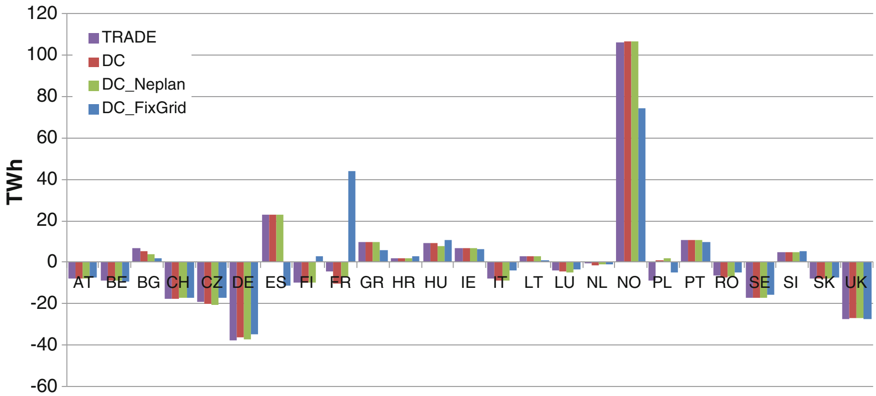

Fig. 5 Net electricity export in 2035

grid extensions but also a shift in generation and consumption to make the physical flows stay in the limits of the grid network. As we compare a market that does not have physical limitations (copper plate) except net transfer capacity with a market that has physical limitations (grid with power flow constraints) one could consider the changes of generation and consumption as some kind of redispatch, however based only on limitations of interconnectors.

In the JRC-EU-TIMES model the Summer Day and Summer Peak represent times with vast amounts of available solar energy. In fact, because of the limited number of time slices, the Summer Day and Summer Peak show a homogenous high level of solar energy across the regions. The Winter Peak represents times without any contribution from variable renewables. Under these somewhat disruptive circumstances we observe increased investments in interconnection capacity.

First, we look at the impact of summer solar electricity production. In the TRADE scenario, the DC scenario as well as the DC_Neplan scenario, more than 10 GWe cross-border capacity is built between Spain and France. This allows transferring electricity from Spain and Portugal in the summer to Northern Europe. As a consequence, we observe a reduced use and capacity of nuclear power plants in France when compared to the DC_Fixgrid scenario that has limited grid expansion possibilities. Interestingly, when the grid expansion is limited, there is an increased deployment of electric cars in Spain. The reason is that in the year 2035, there is a trade-off between storing part of the solar electricity into the batteries of electric cars and using the grid to export. We conclude that the impact of DC Power Flow and NEPLAN is low although the summer solar production induces grid expansions.

In the Winter Peak no variable renewable electricity is available. This a somewhat extreme assumption—not all countries will be without wind, solar and ocean activity at the same time—which leads us however to an interesting finding. As Fig. 6 shows, in the Winter peak time slice important flows occur making Poland, Belgium, Italy and UK exporting electricity to mainly Switzerland, Sweden and

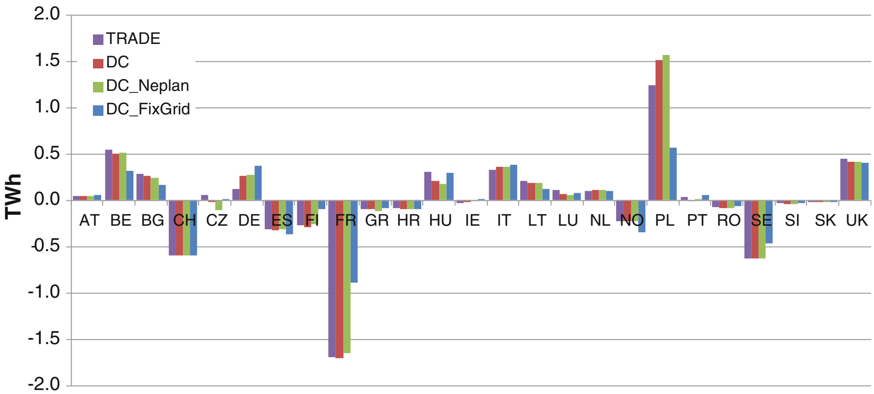

Fig. 6 Net electricity export in the Winter Peak hours (110 h) without availability of variable renewable electricity in the year 2035

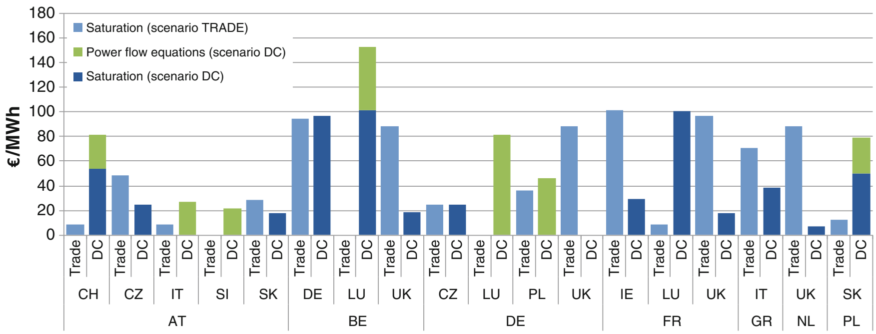

Fig. 7 Electricity price difference between countries in the scenarios TRADE and DC and decomposition for the Winter Peak in 2035

France. Also, the representation of the grid has an impact on some countries such as Germany and Poland.

The electricity market in JRC-EU-TIMES is optimal in this way that it does not have external costs when DC Power Flow is included and it implements nodal pricing in each of the 13 nodes of the synchronous central European grid. The market value of the transmission connection is with nodal pricing equal to the price difference between the areas arising from differences in marginal production cost as well as from congestion costs. Figure 7 shows for the situation in 2035 without available variable renewables the electricity price differences between countries. In the TRADE scenario, electricity price differences are only based on marginal production costs. In contrast, the DC grid representation has another component arising from the power flow constraints. In some connections like Austria-Italy or Germany-Poland it only has the component of power flow constraints.

The traditional representation of the grid, the TRADE approach, uses the network as optimal as possible with the only limitation that the sum of the inflows and outflows in a node is zero. With such a representation, many possible combinations of trade are possible for a given consumption and production in each node. However, the DC power flow approach represents also the physical electricity flows, directed by the grid characteristics. With a given consumption and production in each node (country in our case) and with given trade in radial and asynchronous connections, only one solution of the electricity flow exists in the synchronous grid and investments in new lines are triggered by a combination of regional cost of electricity production and physical limitations. The added value of DC power flow is that it models the physical flow of electricity. This usually leads to higher investments in grid lines than in the TRADE approach.

When the price difference is large enough for a sufficient long period, this can cause a grid expansion at least when this grid expansion is not too costly. Figure 8 shows most of the grid expansions for the three scenarios where investments are free. Most of the connections have higher cross-border capacities when power flow constraints are included such as Austria and Slovakia with all its neighboring

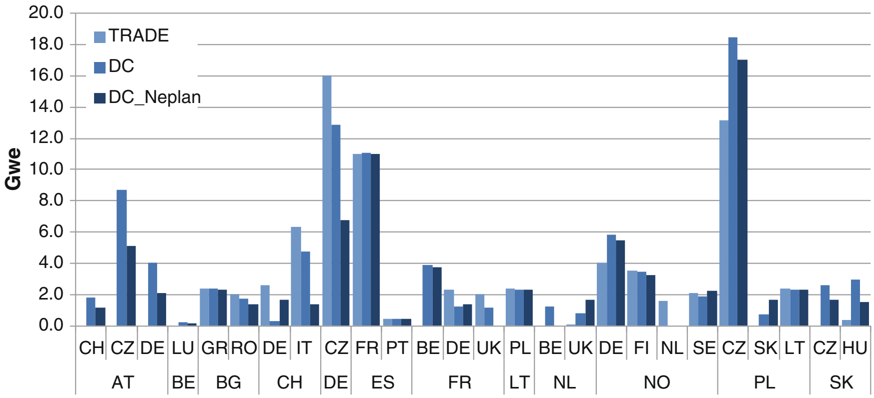

Fig. 8 Electricity grid expansions between countries in the scenarios TRADE, DC and DC_Neplan

countries but also the connection Germany-Norway and Poland-Czech Republic. The main driver for the optimal electricity path is the cost of the combined grid expansions. Typically this cost of the grid expansion is a factor 10–100 lower than the value of the traded commodities. However, the impact of the price component of the power flow constraints is often even smaller than the cost differences between possible grid expansions. Because of this reason the model will typically not drastically change the grid expansion as there are preferred routes based on the cost of these interconnections. We conclude that power flow constraints have an impact on optimal grid expansion and that the accuracy of the grid expansion costs is crucial for proper grid flow analysis.

We evaluated the improvement of the JRC-EU-TIMES modeling mechanisms by including grid related constraints. No substantial increase in modeling time was observed when static DC power flow equations are added to the JRC-EU-TIMES model. However, mainly the discretization loop of the ITNS is time consuming. Depending on the number of new investments, the total ITNS cycle needs 10 up to 100 iterations.

5 Conclusions

To evaluate the improvement of the JRC-EU-TIMES modeling mechanisms, three grid representations are compared in scenarios with free and fixed transmission expansion. We conclude that the impact of power flow constraints is limited for the analyzed case study. However, integrating these constraints has a relevant impact on the value of future possible grid expansions mainly in periods with limited availability of variable renewable electricity, without a substantial increase in model running time and leading to slightly higher cross-border capacities for most countries.

Future research can define restrictions based on the output of the total ITNS cycle so to prevent the iterative procedure of the soft coupling of TIMES with NEPLAN. Further work can also include increasing the number of regional differences such as renewable availability as well as stochastic generation or consumption. This would trigger more disruptive situations that are necessary to understand the true value of grid extensions. We conclude that the perfect foresight assumption of JRC-EU-TIMES requires special attention of the modeler. Indeed, some of the robustness of the JRC-EU-TIMES should be removed in order to get a possibly less optimal distribution of power plants and consumption patterns, as we observe today in many members states. We expect to see more differences between the three grid representations for situations that are more disruptive and less perfect.

Under these conditions, we conclude that the decision making process on transmission expansion can strongly be affected by tools like JRC-EU-TIMES as there is a strong competition between grid extension, storage options, local peak power as well as demand side management.

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wouter.nijs@ec.europa.eu