Addressing the Geo-Spatial Aspects of Variable Renewable Energy in Long-Term Planning

Session 6 – Representing grid investment in capacity expansion models

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Cooptimization of grid investment and renewable investment using the TIMES model

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Multi-regional TIMES Model with transmission grid expansion

The TIMES model

- the optimal technology mix computed by TIMES may not be optimal when considering the geographically specific transmission grid investments resulting from that technology mix

- To find solutions within a reasonable amount of calculations the analysis can include :

  a simple linear flow estimation of the transmission network (e.g. DC load flow)

Methodology Issues

to include the expansion cost of the transmission grid into TIMES

a linear (DC) power flow algorithm is incorporated and resolves an aggregated form of the transmission grid (equivalent grid) simulated in a regional TIMES

transmission grid expansion may be a consequence either of :

- connecting **areas with significant potential** for electricity generation such as RES, coal, etc.
- or **areas with significant increase of generation** and/or demand

Methodology Issues

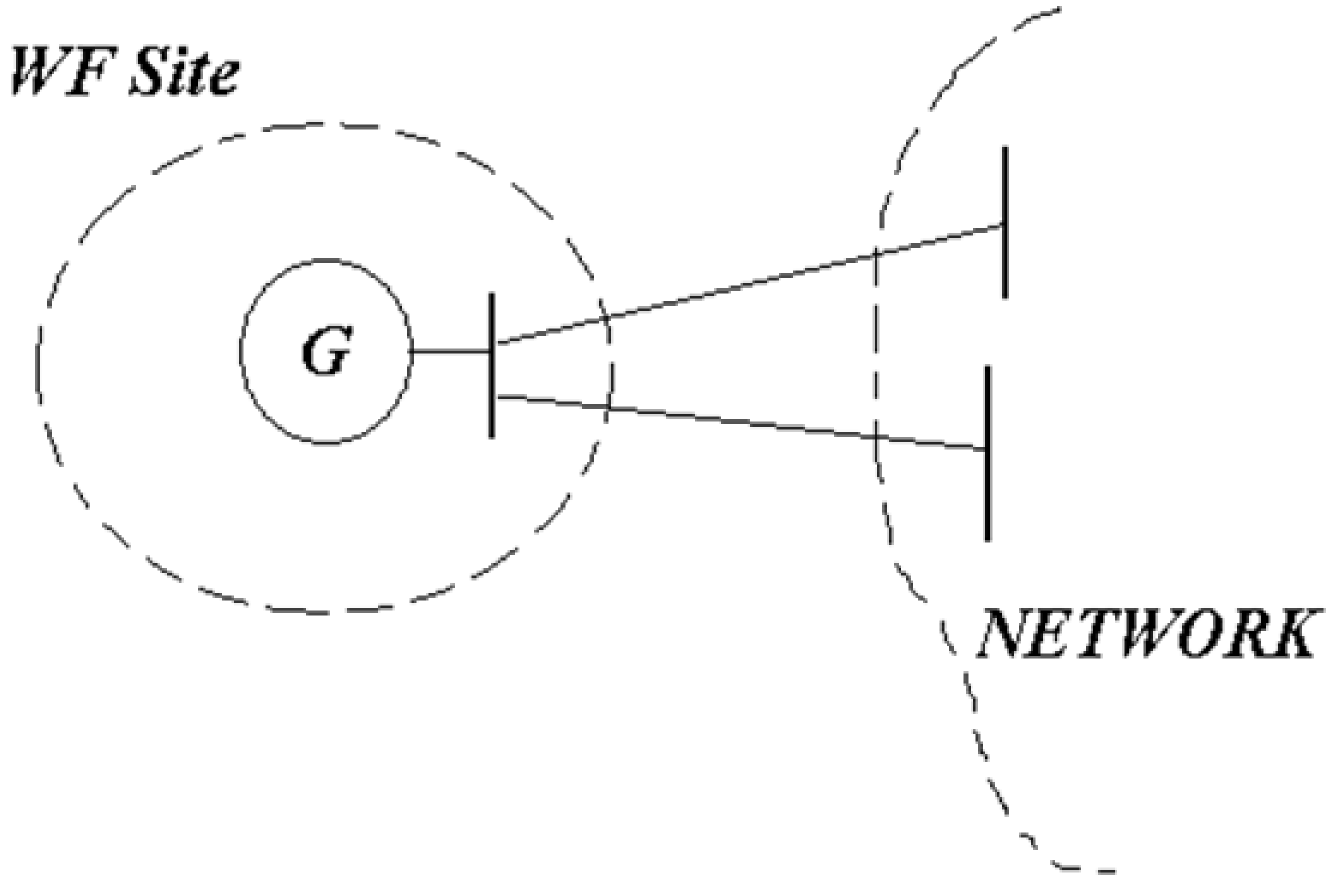
Shallow connections are generally related to connections of wider areas with significant RES potential or other resources (coal, lignite, etc.) to power transmission grid

Deep connections refer to internal grid infrastructure which is related to secure and reliable transmission of electric power

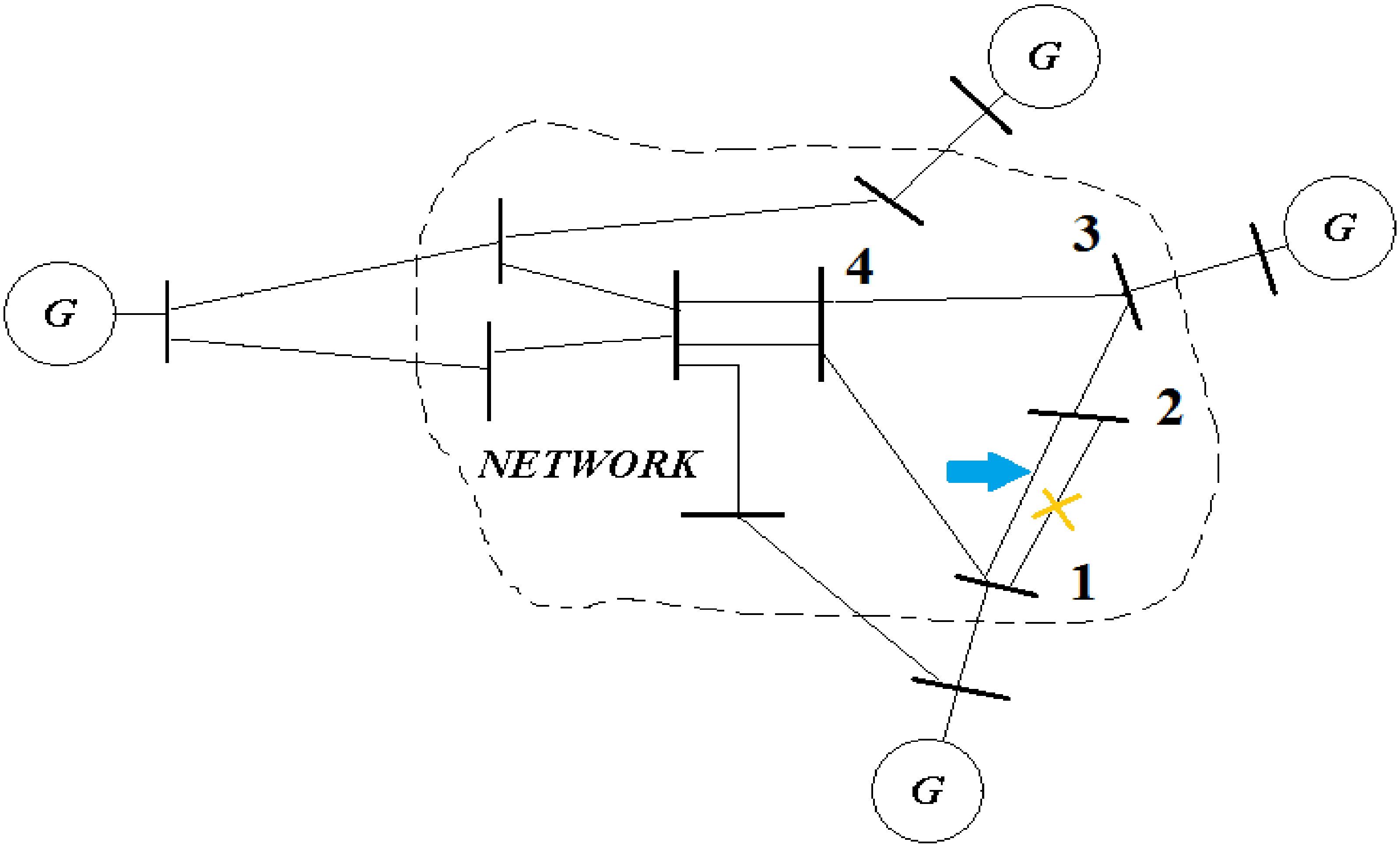
Deep connections can be divided further into :

- The ones in the vicinity of the areas of high RES potential or
- Contingencies caused by the wide scale penetration of RES to the power flows

Shallow Connection



Deep Connection reinforcement



Methodology Issues

The equivalent grid

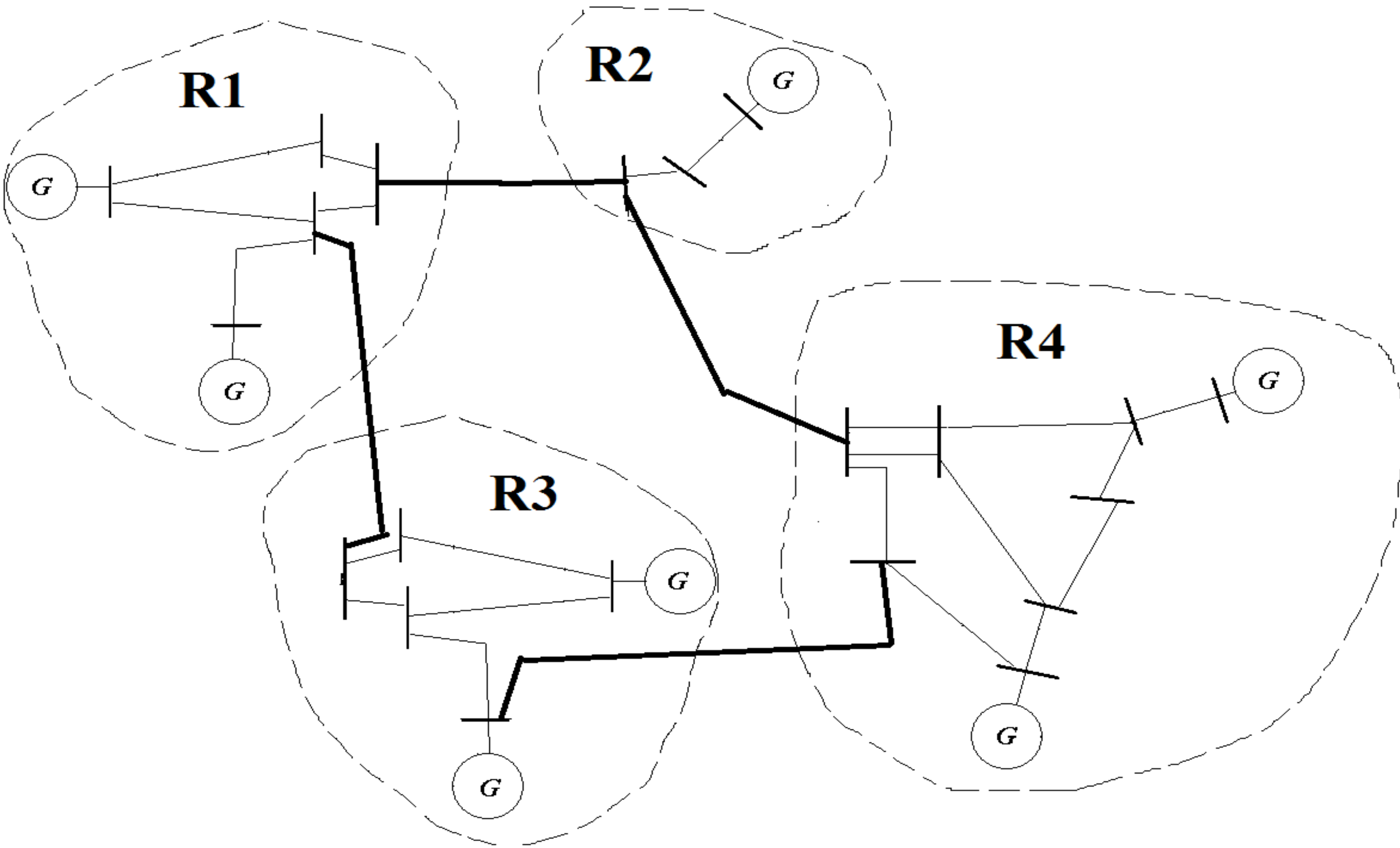
The TIMES model cannot incorporate several thousands circuits for a detailed simulation of the transmission grid

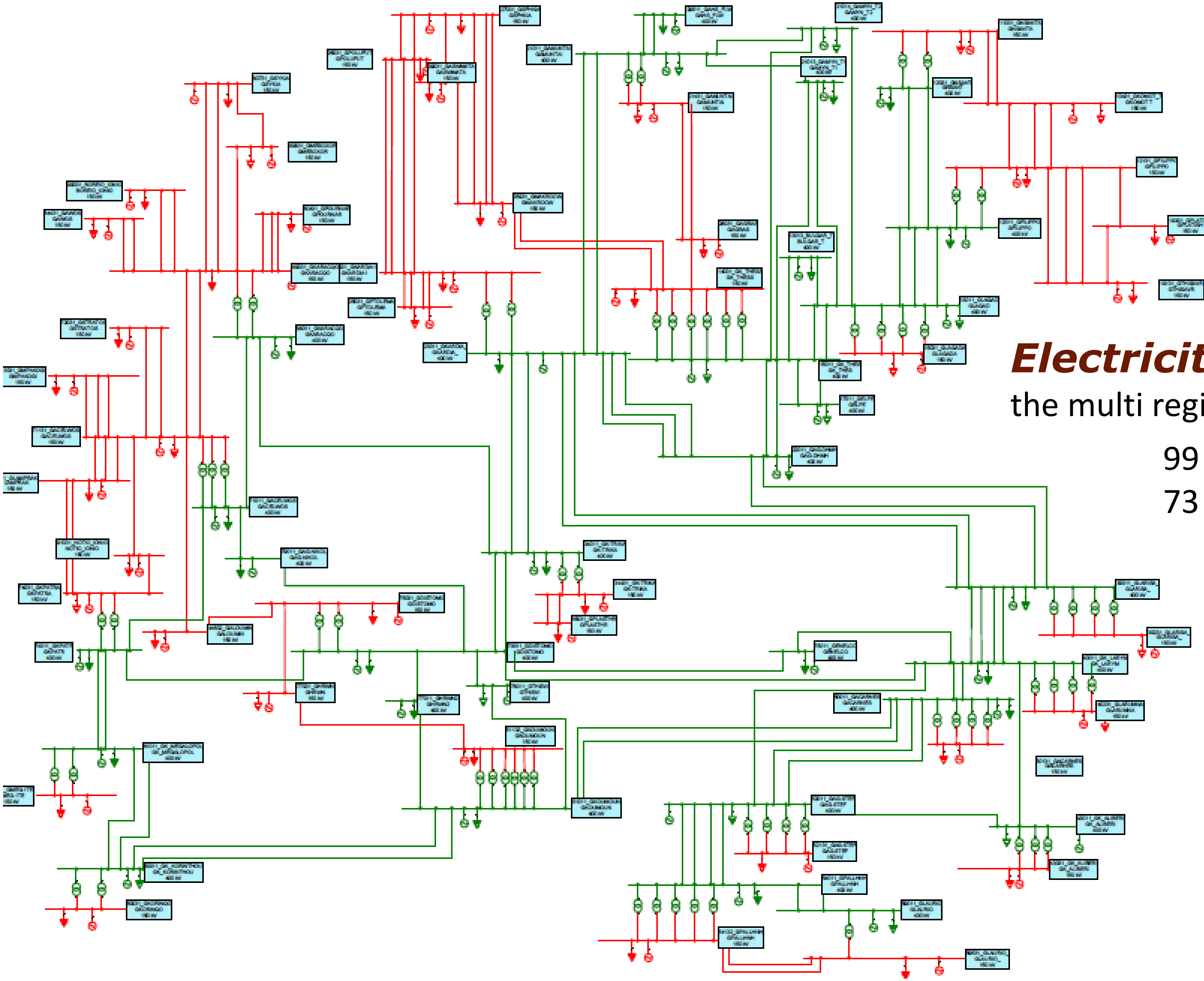
It is necessary to develop an equivalent grid that would incorporate

only a few hundreds circuits and the appropriate simulation that will

allow the identification of potential reinforcements due to a wide scale penetration of Renewables

DC Power Flow simulation in regional TIMES





Electricity Grid for the multi regional model

99 corridors
73 nodes

DC Power Flow equations into TIMES

The general form of the DC power flow equations incorporated into TIMES are as follows:

For every bus (node) i:

$$\boldsymbol{G_i - L_i = P_i} \quad i=1,N \tag{1.1}$$

or

$$\boldsymbol{G_i \;-\; L_i = \sum_{j=1}^{M_i} P_{i,j}} \tag{1.2}$$

and

$$\boldsymbol{P_i = \sum_{j=1}^{M_i} P_{i,j} = \sum_{j=1}^{M_i} B_{i,j} \cdot (\delta_i - \delta_j)} \tag{1.3}$$

where :
N: the total number of nodes
M_i : the number of nodes connected with bus (node) i,
G_i : active power injected into node i by generators
L_i : active power consumed in node i by loads
P_i : net power injected(generation-load) into node i
P_{ij} : branch flow between nodes i and j
B_{ij} : susceptance of the branch connecting nodes i and j
δ_i: voltage phase angles of node i with respect to a reference angle
in TIMES formulation all parallel branches between nodes i and j are represented as one equivalent corridor ij.

DC Power Flow equations into TIMES, N-1 security

The scope behind the present effort was to incorporate a grid topology and Direct Current (DC) power flow analysis in TIMES [6],[16],[21] to dynamically allocate injections in each node of the simulated transmission grid related to generations and loads calculated and finally to incorporate restrictions related to transmission lines, congestions and overloading calculated in TIMES.

According to the DC load-flow modelling incorporated in TIMES, if P_{ij} is the branch power flow in the corridor (equivalent of electricity circuits connecting two nodes) between nodes i and j then:

$$P_{i,j} - \varepsilon_{i,j} \cdot P_{i,j}^{max} \leq 0 \tag{7}$$

The loading coefficient expresses the acceptable loading of the corridor in order to satisfy a N-1 criterion,

In case transmission expansion is required, i.e.

if $P_{i,j} - \varepsilon_{i,j} \cdot P_{i,j}^{max} \geq 0$,

then an additional circuit with $\Delta P_{i,j}^{max}$ is introduced, giving:

$$P_{i,j} \leq \varepsilon_{i,j} \cdot (P_{i,j}^{max} + \Delta P_{i,j}^{max}) \tag{8}$$

The additional connection cost for investing in a new line between nodes i,j is:

$$K_{i,j}^{inv} = K_{i,j} \cdot \Delta P_{i,j}^{max} \tag{9}$$

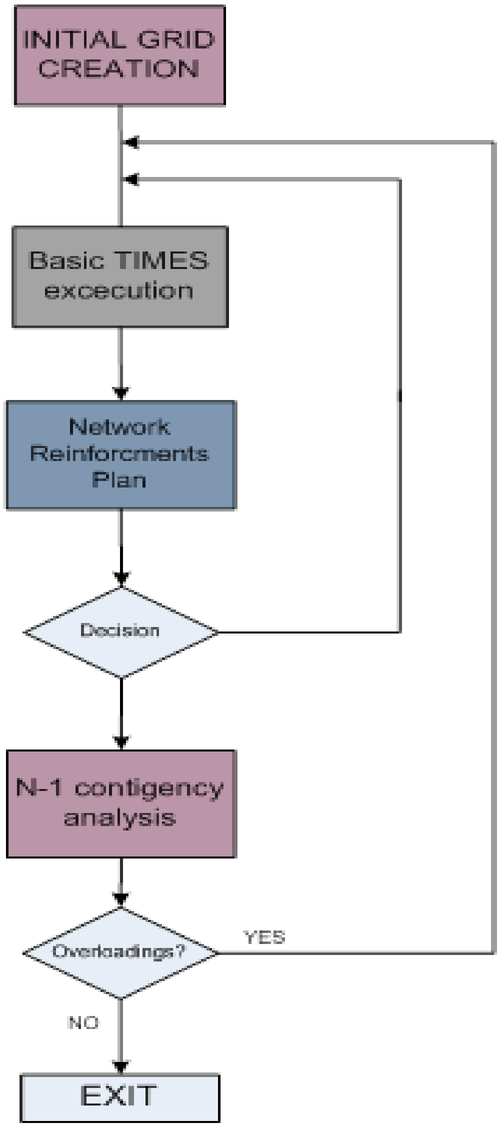
DC Power Flow equations into TIMES, N-1 security

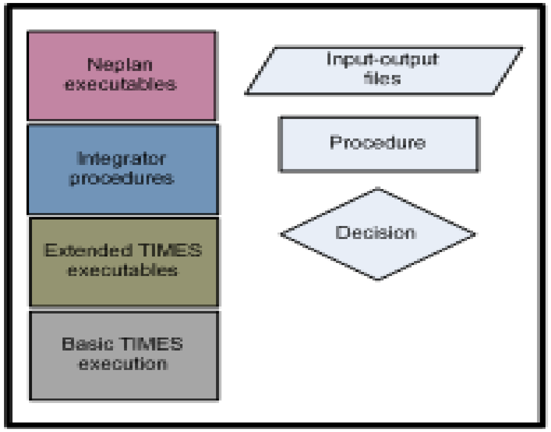
The ε coefficients are calculated from the N-1 security analysis which is carried out **externally** under the load flow **NEPLAN** software or **PSS/E**

Equations are incorporated into TIMES together with the susceptance matrix [B] and an algorithm for calculating and allocating the injections vector $\overline{P}$ which will be a result of the TIMES solution

An initial network topology in the form of matrix [B] and vector $\overline{P}$ is established in TIMES, with an allocation of generations and loads per node and per region

Overall Algorithm and Iterations





Mixed Integer Programming

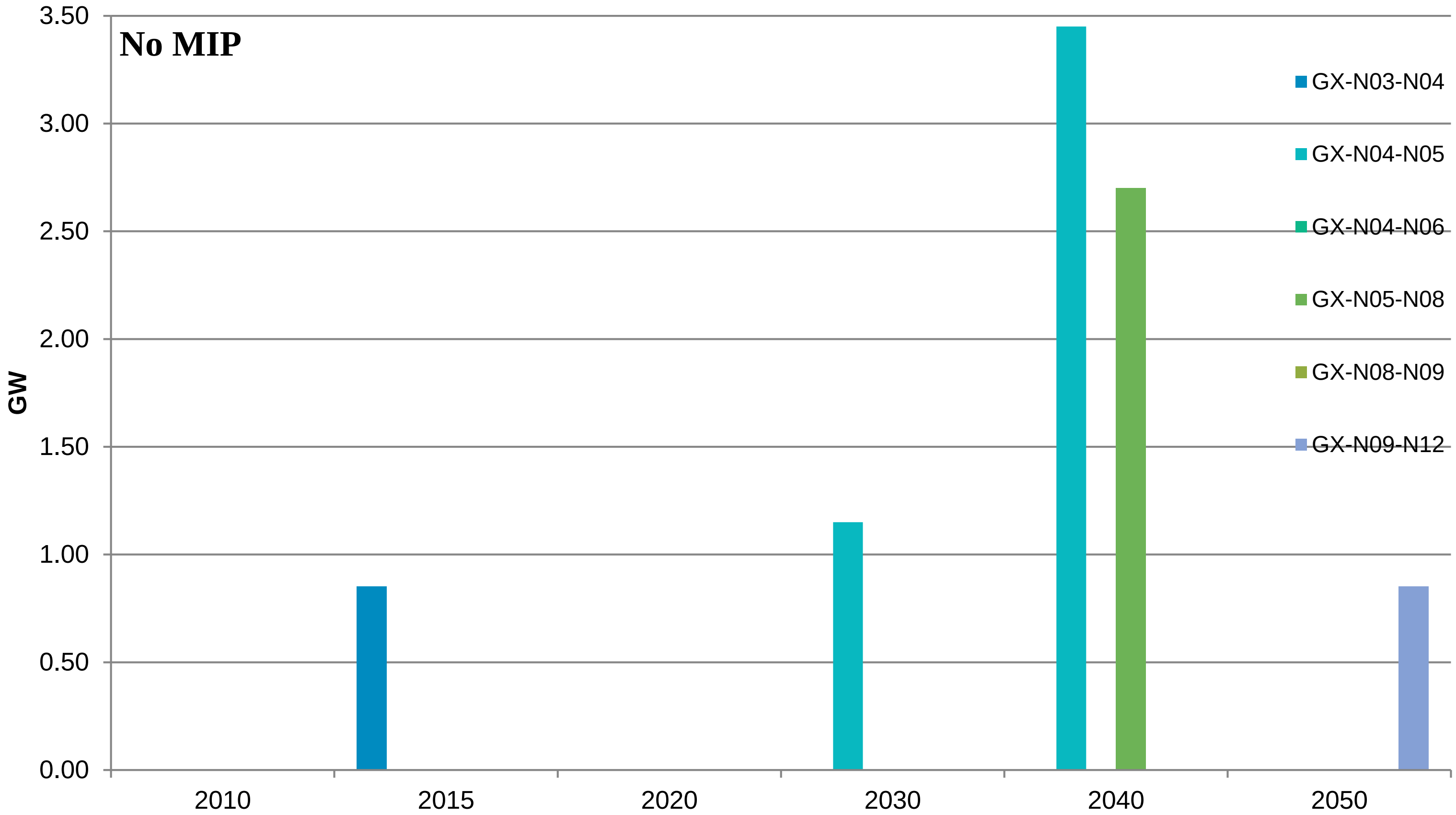
The expansion of the system in a time period from 2010 to 2050 was modelled into TIMES together the grid load flow algorithm, using two alternative formulations :

a) continuous investments option for the grid lines (no-Mixed Integer Programming) and

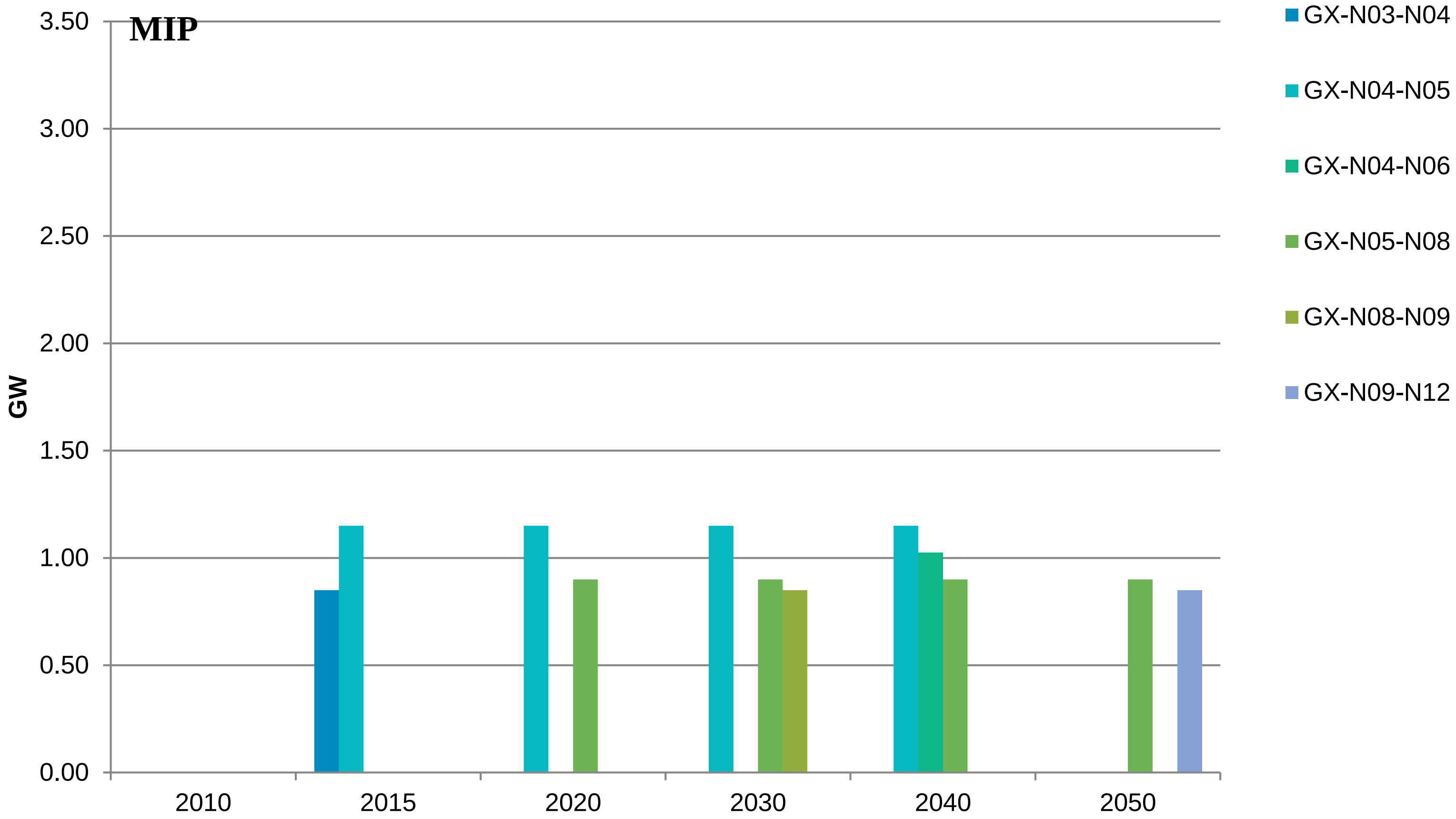
b) b) discrete investment options for the grid lines (with MIP), in order to examine the effect of the two approaches on the result

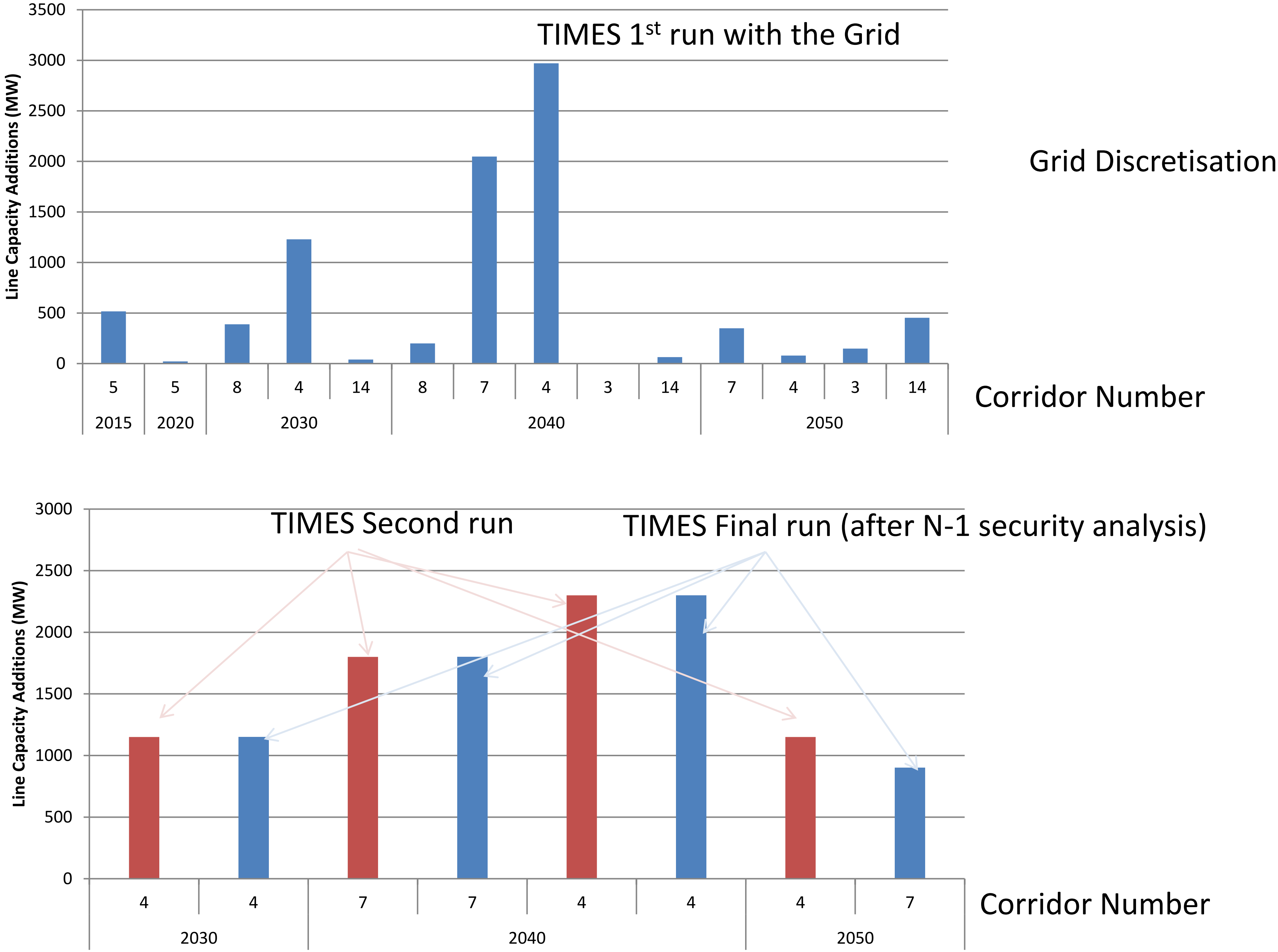
the MIP approach leads to a gradual increase of the grid lines capacities

Transmission Investments cost without Mixed Integer Programming (GX-Ni-Ni is the grid line connecting node i with node j).



Transmission Investments cost with Mixed Integer Programming (GX-Ni-Ni is the grid line connecting node i with node j).




TIMES 1st run with the Grid
Grid Discretisation
Line Capacity Additions (MW)
3500
3000
2500
2000
1500
1000
500
0
5 5 8 4 14 8 7 4 3 14 7 4 3 14
2015 2020 2030 2040 2050
Corridor Number
TIMES Second run
TIMES Final run (after N-1 security analysis)
Line Capacity Additions (MW)
3000
2500
2000
1500
1000
500
0
4 4 7 7 4 4 4 7
2030 2040 2050
Corridor Number

Incorporating Shallow connections cost into RES technologies generation cost

Methodology Issues

To obtain an **accurate least cost solution for RES penetration**

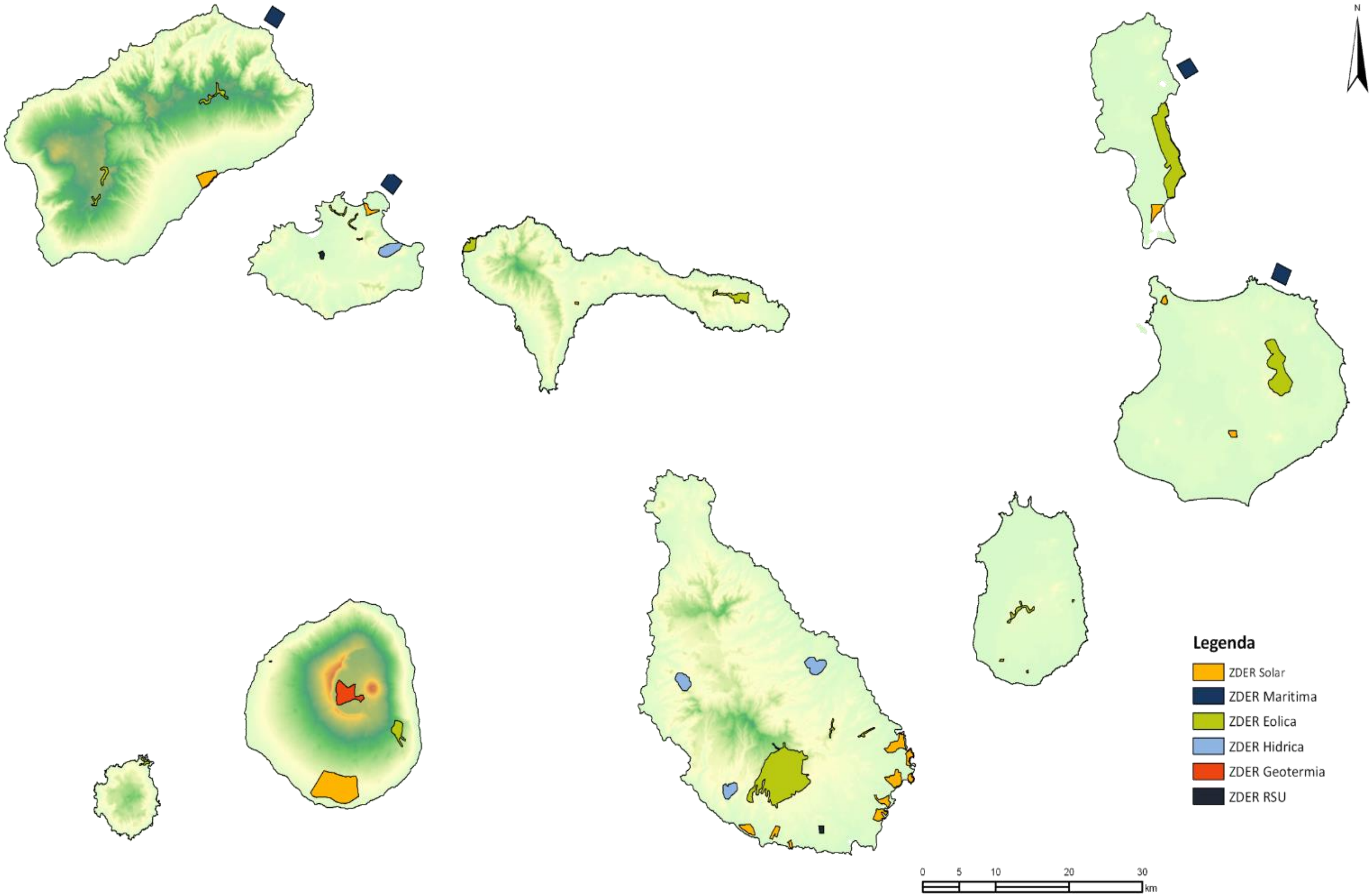
it is necessary to develop

geographical databases with RES potential

which will be connected to the TIMES model describing areas with **classes of the same RES technology with different costs**

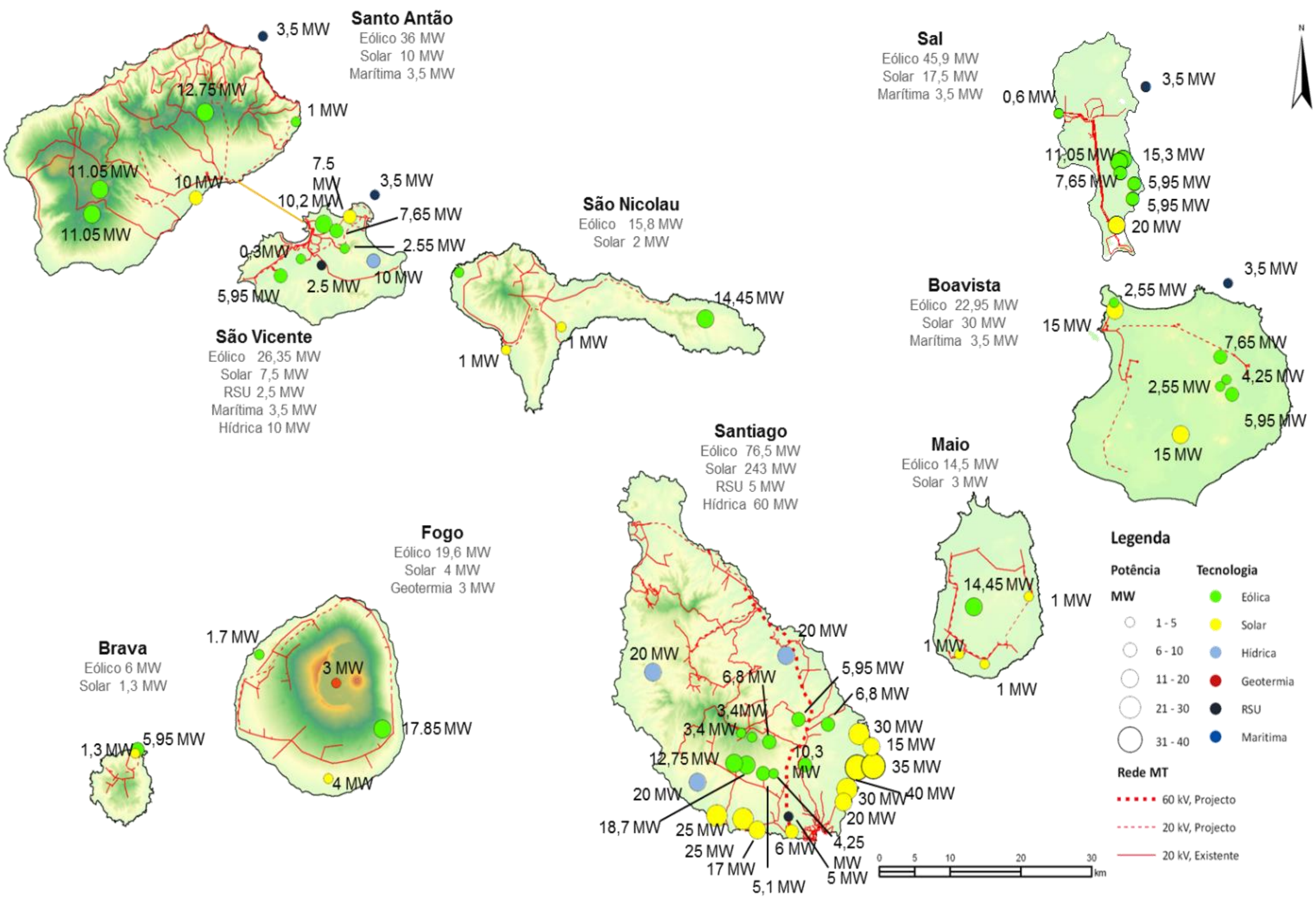
Different costs occur due to different capacity factors and grid connection costs

Renewable energy development zones



Source:
Atlas Energias Renováveis de CaboVerde

Priority Renewable Projects Map (650 MW)



Source:
Atlas Energias Renováveis de CaboVerde

Estimated Grid connection costs of Renewable Energy Projects

Project	Technology	Island	Capacity (MW)	Energy (GWh/year)	Yield	Closest S/S	Line (type)	Length (km)	Investment Cost (€)
PS de Belmonte	Solar	Boavista	15	27	1800	Rabil	Al XLPE 12/20kV 2x3x1x630 mm2	10	1,348,500 €
PS de Ervadão	Solar	Boavista	15	27.84	1856	Marine club	Al XLPE 12/20kV 2x3x1x630 mm2	0.5	67,425 €
PE de Mesa	Wind	Boavista	7.65	22.8998925	2993.45	Joao Galego	Al XLPE 12/20kV 3x1x630 mm2	2	186,000 €
PE do Chão de Pico Forcado	Wind	Boavista	4.25	12.766575	3003.9	Tarafes	Al XLPE 12/20kV 3x1x630 mm2	4	372,000 €
PS da Furna	Solar	Brava	1	1.785	1785	Furna	Al XLPE 12/20kV 3x1x150 mm2	1	67,000 €
PE de Ventos da Furna	Wind	Brava	5.95	16.359525	2749.5	Furna	Al XLPE 12/20kV 3x1x630 mm2	1	93,000 €
PS do Fogo (I)	Solar	Fogo	4	6.988	1747	Salto	Al XLPE 12/20kV 3x1x300 mm2	2.7	202,500 €
PE de Cova Figueira	Wind	Fogo	17.85	58.094253	3254.58	Cova Figueira	Al XLPE 12/20kV 2x3x1x630 mm2	1.7	229,245 €
PS do Barreiro	Solar	Maio	1	1.749	1749	Bareirro	Al XLPE 12/20kV 3x1x150 mm2	0.5	33,500 €
PE da Batalha	Wind	Maio	14.45	31.649835	2190.3	Calhetta	Al XLPE 12/20kV 2x3x1x630 mm2	3.5	471,975 €
PS de Porto Novo	Solar	S. Antão	10	18.21	1821	PS Porto Novo	Al XLPE 12/20kV 2x3x1x630 mm2	1.5	202,275 €
PE Lombo da Torre	Wind	S. Antão	11.05	27.581463	2496.06	Catano	Al XLPE 12/20kV 2x3x1x630 mm2	5.5	741,675 €
PS da Preguiça	Solar	S. Nicolau	1	1.852	1852	ASA	Al XLPE 12/20kV 3x1x150 mm2	1	67,000 €
PE da Jalunga	Wind	S. Nicolau	14.45	45.7650285	3167.13	Juncalinho	Al XLPE 12/20kV 2x3x1x630 mm2	0.8	107,880 €
PE da Praia Branca	Wind	S. Nicolau	1.32	4.2504	3220	Praia Branca	Al XLPE 12/20kV 3x1x150 mm2	2.5	167,500 €
PS de Salamanza	Solar	S. Vicente	7.5	13.6275	1817	PTS Baia	Al XLPE 12/20kV 3x1x630 mm2	0.5	46,500 €
PE de João D'Évora	Wind	S. Vicente	10.2	46.451412	4554.06	Fontinha DS	Al XLPE 12/20kV 3x1x630 mm2	1.5	139,500 €
PS do Sal	Solar	Sal	20	36.3	1817	Vila Verde	Al XLPE 12/20kV 2x3x1x630 mm2	0.8	107,880 €
PE da Curralona	Wind	Sal	11.05	29.99633	2714.6	Governo	Al XLPE 12/20kV 3x1x630 mm2	4.5	418,500 €
PE de Serra Negro	Wind	Sal	5.95	18.008865	3026.7	Cotton Bay	Al XLPE 12/20kV 3x1x300 mm2	3.5	262,500 €
PS da Achada Bela Costa	Solar	Santiago	30	51.78	1726	Sao Tome	Al XLPE 12/20kV 2x3x1x630 mm2	1	134,850 €
PS da Achada da Cidade Velha	Solar	Santiago	17	29.393	1729	Citade Velha	Al XLPE 12/20kV 3x1x630 mm2	1	93,000 €
PS da Achada do Salineiro	Solar	Santiago	25	43.35	1734	Salineiro	Al XLPE 12/20kV 2x3x1x630 mm2	0.8	107,880 €
PE de Achada da Mostarda	Wind	Santiago	18.7	60.84232	3253.6	J. Varela	Al XLPE 12/20kV 3x1x630 mm2	3.8	353,400 €
PE de Monte Leão	Wind	Santiago	3.4	13.56923	3990.95	Rui Vaz	Al XLPE 12/20kV 3x1x150 mm2	1.4	93,800 €
PE de Pedra Branca	Wind	Santiago	6.8	22.89084	3366.3	Sao Domingos	Al XLPE 12/20kV 3x1x300 mm2	1.2	90,000 €
PE de Rui Vaz	Wind	Santiago	3.4	12.23847	3599.55	Rui Vaz	Al XLPE 12/20kV 3x1x150 mm2	1.2	80,400 €

Total	6,285,685 €

Steady state analysis:
Deep Connection reinforcement requirements in the vicinity of candidate RES plants

Based on load flow analysis the table was formulated to present the capacity of the grid to absorb RES energy, based on the known grid topology.

- Green colour is given to investments not requiring grid reinforcements
- Red colour for defining necessary reinforcements in particular after the year 2025.

Island	Project	Technology	Capacity (MW)	MW in 2025	Total (in 2030)
Santiago	PE de Monte Leão	Wind	3,40	3,4	3.4/3.4
Santiago	PE de Rui Vaz	Wind	3,40	3,4	3.4/3.4
Santiago	PE de Pedra Branca	Wind	6,80	3,4	6.8/6.8
Santiago	PE de Achada da Mostarda	Wind	18,70	0,0	17.0/18.7
Santiago	PS da Achada do Salineiro	Solar	25,00	6/15,0	25.0/25.0
Santiago	PS da Achada da Cidade Velha	Solar	17,00	0,0	17.0/17.0
Santiago	PS da Achada Bela Costa	Solar	30,00	0,0	8.0/30.0
Sal	PE de Serra Negro	Wind	5,95	3,4	5.95/5.95
Sal	PE da Curralona	Wind	11,05	0,0	2.65/11.05
Sal	PS do Sal	Solar	20,00	10,1	20.0/20.0
Sal	new PV Sal	Solar	17,00	0,0	17.0/17.0
S. Vicente	PE de João D'Évora	Wind	10,20	0,9	5.8/10.2
S. Vicente	PS de Salamanza	Solar	7,50	7,5	7.5/7.5
S. Vicente	new PV Sao Vicente	Solar	15,00	0,5	15.0/15.0
Boavista	PE do Chão de Pico Forcado	Wind	4,25	3,4	4.25/4.25
Boavista	PE de Mesa	Wind	7,65	0,0	7.65/7.65
Boavista	PE de Falcão	Wind	5,95	0,0	0.2/5.95
Boavista	PS de Ervadão	Solar	15,00	4.5/7,2	15.0/15.0
Boavista	PS de Belmonte	Solar	15,00	0,0	8.5/15.0
S. Antão	PE Lombo da Torre	Wind	11,05	0,0	1.4/1.4
S. Antão	PS de Porto Novo	Solar	10,00	1,2	5.5/10.0
Fogo	PE de Cova Figueira	Wind	17,85	3,0	3.8/17.85
Fogo	PS do Fogo (I)	Solar	4,00	1,3	1.3/4.0
S. Nicolau	PE da Praia Branca	Wind	1,32	1,0	1.2/1.32
S. Nicolau	PE da Jalunga	Wind	14,45	0,4	0.7/14.45
S. Nicolau	PS da Preguiça	Solar	1,00	0,4	0.4/1.0
Maio	PE da Batalha	Wind	14,45	1,2	2.3/14.45
Maio	PS de Esgrovere	Solar	1,00	0,4	0.4/1.0

Definition and Selection of classes of RES technologies with different capacity factors and grid connection costs

Sao Vicente Supply Options

Fuel Availability for Thermal : F380 for future investments

Renewable Generation Project Candidates

Island	Project	Technology	Capacity (MW)	Energy [GWh/year]	Yield	Investment (M€)	Capex [€/KW]	Annua AF [% x 100]	Ratio VS Reference Plant
S. Vicente	PE de João D'Évora	Wind	10.20	46.5	4554	22.4	1750	51.99	1.300
S. Vicente	PE Pé de Verde	Wind	2.55	11.2	4415	5.6	1750	50.13	1.253
S. Vicente	PE da Areia Branca	Wind	7.65	33.8	4391	16.8	1750	50.40	1.260
S. Vicente	PS de Salamanza	Solar	7.50	13.6	1817	6.0	800	20.7	1.037

Least Cost Capacity Expansion Sao Vicente-Retained Scenario

Scenario 1 is a Least cost scenario which is securing 50 % average RES penetration in 2030
The use of battery storage is necessary for the 50% target

Generation Expansion															
Active Unit: kW															
Attribute	Process\Period	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030		
	New_DSL_01														
	New_DSL_02														
	New_LFO_01														
	New_LFO_02														
	New_HFO_01	5000													5000
	New_HFO_02														0
	New_HFO_03														0
	New_HFO_04														0
														HFO	5000
	Wind_New_01							850	2040	1250	950	30	660		5780
	Wind_New_02		850												850
	Wind_New_03													wind	6630
	Wind_New_04														
	PV_New_01		3200	3200	1600				2310	1830	4450	3390	2630	PV	22610
	PV_New_02														0
			850					1700					6630	wind	
			3200					8000					22610	PV	
			4050					9700					29240	RES	
	BATTERY1										9600	9600	9600	LFR	36000
	Converter1 Charging										3200	2254	1834	Converter1 Charging	7288
	Converter1 Discharging										3008	2119	1724	Converter1 Discharging	6851
	BATTERY2								4000	4000				Lead Acid	20000
	Converter2 Charging								1333	1333				Converter2 Charging	2667
	Converter2 Discharging								1253	1253				Converter2 Discharging	2507

Renewable Generation Projects Selected

Island	Project	Technology	Capacity (MW)	Energy [GWh/year]	Yield	Investment (M€)	Capex [€/KW]	Annua AF [% x 100]	Ratio VS Reference Plant
S. Vicente	PE de João D'Évora	Wind	10.20	46.5	4554	22.4	1750	51.99	1.300
S. Vicente	PS de Salamanza	Solar	7.50	13.6	1817	6.0	800	20.7	1.037

Dynamic Stability Analysis

Influence on curtailment and capacity factors

Need for dynamic stability analysis to study generation expansion

- Dynamic Stability Analysis will provide the upper limits of instant power injection of variable Renewable plants such as Wind, PV and Small Hydro.

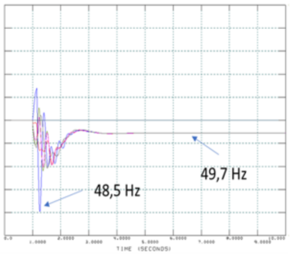
Dynamic stability analysis

- Assesses the system stability, by **examining separately a series of typical and credible incidents, which might expose the grid on certain types of instability (frequency, voltage, rotor angle)**
  - **partial or total loss of wind and/or solar generation** due to renewable energy intermittency
  - **symmetrical short-circuits with or without cascaded loss of generation**
  - **loss of considerable system load**

- **Each power system is considered secure if it can withstand these disturbances without exposing the fundamental electrical quantities** (e.g. voltage, frequency among others) **beyond the secure limits imposed by the *local grid code***

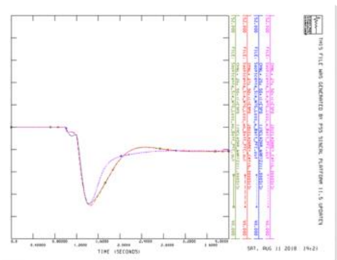
Dynamic stability analysis – Results from Cabo Verde Study

Examples of dynamic study simulations:



Santiago

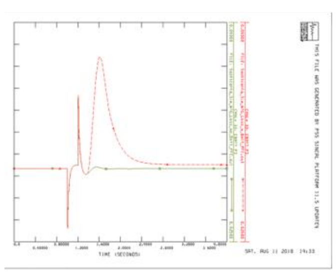
Dynamic Responses of Scenario 1b-Machine Speeds(Frequency)



Sao Vicente

- **Disturbance:** Short circuit and loss of wind production.
- Comparison **with and without battery primary frequency control**

- ***Scenario 1 - Island frequency enhancement***



Sao Vicente

- **Disturbance:** Short circuit and loss of wind production.
- Comparison **with and without battery primary frequency control**

- ***Scenario 1 - Battery active power***

Some conclusions:

- **The frequency and voltage disturbances after raising the instant maximum injection of RES from 40% into 50%**
- We then increased the yearly average penetration of RES **beyond 50% by violating this upper limit with the use of storage**

Reference Scenario results RES penetration levels in 2025 and 2030

	Scen. 1				
	NPV (2018-2030)	Demand 2025 (GWh)	Demand 2030 (GWh)	RES % 2025	RES % 2030
Santiago	303,393,546	310.7	333.3	31.0%	55.8%
Sal	153,758,510	155.6	180.6	**29.9%**	54.3%
Sao Vicente	106,263,946	103.3	115.2	31.5%	57.5%
BoaVista	128,011,481	126.9	154.7	23.0%	44.2%
Santo Antao	27,622,301	20.5	21.4	17.5%	56.3%
Fogo	25,739,319	18.6	20.4	47.5%	48.3%
Sao Nicolau	12,959,793	7.5	7.9	40.6%	45.1%
Maio	14,587,652	7.3	8.6	40.9%	46.8%
Brava	7,846,889	5.2	5.4	94.9%	94.6%
TOTAL	**780,183,437**	755.62	847.53	**30.15%**	**53.5%**

Dynamic constraint

The actual dynamic constraint is a function of:

- the thermal minimum of the generation capacity,
- the mechanical inertia provided by the generation system,
- the size of the associated storage capacity

It is necessary for the assessment of the RES curtailment and therefore the RES capacity factors

Overall Methodology

The final cost incorporated in the TIMES model solution
Is formulated by the :

- balancing units and storage units costs
- grid expansion and connection costs
- utilization factors of RES in specific areas

These are derived from a number of additional models as
presented in the flow chart that follows :

Overall Expansion Planning Methodology