Supplementary document of "GEDM: A Python module for electricity sector decarbonization modelling"

# Formulation of the electricity dispatch model and the capacity expansion model

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GEDM is a tool developed to estimate the capacity and generation mixes of energy technologies in large-scale electricity systems with a focus on renewabls. This tool consists of two core optimization models: an economic dispatch (ED) model and a capacity expansion (CE) model. This document explains the detailed formulation of the models.

## Symbols:

| | |
|---|---|
| $BAT$ | Battery storage technology (set) |
| $BF_y$ | Generation declining factor (Parameter) |
| $C_{max}$ | Maximum cost value in the solution set (Parameter) |
| $C_{min}$ | Minimum cost value in the solution set (Parameter) |
| $ca_{z,i,t}^{T1}$ | Capacity of primary reserve provided by generator $i$ in zone $z$ at time $t$ (variable) |
| $ca_{z,i,t}^{T2}$ | Capacity of secondary reserve provided by generator $i$ in zone $z$ at time $t$ (variable) |
| $ca_{z,i,t}^{T3}$ | Capacity of tertiary reserve provided by generator $i$ in zone $z$ at time $t$ (variable) |
| $CAF_i$ | Equivalent availability factor of generator $i$ (Parameter) |
| $CAM_i^{T1}$ | Maximum capacity for primary reserve of generator $i$ (variable) |
| $CAM_i^{T2}$ | Maximum capacity for secondary reserve of generator $i$ (variable) |
| $CAM_i^{T3}$ | Maximum capacity for tertiary reserve of generator $i$ (variable) |
| $CCF_i$ | Annualized fixed cost per unit capacity of generator $i$ (parameter) |
| $CCG_i$ | Variable generation cost per unit generation of generator $i$ (parameter) |
| $CDU_i$ | Storage duration (energy/power ratio) of storage system $i$ (parameter) |
| $CEF_i$ | Conversion efficiency (LHV) of generator $i$ (parameter) |
| $cfc_{z,i,t}$ | Fuel consumption of generator $i$ in zone $z$ at time $t$ (variable) |
| $CF^{disp}$ | The minimum capacity factor of a large hydropower plant to dispatch generation |
| $CPM_{n,y,p}$ | Maximum capacity of technology $p$ in country $n$ in year $y$ (parameter) |
| $CRE_{z,t}$ | Electricity generation from non-dispatchable renewables in zone $z$ at time $t$ (Parameter) |
| $ce_{i,t}$ | Net power output of operational generator $i$ at time $t$ (variable) |
| $ce_{i.t}^{charge}$ | Charging power of operational storage system $i$ at time $t$ (variable) |
| $ce_{i.t}^{gross}$ | Gross power output of operational generator $i$ at time $t$ (variable) |
| $CF_{i,t}$ | Capacity factor of generator $i$ at time $t$ (parameter) |
| $Cov$ | Covariance matrix |
| $Cov_m^{DAY}$ | Covariance matrix calculated from daily mean output profile in month $m$ (Parameter) |
| $Cov_t^{TS}$ | Covariance matrix calculated from hourly output profile at time-slice $t$ (Parameter) |
| $COU_i$ | Electricity own use of generator $i$ (Parameter) |
| $cp_i$ | Capacity of generator $i$ (variable) |
| $CP_i$ | Capacity of generator $i$ (Parameter) |
| $CP_{z,i}^{max}$ | Maximum capacity of generator $i$ in zone $z$ (Parameter) |

| | |
|---|---|
| $d$ | Day (index) |
| $D_{z,t}$ | Electricity demand in zone $z$ at time $t$ (Parameter) |
| $D_{n,t}$ | Electricity demand in country $n$ at time $t$ (Parameter) |
| $EC_y$ | Emission cap in year $y$ (parameter) |
| $FBI_{n,y}$ | Biomass supply in country $n$ in year $y$ (parameter) |
| $HD_t$ | Representing hours of the time-slice $t$ in a day (Parameter) |
| $i$ | Generation unit / process (index) |
| $j$ | New generation unit / process (index) |
| $LA_z^{solar}$ | Available land area for PV and CSP deployment in zone $z$ (Parameter) |
| $LR_{z,i}$ | Required and area per unit installation of generator $i$ in zone $z$ (Parameter) |
| $LHYD$ | Large hydropower (set) |
| $n$ | Countries (index) |
| $NRE$ | Non-dispatchable renewable technology (set) |
| $OFZ$ | Offshore zones (set) |
| $P_{max}$ | Maximum value of portfolio output variance in the solution set (Parameter) |
| $P_{min}$ | Minimum value of portfolio output variance in the solution set (Parameter) |
| $R_{max}$ | Maximum value of residual load variance in the solution set (Parameter) |
| $R_{min}$ | Minimum value of residual load variance in the solution set (Parameter) |
| $r$ | Transmission link between two zones (index) |
| $rl_{z,t}$ | Residual load in zone $z$ at time $t$ (variable) |
| $RR_{z,t}^{T1}$ | Required capacity of primary reserve service in zone $z$ at time $t$ (Parameter) |
| $RR_{z,t}^{T2}$ | Required capacity of secondary reserve service in zone $z$ at time $t$ (Parameter) |
| $RR_{z,t}^{T3}$ | Required capacity of tertiary reserve service in zone $z$ at time $t$ (Parameter) |
| $RT_z$ | Mean of residual load in zone $z$ (Parameter) |
| $SL$ | Limit of energy spill in a country/district (Parameter) |
| $sp_{z,t}$ | Spilled electricity in zone $z$ at time $t$ (variable) |
| $STOR$ | Storage technology (set) |
| $t$ | Time-slice (index) |
| $TEST$ | Time-slice of testing cases (set) |
| $TCF_r$ | Annualized fixed cost per unit capacity of transmission link $r$ (Parameter) |
| $TG$ | Target of the share of renewable generation in a country/district (Parameter) |
| $te_{r,t}^{in}$ | Instantaneous electricity input in transmission link $r$ at time $t$ (variable) |
| $te_{r,t}^{out}$ | Instantaneous electricity output in transmission link $r$ at time $t$ (variable) |
| $TIC$ | Electricity importing price (Parameter) |
| $TL_r$ | Transmission loss of link $r$ (Parameter) |
| $tp_r$ | Transmission capacity of link $r$ (variable) |
| $TP_r$ | Transmission capacity of link $r$ (Parameter) |
| $tp_r^{add}$ | Capacity addition of transmission link $r$ (variable) |
| $y$ | Year periods in the time horizon (index) |
| $z$ | Zone (index) |
| $ze_{z,t}$ | Electricity supply in zone in zone $z$ at time $t$ (variable) |

## 1. Electricity dispatch model

The objective function of the ED model is based on minimal variable generation cost as shown in (1.1). The cost comprises of two elements: variable generation cost of all electricity generators and cost of electricity import from other markets. The electricity import here is not inter-zone flow in the market modelling instance. It is the energy imported from the connected zones in another market.

$$min.\, variable\ gen.\, cost\ C = \sum_{i,t} ce_{i,t} \cdot CCG_i + \sum_{r \in int.t} te_{r,t} \cdot TIC \tag{1.1}$$

In the function (1.1), $ce_{i,t}$ is the net power output of operational generator $i$ at time $t$, and $CCG_i$ denotes the parameters of variable generation cost per unit generation (USD/kWh) of generator $i$. The cost includes three elements: variable operation and maintenance cost, fuel cost, and carbon cost. The fuel cost can be calculated from the conversion efficiency of the generator and the fuel price at each time period step. The carbon cost can be derived from fuel consumption and emissions factor. The $te_{r,t}$ is electricity import from other market. This variable preserves an electricity supply source in extreme conditions. It is added into the model to reduce infeasible conditions. The electricity import price $TIC$ should be high enough to discourage import from other markets. This price should not be confused with the endogenous zonal price within a market.

Equation (1.2) and (1.3) are basic power output constraints applied to all generators except for variable renewable energies (VREs). The gross power output $ce_{i,t}^{gross}$ of a generator is bounded by its rated capacity $CP_i$ and takes into account an equivalent availability factor $CAF_i$. This factor is a general availability of the generators which takes account of planned outage and forced outage rates. Net output $ce_{i,t}$ is deduced by the fraction of own use electricity $COU_i$.

$$ce_{i,t}^{gross} \leq CP_i \cdot CAF_i \quad \forall t, i \tag{1.2}$$

$$ce_{i,t} = ce_{i,t}^{gross} \cdot (1 - COU_i) \quad \forall t, i \tag{1.3}$$

For storage system, the power output constraints (1.2) and (1.3) are applied. The $ce_{i,t}$ in storage system denotes the energy discharge. Its energy charging capability $ce_{i,t}^{charge}$ is also limited in a similar way as shown in (1.4)

$$ce_{i,t}^{charge} \leq CP_i \cdot CAF_i \quad \forall t, i \in STOR \tag{1.4}$$

It is assumed that all storage units can only discharge the amount of energy of one full charge per day, but the state of charge and discharge can change without limit. The maximum daily energy output is equal to the maximum energy storage which is the product of its rated capacity and storage duration hours, as shown in (1.5), where $HD_t$ denotes the representing hours of the time-slice in a day and $CDU_i$ is the storage duration (energy/power ratio) of the storage system. This constraint is based on the fact that most existing pumped hydro storage are used for load shifting. In general, the main application of battery storage is to provide primary and secondary reserve services. This storage operation constraint is also applied on battery system without distinguishing it from pumped hydro storage.

$$\sum_{t\in d}\left(ce_{i,t}\cdot HD_t\right) \ \leq CP_i \ \cdot \ CDU_i \quad \forall\, d, i \in STOR \tag{1.5}$$

The equation of daily energy balance of a storage unit is show in equation (1.6) which considers operational efficiency $CEF_i$ (LHV). The left-hand side of the equation is total energy charged in one day and the right hand side is daily energy output.

$$\sum_{t\in d}\left(ce_{i,t}^{charge}\cdot HD_t\right)\cdot CEF_i \ = \ \sum_{t\in d}\left(ce_{i,t}\cdot HD_t\right) \quad \forall\, d, i \in STOR \tag{1.6}$$

Small hydropower plants are regarded as non-dispatchable and is assigned a fixed load pattern. For large hydropower plants, the monthly CF data is also applied as default value. However, they are regarded as dispatchable systems when the flow exceeds a certain level. For both types of hydropower, their net output is also limited by equation (1.2) and (1.3). For large hydropower system, when the default CF, noted as $CF_{i,t}$, is below a minimum capacity factor $CF^{disp}$, it is considered as not dispatchable. When the CF is above $CF^{disp}$, the system can dispatch the generation on daily basis with an output floor at $CF^{disp}$ (1.7). Equation (1.8) describes the total dispatchable energy in a day $d$ which is equal to default energy discharge in the system derived from default daily CF.

$$ce_{i,t}\begin{cases} \geq CP_i\cdot CF^{disp}\,, & if\ CF_{i,t}\geq CF^{disp} \\ = CP_i\cdot CF_{i,t}\,, & if\ CF_{i,t}< CF^{disp} \end{cases} \quad \forall t, i \in LHYD \tag{1.7}$$

$$\sum_{i,t\in d}\left(ce_{i,t}\cdot HD_t\right) = \sum_{i,t\in d}\left(CP_i\cdot CF_{i,t}\cdot HD_t\right) \quad \forall\, d, i \in LHYD \tag{1.8}$$

For each transmission link, its maximum power input $te_{r,t}^{in}$, exported to the other zone, is bounded by its capacity $TP_r$ (1.9). The power output at the other end $te_{r,t}^{out}$, in another zone, takes account of transmission losses $TL_r$ as noted in equation (1.10).

$$te_{r,t}^{in} \ \leq \ TP_r \quad \forall t, r \tag{1.9}$$

$$te_{r,t}^{out} = te_{r,t}^{in}\cdot TL_r \quad \forall t, r \tag{1.10}$$

Total power output in a zone $ze_{z,t}$ at time $t$ is the sum of the output from all local generation units. The equation is written in (1.11). It is either provided by conventional thermal plants, storage systems and hydropower plants $ce_{z,i,t}$ or non-dispatchable renewable plants $CRE_{z,t}$. In this equation, generation from non-dispatchable renewables is a parameter that can be calculated before each iteration with the given capacity and CF.

$$ze_{z,t} = \sum_{i \notin NRE} ce_{z,i,t} \; + CRE_{z,t} \quad \forall z,t \tag{1.11}$$

Zonal electricity balance constraints are shown in equation (1.12). Electricity demand in a zone $D_{z,t}$ can be served by local generation $ze_{z,t}$ and import from connected zones through transmission links, denoted as $\sum_{(r \; in \; z)} te_{r,t}^{out}$. Electricity can also be exported to other zones, noted as $\sum_{(r \; in \; z)} te_{r,t}^{in}$, or can be spilled, noted as $sp_{z,t}$. Note that when a transmission link connects to a zone outside the present market, it is categorized as inter-market transmission. Electricity import cost in the objective function $\sum_{r \in int.} te_r \cdot TIC$ is applied on this type of inter-market link. The energy spill variables together with this inter-market import/export variables are crucial in both the ED and CE models. They reduce the chance of obtaining infeasible results or unreasonable solutions.

$$D_{z,t} = ze_{z,t} + sp_{z,t} + \sum_{(r \; in \; z)} te_{r,t}^{out} - \sum_{(r \; in \; z)} te_{r,t}^{in} \quad \forall z,t \tag{1.12}$$

The equation of energy balance for offshore zones is simpler, as described in (1.13). Electricity can only be exported to the connected terrestrial zones or be spilled.

$$ze_{z,t} = \; sp_{z,t} + \sum_{(r \; in \; z)} te_{r,t}^{in} \quad \forall z \in OFZ, t \tag{1.13}$$

Three types of reserve services are modelled in this work. The reserve requirements in zone $z$ at time-slice $t$, noted as $RR_{z,t}^{T1}$, $RR_{z,t}^{T2}$ and $RR_{z,t}^{T3}$ respectively, are determined by demand profile. The input data section describes details of this configuration. Each type of reserve is served by an available generation unit in the zone, noted as $ca_{z,i,t}^{T1}$, $ca_{z,i,t}^{T2}$ and $ca_{z,i,t}^{T3}$ in (1.14). Non-dispatchable renewable units are excluded from reserve services.

$$\sum_{i \notin NRE} ca_{z,i,t}^{T1} = RR_{z,t}^{T1} \quad \forall z,t \tag{1.14a}$$

$$\sum_{i \notin NRE} ca_{z,i,t}^{T2} = RR_{z,t}^{T2} \quad \forall z,t \tag{1.14b}$$

$$\sum_{i \notin NRE} ca_{z,i,t}^{T3} = RR_{z,t}^{T3} \quad \forall z,t \tag{1.14c}$$

Each generator can provide multiple types of reserve at the same time but are limited by their ramping capability $CAM_i^{T1}$, $CAM_i^{T2}$ and $CAM_i^{T3}$. This limit is presented in (1.15) below.

$$ca_{i,t}^{T1} \leq CAM_i^{T1} \quad \forall i,t \tag{1.15a}$$

$$ca_{i,t}^{T2} \leq CAM_i^{T2} \quad \forall i,t \qquad (1.15b)$$

$$ca_{i,t}^{T3} \leq CAM_i^{T3} \quad \forall i,t \qquad (1.15c)$$

The power output together with reserve capacity of a generation unit is constrained by its available capacity at any time as shown in equation (1.16).

$$ce_{i,t} + ca_{i,t}^{T1} + ca_{i,t}^{T2} + ca_{i,t}^{T3} \leq CP_i \cdot CAF_i \quad \forall\, t, i \notin NRE \qquad (1.16)$$

Several types of plants can only provide reserve services when in the spinning state because of long start-up times and low ramp speeds. Equation (1.17) ensures that a plant can only offer reserves when it is producing electricity. The parameter 2 on the right-hand side of the equation implies that the maximum provision of the reserves is about two third of available capacity of a plant. It is designed to ensure minimum load of the plant, typically between 30%-40%, when offering the reserves. Since this is a linear programming model, it is difficult to ensure minimum load of a plant at spinning state. The constraint (1.17) at least requires a plant to offer reserve when in the generating state, instead of from an offline state.

$$ca_{i,t}^{T1} + ca_{i,t}^{T2} + ca_{i,t}^{T3} \leq ce_{i,t} \cdot 2 \quad \forall i,t, i \notin ST, OCGT, NRE \qquad (1.17)$$

The constraint (1.17) does not apply to oil steam turbine generator (mixed with an internal combustion engine in this study) and OGCT since they have fast start-up speeds. However, for primary reserve which has to be active within a minute, it needs to be executed at spinning state for any type of plant. Equation (1.18) below is to ensure the spinning state. Similar to (1.17), the parameter 0.5 is to guarantee a reasonable spinning output level.

$$ca_{i,t}^{T1} \leq ce_{i,t} \cdot 0.5 \quad \forall i,t \qquad (1.17)$$

The operation of battery storage is rather flexible and dynamic. It cannot provide downward reserve when the storage is full and cannot provide upward reserve when the storage is empty. Battery storage system is usually used for supporting frequency regulation services, and is normally operating at a range based on the 50% state of charge (SOC) point, which allows it to absorb and deliver power. Therefore, the maximum reserve provision of battery systems is set at 50% of its available capacity, as shown in (1.19) below.

$$ca_{i,t}^{T1} + ca_{i,t}^{T2} \leq CP_i \cdot CAF_i \cdot 0.5 \quad \forall\, t, i \epsilon BAT \qquad (1.19)$$

## 2. Capacity expansion model

The CE model is developed to optimize the new installation for each time period step. The CE model is in fact an extension of the ED model. Existing units which still operate in the period are included in the formulation, but with reduced temporal resolution. The new installation capacity of all candidate options in each zone are the main decision variables in the CE model. In addition to the configured time-slices, another 12 cases are selected for a reliability test to ensure system stability in extreme conditions. Consequently, this model is more complex with these two extra considerations when compared with the ED model.

In the objective function (2.1), variable generation cost $\sum_{i,t} ce_{i,t} \cdot CCG_i$ of existing plants $i$ and electricity import cost $\sum_{r \in int.t} te_{r,t} \cdot TIC$ are the same elements as those in the ED model. The third element is the parameter of annualized fixed cost of existing plants, where $CCF_j$ denotes the parameter of annual fixed cost per unit capacity. This element in fact does not influence the result since it is a summation of parameters. The variable generation cost and fixed annual cost of a new installation plant $j$ are noted as $\sum_{j,t} ce_{j,t} \cdot CCG_j$ and $\sum_j cp_j \cdot CCF_j$, where $cp_j$ is the variable of its installation capacity. The last element is the annual cost of total transmission links, including new expansion capacity, where $TCF_j$ represents the fixed cost per unit capacity of the link $r$.

$$min. total\ system\ cost\ C = \sum_{i,t} ce_{i,t} \cdot CCG_i + \sum_{r \in int.t} te_{r,t} \cdot TIC$$

$$+ \sum_i CP_i \cdot CCF_i + \sum_{j,t} ce_{j,t} \cdot CCG_j + \sum_j cp_j \cdot CCF_j + \sum_r tp_r \cdot TCF_i \qquad (2.1)$$

The general power output constraints of a generation unit in equation (1.2) and (1.3) are still applied on existing units. For new installation options, their installation capacity become variables $cp_j$. Therefore, equation (2.2) which limits the gross output of a plant is applied to replace constraint (1.2), while equation (1.3) is kept the same.

$$ce_{j,t}^{gross} \leq cp_j \cdot CAF_j \quad \forall j,t \qquad (2.2)$$

Some formulations are created to avoid abrupt change of generation mix. Usually when the cost of a specific option become competitive, the option can quickly make up a large share of new installation in the market. This model applies a minimal generation requirement for existing dispatchable plants which are in service in the base year. It is assumed that their minimum electricity generation declines gradually from base year level to 0. This constraint does not apply on any new installation. The related equation is shown in (2.3) where $CF_{y=base,i,t}$ denotes the generation capacity factor at base year and $BF_y$ is the declining factor.

$$\sum_{i,t\in d}\left(ce_{i,t}\cdot HD_t\right)\geq \sum_{i,t\in d}\left(CP_i\cdot CF_{y=base,i,t}\cdot HD_t\right)\cdot BF_y \quad \forall\, d,i\in DISP \tag{2.3}$$

Similar to the general output constraints for dispatchable thermal plants, the new installation capacity of storage systems is decision variable $cp_j$. Equations for storage charge and output limit (1.4) and (1.5) are replaced by (2.4) and (2.5) shown below.

$$ce_{j,t}^{charge} \leq cp_j\cdot CAF_j \quad \forall t,j\in STOR \tag{2.4}$$

$$\sum_{t\in d}\left(ce_{j,t}\cdot HD_t\right) \leq cp_j \cdot CDU_j \quad \forall\, d, \qquad j\in STOR \tag{2.5}$$

In the 12 reliability test cases, the output of both existing and new storage options is fixed since the daily operation is not formulated. In creating this model instance, the maximum output is initially capped at their available capacity. However, this configuration may result in overestimating their output in these extreme cases. When fed with this result, the ED model in the next iteration frequently produced infeasible outcomes. Therefore, a relatively conservative configuration is applied, as shown in (2.6). It implies that the storage system operates with equal charge and discharge time intervals in the day (12 hours) and with one storage cycle.

$$ce_{j,t} \leq cp_j\cdot CAF_j\cdot CDU_j/12 \quad \forall t\in TEST, j\in STOR \tag{2.6}$$

The new installation capacity of large hydropower plant is also decision variable $cp_j$, not fixed parameter $CP_i$. Equation (2.7) and (2.8) were applied to replace (1.7) and (1.8) for new plants herein.

$$ce_{j,t}\begin{cases} \geq cp_j\cdot CF^{disp}, & if\ CF_{j,t}\geq CF^{disp} \\ = cp_j\cdot CFA_{j,t}, & if\ CF_{j,t}< CF^{disp}\end{cases} \quad \forall t,j\in LHYD \tag{2.7}$$

$$\sum_{j,t\in d}\left(ce_{j,t}\cdot HD_t\right)=\sum_{j,t\in d}\left(cp_j\cdot CF_{j,t}\cdot HD_t\right) \quad \forall\, d,j\in LHYD \tag{2.8}$$

In the reliability test cases, the output of large hydropower system is fixed at their default CF as presented in (2.9). This is also because the daily dispatch operation is not formulated.

$$ce_{j,t} = cp_j\cdot CF_{j,t} \quad \forall t\in TEST, j\in LHYD \tag{2.9}$$

In this CE model, investment decision can also be made on transmission capacity. The new upgrade capacity noted as $tp_r^{add}$. The maximum transmission input constraint (1.9) is modified into (2.10) while the transmission loss constraint (1.10) is kept unchanged.

$$te_{r,t}^{in} \leq TP_r + tp_r^{add} \quad \forall t,r \tag{2.9}$$

For new non-dispatchable renewable plants, their output $ce_{j,t}$ is the product of their capacity $cp_j$ and the given capacity factor $CF_{j,t}$, shown in (2.10). For all existing plants, the power output is aggregated into the same term $CE_{z,i,t}$ as shown in (1.11)

$$ce_{j,t} = cp_j \cdot CF_{j,t} \quad \forall t, j \in NRE \tag{2.10}$$

The overall power supply in zone $z$ at time $t$ can be formulated as (2.11) that replaces (1.11) in the ED model. The four elements in this equation are: generation from existing dispatchable, existing non-dispatchable renewable, new dispatchable and new non-dispatchable renewable generation units. Hydropower and storage system belong to dispatchable elements in these equations. Other zonal supply and demand constraints (1.12) and (1.13) in the ED model are remained the same.

$$ze_{z,t} = \sum_{i \notin NRE} ce_{z,i,t} + CRE_{z,t} + \sum_{j \notin NRE} ce_{z,j,t} + \sum_{j \in NRE} ce_{z,j,t} \quad \forall z, t \tag{2.11}$$

The reserve services can be provided by existing and new generation units. The equation (1.14) is modified into (2.12). For instance, the required primary reserve in zone $z$ at time $t$, written as $RR_{z,t}^{T1}$, can be served by all existing plants $ca_{z,i,t}^{T1}$ and new plants $ca_{z,j,t}^{T1}$. Other constraints on the reserves service in the ED model, from (1.15) to (1.19), are kept the same form but applied to both existing and new plants.

$$\sum_{i \notin NRE} ca_{z,i,t}^{T1} + \sum_{j \notin NRE} ca_{z,j,t}^{T1} = RR_{z,t}^{T1} \quad \forall z, t \tag{2.12a}$$

$$\sum_{i \notin NRE} ca_{z,i,t}^{T2} + \sum_{j \notin NRE} ca_{z,j,t}^{T2} = RR_{z,t}^{T2} \quad \forall z, t \tag{2.12b}$$

$$\sum_{i \notin NRE} ca_{z,i,t}^{T3} + \sum_{j \notin NRE} ca_{z,j,t}^{T3} = RR_{z,t}^{T3} \quad \forall z, t \tag{2.12c}$$

Total capacity of technology $p$ in a country $n$ in year $y$ can be subject to several constraints. For example, equation (2.13) shows the maximum capacity $CPM_{n,y,p}$. In each time period step, the framework first checks the limits of available installation capacity taking into account the retirement of existing plant and other capacity limits. The capacity limits may include: assumption on technology readiness, e.g. CCS technology is mostly not available for commercial deployment before 2025; nuclear policy; maximum renewable deployment capacity in a zone; and hydropower capacity limits.

$$\sum_{z \in n, i \in p} cp_i + \sum_{z \in n, j \in p} cp_j \leq CPM_{n,y,p} \qquad \forall n, p \tag{2.13}$$

Likewise, there are limits on minimum new build capacity, as shown in (2.14). Also, most existing biomass plants (including CHP plants) consume MSW and other wastes. The capacity and generation is not expected to decline, and they are set to be at least higher than base year in each period. Equation (2.14) is applied in this case.

$$\sum_{z\in n,i\in p} cp_i + \sum_{z\in n,j\in p} cp_j \ \geq \ CPM_{n,y,p} \quad \forall\, n,p \tag{2.15}$$

Annual biomass supply is limited in each country. The total biomass consumed in existing and new plants should be less than total supply $FBI_{n,y}$ in a country, as shown in equation (2.16) below.

$$\sum_{z\in n,i\in BIO,t} cfc_{z,i,t} + \sum_{z\in n,j\in BIO,t} cfc_{z,j,t} \ \leq FBI_{n,y} \quad \forall\, n \tag{2.16}$$

As mentioned previously in the discussion on equation (2.3), some constraints may be needed to avoid abrupt change in capacity mix. The equation targets a sudden drop of generation from old plants committed before base year. On the other hand, limiting the renewable growth may be necessary to produce more plausible results. Equation (2.17) is applied to limit the generation growth from all renewable energies, including hydropower and biomass. The cap is set to 25% of the electricity demand in the next time period. It is not a strict constraint but potentially reduces an unreasonable surge in some cases. With this configuration, a country still can attain 100% renewable generation within 4 step periods, starting from zero.

$$\sum_{z\in n,i\in(NRE,HYD,BIO),t} CE_{z,i,t} + \sum_{z\in n,i\in(NRE,HYD,BIO),t} ce_{z,j,t} \ \leq$$

$$\sum_{z\in n,y-1,i\in(NRE,HYD,BIO)} CE_{z,y-1} + \ D_{n,t}\cdot 0.25 \quad \forall\, n \tag{2.17}$$

The emissions in a market can be limited throughout the time horizon. This limit can be written in equation (2.18) where $em_{z,i,t}$ denotes the emission of unit $i$ in zone $z$ at $t$ and $EC_y$ is the emission cap in the period $y$ in this market.

$$\sum_{z,i\in DISP,t} em_{z,i,t} + \sum_{z,j\in DISP,t} em_{z,j,t} \ \leq EC_y \quad \forall\, y \tag{2.18}$$