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A Generic Method to Model Carbon Emission of Combined Cycle for Environmental Power Dispatch

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Abstract—This paper proposes a generic methodology for combined cycle gas turbines (CCGT) modeling. The main objectives are the estimation of the CO₂ emissions for specific units and their integration in an environmental power dispatch that considers several plants. At first a design procedure aims at calibrating the model using the sparse information advised by the manufactures. Off-design points are also investigated in order to estimate the CO₂ emissions on the whole operating range of the units. The obtained results show a good consistency with the emission coefficients found in the literature for that type of units. Then those carbon costs are used as input parameters for a unit commitment problem (UC). The Mixed Integer Linear Programming (MILP) formulation minimizes the global emissions for a set of different units on Jurong Island in Singapore. The grid emission factor finally obtained for the simulated network displays values close to the registered field data which validates the developed model.

Keywords—combined cycle gas turbine, design, CO₂ emissions, environmental unit commitment, power dispatch, optimization

I. INTRODUCTION

The work presented in this paper has been led in the framework of a wider study whose objective is to simulate the operation of the Jurong Island power grid in Singapore. The island has four thermal power plants with thirteen identified combined cycle gas turbines (CCGT) [1]. The first concern is to model the power generation on site to perform a power dispatch that minimizes the amount of CO₂ generated. Such unit commitment (UC) problems have been widely studied in the literature. The traditional objective is to minimize the generation cost while meeting the load and fulfilling system operating constraints [2]. Here the objective only refers to the minimization of the CO₂ emissions. Most of the time those emissions are added to the objective function as a linear cost with the generated power as in [3]. Another alternative consists in considering a quadratic curve for the CO₂ emissions – the same way it is commonly done for the generation cost – as well as CO₂ start-up costs [4]. Then either a bi-objective (cost/CO₂) optimization is performed or the CO₂ is simply added to the conventional objective function while introducing carbon penalties [2]. Cubic functions can also be found in the literature [5] as well as exponential formula when other types of pollutant are considered [6]. In addition to that variety of cost models, their attached coefficients are rarely justified. They

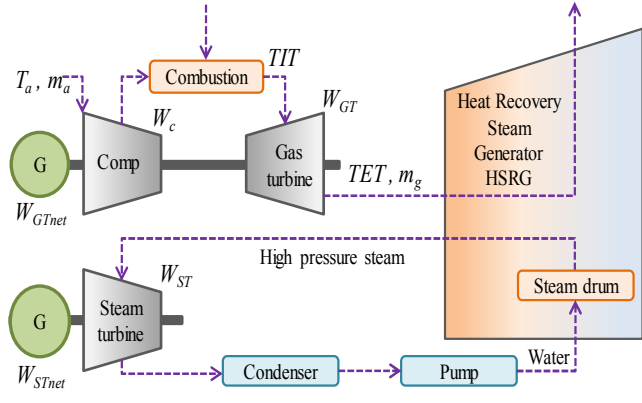
come from pre-established test cases and can display wide ranges of values even for the same type of unit. Indeed, a great part of such power systems studies mainly focus on validating the problem formulation and the algorithms used to solve them. In order to accurately model those emissions for thermal units one must pay attention to energy conversion aspects and model calibration. CCGT has received extensive attention, since it offers enhanced performances compared to conventional gas turbines (GT). An increasing number of heavy duty units has been installed in electrical systems across the world in recent decades to replace conventional coal/oil power plants [7]. Most CCGT studies are concerned with optimal design that minimizes the cost for the plant owner as in [8]. However, their performance dramatically decreases when deviating from their nominal operating point. Thus off-design operations have to be considered carefully, especially when a power dispatch will require the system to work on its whole operating range [9]. The main motivation of the present study is then to use a CCGT model in order to get realistic coefficients for carbon emissions in the environmental UC problem. The biggest challenge lies in obtaining consistent values from the sparse information given by the manufacturers for the identified units - usually only the rated power and efficiency are advised. Then major contributions of this work are:

- The cross disciplinary bridge between CCGT modeling and power dispatch strategies.
- The development of a systematic comprehensive CCGT model whose granularity is adapted to with the MILP formulation for UC problems.
- The CO₂ start-up costs are not explicitly entered as parameters in the UC. Instead the off design performance is estimated below the minimum operating point and start-up phases are modeled.

The rest of the paper is organized as follows. Section II describes the model used to represent the considered units and the obtained results. The general equations are given and a particular attention is attached to the optimal procedures that allow estimating both nominal and off design performance. Then Section III introduces the environmental unit commitment performed while considering four distinct power plants. Some constraints equations are presented. The conclusions are then presented in Section IV.

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Fig. 1. Simplified diagram of a typical CCGT unit



II. CCGT MODELING

A. Fundamentals and Identified Generation on Site

Fig. 1 shows a simplified diagram of a CCGT. The operation of such a unit lies on the combination of two thermodynamic cycles. In the top Brayton cycle the input air mass flow m_a (in kg/s) at ambient conditions is compressed with a ratio r_c before entering the combustion chamber of the gas turbine. The combustion with a fuel mass flow m_f (in kg/s) allows the flue gases to reach the turbine inlet temperature TIT (in $^{\circ}\text{C}$) before their expansion that produces a work W_{GT} (in MW). A nomenclature of all the considered parameters is given on Table I. Among those both r_c and TIT have the greatest influence on the GT performances with highest values around 40 and 1600 $^{\circ}\text{C}$ respectively for the most efficient systems [7]. The main limitations come from the maximum stress that the different materials can endure under operating constraints. In the bottom Rankine cycle, the hot gases at the turbine exhaust temperature TET (in $^{\circ}\text{C}$) are used in a heat recovery steam generator (HSRG) to produce superheated steam at high temperature for a steam turbine. Note that typical architectures for HSRG display up to three different pressure systems with corresponding low, intermediate and high pressure steam turbines. Thus the combine cycle (CC) units allow exploiting the available heat in the exhausts gas of heavy duty and enhancing the power generation efficiency from 40% (η_{GT}) to 60% (η_{CC}) [7].

Such units represent more than half the installed power generation capacity in Singapore and up to 95% of mix in term of electricity generation [1]. Field data and manufacturers websites identify five types of units on Jurong Island with the characteristics advised in Table II and distributed among four power plant as follows:

- Keppel Merlimau (KPL): Units A₁ and A₂, Units B₁ and B₂.
- Pacific Light Power (PLP): Units C₁ and C₂.
- SembCorp Cogen (SMB): Unit A₁, Units D₁ and D₂.
- YLT Seraya (SRY): Units C₁ and C₂, Units E₁ and E₂.

TABLE I. NOMENCLATURE FOR THE CCGT MODEL

T_a	ambient temperature	$^{\circ}\text{C}$
r_c	compression ratio	-
n_c	compressor isentropic efficiency	-
n_m	mechanical efficiency	-
m_a	air mass flow	kg/s
γ_c	air specific heat ratio in compression	-
W_c	compressor consumed power	MW
C_{pa}	specific heat of air	kJ/kg/K
n_{cc}	combustion chamber efficiency	-
λ	air/fuel ratio in combustion chamber	-
LHV	fuel lower heat value	kJ/kg
TIT	turbine inlet temperature	$^{\circ}\text{C}$
m_f	fuel mass flow	kg/s
m_g	flue gas mass flow	kg/s
C_{pg}	specific heat of flue gas	kJ/kg/K
γ_e	air specific heat ratio gas turbine expansion	-
n_{gt}	gas turbine isentropic efficiency	-
TET	turbine exhaust temperature	$^{\circ}\text{C}$
W_{GTnet}	gas turbine net output power	MW
Q_{GT}	heat supplied to the gas turbine	kJ/s
n_{gen}	electrical generator efficiency	-
η_{GT}	gas turbine efficiency	-
Q_{AV}	available heat in the flue gas	kJ/s
W_{STnet}	steam net output power	MW
W_{CC}	combined cycle net output power	MW
η_{CC}	combined cycle efficiency	-
SCE	specific carbon emission	kg/MWh
\cdot_{des}	subscript for design values	-

TABLE II. IDENTIFIED UNITS ON SITE

	Unit A	Unit B	Unit C	Unit D	Unit E
W_{GTnet} (MW)	240.0	165.0	260.0	256.0	292.0
W_{STnet} (MW)	160.0	85.0	140.0	152.0	115.0
W_{CC} (MW)	400.0	250.0	400.0	408.0	407.0
TET ($^{\circ}\text{C}$)	630.0	505.0	580.0	596.0	580.0
η_{GT} (%)	37.0	36.4	38.5	37.8	40.7
η_{CC} (%)	32.0	53.1	58.8	56.7	59.0

B. Model Equations

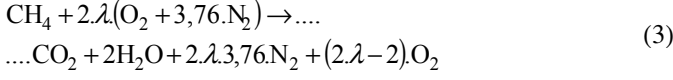
This subsection describes the steady state equations commonly used in the literature for the modeling of CCGT units. Firstly the temperature at the output of the compressor $T_{c,out}$ (in $^{\circ}\text{C}$) is computed as well as the corresponding work W_c (in MW) as in (1) and (2) [10]. Note that C_{pa} (in kJ/kg/K) is estimated at the average temperature between T_a and $T_{c,out}$ and referring to the tables for air properties.

$$T_{c,out} = T_a \times \left(1 + \frac{r_c^{\gamma_c} - 1}{n_c \gamma_c} \right) \quad (1)$$

$$W_c = \frac{m_a \times C_{pa} \times (T_{c,out} - T_a)}{1000 \times n_m} \quad (2)$$

A complete combustion of pure methane is considered (3). Similarly to [9] the combustion equations has to be solved in order to estimate the fuel mass flow m_f (in kg/s) required to reach the turbine inlet temperature. The heat capacity of the flue gas C_{pg} (in kJ/kg/K) is also obtained after solving a second

order polynomial equation with the molar air fuel ratio λ (4). C_{pg} is computed with the molar quantities and specific heat of each component in the flues gas and using the corresponding property tables. M_a , M_f , n_a , and n_f denote the molar masses and quantities of fuel and air.



$$\begin{cases} m_a \times (C_{pg} \times TIT - C_{pa} \times T_{c,out}) = m_f \times (LHV \times n_{cc} - C_{pg} \times TIT) \\ \frac{m_f}{m_a} = \frac{M_f \times n_f}{M_a \times n_a} = \frac{M_f}{M_a \times \lambda} \\ C_{pg} = \frac{n_{\text{CO}_2} \cdot C_{p\text{CO}_2} + n_{\text{H}_2\text{O}} \cdot C_{p\text{H}_2\text{O}} + n_{\text{N}_2} \cdot C_{p\text{N}_2} + n_{\text{O}_2} \cdot C_{p\text{O}_2}}{n_{\text{CO}_2} + n_{\text{H}_2\text{O}} + n_{\text{N}_2} + n_{\text{O}_2}} = \dots \\ \dots \frac{C_{p\text{CO}_2} + 2C_{p\text{H}_2\text{O}} - 2C_{p\text{O}_2} \cdot C_{p\text{N}_2} + (2 \times 3.76 C_{p\text{N}_2} + 2C_{p\text{CO}_2}) \lambda}{1 + (2 \times 3.76 + 2) \lambda} \end{cases} \quad (4)$$

The computation of the GT output work W_{GTnet} (in MW) requires the estimation of the turbine exhaust temperature TET (in °C) as shown in (5) and (6). The overall CC net output power is then obtained following (7). Note that the HSRG is not fully modeled here with the superheater, the economizer, the deaerator and condenser equations. In this work the steam turbine work output W_{STnet} , once the heat is extracted from the exhaust gas, is given as an input fixed parameter at design conditions (input parameter W_{STnet}). The specific CO₂ emissions SCE (in kg/MWh) consider the CO₂ molar mass M_{CO_2} and the fuel molar quantity n_f (9).

$$TET = TIT \times \left(1 - n_{gt} \times \left(1 - \frac{1}{r_c \gamma_e} \right) \right) \quad (5)$$

$$W_{GTnet} = \frac{m_g \times C_{pg} \times (TIT - TET)}{1000} \times n_m \times n_{gen} - W_c \quad (6)$$

$$W_{CC} = W_{GTnet} + W_{STnet} \quad (7)$$

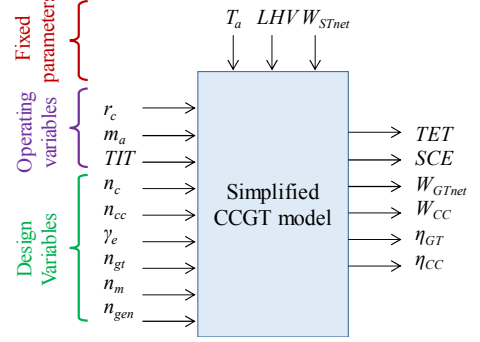
$$SCE = \frac{n_f \times M_{\text{CO}_2} \times 3600}{1000 \times W_{CC}} \quad (9)$$

The heat supplied to the gas turbine Q_{GT} (in MW) [8] is used to compute the thermal efficiencies for the GT and the overall CC unit as follows:

$$Q_{GT} = \frac{m_g \times C_{pg} \times (TIT - T_{c,out})}{1000} \quad (8)$$

$$\eta_{GT} = \frac{W_{GTnet}}{Q_{GT}} \quad \text{and} \quad \eta_{CC} = \frac{W_{CC}}{Q_{GT}} \quad (9)$$

Fig. 2. Inputs/Outputs of the CCGT model



C. Off-Design Operations

The previous equations describe the behavior of a typical CCGT at the design operating point. Such a representation with a more detailed model of the HSRG is used in [8] to perform the optimal sizing of a CCGT unit with regard to capital and operating costs. In power system studies the units never operate at the nominal point all along the considered time horizon [9]. It is obvious with the totality of a variable load fed by a finite numbers of units as it is the case in the system modeled here. Thus a particular attention has to be paid to the off-design operating points and constraints. Especially the objective is to estimate the carbon emissions on the whole operating range of the units. The first off-design constraint refers to the fulfillment of the schoked conditions of the gas turbine with a constant swallowing capacity (10). Here the compression ratio is used instead of the compressor output pressure [9].

$$\frac{m_a \times \sqrt{TIT}}{r_c} = \frac{m_{a,des} \times \sqrt{TIT_{des}}}{r_{c,des}} \leftrightarrow G_{sh} = G_{sh}^D \quad (10)$$

Reference [11] establishes semi empirical equations for the behavior of the steam turbine under off-design conditions. The output power has to be corrected regarding the deviations of the flue gas mass flow m_g (in kg/s) and TET from their design values while considering η_c , the Carnot cycle efficiency (9). W_{STnet} then tends to decrease in the same time than Q_{AV} the heat available in the GT exhaust gas ((10) and (11)). Note that a more accurate representation of the off-design performances should take the deviations of the isometric efficiencies for the compressor and the gas turbine into account. It is not considered here and constant values are used.

$$\eta_c = 1 - \frac{T_a}{TET} \quad (9)$$

$$\frac{Q_{AV}}{Q_{AV,des}} = \left(\frac{TET}{TET_{des}} \right)^2 \left(\frac{m_g}{m_{g,des}} \right) \quad (10)$$

$$\begin{aligned} W_{STnet} &= \frac{W_{STnet,des}}{n_m \times n_{gen}} \times \left(\frac{\eta_c}{\eta_{c,des}} \right) \times \dots \\ &\dots \left(-0.32063 + 1.64575 \times \frac{Q_{AV}}{Q_{AV,des}} - 0.32872 \times \frac{Q_{AV}^2}{Q_{AV,des}^2} \right) \end{aligned} \quad (11)$$

D. Optimization for Design and Part Load Operating Points

The model developed for CCGT units displays the architecture shown on Fig. 2 with fixed parameters $LHV = 48685$ kJ/kg and $T_a = 30$ °C. The next step consists in calibrating the model. The objective is to optimize all the inputs (i.e. both design and operating variables) in order to minimize the error between the outputs and the values advised by the manufacturers (noted with the superscript $.^D$). The design objective obj^D is then expressed as the sum of the errors regarding the values for TET , W_{GTnet} and η_{GT} . (12). The CC output power and efficiency are implicitly fit as the ST net power is entered as a fixed parameter here. For the off-design operations only the three operating variables are optimized. The unit operation consists in the control of the inlet guide vane of the compressor. The operation is based on IVG control up to 30 % air flow reduction with constant TET followed by a maximum air flow control [9]. The operating controls are then optimized considering their design values as upper bounds ($m_a > 0.7 \times m_{a,des}$). The off-design objective obj^{OD} aims at ensuring the shocked conditions, maintaining TET at the highest possible value while minimizing the error with the part load CC output power W_{CC}^{OD} .

$$obj^D = \frac{(W_{GTnet} - W_{GTnet}^D)^2}{W_{GTnet}^D{}^2} + \frac{(TET - TET^D)^2}{TET^D{}^2} + \frac{(\eta_{GT} - \eta_{GT}^D)^2}{\eta_{GT}^D{}^2} \quad (12)$$

$$obj^{OD} = \frac{(W_{CC} - W_{CC}^{OD})^2}{W_{CC}^{OD}{}^2} + \frac{(TET - TET^D)^2}{TET^D{}^2} + \frac{(G_{sh} - G_{sh}^D)^2}{G_{sh}^D{}^2} \quad (13)$$

The two optimization problems described above are solved using the Sequential Quadratic Programming embedded in the Matlab Optimization Toolbox. For every design and every part load point of each unit the problems are run with a hundred starting points randomly taken within the bounds for the variables. Note that the off-design operation points are considered between 30 % and 100 % off the nominal load with a step of 5 %.

E. Obtained Results

Design results shows good performances. The errors for the output CC power and TET are below 0.1 % while e the maximum registered deviation for the efficiencies is only 0.6 %. The results also display the specific CO₂ emission estimated for the different units ranging from 391 kg/MWh to 457 kg/MWh The observed values are close as it is expected for units with similar performances in terms of efficiency. Those SCE values are consistent with the ones found in the literature for Singapore field data [1]. Fig. 3 shows the results obtained while running the off-design model for Unit A. Especially the operating variables variations are consistent with the considered control strategy [12]. TET remain constant while the air mass flow and the compressions ratio decrease to reach load points below 100 % of the nominal load (Fig. 3a). Once the lower bound for m_a is met (0.7), TET starts decreasing allowing the unit to work a lower output powers.

Fig. 3. Performances of Unit A – a) Operating veriables – b) efficiencies

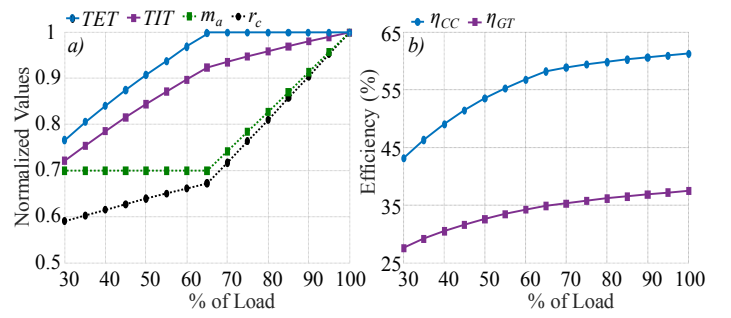
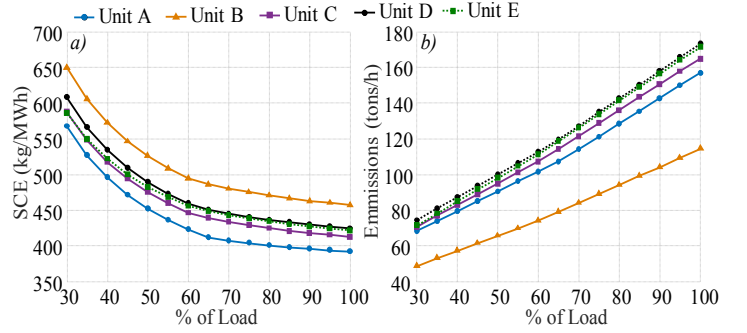


Fig. 4. Units performances – a) SCE – b) CO₂ emissions



Consequently, the CC efficiency drops around 20% for the unit works at 30 % of the nominal load. The same observation can be made concerning the SCE which increase significantly when the output power decreases (Fig. 4a). Plotting the SCE allows ranking the units from the dirtiest (Unit B) to the cleanest (Unit A). Multiplying the specific emissions by the corresponding output power for the units allows estimating the net emissions in tons. Note that the emission for Unit B are significantly lower as the rated power is less important than for the other technologies (250 MW Vs 400 MW). Fig. 4b highlights the fact that the emissions E_i for for the i^{th} unit can be expressed with a linear formulation (14). That will be used as an input parameter for the objective function of the UC problem in the next part. Table III gives the values for the different a_i , b_i obtained with regression coefficients greater than 0.99.

$$E_i(W_{CC}) = a_i \times \frac{W_{CC}}{W_{CC,des}} + b_i \quad (14)$$

III. ENVIRONMENTAL UC

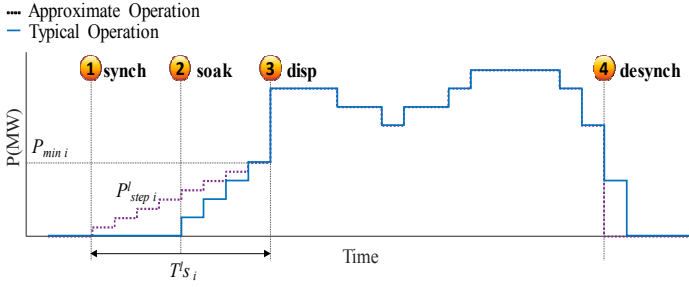
A. CCGT Units Operations

Typical constraints for thermal units in power dispatch procedures refer to the ramping limitation and minimum up/down times [2]. More accurate approaches for thermal units consist in introducing the different phase for the operations as well as discriminating the start-up types [20].

TABLE III. LINEAR COEFFICIENTS FOR CO₂ EMISSIONS

	Unit A	Unit B	Unit C	Unit D	Unit E
a_i (in tons)	126.56	94.00	135.16	141.51	143.34
b_i (in tons)	27.67	19.13	28.00	29.59	26.94

Fig. 5. CCGT unit operation



When a CCGT unit is committed it first enters in a synchronization phase where the turbine shaft reaches the synchronization speed with the grid frequency (Fig. 5). Then a soak phase occurs with the output power that increases until the minimum operating point. The dispatchable phase then starts with the i^{th} unit power flowing within the range $P_{min,i}$ and $P_{max,i}$. When the unit is decommitted the power then returns to zero during the desynchronization phase. In this work both synchronization and soak phase are combined as the only available duration is the total start time (dotted line model in Fig. 5). The start-up time tends to increase with the prior reservation time during which the unit is turned off. Three start-up types $l = \text{hot, warm, cold}$ are then commonly considered with associated duration $T_s^{l,i}$.

TABLE IV. OPERATING PARAMETERS

	Unit A	Unit B	Unit C	Unit D	Unit E
Ramp (MW/min)	50	30	10	22	10
$T_s^{\text{hot},i}$ (min)	30	60	60	30	60
$T_s^{\text{warm},i}$ (min)	90	120	120	90	120
$P_{min,i}$ (MW)	80	75	120	142	122
$P_{max,i}$ (MW)	400	250	400	408	407

Table IV gives the operating variables for the considered units. Note that with a daily UC cold start (after more than 120 h off) is not considered. The load is considered with a 30 min discretization ($\Delta t = 30$ min) based on the data for the whole year 2016 [1]. With such a time step the ramp constraints do not need to be considered. It appears that the studied units can fully operate on their whole range during only one increment of time. Also the duration of the desynchronization phase is neglected as they are usually lower than the start-up phase time.

B. Problem Formulation

In the present study the MILP is considered for the UC formulation. The problem is formulated in MATLAB using YALMIP and is solved using CPLEX 12.7.1. As already mentioned the objective of the UC here is to meet the load with the minimum amount of CO₂. The objective function is expressed as in (15) with the output power of the i^{th} unit at time t $P_{i,t}$ and the on/off status $u_{i,t}$. A nomenclature for some of the symbols used in the UC is given in Table V.

$$\text{obj: Min } \sum_{i \in T} \sum_{i \in U} \left(a_i \times \frac{P_{i,t}}{P_{max,i}} + b_i \times u_{i,t} \right) \times \Delta t \quad (15)$$

Note that the start-up costs (in tons of CO₂) don't appear in the function as it is commonly done in such studies [5]. That information is not available for the considered units. Thus the models previously developed are used to estimate the start-up emissions while extending the off-design operations a lower values of the delivered power. With a non null duration for the start-up phase the corresponding CO₂ cost is computed when considering the output power trajectories from 0 to $P_{min,i}$ (Fig. 5). Consequently, and as expected, warm start-ups will be costlier with a longer duration. Then the first set of constraints attached to the UC problem describes the start up type selection based on the reservation times bounds T^d_l and T^u_l prior the start up. $T^u_l = 8$ h for hot start and $T^u_l = 24$ h for warm start. $T^d_l = 0$ h for hot start and $T^d_l = 8$ h for warm start. The constraints in (16) allows selecting the start-up type depending on the prior reservation time and Eq. (17) ensures that only one type is selected among S [12]. The unit immediately enters in start-up phase when $v_{i,t}$ is set to 1 (18) while Eq. (19) ensures that only the appropriate start phase is considered. The power delivered by the unit i in start-up phase l at time t is computed by multiplying the step power $P^{l,step,i}$ by the duration of the phase before t (20). The reader can refer to [12] for a complete formulation of the UC involving logical constraints for the units operations.

$$v_{i,t}^l \leq \sum_{t-T_i^d+1}^{t-T_i^u} w_{i,t} \quad (16)$$

$$v_{i,t} = \sum_{l \in S} v_{i,t}^l \quad (17)$$

$$us_{i,t}^l = \sum_{t-T_s^l+1}^t v_{i,t}^l \quad (18)$$

$$us_{i,t} = \sum_{l \in S} us_{i,t}^l \quad (19)$$

$$Ps_{i,t} = \sum_{t-T_s^l+1}^t \sum_{l \in S} us_{i,t}^l \times P^{l,step,i} \quad \text{and} \quad Ps_{i,t} \leq P_{max,i} \times us_{i,t} \quad (20)$$

TABLE V. NOMENCLATURE FOR UC PROBLEM

$u_{i,t}$	unit i committed at time t
$us_{i,t}$	unit i in start phase at time t
$us_{i,t}^l$	unit i in start phase type l at time t
$v_{i,t}$	unit i started at time t
$v_{i,t}^l$	unit i started type l at time t
$w_{i,t}$	unit i shut down at time t
$P_{i,t}$	power generated by unit i at time t
$Ps_{i,t}$	power generated by unit i in start phase at time t
a_i, b_i	coefficients for the CO ₂ emissions of unit i
$P_{min,i}/P_{max,i}$	min/max power of unit i in dispatchable phase
T_s^l	start up type l duration
$P^{l,step,i}$	power increment of unit of during start up type l
T^d_l, T^u_l	bounds for start up type l intervals
T, U, S	set of time steps, units and start-up types

Fig. 6. UC without start-up phases – a) KPL – b) PLP – c) SMB – d) SRY

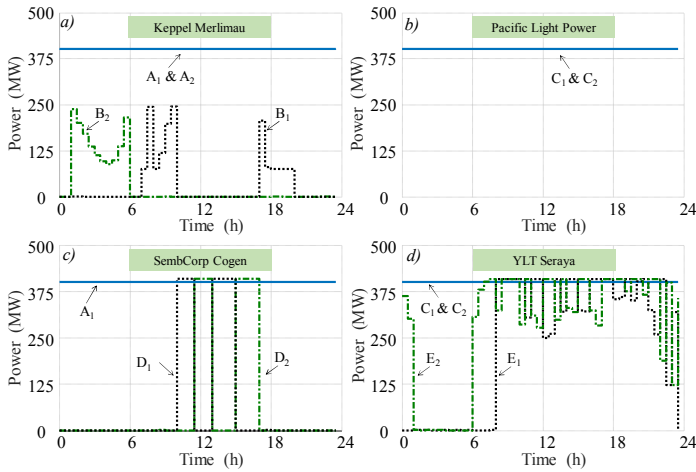
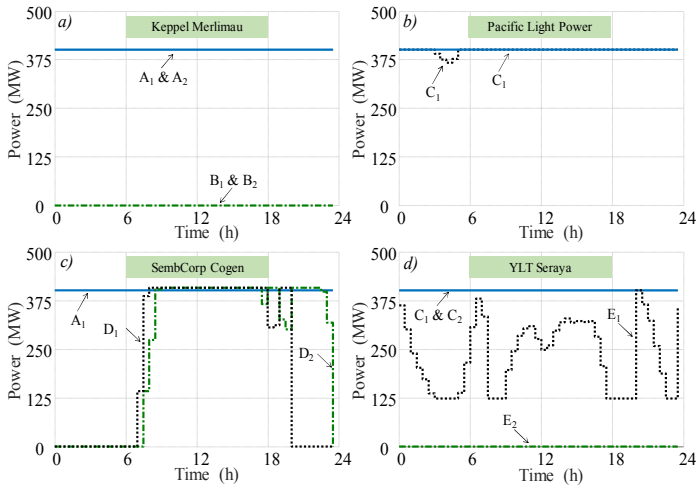


Fig. 7. UC with start-up phases – a) KPL – b) PLP – c) SMB – d) SRY



A. Obtained Results

At first the simulation is performed without considering the constraints for the start-up phases. The obtained confirms that the cleanest units (A and C) are run in priority all along the day while the dirtiest (D) are much less solicited (Fig. 7). Without considering the start-up phases some units displays multiple starts and stops during the simulated day which is unrealistic and would dramatically increases the costs of generation (Fig. 7a). Introducing the start-up constrains solves the problem by avoiding multiple commitments within the same day for the dirtiest units as shown on Fig. 8. It can be noticed that the base load is still fed by the cleanest units while the peak load is meet with the commitment of units D in PLP and E₁ in SRY (Fig. 8b and Fig. 8d). Note that the dirtiest units B in KPL are not used at all. The simulation allows computing the grid emission factor (*GEF*) which represent the amount of CO₂ per kWh generated. The obtained values is 0.406 kg/kWh. That is consistent with the recorded *GEF* of 0.431 kg/kWh for the year 2016 in Singapore which also considers grid losses as well as well 5 % of the electricity mixed coming from oil steam plants [1].

IV. CONCLUSIONS

The CCGT model described in this paper aims at estimating the CO₂ emission coefficients that are used in an environmental UC. Compared to conventional UC studies with CO₂ costs taken from the literature, the methodology developed here allows the representation of specific units. Especially the start-up emission doesn't have to be guessed and is estimated by introducing the start-up phase with a specific duration. Despite the sparsity of the information available from unit manufacturers, the calibrated models display very good agreement with real data in terms of GEF. The global objective of the study is to model the power system management on Jurong Island in Singapore. Further work should focus on the grid modeling that would lead to additional operating constraints to be fulfilled in UC. Attention will have to be paid to the problem formulation in order to avoid prohibitive computational times. The aggregation of the units in the same plant could be investigated in order to reduce the number of variables and the attached solution time.

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