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# Optimization of Hybrid Renewable Power Generation Flowsheets Using Generic Structural and Temporal Models

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This work addresses the systemic modelling and optimization of renewable power generation and hydrogen/power storage flowsheets based on representations integrating structural, temporal and logical features. Generic concepts are used based on superstructure models to describe flows and tasks of conversion and accumulation, integrating streams utilized in multi-component material/energy conversions and resulting in flexible representations. These are coupled with the use of logical propositions assembled around generic temporal operating features, supporting the development of conditional statements that represent operating requirements as constraints. The proposed developments are used in the optimum design of an extended power generation and hydrogen storage flowsheet considering multiple power management strategies as decision options in addition to various operating and design parameters.

## 1. Introduction

To address the intermittent nature of largely unpredictable environmental phenomena, renewable energy sources (RES) are often transformed into dependable power flows by simultaneous utilization of different types of conversion equipment and storage media (e.g. PV panels, wind generators, chemical accumulators etc.). Hydrogen-based technologies are also receiving considerable attention as they enable flexible and long-term power storage, increasing the capacity provided by conventional accumulators. Such features result in hybrid infrastructures combining multiple sub-systems of heterogeneous characteristics that need to operate smoothly and efficiently within an integrated flowsheet. Their optimum design and operation involves significant complexities due to the existence of a very large number of interactions affecting the overall system performance. In addition to numerous structural options, the intense variability of renewable energy sources inflicts a varying temporal behaviour resulting in significant operating transitions among temporally different flowsheet topologies. Optimization can be used to systematically address such complexities by treating system features as decision options, yet this requires systemic models for the efficient representation of structural and temporal flowsheet alternatives.
Recently reported works address the structural design of power and/or heating/cooling co-generation systems (Martínez-Patiño et al., 2012), through modelling concepts developed around generic flow characteristics (e.g. energy hub and power node concepts - Heussen et al. (2012), matrix-based models - Chicco et al. (2009)). In a similar context, superstructure-based approaches have also been considered in the design of extensive polygeneration flowsheets, focusing mostly on chemical conversion processes for the co-generation of chemicals, fuels and power (Baliban et al., 2012). Clearly, there is a lot of scope in exploiting the merits of both approaches for the efficient modelling and design of flowsheets integrating renewable power generation systems including hydrogen/power storage. On the other hand, generic

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models addressing the varying temporal behaviour of combined power and heat generation systems have also been proposed (Kopanos et al., 2013). For systems considered in this work the models capturing temporal transitions are called power management strategies (PMS) and available models are often case-specific (González et al., 2013). They mostly utilize conditional rules to develop empirical representations determining the appropriate instant for activation/deactivation of the desired equipment, ultimately aiming to maintain feasible, stable and prolonged system operation (Ipsakis et al., 2009). Although useful, this practise requires the manual addition of terms and conditions in the event that new options (e.g. streams, equipment, rules etc.) need to be considered in the performed calculations. Whilst marginally feasible for reasonably small systems, the exhaustive consideration of all possible temporal combinations becomes impractical as the number of incorporated structural options increases.

## 2. Proposed flowsheet representation models

### 2.1 Description of motivating system

Prior to presenting the generic models proposed in this work it is necessary to describe the considered hybrid RES-based power system. It consists of PV panels (PV) and wind generators (WG) for power generation. Surplus energy is supplied to an electrolyzer (EL) after the specified load demand (LD) for a targeted application is satisfied. The produced hydrogen is stored in pressurized cylinders (BF) and in cases of energy deficit, is utilized in a fuel cell (FC) to provide the needed power to the system. Lead-acid accumulators (BAT) are used to regulate the power flows in the system through frequent charging and discharging cycles induced by the RES variability. In case of energy excess, units such as the hydrogen compressor (CP) utilize this energy to store hydrogen in long-term storage tanks (FT). A diesel generator (DSL) is also attached to the system and utilized only in cases of emergency (i.e. power demands of the application can not be covered by RES or stored hydrogen), while a water tank (WT) is also used to support the EL and FC. As a case study here, the system under study is located in Xanthi, Greece, the load is set at 1 kW, and the rated power of the FC, EL and DSL are set to 1 kW, 5 kW and 1 kW.

Regardless of equipment characteristics and operating conditions, the system flowsheet represents a structure containing sub-systems interconnected through streams, facilitating the uninterrupted power supply of an end-user. Based on this observation all the particular system features can be organized under the following generic sets: a) the set of *States* ($St$) representing the composition of streams interconnecting different sub-systems and consisting of two main subsets including the states of Energy (*Nrg*) and Matter (*Mat*), hence $St=\{St^{Nrg}, St^{Mat}\}$, b) the set of *Tasks* ($Ts$) representing methods to process states and including subsets $Ts^{Acc}$ and $Ts^{Conv}$, hence $Ts=\{Ts^{Acc}, Ts^{Conv}\}$ where the two subsets represent the accumulation ($Acc$) and conversion ($Conv$) tasks, c) the set of *Resources* ($Rs$) indicating the type of equipment employed to perform each task and including the subsets $Rs^{Acc}$ and $Rs^{Conv}$, hence $Rs=\{Rs^{Acc}, Rs^{Conv}\}$.

### 2.2 Structural representation

This work employs an inclusive synthesis model in the form of a superstructure to systemically capture structural and operating characteristics of RES-based flowsheets (Figure 1).

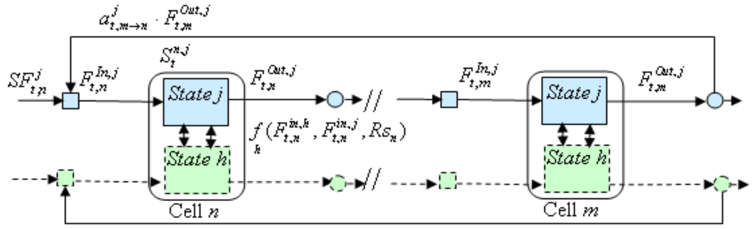


*Figure 1: Superstructure model and terms of associated flows*

In a superstructure all streams may be connected to any desired systems, while the additional incorporation of constraints in states, tasks and resources enables the feasible interoperation of all the subsystems comprising a flowsheet. Based on the definition of tasks each cell may represent a converter or an accumulator, hence establishing connections between two subsequent cells. From Figure 1 it appears that different tasks can be allocated to different cells by assigning the appropriate mathematical equations associated with particular resources. The mixers and splitters represent the summation of streams prior to entering the cell and the distribution of streams leaving the cell. Every cell is separated into compartments indicating tasks taking place separately. The streams entering each compartment in a particular state *j* exchange mass or energy with their corresponding compartments in a different state *h*, enabling an implicit modeling of the driving forces behind conversion. The flow entering cell *n* at time *t* is described by the following equation:

$$F_{t,n}^{In,j} = SF_{t,n}^{j} + \sum_{m}\left(\varepsilon_{t,m\to n}^{j} \cdot F_{t,m\to n}^{Out,j}\right) \tag{1}$$

In (1) $SF_{t,n}^{j}$ is an external feed that may be received by the mixer, $\varepsilon_{t,m\to n}^{j}$ is a binary variable receiving a value of 1 if a connection between cells *m* and *n* is active or 0 otherwise and $F_{t,m\to n}^{Out,j}$ is used to replace the term $a_{t,m\to n}^{j} \cdot F_{t,m}^{Out,j}$, where *a* represents the elements of an adjacency matrix distributing the output stream to different cells. For the cells and splitters it holds that:

$$F_{t,m}^{Out,j} = f_{m}^{j}\left(F_{t,m}^{In,h}, F_{t,m}^{In,j}, Rs_{m}\right) \tag{2}$$

$$S_{t}^{n,j} = S_{t^{-}}^{n,j} + \frac{F_{t,m\to n}^{in,j} - F_{t,n\to m}^{out,j}}{C_{n,j}} \tag{3}$$

$$\sum_{n}\left(a_{t,m\to n}^{j}\right) = 1 \qquad \forall n \in Ts^{Acc}, m \in Ts \ , j \neq h \in St \tag{4}$$

Eq.(2) (also applicable to cell *n*) states that the outlet flowrate is determined through a function related to the particular equipment used to specialize the tasks performed in each cell. This function transforms incoming flows in states *h* and/or *j* into flows in state *j*. Eq.(3) enables the calculation of the stored amount of energy and/or materials through term $S$ (State of Accumulator), assuming that cell *n* is an accumulator. Term $C$ in (3) is the capacity of accumulator *n* in state *j*. Eq.(4) states that the streams distributed to different cells cannot be more than the available output flow.

**2.3 Temporal representation**

To apply the above balance equations it is necessary to define variables $\varepsilon$ of Eq.(1) as they enable the activation/deactivation of connections between devices *m* and *n* based on temporally evolving constraints. Decisions whether to activate a connection are based on conditions considering: a) the availability of material or energy from device *m*, b) the requirement for material or energy of device *n*, and c) additional specific conditions that are not associated with the above two and may be desirable. In this context, variable $\varepsilon_{t,m\to n}$ can be defined in the form of a logical proposition as follows:

$$\varepsilon_{t,m\to n} = L\left(\varepsilon_{t,m\to n}^{Avl}, \varepsilon_{t,m\to n}^{Req}, \varepsilon_{t,m\to n}^{Gen}\right) \tag{5}$$

$$\varepsilon_{t,m\to n}^{i} = L_{m\to n}^{i}\left(L_{m\to n}^{S^{n}}\left(\rho_{t,m\to n}^{S^{n}}, r_{t,m\to n}^{S^{n}}\right)\right) \forall i = \{Avl, \mathrm{Re}q\}, n \in Ts^{Acc}, m \in Ts \tag{6}$$

In Eq(5) and Eq(6) $L$ is a logical operator, indices $Avl$ and $Req$ correspond to the previously discussed conditions (a) and (b) with respect to variables $\boldsymbol{\varepsilon}$ while index *Gen* of condition (c) represents a free use of variable $\varepsilon^{Gen}$ to incorporate any desired condition. Binary variables $\rho$ and *r* are parameters associated with temporal conditions imposed on the power or materials stored in the accumulator *n* ($S^n$). Given the consideration of converters and accumulators, the operation of converters is associated with activation and de-activation (e.g. the fuel cell can be ON or OFF) while the accumulators are practically always active because the task of accumulation is always ON. This ON/OFF behaviour results in the generation of hysteresis zones (Ipsakis et al., 2008). The potential actions are: a) If the accumulated energy/material ($S^n$) value is higher than a pre-specified limit $Up_{t,m\to n}^{S^{n}}$, the converter is not connected to any other device hence it remains idle, b) If it is lower than $Lo_{t,m\to n}^{S^{n}}$ the converter is connected to another device hence it is activated, c) If it is in the interval between the two limits, it will remain idle if the converter was idle in the previous instant, or active if it was previously active. These *if-else* statements can be represented through generic logical propositions. Each converter is associated with multiple potential accumulators by which it is affected and activated/deactivated based on their synergy. The *S* value of each accumulator *n* is divided into 3 zones based on the actions applied on the converter *m* which is affected, represented by conditions:

$$\rho^{S^n}_{t,m\rightarrow n} = \left[S^n_t < Lo^{S^n}_{t,m\rightarrow n}\right] \vee \left[\left[Lo^{S^n}_{t,m\rightarrow n} < S^n_t < Up^{S^n}_{t,m\rightarrow n}\right] \wedge \left[\varepsilon_{t^-,m\rightarrow n} = 1\right]\right] \quad (7)$$

In Eq(7) the first inequality represents the simple ON-OFF behaviour, while the subsequent expression represents the hysteresis behavior, hence symbol $t^-$ indicates that the previous instance must be checked. Parameter $r$ appearing in Eq(6) is used in combination with $\rho$ to impose or ignore a condition if necessary. Clearly, there is only a need to investigate three accumulation areas associated with each accumulator $n$. This is simply repeated for every connection. The values of the limiting parameters may become decision variables for the investigation of the overall system performance. In addition to changing the values of the limiting parameters, different terms can be added, removed or altered in Eq(5) to Eq(7) capturing all the potential or desirable connections among different devices and resulting in different PMSs.

## 3. Implementation

### 3.1 Power management strategies

This work considers 6 PMSs to evaluate the performance of the system under investigation. The PMSs are developed using $PMS_1$ as a reference (Table 1) which is then changed by adding, removing or altering constraints using Eq.(5) to Eq.(7). For brevity in Table 1 symbol $S$ has been omitted from variables $\rho$, $Lo$ and $Up$. The arrow is also omitted but the connections between different devices are clearly shown.

*Table 1: Reference $PMS_1$*

| Device | Activation condition |
|---|---|
| PV, WG | $\rho^{BAT}_{t,PV,BAT} = S^{BAT}_t < Lo^{BAT}_{t,PV,BAT}; \rho^{BAT}_{t,WG,BAT} = S^{BAT}_t < Lo^{BAT}_{t,WG,BAT}$ |
| | $\varepsilon^{Req}_{t,(PV,WG),BAT} = \rho^{BAT}_{t,(PV,WG),BAT} \vee r^{BAT}_{t,(PV,WG),BAT}; \varepsilon^{Avl}_{t,(PV,WG),BAT} = \varepsilon^{Gen}_{t,(PV,WG),BAT} = 1$ |
| DSL | $\rho^{BAT}_{t,DSL,BAT} = \left[S^{BAT}_t < Lo^{BAT}_{t,DSL,BAT}\right] \vee \left[\left[Lo^{BAT}_{t,DSL,BAT} < S^{BAT}_t < Up^{BAT}_{t,DSL,BAT}\right] \wedge \left[\varepsilon_{t^-,DSL,BAT} = 1\right]\right]$ |
| | $\varepsilon^{Avl}_{t,DSL,BAT} = \varepsilon^{Gen}_{t,DSL,BAT} = 1; \varepsilon^{Req}_{t,DSLBAT} = \rho^{BAT}_{t,DSL,BAT} \vee r^{BAT}_{t,DSL,BAT}$ |
| FC | $\rho^{FT}_{t,FC,BAT} = S^{FT}_t > Lo^{FT}_{t,FC,BAT}; \rho^{WT}_{t,FC,BAT} = SOAcc^{WT}_t < Lo^{WT}_{t,FC,BAT}; \varepsilon^{Gen}_{t,FC,BAT} = 1$ |
| | $\rho^{BAT}_{t,FC,BAT} = \left[S^{BAT}_t < Lo^{BAT}_{t,FC,BAT}\right] \vee \left[\left[Lo^{BAT}_{t,FC,BAT} < S^{BAT}_t < Up^{BAT}_{t,FC,BAT}\right] \wedge \left[\varepsilon_{t^-,FC\rightarrow BAT} = 1\right]\right]$ |
| | $\varepsilon^{Avl}_{t,FC,BAT} = \left[r^{FT}_{t,FC,BAT} \vee \rho^{FT}_{t,FC\rightarrow BAT}\right] \wedge \left[r^{WT}_{t,FC\rightarrow BAT} \vee \rho^{WT}_{t,FC\rightarrow BAT}\right]; \varepsilon^{Req}_{t,FC,BAT} = \rho^{BAT}_{t,FC,BAT} \vee r^{BAT}_{t,FC,BAT}$ |
| EL | $\rho^{WT}_{t,EL,BF} = S^{WT}_t > Lo^{WT}_{t,EL,BF}; \rho^{BF}_{t,EL,BF} = S^{BF}_t < Lo^{BF}_{t,EL,BF}; \varepsilon^{Gen}_{t,EL,BF} = 1$ |
| | $\rho^{BAT}_{t,EL,BF} = \left[S^{BAT}_t > Lo^{BAT}_{t,EL,BF}\right] \vee \left[\left[Up^{BAT}_{t,EL,BF} < SOAcc^{BAT}_t < Lo^{BAT}_{t,EL,BF}\right] \wedge \left[\varepsilon_{t^-,EL,BF} = 1\right]\right]$ |
| | $\varepsilon^{Avl}_{t,EL,BF} = \left[r^{BAT}_{t,EL,BF} \vee \rho^{BAT}_{t,EL,BF}\right] \wedge \left[r^{WT}_{t,EL,BF} \vee \rho^{WT}_{t,EL,BF}\right]; \varepsilon^{Req}_{t,EL,BF} = r^{BF}_{t,EL,BF} \vee \rho^{BF}_{t,EL,BF}$ |
| CP | $\rho^{FT}_{t,CP,FT} = SOAcc^{FT}_t < Lo^{FT}_{t,CP,FT}; \varepsilon^{Gen}_{CP\rightarrow FT}(t) = 1; \varepsilon^{Avl}_{t,CP,FT} = r^{BF}_{t,CP,FT} \vee \rho^{BF}_{t,CP,FT}$ |
| | $\rho^{BF}_{t,CP,FT} = \left[SOAcc^{BF}_t > Lo^{BF}_{t,CP,FT}\right] \vee \left[\left[Up^{BF}_{t,CP,FT} < S^{BF}_t < Lo^{BF}_{t,CP,FT}\right] \wedge \left[\varepsilon_{t^-,CP,FT} = 1\right]\right]$ |
| | $\varepsilon^{Req}_{t,CP,FT} = r^{FT}_{t,CP,FT} \vee \rho^{FT}_{t,CP,FT}$ |

$PMS_1$ to $PMS_6$ are developed based on different combinations of two parameters affecting the system performance. These combinations result in different formulations of the variables described in Table 1 (e.g. altered logical operators, additional or fewer equations depending on the PMS). The first parameter is associated with the surplus or deficit of power produced by the PVs/WGs and consumed by the load, namely $F_{t,RES}$. The consideration of this parameter in a PMS directly affects the operating regime of the FC and EL. For example, in case that the value of $F_{t,RES}$ is accounted for, then if there is energy surplus, the FC will be not operated even if $S^{BAT}$ is low, while it will be operated only when there is an energy deficit and $S^{BAT}$ is low. In the latter case the FC will provide the additional energy required in order to null the energy deficit. Similar conditions apply for the EL. The consideration of $F_{t,RES}$ is represented through variables

$\varepsilon^{Gen}$. For example the expression $\varepsilon^{Gen}_{t,FC,BAT} = [F_{t,RES} < 0]$ indicates that for the connection between FC and BAT $F_{t,RES}$ has to be considered. In $PMS_1$ the condition $\varepsilon^{Gen}_{t,FC,BAT} = 1$ means that $F_{t,RES}$ is not considered. Similar expressions hold for the other devices in different PMSs. The second parameter of interest is the length of the hysteresis zone, which may be represented as ΔH=$\left| Lo^{S^n}_{t,m\to n} - Up^{S^n}_{t,m\to n} \right|$. This may receive a fixed value, while it may also vary depending on a) the time that a connection between two devices is active (e.g. the length of the hysteresis zone will decrease for a connection that stays active for long) and b) on weather conditions (e.g. during the summer months the hysteresis zones of the FC and EL may be reduced and increased for improved operation). Hence in total the 6 PMSs considered result as a combination of these parameters (Table 2).

*Table 2: Considered PMSs as a combination of associated parameters*

| | | ΔH | | |
|---|---|---|---|---|
| | | Fixed | Varied-Duration of connection | Varied-Weather conditions |
| $F_{t,RES}$ | Not considered | $PMS_1$ | $PMS_3$ | $PMS_5$ |
| | Considered | $PMS_2$ | $PMS_4$ | $PMS_6$ |

**3.2 Decision parameters, objective functions and constraints**

In order to quantify the performance of the system under each PMS the operation of the FC and EL were recorded as well as the volume of the hydrogen in the FT after 1 year of operation. These variables were combined to determine the following objective function of the form $J=(T_{FC}+T_{EL})/H_{HP}$ where $T_{FC}$, $T_{EL}$ are the costs of using the FC and EL and $H_{HP}$ is the amount of hydrogen that was available in the FT after 1 year of operation. Furthermore, additional constraints involve the need a) to produce more hydrogen than consumed after a year of operation, b) to completely avoid activation of the DSL and c) to completely avoid losses from the PVs. The considered decision variables involve the power produced by the PVs $(F^{out}_{PV})$ and WGs $(F^{out}_{WG})$, the nominal capacity of BAT ($C^{BAT}$) and FT ($C^{FT}$), as well as the upper and lower limits on $S^{BAT}$ associated with the FC and EL, namely $Lo^{BAT}_{t,FC,BAT}$, $Up^{BAT}_{t,FC,BAT}$ and $Up^{BAT}_{t,EL,BF}$, $Lo^{BAT}_{t,EL,BF}$.

## 4. Results and discussion

In this section the performance of the system under the 6 aforementioned PMSs is presented and discussed (Table 3 and Figure 2). In all strategies the optimum rated power is around 10 - 11 kW which produce 15.5 kWh/d-16.5 kWh/d during the month with the least sun peak hours (December – 1.59 h/d) and 60 kWh/d – 65 kWh/d during the month with the highest sun peak hours (July 6.2 h/d). This implies that in December the RES will not produce the required 24 kWh/d and hence extra power has to be supplied either from the battery or from the FC. The battery capacity is at 1,300 Ah – 1,700 Ah which corresponds to 62.4 kWh - 81.6 kWh or to 2.6 or 3.4 d of autonomy. With these power specifications the battery will not be fully charged even during July hence the FC will be frequently activated.

*Table 3: Performance of the system under the 6 PMSs shown in Table 2*

| PMS | $J$ | $P_{RES}$ $[kW]$ | $C^{FT}$ $[m^3]$ | $C^{BAT}$ $[Ah]$ | $Lo^{BAT}_{t,FC,BAT}$ | $Up^{BAT}_{t,FC,BAT}$ | $Up^{BAT}_{t,EL,BF}$ | $Lo^{BAT}_{t,EL,BF}$ | $T_{FC}$ $[H]$ | $T_{EL}$ $[H]$ | Change of $H_2$ $[m]^3$ |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 29.28 | 11.3 | 470 | 1,300 | 0.31 | 0.35 | 0.71 | 0.62 | 803 | 1184 | 9,807 |
| 2 | 31.89 | 10.3 | 480 | 1,500 | 0.31 | 0.34 | 0.67 | 0.45 | 941 | 1552 | 0,416 |
| 3 | 29.07 | 10.7 | 470 | 1,400 | 0.31 | 0.34 | 0.77 | 0.38 | 911 | 1031 | 0,935 |
| 4 | 31.82 | 10.3 | 460 | 1,350 | 0.31 | 0.34 | 0.68 | 0.42 | 950 | 1554 | 0,093 |
| 5 | 29.65 | 11.3 | 480 | 1450 | 0.32 | 0.35 | 0.72 | 0.59 | 813 | 1187 | 9,449 |
| 6 | 32.01 | 10.5 | 500 | 1700 | 0.32 | 0.35 | 0.72 | 0.49 | 872 | 1590 | 3,722 |

From Table 3 it is seen that the FC will be activated from 803 h/y to 950 h/y, which is around 10 %. The EL will be activated around 12.5 % of the total operation time which is necessary to cover the usage of the FC and the required extra hydrogen in the FT. For example for PMS1 the EL produced in 1 y approximately 38 $m^3$ hydrogen and the FC consumed 28 $m^3$ hydrogen which result in 10 $m^3$ of hydrogen surplus in the FT. From Table 3 two extra conclusions can be drawn. The first one can be deduced by Figure 2 where $FC_{Start}$,

$FC_{Stop}$, $EL_{Start}$ and $EL_{Stop}$ are the $Lo^{BAT}_{t,FC,BAT}$, $Up^{BAT}_{t,FC,BAT}$, $Up^{BAT}_{t,EL,BF}$, $Lo^{BAT}_{t,EL,BAT}$. In this Figure, it can be seen that while the zone of the FC is more or less fixed, the operation zone of the EL varies depending on the PMS. The last point that needs to be discussed from Table 3 is that the best PMS are the 1$^{st}$, 3$^{rd}$ and the 5$^{th}$ strategies which do not take into account the extra information of the energy deficit/surplus. This is probably happening as the EL is operated in these cases at maximum available power and hence it requires less time to consume the available energy and produce hydrogen.

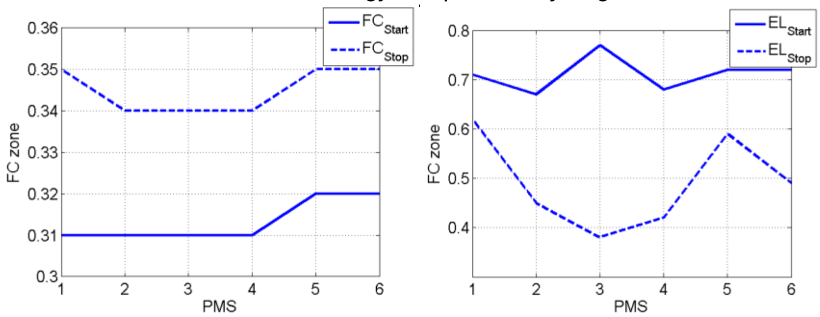


*Figure 2: Operational zones of the FC and EL for each PMS*

## 5. Conclusions

This work has presented a systemic framework for the optimum design of hybrid power generation systems. The framework is based on generic models for the representation of the structural flowsheet features and the temporal variations observed during the operation. The proposed approach has allowed a flexible representation of operating policies as logical schemes that maintain the generic features of a superstructure-based approach. The resulting schemes were developed around the hysteresis zone concept supporting the temporal evolution of flowsheet topologies based on the conditions associated with time-dependent constraints. The proposed developments are illustrated through a case study on a system currently in operation in Greece. The consideration of different power management strategies in combination with optimum design characteristics has highlighted considerable performance improvements.

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