Session 3.3 Advanced Building Systems - Energy Generation (1)

Analysis of Fourth-Generation District Energy Systems with Renewable Energy Cogeneration by Using Rational Exergy Management Model

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ABSTRACT

Recent 4th-generation district energy systems envision optimum bundling of different energy resources and conversion systems with main emphasis on sustainability and renewable energy use. Because renewable energy sources generally have low exergy and some of them are interrupted, they must be stored, time and exergy matched with low-exergy demands. The complex nature of the source and demand hybridization requires new exergy focused controls based on *Rational Exergy Management Model*. This need actually defines the main concept of smart metropolis. In this paper a new algorithm for optimizing the exergy bundling of renewable energy and conversion systems in cogeneration format with low-exergy metropolis demands is described with the objective of minimizing the CO_2 emissions. A second algorithm for the control of the hybrid system, which is tested in a smaller scale in a LEED Platinum building Ankara has been adopted and projected to typical metropolis. New definitions like Net-Zero Exergy Metropolis, Net-Zero Carbon Metropolis are also described. The paper concludes that the Second Law of thermodynamics leading to the exergy concept is the primary player in developing smart metropolis and minimizing their carbon foot print.

Keywords: *sustainable neighbourhood, cogeneration, rational exergy management model*

1. INTRODUCTION

Districts have several tasks to accomplish with highest reliability and best sustainability while facing time-dependent loads of different forms and exergy. Figure 1 shows typical hourly variation of thermal and power loads of a District. According to this figure, peaks of different loads are not coincident and every different load has a different profile. Consequently, not only the magnitudes but also the load proportions change with time. Large variations of different load proportions are particularly important for cogeneration systems, because they deliver heat and power almost at a constant ratio over their regular operational range. All these factors make it necessary to employ more than one energy conversion system and to bundle various energy sources, preferably by utilizing different sustainable systems. This makes it essential to extensively use TES (Thermal Energy Storage) systems and –if feasible to employ- electrical storage systems, besides grid exchange. One also needs to know the availability of renewable energy systems on an hour-by-hour basis for a sustainable and near-zero design and operation. In addition, controls, systems, and equipment primarily respond to comfort cooling and heating loads, which impose time-dependent temperatures: not only the magnitudes and proportions of loads change but at the same time demand temperatures for thermal equipment and systems change continuously. For example, in a HVAC system supply temperatures are proportionately controlled with respect to outdoor air temperature, which affect the system and equipment performance. Finally, the factors that affect part-load efficiency of the equipment must be also considered in order to yield accurate hourly equipment energy demand data.

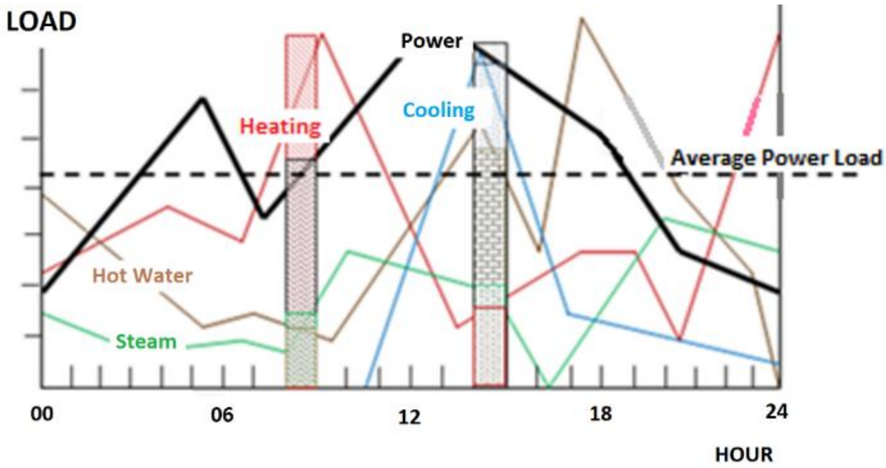

Figure 1: Typical Daily Load Profiles in a District

On the other hand, Districts are becoming a vital partner of the built environment and get multi-dimensionally connected to the cities forming a nexus of economy, energy (exergy), and environment. For example, Districts send their trash to biogas plants in the nearby cities and receive power and energy in return. For a sustainable future, the most recent trend is to connect Districts to 4DE (Fourth Generation) district energy systems in the built environment, where low-temperature heat (for DHW, LowEx heating), high-temperature heat (for conventional space heating, process heat), moderate-temperature cold (space cooling), low-temperature cold (process cold) and power generated with conventional and renewable energy systems and resources are exchanged at various exergy levels. Solar energy is used to generate power in the built environment widely. However, when it comes to harvest solar and wind energy, Districts face serious limitations due to air traffic safety. Generally new District construction and their operation may impose serious environmental risks. In spite of all these complexities, U. S. Department of Energy (DOE) has recently defined Zero-Energy Building (ZEB) in an over simplistic format by using only the First-Law of Thermodynamics. In their definition, energy supplied-received balance is simply based on an annual single cumulative basis of all kinds of energy with different exergy values without taking into account the exergy variations and associated CO_2 emissions, which are hidden in the Second-Law. This issue was first addressed by [5] by developing new definitions for net or near building in terms of exergy (NZEXB, nZEXB). In fact, according to Marszal and Heiselberg, the definition of net or near zero building is quite complicated.

2. THEORY

Several European countries are in the process of developing and implementing their road maps for near-zero energy buildings (nZEB) according to the relevant EU Directive for High Performing Buildings. There are several definitions for nZEB concept and all models, definitions, and implementations are based on the First-Law, which only deal with the quantity of the energy exchange between the building, grid, and the district. Current practice is primarily focused on electric power exchange. Today, Denmark is the only EU country that factors-in the thermal energy exchange. Thermal energy at different states and temperatures mean a wide variation of the thermal energy quality (exergy). Other shortcomings of the current NZEB or nZEB definitions, which may be inferred from Kılkış, Ş. are:

- Thermal energy exchange definitions must distinguish different forms of heat like steam, hot water, service water, cold water etc.
- Quality of energy exchange needs to be embedded in the nZEB definition.
- The quality of energy exchanged in calculating the harmful emissions must be taken into account by a new definition.

More importantly, the temperatures of the heat received from and supplied to a district system must be taken into account in determining the supply and demand exergy balance as shown in Figure 2. For example, an exergy exchange deficit occurs in the grid-connected building if the building delivers 30^{o}C water to the district but receives 40^{o}C water from the district in the same amount over a given period of time. A similar deficit occurs for cooling, because exchange temperatures of the chilled water are different.

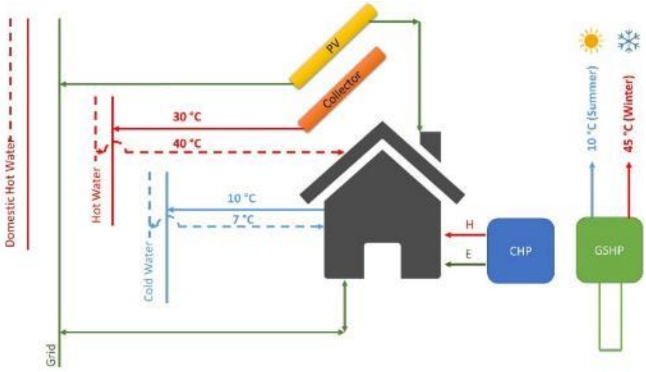

Figure 2: Supply and return temperatures between a sustainable building and de system

Therefore, the unit exergy of each 1 kW-h of the supply heat, ε_{sup} according to the ideal Carnot Cycle must be considered. Equation 1-a may also be used for destroyed exergy and demand exergy. Equations 1-a,1-b, 2, and 3 establish the energy, environment, and economy nexus, respectively.

Energy

$$\varepsilon_{\mathrm{sup}} = \left(1 - \frac{T_{ref}}{T_{sup}}\right) \times (1\,\mathrm{kW\text{-}h})$$

Equation 1-a: Unit exergy

$$E_x = \varepsilon_{\mathrm{sup}} \times Q_{\mathrm{sup}}$$

Equation 1-b: Energy and exergy

$$\psi_R = 1 - \frac{\sum \varepsilon_{des}}{\varepsilon_{\mathrm{sup}}}$$

Equation 1-b: Rationality of energy use

Equation 1-a through 1-c establish the energy and exergy metric of the nexus. For a green district and subscribing building the annual average of ψ_R must be greater than 0,70.

Environment

$$\sum CO_2 = \left[\frac{c_l}{\eta_l} + \frac{c_m}{\eta_m \eta_T}(1 - \psi_R)\right] Q_H + \frac{c_m}{\eta_m \eta_T} E$$

Equation 2-a: Environment

Equation2-a, which is derived from the Rational Exergy Management Model (REMM) establishes the environment metric of the nexus. At below, *EDR* is the Ratio of Emissions Difference. The CO_{2base} term is the standardized emission rate calculated with practical defaults for 0,5 kW-h thermal and 0,5 kW-h electrical load per hour

(*C* =1). See Equation 2-c, where CO_{2base} is 0,63 kg CO_2/ kW-h, which is derived from Equation 2-a. *EDR* must be close to one.

$$EDR = 1 - [CO_{2on\text{-}site}/CO_{2\,base}]$$

Equation 2-b: Emissions are based on REMM

$$\sum CO_2 = \left[\frac{0{,}2}{0{,}85} + \frac{0{,}2}{0{,}35}(1 - 0{,}2)\right] 0{,}5 + \frac{0{,}2}{0{,}35} 0{,}5$$

Equation 2-c

Economy

$$PES = \left[1 - \frac{1}{\left(\frac{\text{CHPH}\eta}{\text{RefH}\eta} + \frac{\text{CHPE}\eta}{\text{RefE}\eta} \right) \times \frac{(2 - \text{Ref}\,\psi_R)}{(2 - \psi_R)}} \right] \times 100$$

Equation 3: Economy

Equation 3 provides the economy metric, where *PES* must be greater than 35% in order to qualify for a green status. In order to satisfy the above metrics, a complex design example for achieving NZEXAP status is shown in Figure 3 (Kilkis, B., 2012). In this design the combined heat and power system (CHP) is supported by renewable energy systems including solar collectors, PV systems, and their derivatives, and remote green electricity power from wind. Buildings and large complexes need to use radiant heating and cooling systems and thus may easily qualify for Low-Exergy Building status, while they employ moderate working temperatures. Thus solar energy may be directly utilized in their HVAC systems. Hot water, chilled water, and ice tanks shave the peak loads, shift the loads to converge to the supply profiles, and match the thermal exergy levels of various supplies and demands in the complex.

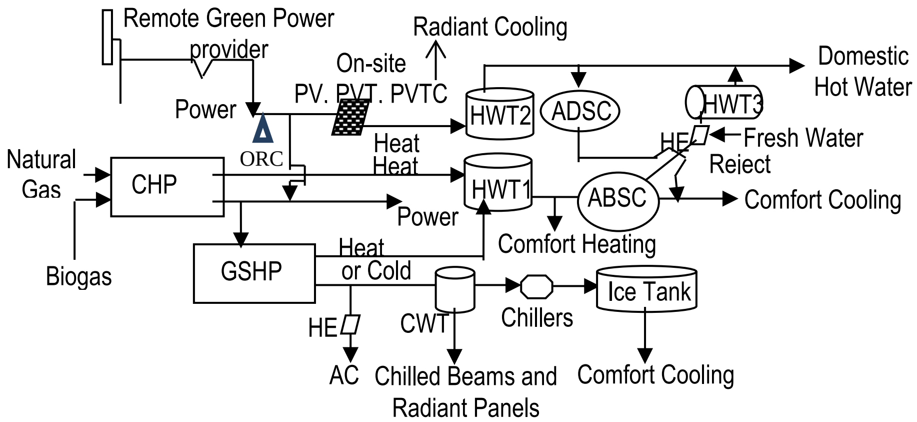

Figure 3: NZEXAP tri-generation plant design

3. OPTIMIZATION OF 4DE SYSTEMS

Figure 5 shows a typical daily power load profile at different (*c*) values with respect to P_P (Peak power load). (*c*) is the ratio of the selected capacity of a cogeneration plant to the peak power load. For example, if a tri-generation system in Figure 5 is selected with a capacity equal to P_P, then it will only operate for about only two hours at a capacity near to its full capacity. At the same time because most CHP engines are not allowed to operate below 40% capacity, it will remain idle for about 9 hours in a typical day. Unless cascaded, the CHP unit at part load will have reduced efficiency. It is obvious that NZEXAP or nZEXAP conditions may only be satisfied and energy, environment, and economy nexus be established by a careful selection of the tri-generation plant. Therefore, the capacity(ies) of CHP systems must be carefully optimized and cascaded, if necessary.

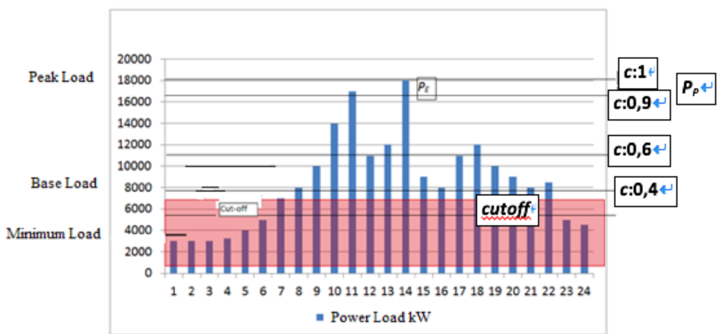

Figure 5: Typical hourly change of power demand

3.1 Objective function and its simplification

The primary objective is to maximize the performance of a CHP system under the energy, environment, and economy nexus. Main parameters are First-Law efficiency (η), (c) value, Operating Factor (IF), Rational Exergy Management Efficiency (ψ_R), CO_2 emissions, and economic return. Terms (j) and (l) are correlation parameters.

$$OF = f(\eta, c_i, IF, \Psi_R, CO_2)$$

Equation 4-a: Maximize

(c_i) for natural gas it is 0,2 kg CO_2/ kWh-h. IF depends on (c) that is shown in Figure 6, where $IF = f(c)$ [8].

$$OF = \left[\frac{0{,}6 + j(IF - 0{,}6)^l}{0{,}9}\right] + \left[\frac{IF)}{0{,}9}\right] + \left[\frac{0{,}088}{\left(\frac{c_i}{\eta}\right)(1-\psi_R)}\right]$$

Equation 4-b

Where,

$$\eta_I = \left[\frac{0{,}6 + j(IF - 0{,}6)^l}{0{,}9}\right]$$

Equation 5

After taking the upper limit of $\Psi_R \leq \eta_{EX}$ conditional inequality, assuming $C = 1$, and using the upper limit of the $\eta_{EX} \leq 0{,}9 \cdot \eta_I$ conditional inequality, Equation 4-b reduces to a single-variable expression.

$$OF = f^*(c)$$

Equation 6-a: Maximize

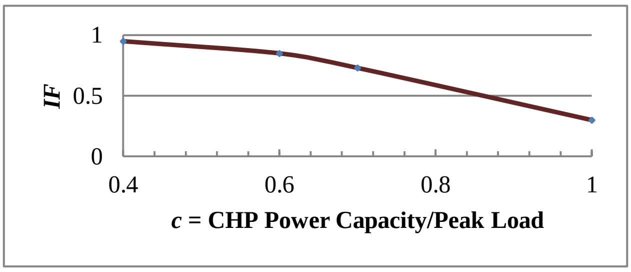

Figure 6: Approximate change of IF with (c)

Provided that for gas engines (c) must be greater or equal to 0,4, Equation 6-b gives the initial solution:

$$\frac{dOF}{dc} = 0$$

Equation 6-b

<u>Constraints of the nexus:</u>

$\eta_I \geq 0{,}80$,

$0{,}4 \leq c \leq 0{,}75$, $0{,}7 \leq IF \leq 1$,

$\Psi_R \geq 0{,}6$, $CO_2 \leq CO_{2base}$.

Once the optimal (*c*) value is determined, the CHP system may be cascaded, in optimal numbers and individual capacities depending upon the daily-averaged hourly load profiles. In general, the first cascade is allocated to the minimum continuous load (24 hours a day), the second one is sized such that it operates about 16 hours a day between its full capacity and 60% capacity, and the remaining one(s) are sized for peaking purposes such that they operate about 8 hours a day between full capacity and 75% capacity. Extreme caution must be exercised for these practical set of capacities and cascading schemes. Instead, they must be selected after an hourly load-based economic analysis, with an objective of achieving a simple return period of at most four years.

3.2 Automation

Without a dedicated general automation system, a 4DE system will not operate successfully. A novel automation system was developed for the ESER LEED Platinum Building in Ankara Turkey, keeping in mind that the same algorithm is expandable to the district level. A green and hybrid electromechanical system consists of several energy sources, energy conversion systems, and varying time based performance values, as a requirement of the system. Eser Green Building is also designed and constructed as a high performance green building and has various green and hybrid systems incorporated within its electromechanical structure. The building has platinum certification from LEED. Winter and summer operation diagrams of ESER Green Building are given in Figure 1 and Figure 2. It is almost impossible for these different systems to work together in harmony and supply various energy and power demands of the building and achieve the desired energy savings with the use of the existing Building Management Systems. An automation algorithm for high performance buildings, based on exergy balance between supply and demand was developed. This software is called as “Rational Exergy Automation (AEO) Program”. The main objective of the algorithm is to deliver exergy from on-site sustainable systems and other equipment to various demand points with maximum supply and demand exergy balance. Increasing the balance reduces exergy destructions and thus compound CO_2 emissions. The method is based on Rational Exergy Management Model (REMM).

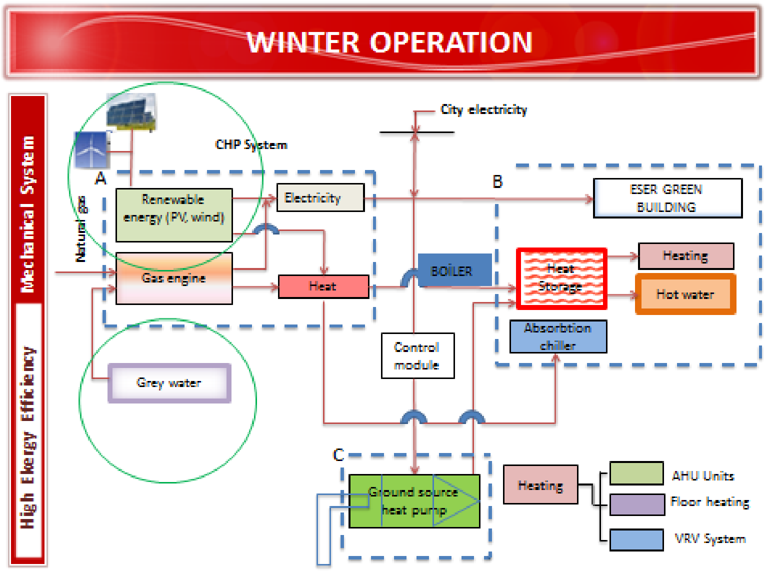

Figure 7: Winter operation scheme for the district

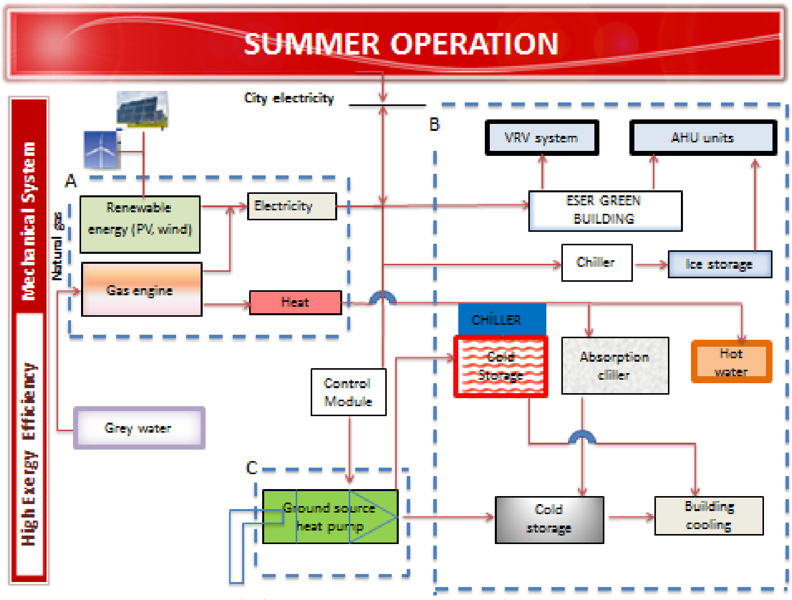

Figure 8: Summer operation scheme for the district

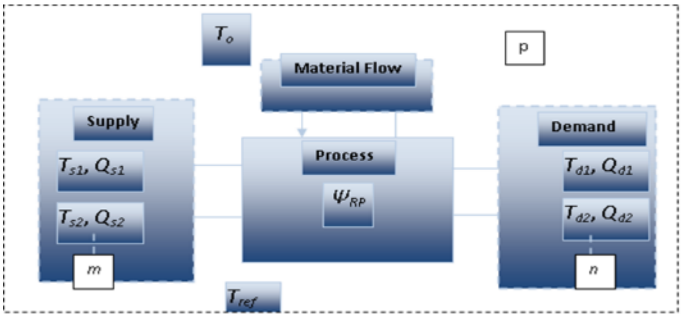

Figure 9: Basic REMM Block

$$\overline{\Psi}_R = \frac{\sum \Psi_{ij} \times \frac{Q_{ij}}{\eta_{ij}}}{\sum \frac{Q_{ij}}{\eta_{ij}}}$$

Equation 7

Equation 7 gives the overall REMM efficiency of the district with *m* supply points and *n* demand points. If there are a colocation of sub-districts, then *p* is the number of sub-districts.

4. CONCLUSIONS

n this paper the importance of exergy rationality in net-zero or near-zero buildings connected to 4DE systems was discussed and new definitions were made. It has been shown that net-zero or near-zero exergy building definitions are more realistic and definitive compared to the DOE definition. In the same token, CO_2 emissions need to be calculated according to both First and Second Laws of thermodynamics. In this respect a new zero carbon definition was also made, which supersedes previous definitions, being developed only in terms of the First-Law.

5. SYMBOLS

c	Ratio of the selected CHP power generation capacity to the peak power demand
c_i	Unit CO_2 emissions of any fuel combustion (*i*), kg CO_2/ kW_h-h
C	Power to heat ratio of CHP, dimensionless
CHPEη	Partial electrical power generation efficiency of CHP, dimensionless

$CHPH\eta$	Partial thermal power generation efficiency (including steam) of CHP, dimensionless
CO_2	Carbon dioxide emission, kg CO_2
EDR	Ratio of carbon CO_2 emissions difference to the base emission, dimensionless
E_x	Exergy, kW or kW-h
IF	Operating factor, dimensionless
OF	Objective function, dimensionless
PES	Primary energy savings percentage (According to Rational Exergy Management Model, REMM)
Q	Thermal load, kW-h
$RefE\eta$	Reference value for partial power generation efficiency of CHP, dimensionless
$RefH\eta$	Reference value for partial thermal generation efficiency of CHP, dimensionless
T	Temperature, K

<u>Greek Symbols</u>

$\mathrm{Ref}\psi_R$	Reference value of ψ_R, 0,2
η	First-law efficiency, dimensionless
η_{EX}	Second-law efficiency, dimensionless
η_T	Power transmission and distribution efficiency (Equation 2-a)
ψ_R	Rational exergy management efficiency, dimensionless
ε_{dem}	Unit demand exergy, kW/ kW, or kW-h/ kW-h
ε_{des}	Unit destroyed exergy, kW/ kW, or kW-h/ kW-h
ε_{sup}	Unit supplied exergy, kW/ kW, or kW-h/ kW-h

<u>Subscripts</u>

$_E$	Electric
$_H$	Thermal
$_{l,\ m}$	Local power plant, distant power plant, respectively
$_P$	Peak
$_{ref}$	Reference
$_{sup}$	Supply

<u>Superscripts</u>

j, l	Correlation parameters in Equation 4-b

Abbreviations

ABS	Absorption chiller
AFT	Adiabatic flame temperature, K
AC	Air conditioning
ADS	Adsorption chiller
CHP	Combined heat and power
CWT	Cold water tank
DHW	Domestic hot water
DOE	US Department of Energy
HVAC	Heating, ventilating, air-conditioning
HE	Heat Exchanger
HWT	Hot water tank
IT	Ice tank
LowEX	Low-exergy
Mtoe	Megaton of oil equivalent (According to First Law)
MtoEX	Megaton of oil equivalent exergy (According to Second Law)
nZCB	Near-zero carbon building
NZCB	Net-zero carbon building
NZEXD	Net-zero exergy District
NZEXB	Net-zero exergy building
nZEXB	Near-zero exergy building
OF	Objective function
ORC	Organic Rankine cycle
PV	Photo-voltaic
PVT	Photo-voltaic-thermal
PVTC	Photo-voltaic-thermal-cooling
PHVT	Photo-thermal-voltaic-heat
REMM	Rational Exergy Management Model
TES	Thermal energy storage

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