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AN OPTIMUM DEEP SUSTAINABILITY RETROFIT DESIGN ALGORITHM USING RATIONAL EXERGY MANAGEMENT MODEL: AMSTERDAM SCHIPHOL AIRPORT CASE

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ABSTRACT

The objective of this paper is to demonstrate how the Rational Exergy Management Model (REMM) may be instrumental in optimizing a deep retrofit of an airport in order to upgrade it to the newly defined Nearly-Zero Exergy Airport (nZEXAP) status. The new definition encompasses four components of renewables, subject to FAA regulations for flight, landing, and take-off safety. These are namely solar, wind, ground, and biomass. This model was applied to the Amsterdam Schiphol *Airport and it has been found that the airport may be optimally transformed to the nZEXAP status by improving its current situation of almost zero share of renewables to 70% of the total exergy input at winter design conditions and 60% at summer design conditions from onsite renewable energy resources and sustainable systems.* The paper provides the fundamentals of REMM, the new nZEXAP concept with its new definitions and metrics along with an optimum design of Amsterdam Schiphol Airport in The Netherlands.

INTRODUCTION

This paper introduces the Nearly-Zero Exergy Airport (nZEXAP) concept that brings an energy, environment, and economy nexus to a common basis using the Second-Law of Thermodynamics. An nZEXAP airport has a district energy plant of its own, which receives at least 70% of the total exergy input at winter design conditions and 60% at summer design conditions, from onsite renewable energy resources and sustainable systems. These numerical criteria are consistent with the fact that especially ground heat, and solar heat have low exergy, compared to fossil fuels, and solar and wind energy applications in airports are limited. This definition is the basis of the new optimum plant design model for satisfying these new conditions with the least cost that is attributed to the cogeneration (aka CHP) system using an optimum mix of fossil and alternative fuels, such as on site-produced biogas. The main renewable exergy inputs are biogas, ground heat, building integrated or attached PV, and waste heat. Extensive use of on-site wind and roof-top or on-land type of solar applications are limited in compliance to Federal Aviation Administration (FAA) regulations against glint and glare to pilots and air traffic controllers besides potential electromagnetic hazards on avionics. The exergetic performance of the airport district plant is defined and analyzed with the use of the Rational Exergy Management Model (REMM). New exergy metrics for the performance analysis and rating of nZEXAP airports, based on energy, economy, and environment nexus were also developed. The optimization problem has three primary design variables, namely the ratio of the optimum cogeneration engine

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capacity to the peak power load, the split of the generated power supply between the airport and the ground-source heat pumps, and the natural gas to biogas mixing ratio. The objective function solves the primary design variables by a simple search method. The new tool was applied to a conceptual study for the Amsterdam Schiphol Airport in order to compare the impact of an nZEXAP design with the ongoing deep retrofit work. Amsterdam Schiphol Airport aims to make its own activities climate neutral and to generate 10% of its own energy sustainably by 2020. In this comparison, the relative impact of the biogas share, solar input, size and performance of the ground-source heat pumps, and the power-to-heat ratio of cogeneration and absorption cooling were investigated. The results indicate that with the new optimization model, nZEXAP objectives may be satisfied, if techno-economic constraints are also satisfied. Further refinements in the definition may be needed in order to incorporate economic aspects.

METHOD

The objective of this research is primarily to develop a dedicated optimization model for the plant of district energy systems in airports. Airports face several restrictions about the utilization of renewables, especially solar and wind. Other optimizable components of such a district energy system, such as the energy and power distribution and collection piping and the grid may be designed by the First Law. The demand side is mainly a matter of nZEB design. Both latter cases are sufficiently covered in the literature, even with a certain amount of exergy analyses (LowEX buildings). Therefore, a core model is essential for the optimization of the plant itself, which must respond to the demand profiles both energetically and exergetically. This core model also needs to be flexible and expandable to other DE applications with more solar and wind energy contributions in the built environment. Such a fundamental core model is expected to advance the sustainable airport district energy systems with Exergy-based principles and new metrics. In this token, one of the other objectives is to introduce new exergy-based metrics or design and evaluation tools. For such a model, the Rational Exergy Management Model (REMM) is to establish the background platform.

Based on the three elements of the nexus, an exergy-based district plant optimization model was developed, which is shown in Figure 1. By recognizing the wind and solar system limitations mainly based on aviation reliability and security, in airports, CHP (Combined Heat and Power), GSHP (Ground-Source Heat Pump, ABS (Absorption cooling that may also include adsorption cycle), TES, and IT (Ice tank for cold storage) are the major components of the optimization model at the plant level. In this model, natural gas is a transition fuel, mixed with biogas, for decarbonization Soltero et al. [Soltero et al., 2016] towards 100 % renewable in district energy systems [Markovska et al., 2016]. Biogas intake at an exergy of EXBG is the starting point of the solution in the model, i.e. it is known for the given biogas potential of the airport itself, because waste intake from outside the airport boundaries is not permissible due to security measures. Another study [Taseli, B. and Kılkış B., 2016] has revealed that the cost effective and technically optimal biogas mix with natural gas is about 30% for similar commercial complexes. This mixing ratio then shows the amount of the necessary natural gas intake, EXNG. For a known CHP characteristic and partial efficiencies, the CHP size for the fuel intake is optimally found. The term c in Figure 1 represents the ratio of the selected CHP plant capacity to the peak power demand of the district. The term X is the power split ratio between GSHP and other services at the airport. The biogas production capacity is estimated first. Then, the optimum fuel mix in terms of the ratio of natural gas to biogas, denoted by the symbol m is determined. Because X is related to m, the optimum X value is thus obtained. Finally, the optimum c value is calculated. Other sustainable systems in the model, such as ABS, GSHP, TES, and IT are solved from the First-Law. In this model, Solar PV systems are mainly limited to vertical walls of the airport buildings in order to minimize the glint and glare not only to pilot eyes but also to air-traffic controllers. Some roof-top PV units are permitted, which is subjected to the scrutiny of glare risk calculations.

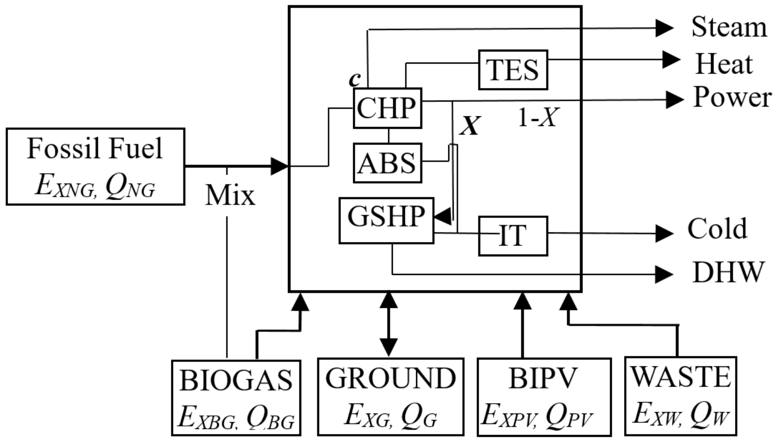

Figure 1. Base model for the exergy-optimum district energy power plant in nearly-zero or Net- zero exergy airports (nZEXAP, NZEXP). *c* and *X* are the main parameters of optimization.

The objective functions for the summer (OF_{1c}) and winter (OF_{1h}) operation periods were developed in the following format:

$$OF_{1h} = \frac{E_{XBG} + E_{XG} + E_{XPV} + E_{XW}}{E_{XNG} + E_{XBG} + E_{XG} + E_{XPV} + E_{XW}} \geq 0.7 \quad , \qquad \{\text{Maximize in heating season}\} \qquad (1\text{-a})$$

$$OF_{1c} = \frac{E_{XBG} + E_{XG} + E_{XPV} + E_{XW}}{E_{XNG} + E_{XBG} + E_{XG} + E_{XPV} + E_{XW}} \geq 0.6 \quad . \qquad \{\text{Maximize in cooling season}\} \qquad (1\text{-b})$$

RESULTS AND DISCUSSION

The new REMM-assisted exergy model was applied to the Amsterdam Schiphol Airport to obtain key findings for the sample design. The envisioned central district energy system with renewables and a cogeneration plant with ground-source heat pumps and thermal storage is shown in Figure 2. The model inputs are given in Table 1 upon which several scenarios were considered. The sample results of the analyses based on the objective functions are given in Figures 3 and 4. Here, *a* and *b* are weighing functions for OF_1 and OF_2, where OF_2 is the performance objective of the cogeneration plant.

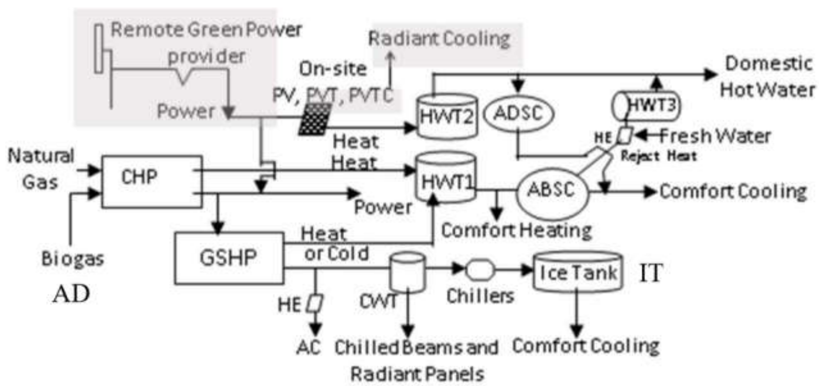

Figure 2. Envisioned Central District Energy System for Schiphol Airport.

Table 1. Model Inputs for the Schiphol Airport.

Exergy Intake	***Q***, MW$_h$ (thermal)		***T***, K	*ε*, W/W	***E$_x$***, MW (Thermal except PV systems)		**Comments**
Natural Gas, *NG*	Low Case	High Case	2200	0.87**	Low Case	High Case	Q_{NG} is $m \cdot Q_{BG}$. Here sample m* is taken 3 for low case and 0.73 for the same total Q for *NG* and *BG*. $\{m \leq 7\}$
	3.42	1.93			2.97	1.68	
Biogas, *BG*	1.14	2.63	2200	0.87	0.99	2.28	Q_{BG} is calculated from Airport biogas capacity (Section 7.2).
NG+BG	4.56	4.56			3.96	3.96	
Ground Heat, *G*	0.876	2.00	293	0.034	0.030	0.068	$Q_G = (COP\text{-}1) \cdot \boldsymbol{X} \cdot P_{eBG}$
Solar, *PV* (All derivatives)	na		na	1	3.55 (electric)		Limited by FAA rules.
Waste, *W*	1.5		293	0.034	0.051		Thermal waste only from the airport complex and the district plant.

*Natural gas to biogas mixing ratio. ** T_{ref} is 283 K.
The average *COP* for GSHP in the winter season is assumed to be 4. ***X and *m* are optimization variables. For the numerical demonstration purposes of this table, sample value for *X* is 0.4.

For the numerical example given above in Table 5 with demonstrative values for $m = 3$ and 0,7,

$OF_1 = (0.99+0.030+3.55+0.051)/(2.97+0.99+0.030+3.55+0.051) = 0.61$, {Low Case}

$OF_1 = (2.28+0.068+3.55+0.051)/(1.68+2.28+0.068+3.55+0.051) = 0.78$. {High Case}

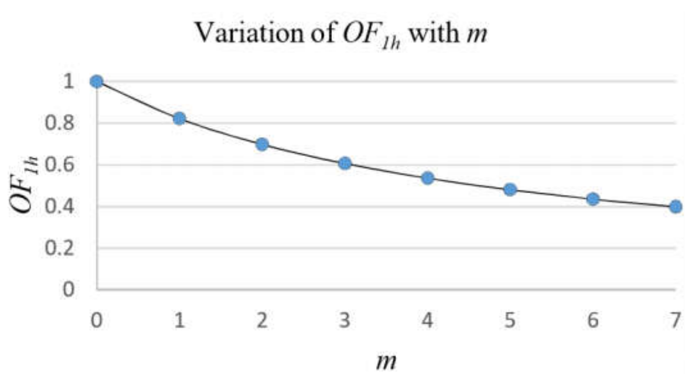

Figure 3. Maximum OF_{1h} with m, natural gas to biogas mixing ratio without OF_2 considered.

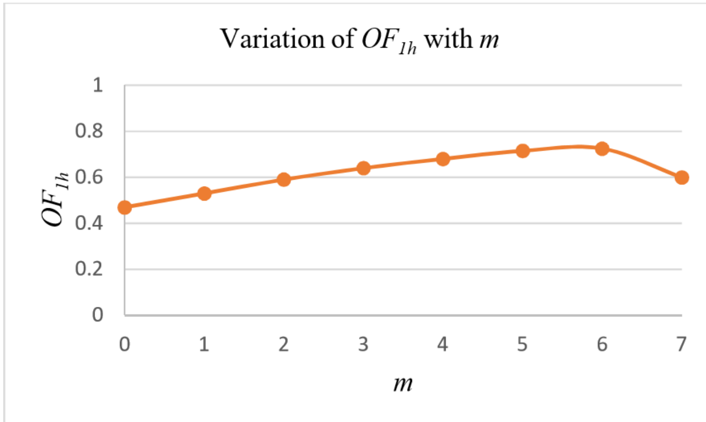

Figure 4. Maximum OF_{1h} with m, natural gas to biogas mixing ratio with OF_2 considered in equal weight (a = b = 0.5)

CONCLUSIONS

In this paper, the importance of exergy rationality in net-zero or nearly-zero buildings that are connected to 4DE (4th generation district energy) systems was discussed and new definitions were put forth in the context of the nZEXAP concept for airports. It has been also shown that net-zero or nearly-zero exergy building definitions are more realistic and definitive compared to net-zero energy definitions [DOE, 2015]. In the same token, CO_2 emissions need to be calculated according to both the First and Second-Laws of Thermodynamics. In this respect, a new zero carbon definition is also proposed, which supersedes previous definitions, being developed only in terms of the First-Law. In addition to the current optimization algorithm, some more optimization tasks await at the buildings side of an nZEXAP airport. Especially for new airports, or deep renovation projects of terminal projects, there exists a chance to further optimize the heating and cooling heat transfer optimization: Lower the heating fluid temperature demand or higher the cooling temperature demand from the GSHP, the *COP* of the heat pump increases. This brings the importance of LowEx buildings forward. However, higher or lower the fluid temperature in cooling or heating, respectively, the temperature drop between the supply and return fluid temperature needs to be smaller, like in chilled beams versus fan-coils, such that pumping size and cost increase and usually heating or cooling equipment must be oversized. These costs factors and exergy inputs and output to from GSHP, pumps, and oversizing establish a challenging optimization problem. But the result will be rewarding [Kılkış et al., 2017].

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