Energy and Exergy Analysis of Integrated Systems of Buildings and District Energy Plants

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ABSTRACT

The purpose of the paper is to influence governments throughout the world to achieve massive improvements in energy and exergy performance in their respective countries by legislation and other policy instruments keyed to the overall or integrated energy and exergy performance of energy transformation systems.

Energy transformation systems include: all types of buildings; electric, heating, and cooling district power plants; water treatment plants, energy and water distribution systems; cars, trucks, buses, motorcycles, trains, planes and other powered transportation systems; and manufacturing processes.

As a first step, governments should require that buildings, power plants, and distribution systems be designed based on forecasted energy and exergy performance and that actual performance be continuously monitored.

This paper simulates the integrated energy and exergy performance of a building and district power plant under three different operating conditions to illustrate the value of this methodology. Only electric, heating, cooling, lighting, and electric loads are considered.

Prevailing practices measure energy performance of isolated energy systems. For example, heating efficiency, cooling efficiency, and lighting efficiency are computed separately. The simulation demonstrates that this policy is seriously flawed.

KEYWORDS

government regulation, energy efficiency, exergy efficiency, efficiency monitoring

GOVERNMENT OBLIGATION TO MAXIMIZE ENERGY & EXERGY EFFICIENCIES

Governments have a fundamental and immutable obligation to their citizens and to the entire planet to ensure that the construction and operation of buildings, transportation vehicles and systems, water treatment and power plants, and manufacturing process utilize energy in the most efficient manner possible.

Over the last few decades many authors have exhaustively detailed the reasons why government policy must ensure that the energy transformation systems listed above address both the quantity and quality (exergy) of energy performance[1,2,3,4,5,6,7]. This paper will demonstrate why it is necessary to consider the combined or integrated system energy and exergy performance of buildings and power plants.

COMPLICATING FACTORS FOR MEASURING INTEGRATED ENERGY AND EXERGY PERFORMACE

The 1st Law of Thermodynamics defines energy performance as: useful energy output/energy input. The 2nd Law of Thermodynamics defines exergy performance as: useful exergy output/exergy input. Several factors complicate the measuring of integrated energy and exergy performance. The current practice of separate energy and exergy performance ratings for heating, cooling, lighting, electrical, and other systems is a result of the failure to address these complications.

The 1st Law of Thermodynamics defines the performance of an energy transformation device as either *efficiency* or *coefficient of performance* (C.O.P). The performance of engines, motors, heaters, fans, pumps, generators, turbines, and transformers are rated in efficiency. The performance of refrigeration systems (reverse heat engines) are rated in C.O.P. The value of efficiency can never exceed one while the value of C.O.P. usually exceeds one. The C.O.P. of a reverse heat engine varies depending on its function, which can be heating (heat pump), cooling (refrigeration), or both. The energy input of a reverse heat engine providing simultaneous heating and cooling cannot be assigned solely to either heating or cooling system or evenly split. For example, a reverse heat engine may be required to operate at a higher input energy to accommodate a lower evaporator pressure or higher condenser pressure.

The operation of individual energy transformation devices will affect energy performance of other energy transformation devices and these effects will vary over time. For example, waste heat from a lighting system in a kitchen may decrease or increase the kitchen heating or cooling loads.

Mass flows of fluids, most notably air and water can be utilized to reduce or eliminate heating and cooling energy outputs of energy transformation devices. For example, in the summer, a manufacturing plant that uses both well water and outside air for its production process can simultaneously reduce heating and cooling equipment loads by heating the cold well water with hot outside air. This will increase both heating and cooling system energy and exergy performance.

A building and district power plant are an integrated system. Electric district power derived from wind, water, solar power, biomass, biogas, and other renewable sources are preferable to power derived from the earth's limited supply of fossil fuels. Cogenerating electric power plant energy performance will vary depending on how waste heat is used to produce district heating and/or district cooling. A few of the preceding complications will be addressed in the following simplified simulation.

SIMPLIFIED SIMULATION OF INTEGRATED SYSTEMS OF BUILDING AND DISTRICT POWER PLANT

Three different integrated systems of building and power plants were simulated at three different loading conditions or "states". The electric and lighting loads were held constant for all three states. State #1 has equal heating and cooling loads. State #2 has the same cooling load but a smaller heating load than State #1. State #3 has the same heating load but a smaller cooling load than State #1.

System #1 uses non-cogenerating district electric power and natural gas fired heating equipment in the building. System #2 uses non-cogenerating district electric power and building air conditioning condenser heat (reverse heat engine) and natural gas fired heating equipment to supply the heating load. System #3 uses electric, heating, and cooling energy from a cogenerating district power plant (*Figure #3*) for all building heating, cooling, and electrical power requirements. The waste heat from the cogenerating combustion turbine is used to power a two stage absorption chiller, which provides district heating and cooling. When the cogeneration plant is fully loaded, the energy output is 158 joules for every 100 joules input as compared to 32 joules energy output for a non-cogeneration electric district plant.

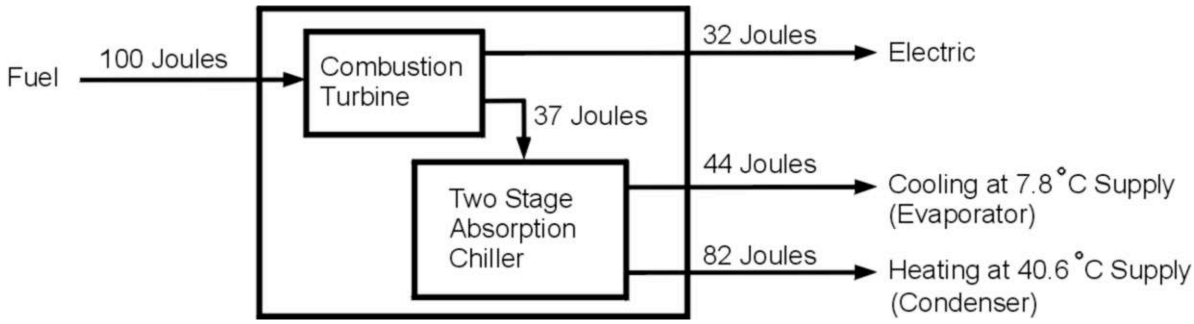

Figure #1: System #3 Cogeneration Power Plant

Refer to *Table #1* for the energy and exergy performance data for district electrical generation, district cogeneration, and building heating, cooling, and lighting systems used in the simulations.

Tables #2, #3, and #4 list the energy and exergy performance data for Systems #1, #2, and #3, respectively. The lighting and electric loads are the same for all systems so they are only shown in Table #1. The average integrated energy performance (η) and exergy performance (ψ) for System #1 over the three states are 61% and 18%, respectively. The average integrated energy performance (η) and exergy performance (ψ) for System #2 over the three states are 76% and 23%, respectively. The average integrated energy performance (η) and exergy performance (ψ) for System #3 over the three states are 118% and 35%, respectively. The importance of taking into account the district electric generation or cogeneration plant energy and exergy performance was documented in the International Energy Agency Annex 37 Guidebook Summary Report[8].

SUMMARY

As can be seen in *Tables #1, #2, and #3*, the integrated energy performance and exergy performance of the three systems vary considerably between the three states. <u>This means for an accurate comparison of integrated systems, the energy and exergy performance of systems must be evaluated at each state</u>. The operating energy and exergy performance of an integrated system can only be determined by evaluating performance at each operating state over a given time interval. Since the ambient conditions will affect equipment energy and exergy performance, this also must be taken into account in defining the operating state.

TABLE #1: Simulation Data

Performance Data for Building and Power Plant

Natural gas combustion equipment exergy (1000 °K heat transfer & 283°K ambient)	71.7%				
Natural gas fuel exergy grade function (exergy/fuel higher heating value)	93.0%				
Building ft^2	320,000				
Lighting watts input/building ft^2	1.2				
Lumens/watt (definition)	683				
Lumens/watt efficiency (building average)	70				
Average building lighting efficiency	10.2%				
Building system kW/ton (chillers, chilled & condenser water pumps, & tower fans)	0.8				
Building cooling system C.O.P.	4.39				
Building chiller condenser heat: evaporator heat (0.65 kW/ton)	0.18				
Electrical building equipment watt/ft^2	3.00				
	η	T_O °K	T_P °K	τ	ψ
Non-cogenerating power plant (32% efficiency) & distribution (94% efficiency): district electric	30.1%				28.0%
Combustion turbine cogenerating district electric, heating, & cooling: (34% electric efficiency); (93% distribution electrical efficiency) (37% heating efficiency)	31.6%				29.4%
Combustion turbine cogenerating district electric, heating, cooling: absorption cooling evaporator 6.1 °C supply chilled water; C.OP. 1.18 (distribution 96% efficiency)	41.9%				39.0%
Combustion turbine cogenerating district electric, heating, &cooling: absorption heating condenser 40.6 °C supply hot water; C.OP. 2.20 (distribution 96% efficiency)	78.2%				72.7%
Space heating (89 % condensing furnace or boiler)	89.0%	273	295	0.075	6.6%
Lighting (0.8% ψ; Energy and Power Needs and Availability in Housing, CMHC, Ottawa, 1993)	3.1%				0.9%
Space cooling (η, electric motor; ψ, Reistad, 1975)	90.0%	283	293	0.034	3.1%

To execute an effective energy policy, government policy should: (1) require designers of buildings and district power plants to forecast integrated energy and exergy performance over the expected range of operating states and to forecast the expected time at each state; and (2) require that the actual energy and exergy performance be recorded at each operating state (based on automation system trend data). Trend data has been readily available from building automation systems since 1992[9]. This policy will allow governments, businesses, and individuals to contract buildings and power plants based on energy and exergy performance.

TABLE #2: System #1 Energy and Exergy Performance

State	System #1: Building using non-cogeneration electric power and natural gas with no reverse engine heat recovery in building	1st Law of Thermodynamics			2nd Law of Thermodynamics		
		Fuel Input Power Watts	Useful Output Power Watts	η	Fuel Input Exergy Watts	Useful Output Exergy Watts	ψ
#1	Natural gas heating	3,160,421	2,812,775	89.0%	2,939,192	209,766	7.1%
	Electric cooling	2,364,066	2,812,775	119.0%	2,198,582	95,999	4.4%
	Electric lighting	1,276,596	39,356	3.1%	915,319	11,010	1.2%
	Electric equipment	3,191,489	960,000	30.1%	2,288,298	960,000	42.0%
	System total	9,992,572	6,624,905	66.3%	8,341,390	1,276,775	15.3%
#2	Natural gas heating	526,737	468,796	89.0%	489,865	34,961	7.1%
	Electric cooling	2,364,066	2,812,775	119.0%	2,198,582	95,999	4.4%
	System Total	7,358,888	4,280,926	58.2%	5,892,064	1,101,970	18.7%
#3	Natural gas heating	3,160,421	2,812,775	89.0%	2,939,192	209,766	7.1%
	Electric cooling	945,626	1,125,110	119.0%	264,533	38,400	14.5%
	System total	8,574,133	4,937,240	57.6%	6,407,342	1,219,175	19.0%

TABLE #3: System #2 Energy and Exergy Performance

State	System #2: Building using non-cogeneration electric power and natural gas with reverse heat engine heat recovery in building	1st Law of Thermodynamics			2nd Law of Thermodynamics		
		Fuel Input Power Watts	Useful Output Power Watts	η	Fuel Input Exergy Watts	Useful Output Exergy Watts	ψ
#1	Building heat recovery		2,812,775			209,766	
	Electric cooling	2,364,066	2,812,775	119.0%	2,198,582	95,999	4.4%
	System total	6,832,151	6,624,905	97.0%	5,402,199	1,276,775	23.6%
#2	Building heat recovery		468,796			34,961	
	Electric cooling	2,364,066	2,812,775	119.0%	2,198,582	95,999	4.4%
	System total	6,832,151	4,280,926	62.7%	5,402,199	1,101,970	20.4%
#3	Natural gas & building heat recovery	1,662,545	2,812,775	169.2%	1,192,045	186,692	15.7%
	Electric cooling	945,626	1,125,110	119.0%	264,533	38,400	14.5%
	System total			69.8%			25.7%
		7,076,256	4,937,240		4,660,195	1,196,101	

TABLE #4: System #3 Energy and Exergy Performance

State	System #3: Building using combustion turbine and 2 stage absorption cogeneration electric, heating, and cooling district power with no reverse heat engine heat recovery in building	1st Law of Thermodynamics			2nd Law of Thermodynamics		
		Fuel Input Power Watts	Useful Output Power Watts	η	Fuel Input Exergy Watts	Useful Output Exergy Watts	ψ
#1	District heating		2,812,775			209,766	
	District cooling		2,812,775			95,999	
	System Total	4,468,085	6,624,905	148.3%	3,203,617	1,276,775	39.9%
#2	District heating		468,796			34,961	
	District cooling		2,812,775			95,999	
	System Total	4,468,085	4,280,926	95.8%	3,203,617	1,101,970	34.4%
#3	District heating		2,812,775				
	District cooling		1,125,110				
	System Total	4,468,085	4,937,240	110.5%	3,203,617	971,010	30.3%

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