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Technical Report

Quantifying Potential of Integrated Energy Systems with a Varying Level of Nationwide Deployment

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ABSTRACT

The potential advantages that distributed energy resources (DER) offer over the current centralized model are in the areas of fuel efficiency, energy reliability, environment, and economics. It is this distinction that has prompted advancement of a wide spectrum of technologies in the DER portfolio, including power generation systems and thermally-activated equipment. However, in addition to technological advancements, the ultimate success of the DER concept also depends on a large-scale deployment of properly configured integrated energy systems (IES) that combine on- or near-site power generation devices and thermally-activated equipment for a broad range of applications.

This study presents a parametric assessment of the energy-saving potential resulting from a nationwide deployment of DER/IES technologies for building applications. Three hypothetical IES scenarios are evaluated to demonstrate the sensitivity of the national energy consumption to the IES system configuration with respect to the buildings' electrical and thermal equipment compositions. A variable for implementation level of DER is incorporated to examine the impact of incremental transformation of the existing centralized energy resources to a fully decentralized model on the national primary energy consumption. To accommodate the continuing advancement of prime movers, a wide range of fuel-to-electricity conversion efficiency is considered for both centralized and decentralized power generation systems. The fact that the demands for electricity and thermal energy in buildings are not always congruent, and implementation of thermal energy storage technology is uncertain is acknowledged by incorporating a variable waste heat utilization index.

The results indicate that DER/IES offers an opportunity for a significant reduction in the primary energy consumption even with moderate utilization of the waste heat resulting from on-site power generation. The conclusions also emphasize the need for strategic deployment of the DER/IES concept with respect to system configuration if the potential benefits are to be fully realized.

INTRODUCTION

The distributed energy resources (DER) program at the U.S. Department of Energy represents a collection of ambitious and synergistic efforts aimed at promoting efficient use of the national energy resources and providing a reliable supply of energy to the end-users. The need for such a program is echoed by the recent energy crisis in California and the rapid growth of the nationwide demand for energy. Development and deployment of efficient and environmentally sound integrated energy systems (IES) for buildings constitute important elements of the strategic plan for achieving the program objectives. Whether referred to as *cogeneration, combined heat and power (CHP),* or *building cooling, heating, and power (BCHP)*, integrated energy systems signify on-site or near-site power generation and utilization of the resulting thermal energy for building HVAC systems. This efficient utilization of energy is a distinguishing attribute that renders the IES concept a promising alternative to the centralized energy resources that are characterized by their inefficient use of fossil fuel and high emissions. The current central power generation and distribution system (Figure 1) offers a low efficiency of slightly higher than 30%, leading to a loss of nearly 70% of the primary energy input. In contrast, optimally designed integrated energy systems for buildings can yield overall energy efficiencies greater than 80%[1].

It is envisioned that "*By the year 2020, Building Cooling Heating and Power (BCHP) will be the preferred method of energy utilization in buildings*" [1]. This long-term goal presents challenges to the engineers and researchers in developing cost-effective components for integrated energy systems that are essential if the IES concept is to be widely accepted in the market. The ongoing research and development activities for advancement of power generation and thermally-activated systems are reflective of an ambitious plan undertaken by the Department of Energy and the stakeholders. However, the R&D efforts alone will not guarantee a complete success of the DER initiatives without direction and guidance from the leaders and policy makers. One of the areas demanding attention from the leadership is the assessment of the potential of the nationwide IES deployment. This is due to the diversities inherent with the integrated energy systems and the complexities involved in their selections that can collectively affect the overall outcome with respect to energy, economics, and environment.

It is the intent of this study to evaluate the potential benefits of deploying the IES technologies as their expansion progresses in the domain of the centralized energy resources and beyond. This study is in line with the mission of the DER program, which encompasses documentation of energy-related benefits associated with the development and deployment of distributed energy resources [2]. The analysis presented here is parametric and exploratory in nature due to the absence of the necessary data. Examination of various "what-if" scenarios encompassing both central energy resources and DER concepts is facilitated by allowing variation in utilization of waste heat and in the extent of IES implementation across the nation. The scope of this paper is confined to evaluation of only the energy consumption for the buildings, commercial and residential. The primary energy consumption profile for the U.S. buildings certainly reflects the magnitude of the potential growth for this technology. In the year 1999, the buildings share of the national primary energy consumption was 36%, which is projected to remain about the same for the year 2010 and 2020 [3]. The buildings share of U.S. electricity consumption is predicted to increase from 67% for the year 1999 to 70% for 2020. The significant building share of the U.S. energy consumption has a great economic implication considering that the 1999 U.S. buildings energy expenditures were $234.2 billion, excluding the costs of wood and coal [3]. This study will serve as the basis for the future studies, which will accommodate the environmental and economic perspectives as well.

DESCRIPTION OF METHOD

To investigate the full potential of the IES technology, three hypothetical scenarios (A, B, and C) are considered for a wide range of on-site power generation efficiencies. As illustrated in Figure 2a, scenario "IES-A" is based on the assumptions that 1) all existing

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[1] This is a first-law efficiency that does not differentiate thermal energy from electrical energy.

electrical equipment including the HVAC and water heating devices are retained, 2) the entire demand for electricity is met by on-site power generation, and 3) the recoverable thermal energy is used to fully or partially offset direct fossil fuel consumption for space and water heating purposes. On the other hand, the intent of scenario “IES-B,” as depicted in Figure 2b, is to limit the use of electricity to lighting and the other electrical devices excluding HVAC and water heating systems. Therefore, in this scenario, all space heating and cooling and water heating systems are assumed to be driven entirely or partially by the recoverable heat from the on-site power generators. At times of insufficient waste heat, auxiliary gas/oil-fired burners provide the balance of the thermal energy requirement in this scenario, which leads to a greater direct use of fossil fuel compared to “IES-A.” Finally, scenario “IES-C” presents a combination of the first two depending on the amount of the available thermal energy, which is negatively correlated with the power generation efficiency. In this scenario, the electric HVAC equipment remain intact if the waste heat from the hypothetical power generation that supplies electricity to non-HVAC equipment (lighting and other) is insufficient to operate thermally-activated HVAC equipment. In this case, only electric water heaters are converted to thermally-driven types utilizing the exhaust heat from the prime movers which is the only factor differentiating from IES-A. The occurrence of this case becomes more likely as the power generation efficiency increases. Otherwise, in the presence of adequate thermal energy from the prime movers, scenario IES-B goes into effect. Table 1 characterizes these three IES scenarios along with the central system.

Hypothetical replacement of the existing HVAC and water heating equipment with thermally-driven systems necessitates assumptions on the national average performance indexes for the building systems. These assumptions combined with the availability of the current primary energy consumption data for equipment facilitate estimating the energy requirements under the different IES scenarios. The postulated values for the performance parameters are provided below.

- The maximum possible recoverable heat is 80% of the waste energy from the prime movers. This assumption stems from the notion that 1) recovery of certain energy losses (such as radiation and vibration) from the prime movers is either impossible or impractical and 2) thermal losses occur in capturing and transferring the thermal energy to the equipment.

- Considering that both electrical furnaces and heat pumps are used for space heating, the equivalent coefficient of performance (COP) for the space heating equipment is assumed to be 1.5 in conjunction with the available data [3]. The accuracy of this assumption is not critical because the primary energy consumption associated with the electrical space heating is about 7% of the national total consumption under the centralized power generation model. (For instance, an error of about 20% in this assumption will result in a maximum error of about 1% on the overall primary energy consumption of scenario IES-B.)

- All heating devices using fossil fuels (e.g., gas-fired heaters) have an efficiency of 80%.

- The average cooling COP is 0.8 for absorption cooling systems and 3.2 for the electrical vapor compression systems.

It should be pointed out that any possible overestimation of the effective COP for the electrical heat pump/furnace and the efficiency for the fossil-fuel driven heaters yields a higher-than-the-actual space heating load that is equivalent to underestimation of the thermal energy availability from the distributed power generators.

In any IES system, the recoverable heat from the prime movers cannot be entirely utilized due to 1) presence of temporal gaps between the demands for electrical and thermal energies and 2) a possible mismatch between the generator exhaust temperature and the operating temperature of the thermally activated equipment. In theory, the usable thermal energy can vary from 0 to 100% of the maximum recoverable heat. (Note that without any significant amount of usable thermal energy, IES is basically reduced to a distributed generation (DG) system.) *In this study, a parameter labeled "Potential Waste Heat Utilization Factor" is defined to represent the average usable portion of the maximum recoverable thermal energy from the power generation exhaust heat.* This parameter is allowed to vary from 0.4 to 1. (A value of 0.6, for instance, represents less than 50% of the power generation waste heat.) A high value of near unity for this factor is feasible with properly configured integrated energy systems and optimum utilization of thermal energy storage (TES) technology, which is not likely to occur as a national average. (Reference [4] has examined the role of TES in integrated energy systems.)

Another variable applied in this study is the hypothetical nationwide implementation level of the DER/IES concept that ranges from 0 to 100%, corresponding to all-central to all-DER models, respectively. Currently, the level of implementation is insignificant but is expected to increase as the IES technologies capture a larger share of the energy resources market. In essence, consideration of this parameter with the prescribed range facilitates evaluation of the short-term to long-term prospects of the DER expansion.

RESULTS AND DISCUSSIONS

The results and discussions presented here are based on the primary energy consumption data for the year of 1999 obtained from the Core Databook [3]. The data projected for the year 2000 are about the same. The energy quantities are expressed in quads (1 quad = 10^{15} Btu = 2.93×10^{11} kWh).

Energy consumption of building equipment

Figure 3 provides a comparison of primary energy consumption for various building equipment and the data required for evaluating the potential of deploying the IES concept. As seen in this figure, space air conditioning comprises about 36% of the total building energy consumption (25% for heating and 11% for cooling). With the water heating included, up to 48% of the total equipment energy demand could be potentially met by the recoverable heat from the on-site power generators should the current centralized energy distribution format be shifted to an entirely DER/IES model. This hypothetical alteration would necessitate modification of the existing HVAC and water heating systems to facilitate waste heat utilization. The label "other" in Figure 3 lumps together all energy requirements for other equipment including refrigeration, cooking, and electronic devices. In addition to HVAC systems, refrigeration presents another opportunity for using recoverable waste heat as the driving energy, which is not covered in this study. Figure 3 also indicates significant market growth potential for efficient absorption (thermally-activated) cooling systems, as nearly 100% of cooling is currently provided by electrical equipment.

Impact of modernizing central plants

The existing central power plants deliver electricity to the building sites at an overall fuel-to-electricity conversion efficiency of about 31% [3]. This represents a loss of nearly 70% of the total primary energy input at the power plants. The continuous need for replacement of the aging plants and the growing demand for electrical energy provide an opportunity for implementing advanced technologies such as combined power cycles and fuel cells. By taking advantage of this opportunity, the average central power generation efficiency can be significantly increased over the next two or three decades. Figure 4 demonstrates the impact of incremental improvement of the average efficiency from the current level of 31% to 50%. At the upper limit, a reduction of 23% in the total energy consumption can be realized. As shown in Figure 4, while the primary energy consumption for electrical power generation decreases with the increasing efficiency, the quantities for direct use of natural gas and other fuels remain intact. It should be pointed out that, with the current technology, combined power cycles can attain efficiencies approaching 60% [5]. Therefore, achieving an overall efficiency of 50% (including all losses) is quite feasible with full modernization of the central power plants.

Performance of DER/IES model

Evaluating the potential of the IES concept is a more complex task due to the diversity in the IES system configurations, difficulties in quantifying the actual use of the recoverable heat, and the market share of the technology. However, performance evaluation of the IES scenarios is facilitated via parametric analyses covering a wide range of "what-if" circumstances.

Shown in Figures 5a, 5b, and 5c are the primary energy consumption of the integrated energy systems corresponding to the three scenarios, IES-A, B, and C, respectively, when the fuel-to-electricity conversion efficiency of the prime movers is 25%. (Currently, microturbines equipped with recuperators offer efficiencies in the range of 23% to 27%. The efficiencies of large gas turbines can exceed 40%, especially with inlet air cooling.) The results are shown for potential waste heat utilization factors ranging from 0.4 to 1 and for different levels of market penetration, from 0 (all-central) to 100% (all-IES). (As stated earlier, a heat utilization factor approaching unity is representative of an ideal arrangement that incorporates a perfect thermal energy storage capability.) When fully adopted, both IES-B and IES-C (Figures 5b and 5c) yield a maximum energy reduction of about 30%, whereas IES-A (Figure 5a) provides less than 10% reduction. Comparison of Figures 5b and 5c indicates that, for heat utilization factors of less than 0.6, scenario IES-C is more attractive than scenario IES-B from the energy standpoint. The insensitivity of the energy consumption for IES-A to the waste heat utilization (Figure 5a) is indicative of the availability of the waste heat in excess of the thermal energy demand even at the lowest waste heat utilization factor (0.4) considered.

Referring to Figures 6a, 6b, and 6c, significantly different performance characteristics are observed for the three IES scenarios when the on-site power generation efficiency is increased to 40%. With the increased efficiency, IES-A and C are considerably more attractive than IES-B. Figure 6a reveals that IES-A reaches its full potential at the waste heat utilization factor of 0.8 (or less), which marks occurrence of excess availability of heat. Note that both IES-A and C are identical in energy use for the waste heat utilization factors of up to 0.8. However, IES-C becomes more efficient when the heat utilization factor exceeds 0.8. The justification for this observation lies with the criteria for configuration selection of IES-C (Table 1). As seen in Figure 6c, compared to the existing central system, IES-C offers a potential reduction of more than 40% in the energy consumption as it requires less than 20 quads of primary energy under full deployment and maximum waste heat utilization. Examination of Figures 5 and 6 points to the positive impact of the increased power generation efficiency (from 25% to 40%) on the energy consumption. (A similar conclusion is drawn in a previous study [6], which has addressed the role of power generation efficiency in the overall performance of BCHP systems.)

Figure 7 provides comparisons of the energy requirements for the central and IES systems for a wide range of power generation efficiencies when the waste heat utilization factor is 0.60 for the IES models. Note that, in this figure, the power generation efficiency of the central system is allowed to vary in correspondence to that of the IES systems. Except for low efficiencies, IES-A and C offer substantial reduction in the primary energy consumption with respect to IES-B and especially in comparison with the centralized energy model performance.

Shown in Figures 8a, 8b, and 8c are the compositions of the energy resources allocated for power generation and direct use as functions of the power generation efficiency for the three IES scenarios. These figures indicate that, as the power generation efficiency increases, the primary energy use for electricity decreases while the direct use of the fossil fuel increases. Considering these figures and Figure 4, it is evident that the direct use of fossil fuel for scenario IES-B is the highest among the models considered. It should be pointed out that the energy reduction quantities shown in Figures 8a, b, and c are obtained with respect to the primary energy consumption of the existing centralized system. The efficiency range (up to 50%) used in these figures is reasonable given the recent advancements in the power generation technologies including combustion engines and fuel cells [7].

CONCLUSIONS

Through parametric analyses, the potential of integrated energy systems in terms of reduction in the primary energy consumption at the national level was quantified and discussed. Consideration of three hypothetical IES scenarios for DER along with the centralized energy resources formed the basis for this study. The first scenario allowed retention of the existing electrical HVAC and domestic hot water systems and facilitated use of recoverable thermal energy for gas/oil-fired equipment. In the second scenario, all HVAC and hot water systems were hypothetically replaced with equivalent thermally-activated equipment that operated with the recovered waste heat of the on-site power generators. Auxiliary burners were incorporated to meet the required energy input in case of insufficient recoverable thermal energy. The third presented a combination of the first two scenarios.

To accommodate the evolving nature of the DER technologies and their continuing expansion in the energy resources market, a number of parameters were adopted in this study: 1) the fuel-to-electricity conversion efficiency of power generators for both on-site and central systems, 2) the potential utilization of the recoverable thermal energy, and 3) the degree of expansion of DER in the nation. Allowing variation of these parameters permitted "what-if" analyses for evaluation of near-term and long-term prospects of DER.

The results indicate an impressive opportunity for reduction in the national primary energy consumption by implementing the IES technologies. With optimum and full implementation of this concept, a reduction of more than 40% in the buildings primary energy consumption can be achieved with respect to the existing central model. Even with a moderate utilization of 60% of the recoverable thermal energy from the on-site power generation, the IES model is demonstrated to be superior to the hypothetically advanced central system from the energy standpoint. Significant reduction in the energy use is also synonymous with reduction in emissions, which is of great environmental importance. These benefits, along with the high degree of reliability in the energy supply, fully support the recent initiatives in accelerating the development and deployment of the IES technologies in the DER context.

Another conclusion that can be drawn from this study is the importance of optimum design of integrated energy systems with respect to the diversities in the building types and load characteristics. To maximize the benefits of the IES concept, advancement and incorporation of thermal energy storage technology have to keep the pace with the progress observed with the other aspects of the DER program.

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Table 1. Description of Central Power Generation System and IES Scenarios

Scenario	**General Characteristics**	**Waste Heat Recovery**
Centralized Model	• Central power generation • Existing building systems • Inherent transmission and distribution losses	• No waste heat recovery
IES-A	• No change in electrical systems • On-site power generation for 100% of electrical load	• Heat recovery for full or partial displacement of direct fossil fuel consumption • Equipped with auxiliary gas/oil-fired burners
IES-B	• Electrical HVAC and water heating devices replaced with thermally-activated types • On-site power generation for electrical demand for lighting and other electrical devices	• Heat recovery for thermally-activated HVAC and water heating equipment • Equipped with auxiliary gas/oil-fired burners
IES-C	• A combination of IES-A and B • IES-B with sufficient heat recovery from power generators meeting electrical load of equipment other than HVAC and hot water heating systems • Otherwise, IES-A with exception of replacing elect. water heaters with thermally-driven types	• Heat recovery for thermally-driven systems depending on IES configuration • Equipped with auxiliary gas/oil-fired burners

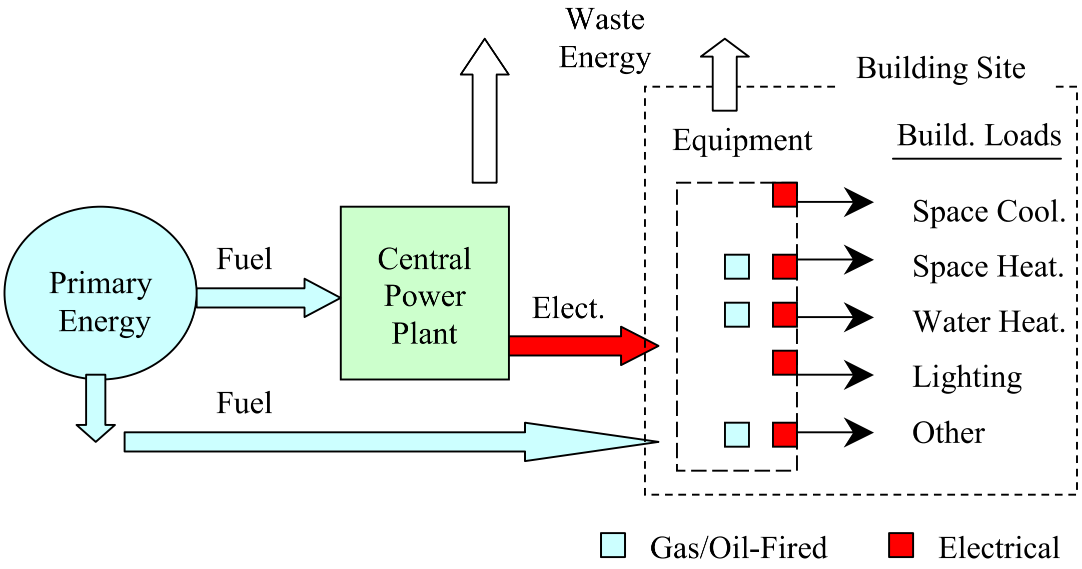

Figure 1. Schematic of centralized energy resources (Baseline).

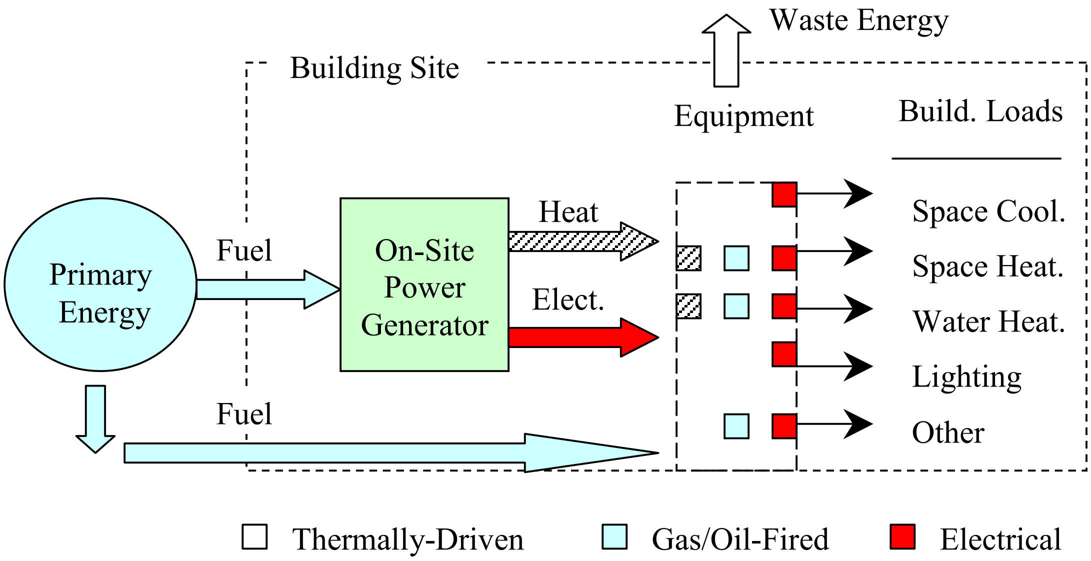

Figure 2a. Schematic of distributed energy resources, scenario "IES-A."

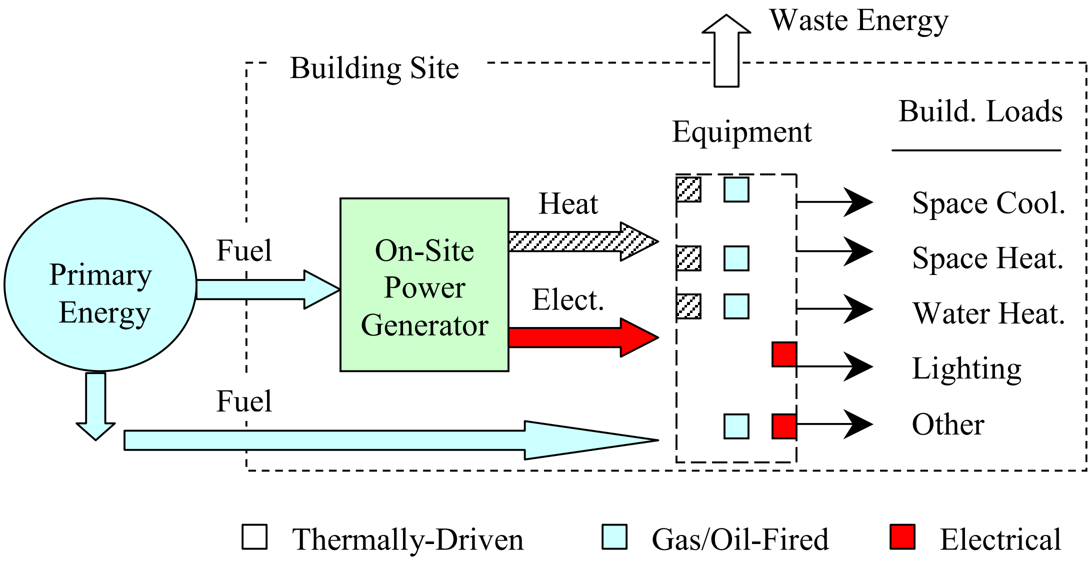

Figure 2b. Schematic of distributed energy resources, scenario “IES-B.”

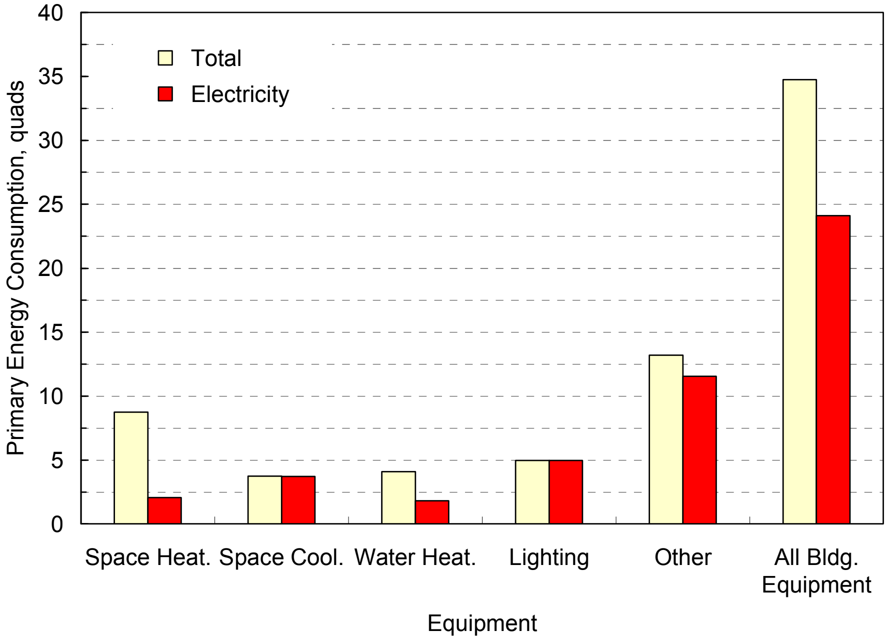

Figure 3. Primary energy consumption of building equipment for year 1999.

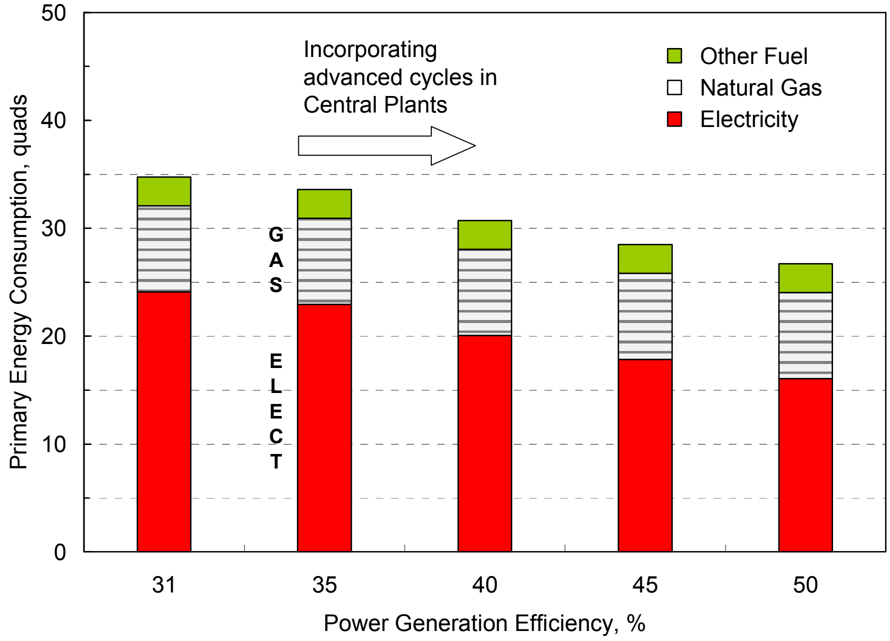

Figure 4. Impact of increasing central power generation efficiency on primary energy consumption.

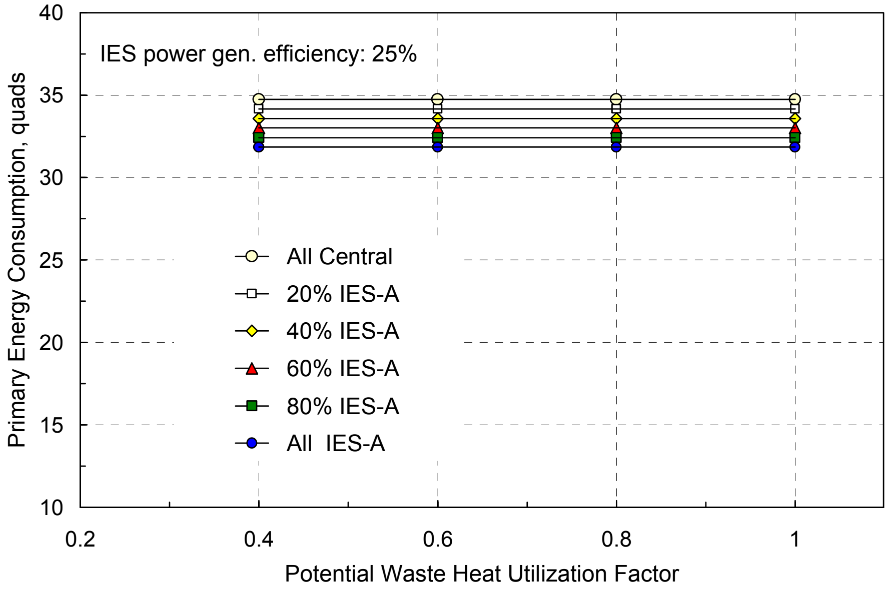

Figure 5a. Primary energy consumption for scenario "IES-A" (power generator efficiency of 25%).

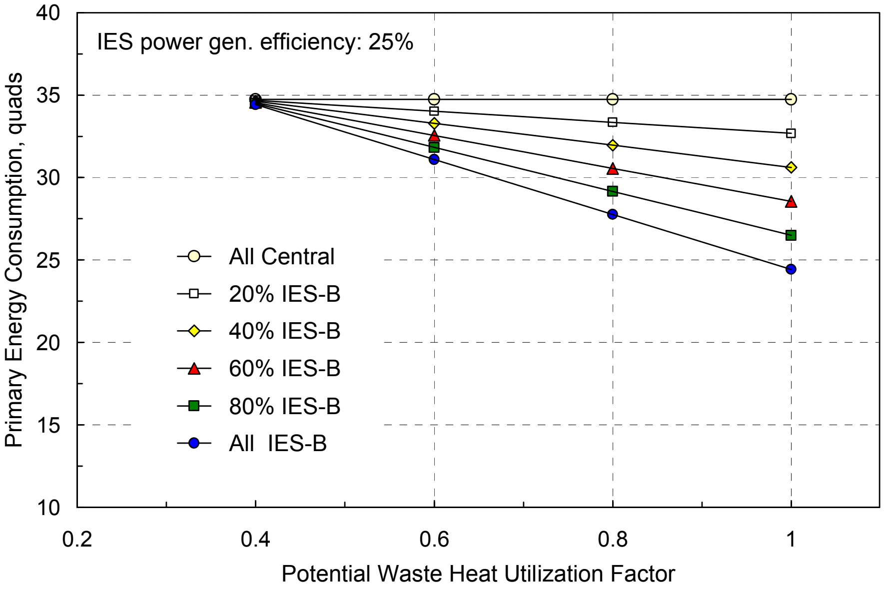

Figure 5b. Primary energy consumption for scenario "IES-B" (power generator efficiency of 25%).

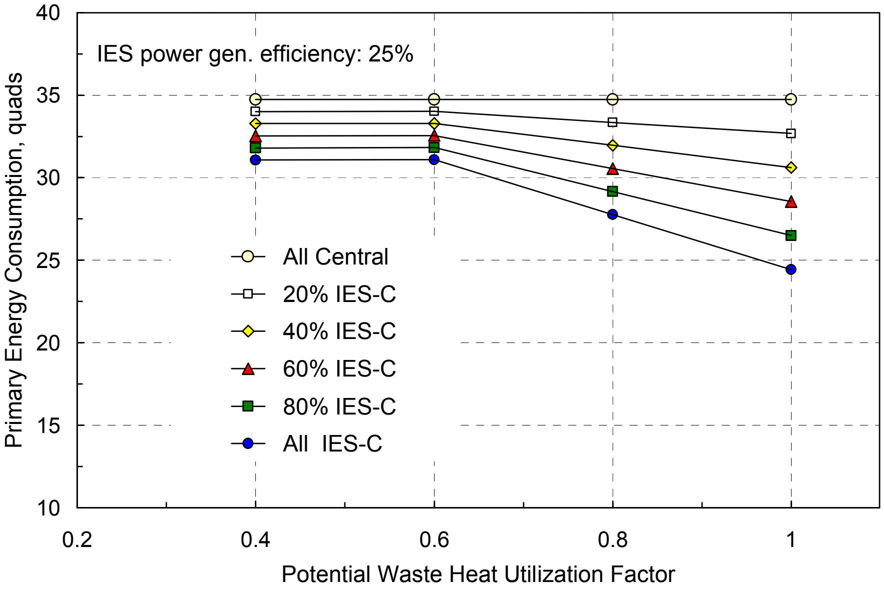

Figure 5c. Primary energy consumption for scenario "IES-C" (power generator efficiency of 25%).

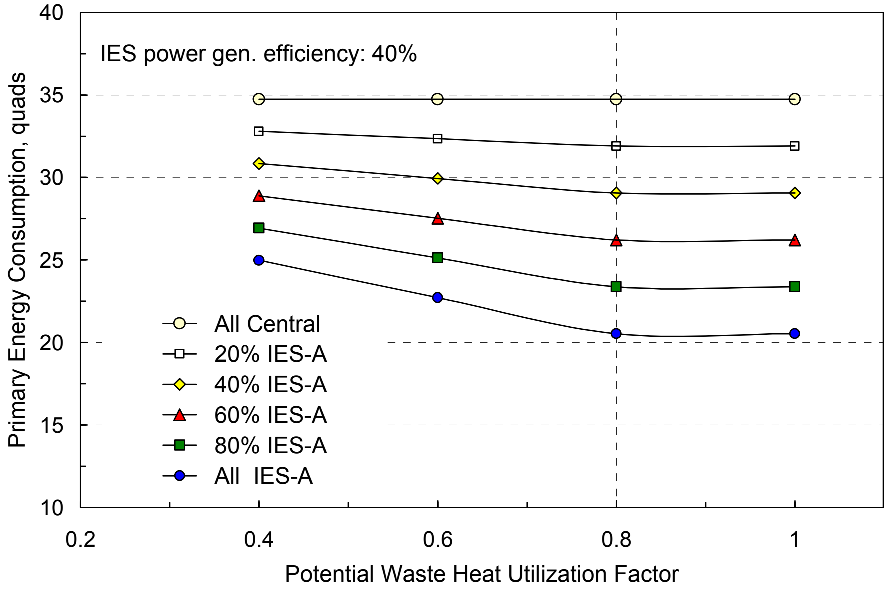

Figure 6a. Primary energy consumption for scenario "IES-A" (power generator efficiency of 40%).

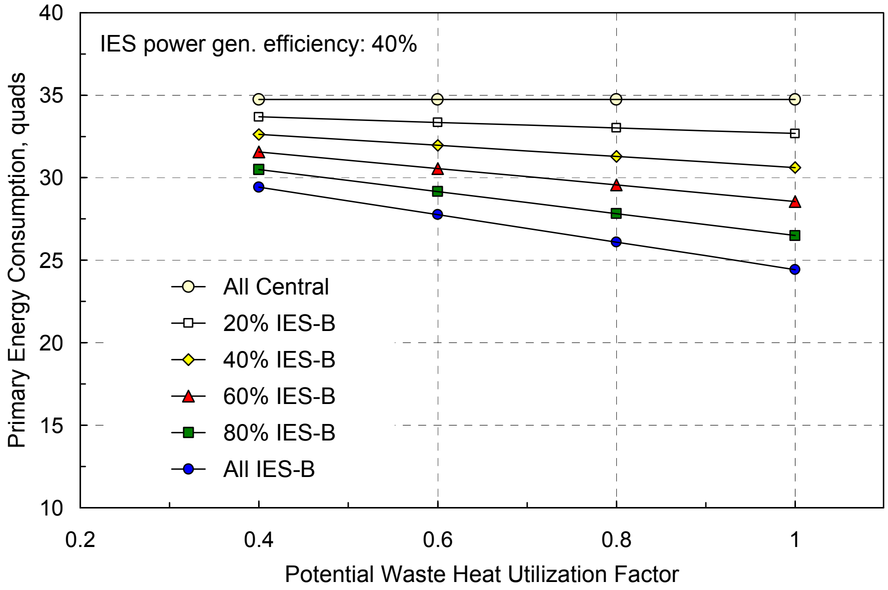

Figure 6b. Primary energy consumption for scenario "IES-B" (power generator efficiency of 40%).

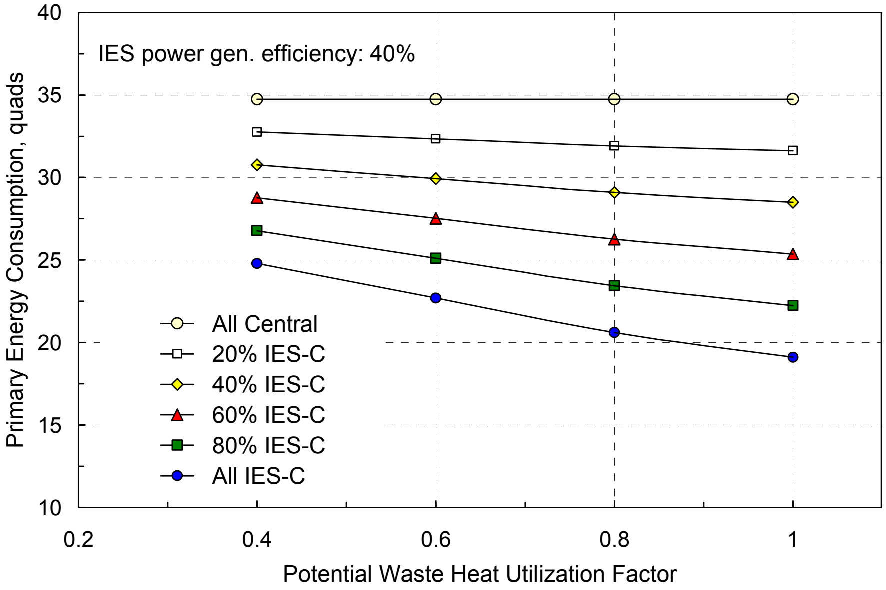

Figure 6c. Primary energy consumption for scenario "IES-C" (power generator efficiency of 40%).

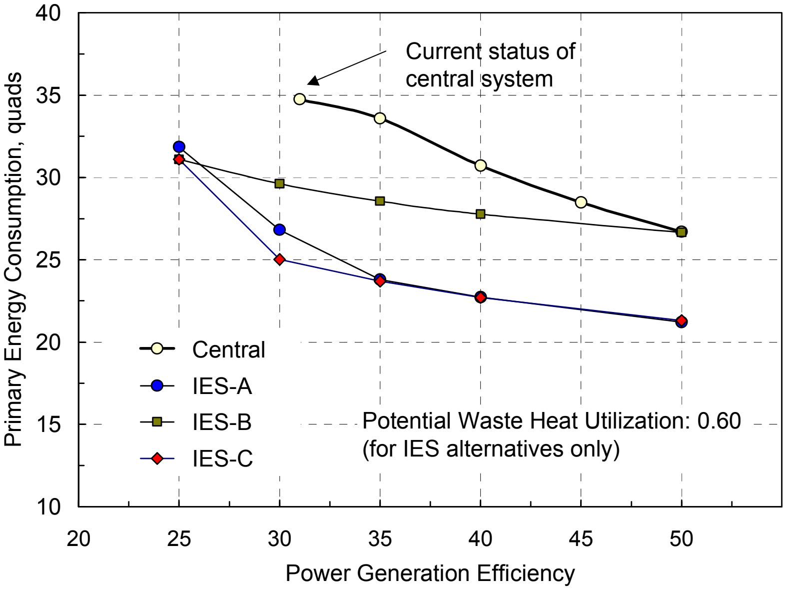

Figure 7. Primary energy comparisons between central and IES systems (potential waste heat utilization factor: 0.60).

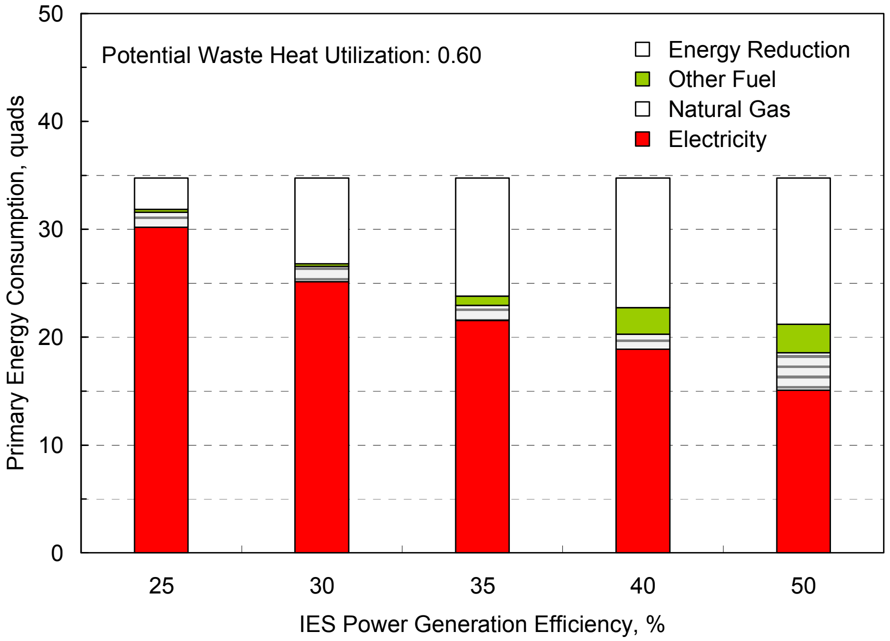

Figure 8a. Impact of efficiency on primary energy consumption for “IES-A” (potential waste heat utilization factor: 0.60).

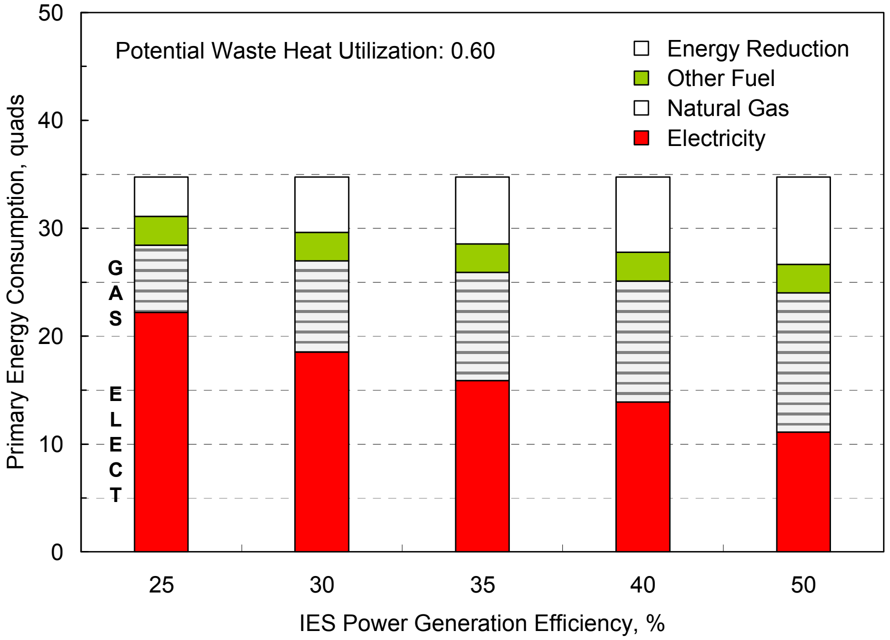

Figure 8b. Impact of efficiency on primary energy consumption for “IES-B” (potential waste heat utilization factor: 0.60).

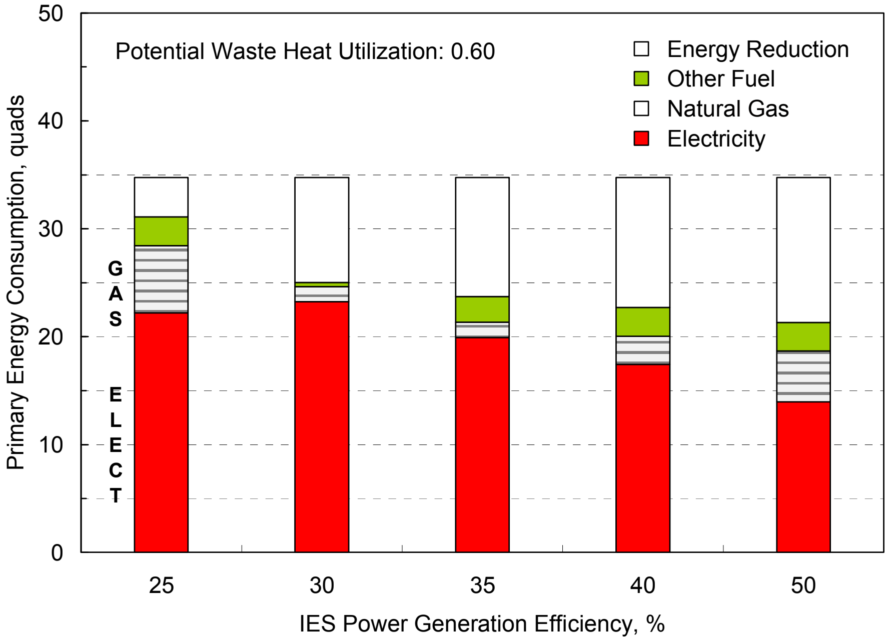

Figure 8c. Impact of efficiency on primary energy consumption for "IES-C" (potential waste heat utilization factor: 0.60).

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