A novel methodology for improving the design of community scale energy systems

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Abstract

The purpose of this paper is to present a new tool for design of integrated energy systems. The initial choice of the energy system components and the way they should interact is a crucial decision which the outcome of the design heavily relies on. Use of a physical law (instead of engineering judgment) as the basis of the decision making is the main advantage of the proposed approach over conventional approaches for design of community scale energy systems. The methodology has been implemented for design of a district heating system for an existing district in arid region of Iran. The optimum level of interaction between the energy system components has been identified by employing an optimization algorithm seeking to minimize the overall cost of the energy system. Some of the relative merits of the optimum design comparing to the present energy system are 6% increase of the energy efficiency, 10.8% reduction in the amount of CO_2 production per capita and 2% reduction in overall energy related costs.

1. Introduction

Efficient use of energy is recognized as a key factor for sustainable development [1], [2]. Although improvement of the efficiency of various energy conversion technologies (as the components of the energy system) are of great importance; but the overall effectiveness of the energy systems heavily relies on how the components of the energy systems interact with each other. Good performance cannot be expected from a system were the interaction between its components haven't been defined correctly; although the state of the art components have been used. In the same way the system possessing ordinary components may perform relatively better, if the interaction between its components has been defined correctly. These facts bring to light the important role of the system designer.

In this research a methodology based on a thermodynamic principle is proposed. The methodology will assist the energy system designers in making better design decisions. Both about the system components and the way they should interact. The proposed methodology is applied for design of an integrated energy system. The integration of a power generation utility with the residential sector by use of district heating has been considered.

Studies have focusing on various aspects concerning district heating systems. Various methodologies have been used for evaluating the performance of district heating systems; such as use of energy and exergy efficiency analysis [3]. The effect of various heating options –including district heating- on fuel demand, cost and CO_2 emissions in Denmark has be investigated [4]. Scenarios for using more local renewable resources for heating in a city in Denmark has been examined in reference [5]. There have been other studies that also attempted to analyze some of the important parameters of the district heating system in order to improve their feasibility. For example Torio et al. [6] examined the effect of input output temperatures on the overall performance of the district heating system. Y.Li. et al. [7] proposed use of absorption heat pumps for better recovery of heat in district heating networks.

It is commonly observed in the previous studies that the initial choice of the components of the energy system, and the way they should interact has been highly dependent on the choice of the system designer. As one reviews the various approaches for design of integrated energy systems (like district heating systems) a gap between the existing methodologies is felt for a methodology that could assist designers to make better decision about the initial structure of the system –based on a principle. The goal of this paper is to fill this methodological gap by introducing a methodology that takes advantage of a thermodynamic principle for identifying the best design options in the initial stages of the system design. Later the optimum design is found –considering the system's objective and various constraints affecting the system- by use of optimization algorithm. The overall result of this practice is that the designer could relatively be far more confident that he has chosen the most suitable components and also the components are interacting with each other optimally.

2. Case setting and modeling

2.1. Case study

Yazd district (composed of ten cities) in central arid part of Iran has been chosen for analysis (see Figure 1). The energy related data for Yazd district -last reported for year 1996 in reference [8]- were used. The total population of this district has been reported as 750,769[8].

Figure 1 The Yazd district, shown with darker color is subject of this study.

The energy flow diagram shown in Figure 2 displays the present flow of various forms of energy from fossil fuel resources through conversion technologies to the end user devices in residential sector. The input energy to each component of the energy system is obtained from reference [8]and the outputs are calculated by performing an energy balance for each component and also using efficiency data provided in Tables 3 and 4.

The total capacity of the power plant is not used in the present condition. Therefore large amount of electricity is imported from grid for meeting the demand of the residential sector and other sectors. Moreover, the amount of energy used and the amount of the lost energy due to in-efficiencies are calculated and shown in the right hand side of the Figure 2. Great amount of energy is consumed in the residential sector, which a large portion of it is for heating and hot water uses. One of the expected outcomes of the integration of the residential sector and the power plant -through design of district energy system- is better utilization of the energy.

2.2. Conceptual design using Exergy Matching Diagram (EMD)

Low economic cost, good energy utilization and minimum negative impact on the environment are the primary design goals of the energy system in this study. The choice of the system elements and the way they should interact with each other is a very important decision that the designer has to take. In the conventional approaches the choice of the components and the way they should interact has been mainly based on engineering judgment. Whereas the alternative approach –proposed in this paper- is use of a thermodynamic principal based on closer matching of the quality levels of energy (exergy) demand with energy supplied.

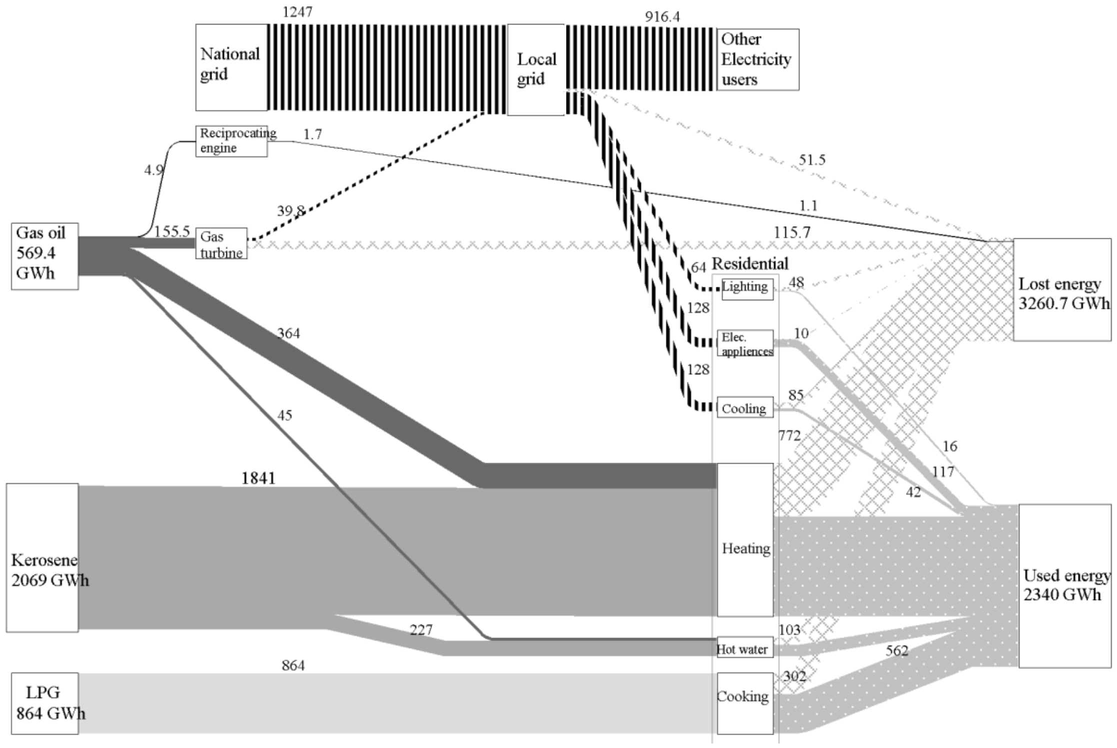

Figure 2 The energy flow diagram showing the quantitative flow of energy at the time of data collection in the analyzed system.

Tools such as composite curves for process integration [9], [10], Energy Utilization Diagram [11–14] have been used for taking in to consideration the quality level of various forms of energy in process design scale. Previous tools - developed for process scale design- are not feasible for community scale energy systems; since simplification in modeling are required for dealing with the complexities of these models. Following the same path, this research is proposing a modified version of previously developed tools appropriate for use in larger scale (community scale) energy systems.

For tailor making the methodology for application to large scale energy systems, the following modifications on previous methodologies [9–14] have been made:

1. Use of energy quality factor instead of temperature for evaluating the quality of energy (see Figure 2). This allows us to show different forms of energy besides heat (such as electricity, chemical potential, kinetic, etc.). Also exergy calculations are possible and also visualized.

   The quality factor of electricity is one, and quality factor of fuel has been calculated and provided in related references. The quality factor for heat (Q) is defined and related to the exergy of heat (E_Q) in the following equation [14].

$$\boldsymbol{E_Q = \underbrace{\left(1 - \frac{T_0}{T_P}\right)}_{quality\ factor} .Q} \tag{1}$$

2. The component average entropic temperature is used for calculating the level of energy quality demand of each component. By doing so we are able to analyze large discrete energy systems (having components such as industrial plants together with residential, commercial etc.).

3. Solid line in the EMD diagram shows the useful energy is drawn –proportional to the energy efficiency of the technology being used. The hatched line shows the amount of lost energy.

Exergy matching diagrams –following the instructions provided above- is drawn for the present case and alternative design cases and shown in Figure 3.

Three main alternatives are identified from Figure 3 which their description is provided in Table 1.

Table 1 General description of each alternative.

Design	**Consideration**
Present system	High amount of high quality fuel used for low quality demands, no heat recovery.
1st design	Energy is recovered for district heating: large amount of fuel saving, poor exergy matching between supply energy and demand.
2nd design	Better exergy matching, less amount of fuel is recovered comparing to the first design but additional electricity is produced.

Table 2 Definition of different design cases analyzed in this study.

	Gas Turbine	**HRSG**	**Steam turbine**	**ST outlet for DH**	**HRSG outlet for DH**
Present	O	X	X	X	X
B. Present	O	X	X	X	X
Case 1	O	O	X	X	O
Case 2	O	O	O	X	X
Case 3	O	O	O	O	X
Case 4	O	O	O	O	O

Based on the general design options explained above, the following design cases are defined in Table 2. The explanation of the different cases is provided below:

Present: The present condition of the energy system shown in Figure 2.

B. Present: The best operation mode of the present system.

Case 1: Heat Recovery Steam Generator (HRSG) is used for recovering heat from gas turbine's exhaust. The recovered heat is used for district heating.

Case 2: The heat recovered through HRSG is used only for generating additional power by steam turbine (ST).

Case 3: The steam turbine outlet is used for district heating.

Case 4: In this case the mix use of heat sources (HRSG and ST's output) is possible for district heating. The model has enough flexibility to choose any of the possible configurations.

The general layout of the integrated system is shown in Figure 4. The components in the hatched rectangle are the additional components required to make cases 1 to 4.

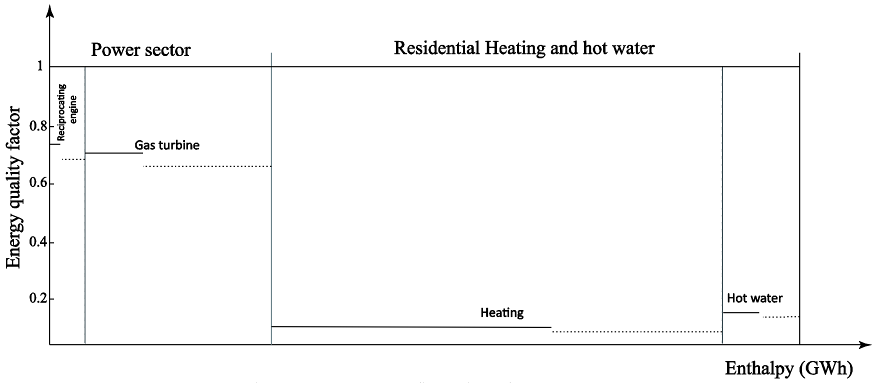

Figure 5a Present configuration of energy system.

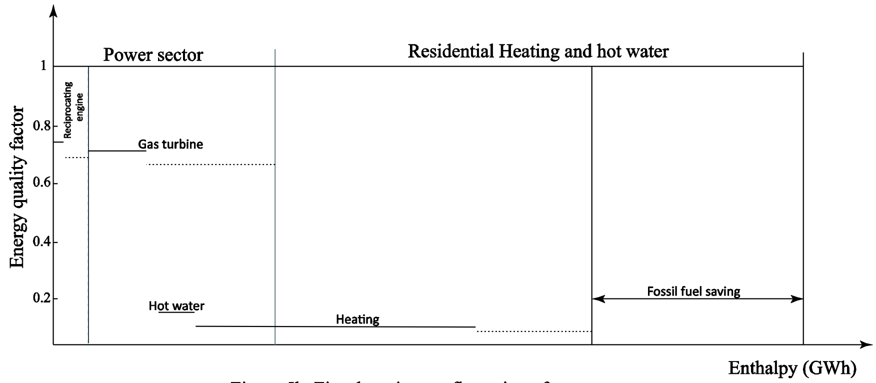

Figure 5b Fist alterative configuration of energy system.

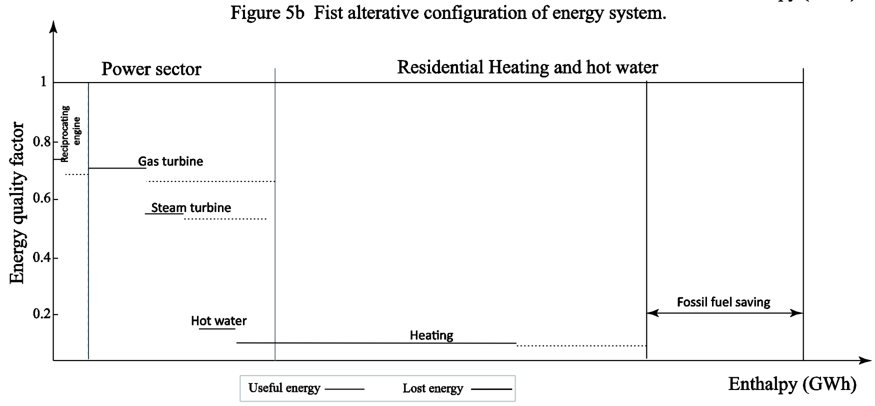

Figure 5c Second alterative configuration of energy system.

Figure 3 The EMD showing the present condition and two alternative design configurations for district heating.

2.3. Assumptions

The following key assumptions have been made for modeling the energy system shown in Figure 4:

1. The average heat losses in the hot water distribution network are 5% of the distributed heat [15].
2. The HRSG (Heat Recovery Steam Generator) recovers 65% of the heat from exhaust gases. Also HRSG is able to produce both average temperature steam (super heater outlet) and also hot water (economizer outlet).
3. The pumping power for pumping water has been neglected due to its relatively small share (0.1% of the thermal energy input [6]).
4. The energy conversion efficiencies used for modeling the various technologies in power plant and residential sector are shown in Table 3 and 4.
5. The domestic energy prices used in this study are shown in Table 5.

For estimating the amount of required piping the average figures of the district's water and waste water company [20] have been used.

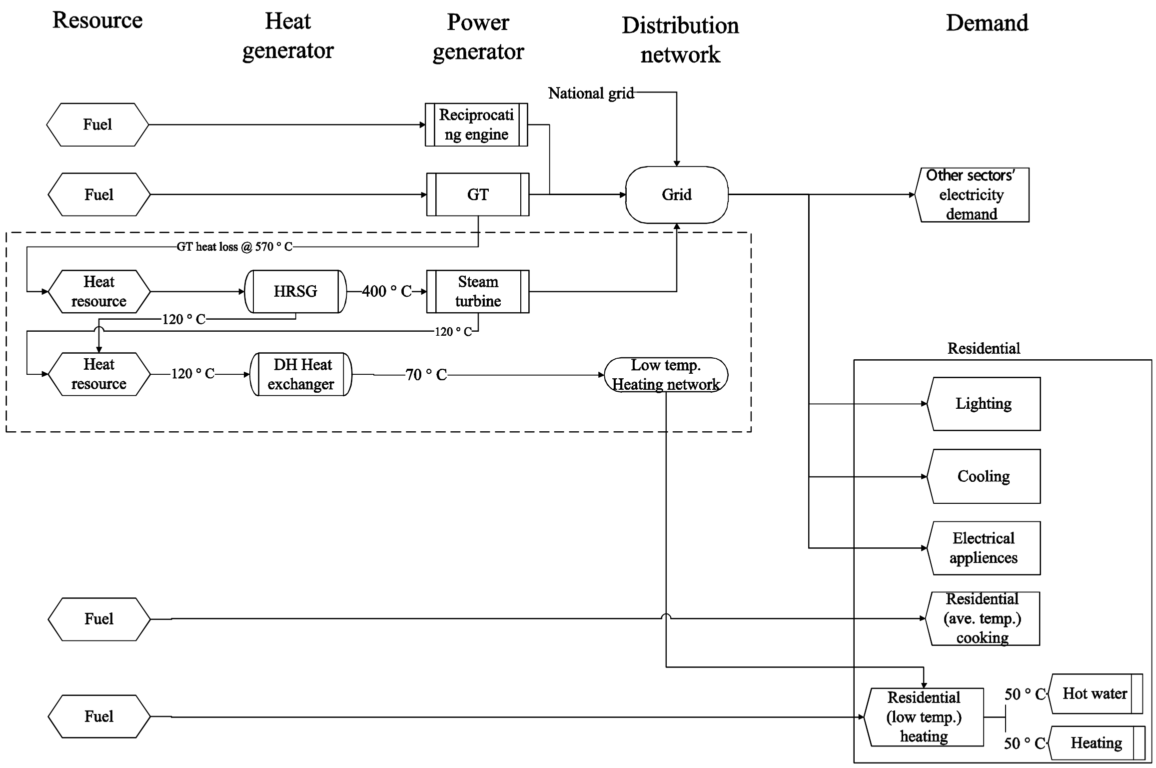

Figure 4 The system diagram of the general configuration of the energy system.

Table 3 The energy efficiencies of the power generation technologies.

Technology	Energy efficiency (%)	Ref.
Gas turbine	25.6	[8]
Steam turbine	36	[16]
Reciprocating engine	34.4	[8]

Table 4 Energy efficiencies of the end use residential consumers.

Technology	Energy efficiency (%)	Ref.
Heating	65	[17]
Water heater	62	[17]
Cooking	65	[18]
Cooling	33	[18]
Electrical appliances	92	[18]
Lighting	25	[18]

Table 5 The domestic energy prices from reference [8], [19].

Fuel type	LPG	NG (res)	Gas oil (res)	Gas oil (PP)	Kerosene	Electricity
Price ($/kWh)	0.0417	0.0555	0.01317	0.0307	0.00944	0.0773

2.4. Optimization formulation

The main objective of the design is minimization of the total annual energy related costs. The economic calculation methodology introduced in reference [9] has been used for formulating various costs:

$$\text{Min } \sum_j \left(\boldsymbol{C_{E,j}}.\boldsymbol{CRF} + \boldsymbol{C_{O\&M,j}}\right) + \sum_j \boldsymbol{C_{f,j}} + \boldsymbol{C_{grid}} \tag{2}$$

In the above equation, various economic costs related to investment and operation of various components of the energy system is considered. The Equipment cost ($C_{E,j}$)of each component has been levelized using the Capital Recovery factor (Equation 17) and added with the annual O&M and Fuel costs (Equations 14 and 15 respectively). The cost of the annual import of electricity from grid has also been considered (C_{grid}).

The following constraints have been defined to ensure feasible outcome from optimization.

Power plant constraints:

$$\boldsymbol{En_{gen)k}} \leq \boldsymbol{En_{gen,cap)k}} \tag{3}$$

$$\sum_i \boldsymbol{R_{used)i}} \leq \boldsymbol{R_{a,i}} \tag{4}$$

$$\sum \boldsymbol{En_{gen,net)k}} + \boldsymbol{E_{imp.}} = \boldsymbol{D_T} \tag{5}$$

$$\boldsymbol{En_{gen)k}} \geq \boldsymbol{0} \tag{6}$$

Residential constraints:

$$\boldsymbol{R_{used)\,j}} \leq \boldsymbol{R_{a)j}} \tag{7}$$

$$\boldsymbol{En_{del)m}} = \boldsymbol{RD_m} \tag{8}$$

The decision variables are the amounts of energy generated ($En_{gen)k}$) by the electric generators in the power plant, and also the amount of different fossil fuels used ($R_{used)\,j}$) for satisfying the energy demand in the residential sector. The constraints defined by Equations 19 to 24 insure that the search for optimum point is performed with in the feasible boundary of the model. Equations 21 and 24 are to insure that the demand for electricity and heat are met. Moreover constraints presented by inequalities 20 and 23 insure that the amount of resource usage doesn't exceed the available quantity. The inequality 19 and 22 insure that the power generators operate within their feasible operation range.

3. Results and discussion

Economic optimization has been performed for different cases. The components of the objective function are calculated separately and shown in Figure 5.

Recovering energy from exhaust gases of the power plant and using them for district heating (Case 1) is economically ineffective; compering to the present configuration of the system. This is mainly due to low cost of kerosene used for heating. The most economically effective design in present domestic energy prices is Case 2, were electricity is produced through recovered heat from exhaust gases of gas turbine using a 100 MW steam turbine. The use of district heating becomes more economically justifiable, in design Cases 3 and 4; were energy is further cascaded down to district heating uses after being used for generating electricity in steam turbine. The partial extraction of heat from intermediate levels HRSG (for example economizer) in Case 4 combined with use of outlet heat from steam turbine is economically more feasible design.

Cases 3 and 4 are the most economically feasible solutions. Moreover the optimum design of Case 4 indicates that there shouldn't be any intermediate extraction from HRSG.

The numerical values obtained from optimization model are used for showing the energy flows of the optimum design case (Case 3) in Figures 6.

Environmental dimension of the energy system (as one of the dimensions of sustainability) is a very important aspect of the energy system. The amount of CO_2 produced per capita for the present condition and the optimum case are shown in Figure 7 and compared with selected international figures.

The design Case 3 and 4 are the most environmentally sustainable design cases. This is due to reduction of the amount of CO_2 corresponding to the electricity from grid.

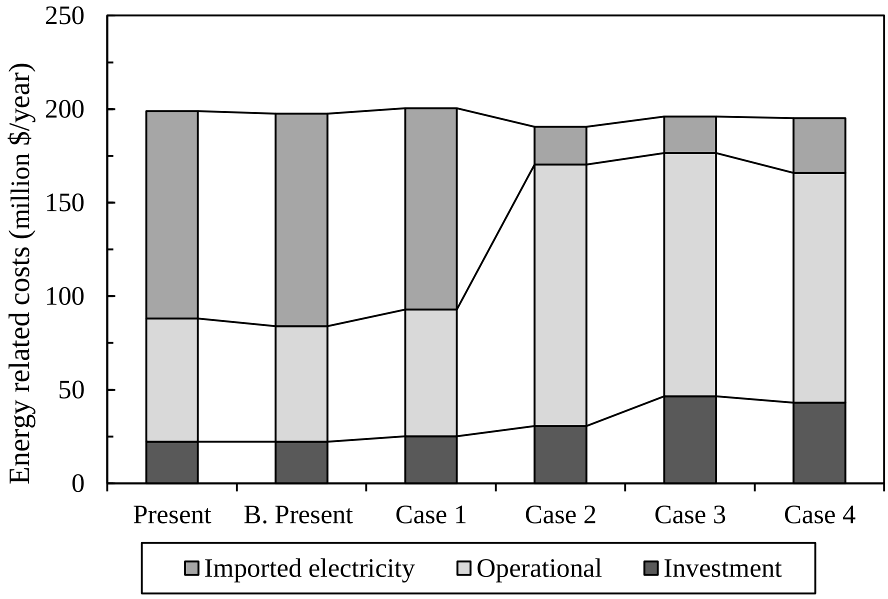

Figure 5 Total energy related costs (economic objective function) and its main components.

3.1. Sensitivity analysis

To examine the effect of possible changes in design due to variations and also uncertainty of some key inputs on the results, sensitivity analysis is performed.

The result of optimization has been found by introducing incremental changes in the electricity and heating fuel prices. The collection of points corresponding to each case has been shown with different colors in the form of a contour diagram (Figure 8).

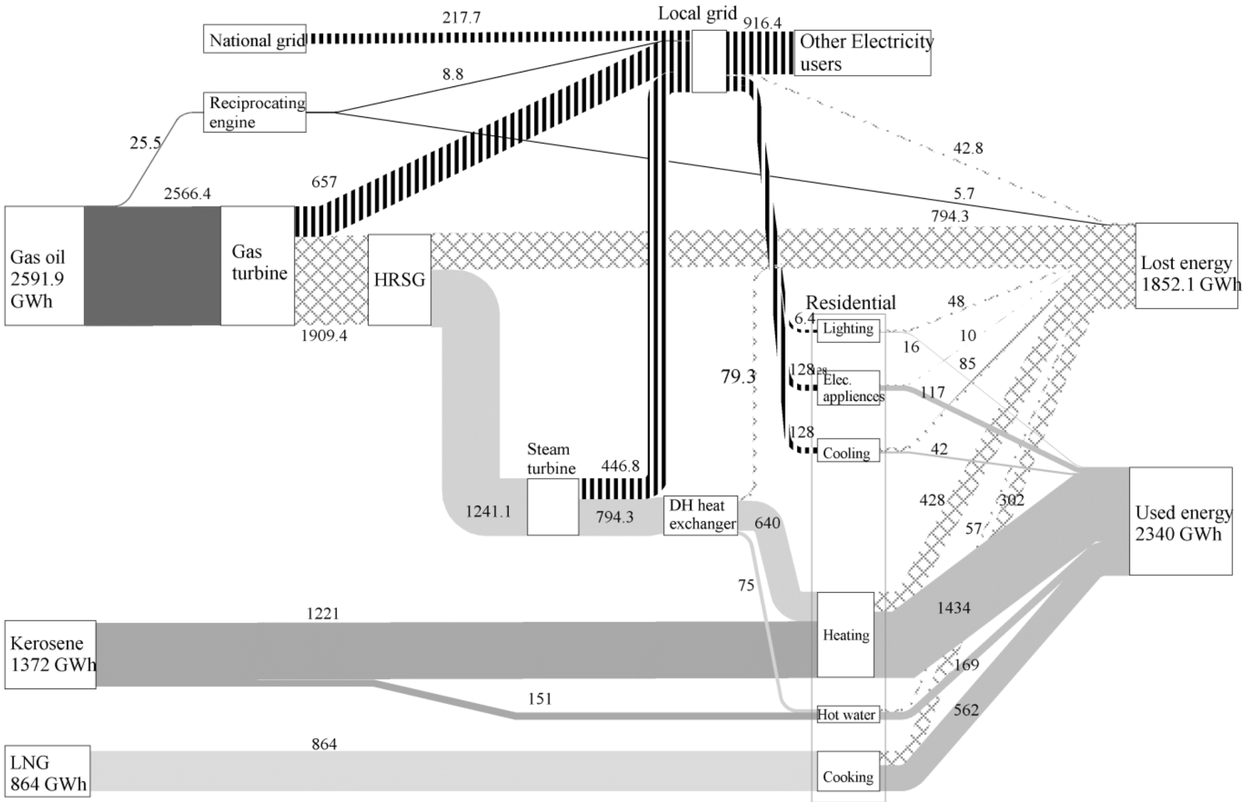

Figure 6 Energy flow for the energy optimum design (Case 3).

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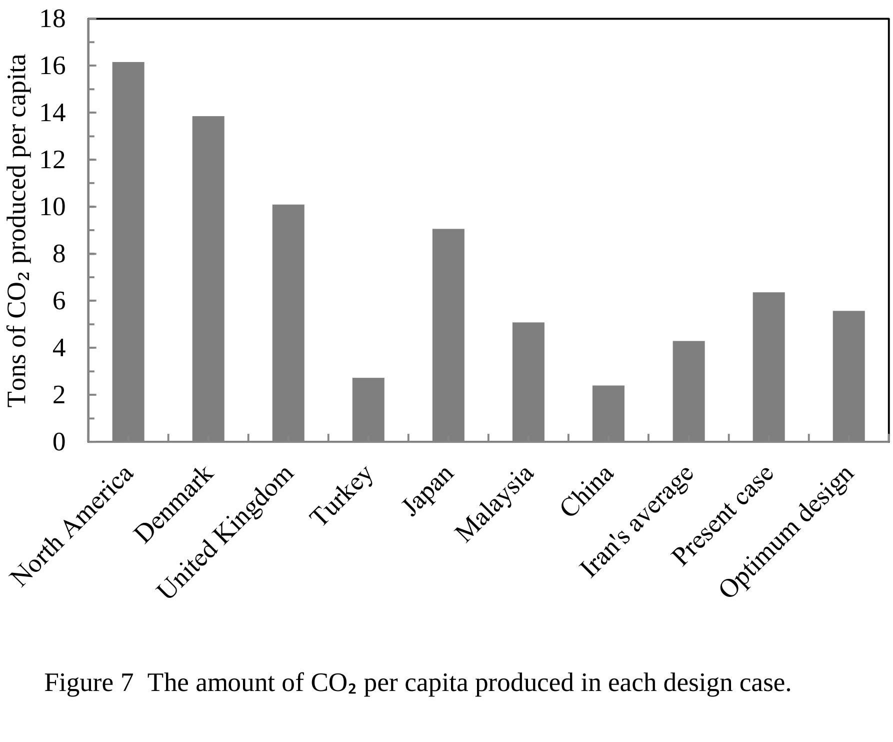

Figure 7 The amount of CO_2 per capita produced in each design case.

The horizontal axis of Figure 8 starts with the present kerosene price and increases covering present natural gas price (0.055 $/kWh) and moving towards higher prices (international prices). Moreover the vertical axis starts from the present electricity price. The increasing trend of the prices shown in Figure 8 is an important factor to consider since the government's policy is to shift the low subsidized prices towards international prices.

4. Conclusion

The use of a physical principal for choosing the design cases–instead of reliance on engineering judgment alone- is the true merit of the proposed methodology. In addition, by use of EMD, the potential design cases were recognized; some of which aren't easily noticeable (such as design Case 4). The agreement of the numerical results obtained in section 4 with the qualitative analysis of different cases using EMD (in subsection 2.2) clearly point out the robustness of the proposed methodology.

From economic point of view the implementation of district heating in present condition –were low cost kerosene is used for heating- is not feasible; the optimum economic design in present situation is to use the recovered heat in power plant for producing additional power through steam turbine (design Case2).

In addition to heating fuel price, the price of electricity has crucial effect on the choice of the optimum design (shown in Figure 8). In presence of relatively lower electricity prices, Case 1 (district heating only) becomes the feasible design; due to high cost of the heating fuels. Design Case 3 becomes the most economically feasible option as both the electricity and heating fuel prices tend to increase. Design Case 3 is recognized as the long term design solution for the case study in this paper. This is because the government policy is to increase the domestic energy prices up to the level of international energy prices. Moreover this design case is the most environmentally sustainable case (Figure 7).

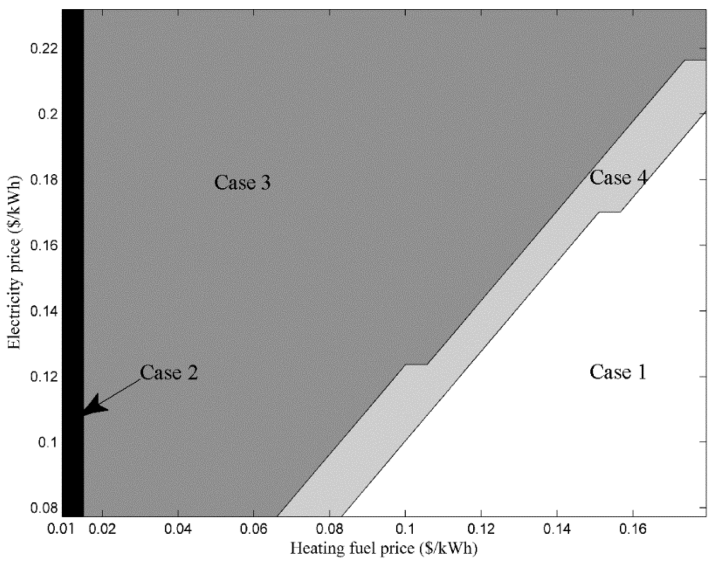

Figure 8 Optimum design case changes as the electricity and heating fuel prices change.

The design Case 4 realized through use of EMD is of special value. More flexibility in design is attained since it's possible to adjust the proportion of usage of the heat sources for district heating (namely the HRSG and steam turbine outlet) according to the changes in the heat demand and also price.

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