System Theoretical Analysis of Decentralized Energy Systems for Residential Buildings

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Abstract

A system theoretical procedure, which is normally used for the design and optimization of microelectronic circuits, is adapted to find the optimal structure of the energy supply system for residential buildings. The approach used in this work is a system model as black box with subsystems inside which uses different (renewable) energies as inputs and electrical energy, heat and cold as outputs. Based on a list of the most important energy converters for residential buildings a so-called compatibility matrix is developed. In this compatibility matrix all possible combinations of pairs of converters is entered. Based on an appropriate definition of the so-called weak compatibility set all theoretically possible compatibility sets of combinable converters are generated algorithmically. In a selection step all compatibility sets are determined, which fulfill the input and output requests of the black box. Finally the remaining compatibility sets are weighted and selected according to the requests of the task. Valuation criteria are for example: Potential of renewable energy, local availability of the primary energy, number of converters in the system, efficiency, costs, technical development potentials, autarky option etc.
First results show that the combination of photovoltaics and heat pump gets in many respects the optimal system structure. This combination supplies the necessary output forms of energy, uses only one renewable form of energy, needs only two converters, is world-wide applicable, low in maintenance and amortizes energetically as well as financially.

1. INTRODUCTION

The energy requirement profile of residential buildings consists in principle of the supply for electrical energy, heat and cold. It is searched for a system structure optimized according to different criteria which uses renewable energy, for the cover of this requirement for residential buildings with good insulation. The demand was going out to find a general procedure for the development and valuation of such systems. A system theoretical procedure, which is normally used for the design and optimization of microelectronic circuits (Paull, M.C.; Unger, S.H, 1959), is adapted to the design and optimization of the structure of the energy supply system for residential buildings.

2. APPROACH

The system theoretical approach was chosen in form of a black box (**Figure 1**). In the example of residential buildings presented here any renewable energy form is admitted as input and the energy forms electric power, heat and cold as output.

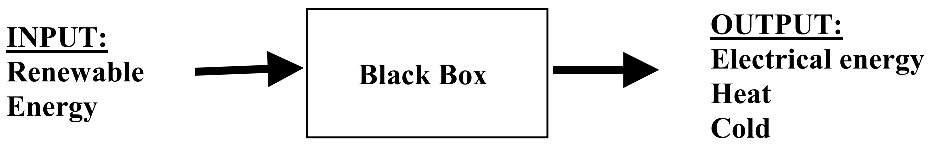

Figure 1: System as black box

As possible subsystems all converters transforming one form of energy into another one are permitted, like solar cells, combustion engines, fuel cells, heat pumps etc..
Table 1 gives an overview of the most important converters for its use to residential buildings.

Table 1: Types of converters

INPUT ENERGY	CONVERTER	OUTPUT ENERGY
Chemical (fossil or renewable energies)	Burner	Heat
Chemical (fossil or renewable energies)	Combustion engine	Heat, kinetic energy
Chemical	Fuel cell	Electrical energy, heat
Chemical (fossil or renewable energies)	Reformer	Chemical
Solar energy	Solar collector	Heat
Solar energy	Photovoltaics	Electrical energy
Electrical energy	Electric heating	Heat
Electrical energy	Electric heat pump	Heat, cold
Electrical energy	Electric motor	Kinetic energy
Kinetic energy	Electric generator	Electrical energy
Heat	Stirling engine	Kinetic energy
Heat	Absorption system	Cold
Environmental heat / cold	Ground heat source system (e.g. heat collector, pipe system)	Heat, cold

A suitable system structure is developed according to the following procedure:

1. The set of the converters is entered into a compatibility matrix. Compatibility criterion for two converters is, whether the output form of energy of one converter fits to the input form of energy of the other converter. By definition the converters are compatible to themselves. **Table 2** shows the corresponding compatibility matrix to **Table 1**.

2. All theoretically possible compatibility sets of combinable converters from the compatibility matrix are generated algorithmically. A precondition of the procedure is a suitable definition of the compatibility set. In a system-theoretical procedure which is normally used during the design and the optimization of microelectronic circuits, the following (classic) definition of the compatibility set is used: Each element of the set must be compatible to every other element of the set. For the combination of converters we need a less severe definition, the so-called weak compatibility set: Each element of the set must be compatible to at least one other element of the set. The procedure finding out the set of the weak compatibility sets to a given compatibility matrix is determined as follows:
   a) all individual elements (here converters) of the compatibility matrix belong by definition to the weak compatibility sets and are listed as valid elements.
   b) the compatible pairs from the compatibility matrix belong to the weak compatibility sets and are also listed.
   c) sets of three elements are formed while selecting the pairs one after another separately and checking all other pairs whether there is a common element in both compared pairs (e.g., ad, ae: common element a). In this case, a triple set is derived from both pairs and added to the list of the weak compatibility sets (e.g. ad, ae - > ade).
   d) The triplets are selected separately and checked again with all pairs whether there is a common element. In this case, a quadruplet is derived from the triplet and the pair and added to the list of the weak compatibility sets.
   e) The procedure is repeated with quadruplets, quintuplets etc., until all weak compatibility sets are determined.

   With this procedure the set of the weak compatibility sets to the compatibility matrix from Table 2 gives:
   {a, b, c, d, e, f, g, h, i, j, k, l, m, ad, ae, ai, al, bd, be, bi, bk, bl, cd, ce, ch, ci, cj, cl, ef, eh, ei,
   em, fi, fl, gh, gi, gj, hk, hl, ik, il, im, jk, lm,
   ade, adi, adl, abd, acd, aei, ael, abe, ace, aef, aeh,
   aem, abl, acl, afl, ahl, ail, alm, ... adel, abde, acde, adef, adem, ...
   abcdefghijklm }

   The largest set covers all converters from the compatibility matrix in **Table 2** and is represented as a structure graph in **Figure 2**. This set is of course suboptimal, because for the energy supply only a subset of the converters is demanded.

3. In a first selection step all compatibility sets are determined, which fulfill the input and output requests of the black box. For that the compatibility sets and the input and output requests may be presented as shown in **Table 3**. In this case the result contains for example all sets with the elements g and i.

4. Finally the remaining compatibility sets are weighted and selected according to the requests of the task. Valuation criteria are for example: Potential of renewable energy, number of necessary primary energies, local availability of the primary energy, number of converters in the system, efficiency of the system including preceding processes of transformation, costs, technical development potentials, autarky option.

Table 2: Compatibility Matrix

		BURNER	COMBUSTION ENGINE	FUEL CELL	REFORMER	ABSORPTION SYSTEM	SOLAR COLLECTOR	PHOTOVOLTAICS	ELECTRIC HEATING	ELECTRIC HEAT PUMP	ELECTRIC MOTOR	ELECTRIC GENERATOR	STIRLING ENGINE	HEAT COLLECTOR
a	Burner	x			x	x				x			x	
b	Combustion Engine		x		x	x				x		x	x	
c	Fuel Cell			x	x	x			x	x	x		x	
d	Reformer	x	x	x	x									
e	Absorption System	x	x	x		x	x		x	x				x
f	Solar Collector					x	x			x			x	
g	Photovoltaics							x	x	x	x			
h	Electric Heating			x		x		x	x			x	x	
i	Electric Heat Pump	x	x	x		x	x	x		x		x	x	x
j	Electric Motor			x				x			x	x		
k	Electric Generator		x						x	x	x	x	x	
l	Stirling Engine	x	x	x			x		x	x		x	x	x
m	Heat Collector					x				x			x	x

Table 3: Checking input-/output-criteria

	INPUT RENEWABLE ENERGY	OUTPUT ELECTRICAL ENERGY	OUTPUT HEAT	OUTPUT COLD
a	X		x	
b	X		x	
....				
i	X	x		
....				
gh	X	x	x	
gi	X	x	x	x
gj	X	x		
....				
acd	X	x	x	
aei			x	x
ael	X		x	
....				
adel	X		x	x
....				
abcdefghijklm	X	x	x	x

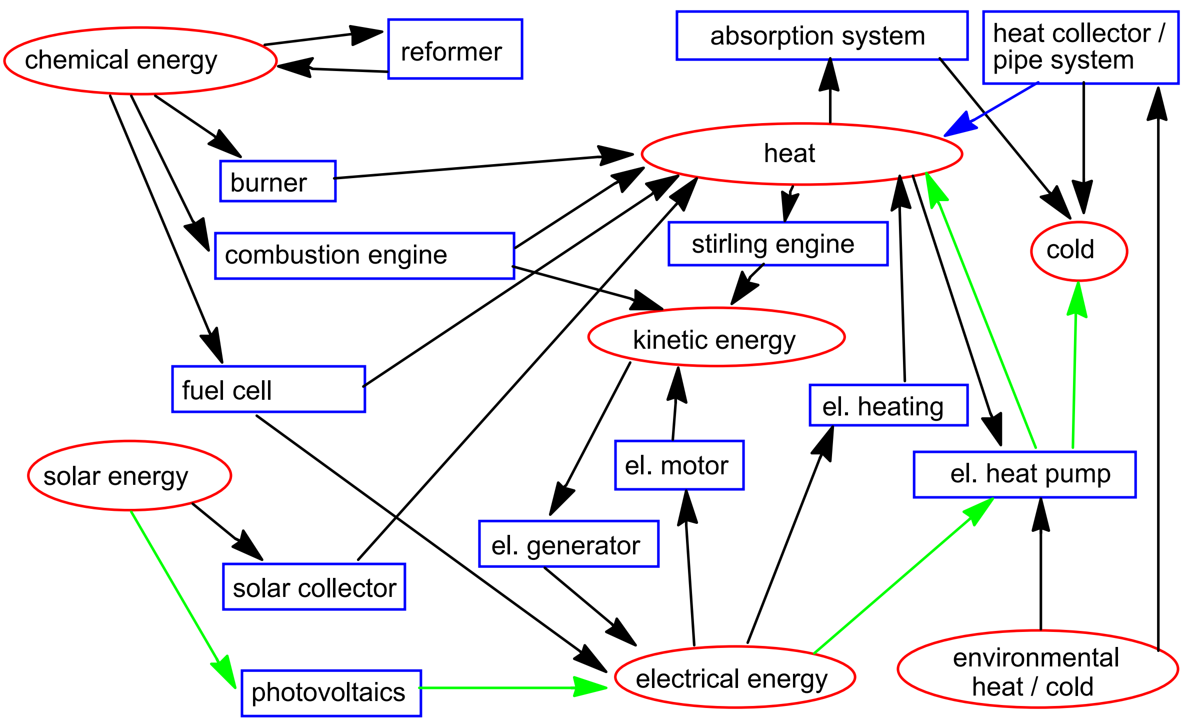

Figure 2: Structure for combination of all converters as listed in Table 2

3. FIRST RESULTS

In the present example of residential buildings with good insulation and about a wide spectrum in various weighting of the choice criteria at the 4th step of the selection procedure, the combination of photovoltaics and heat pump (**Figure 3**) which may be coupled with one of the optional storages gets in many respects the optimal system structure.

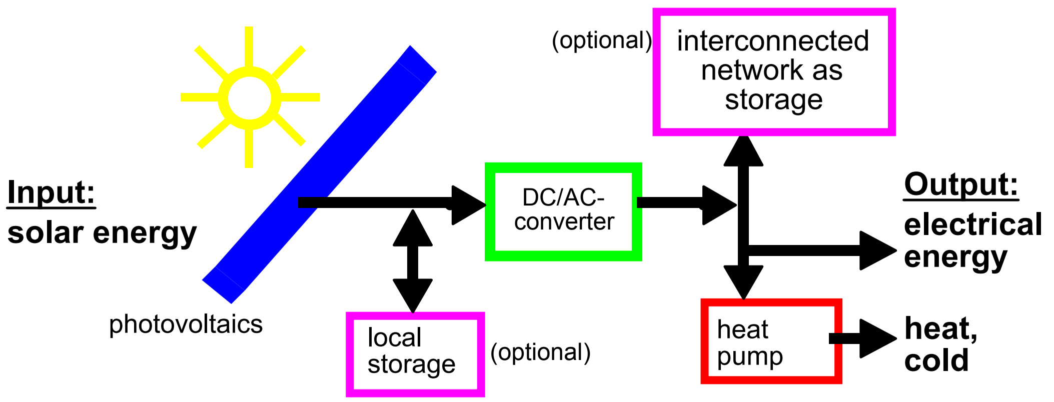

Figure 3: System structure containing photovoltaics and heat pump

This combination supplies the necessary output forms of energy, uses only one renewable form of energy, the renewable form of energy has a very high potential, needs only two converter elements, is world-wide applicable, needs a low-maintenance and amortizes energetically as well as financially during its life cycle.

Independently of the task represented here, the procedure allows the valuation of system structures for the most different demands to systems based on renewable energies.

4. CONCLUSIONS AND FURTHER WORK

The paper describes a new systematic procedure for the development and valuation of the energy supply of residential buildings with renewable energies and high insulation standards. In a first ad hoc result the combination of photovoltaics and heat pump gives the optimal system choice for the energy supply of residential buildings with renewable energies regarding to the above listed selection criteria. In this case only two converters are needed to supply the building with the outputs electrical energy, heat and cold. In further research the selection criteria in the 4th step of the procedure will be determined with the help of a so-called sensitivity analysis (Vester, 1999). Furthermore the procedure will be applied to other energy requirement profiles and to all types of primary energies as well as to other types of buildings.

5. LITERATURE

Paull, M.C.; Unger, S.H (1959), *Minimizing the number of states in incompletely specified sequential switching functions*, IRE Trans. on Electronic Computers EC-8, pp.356 - 367.

Vester, F. (1999), *Die Kunst vernetzt zu denken: Ideen und Werkzeuge für einen neuen Umgang mit Komplexität,* DVA, Stuttgart