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Constructal design of distributed energy systems: Solar power and water desalination

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ABSTRACT

Here we show the fundamental tradeoffs that underpin the design of a distributed energy system with two objectives: the production and distribution of electric power driven by solar heating, and desalinated water produced by consuming solar power. We show analytically that larger solar power plants and desalination plants are more efficient than smaller plants. This phenomenon of economies of scale is countered by the greater losses associated with larger distribution networks. From this conflict emerges the proper allocation of nodes of production of power and water on a territory. We show that as the individual needs of power and water increase in time, the sizes of solar plants and desalination plants increase, and so does the size of the territory served by each power plant. At the same time, the territory served by each desalination plant decreases, and this means that the number of desalination plants allocated to one power plant increases.

Contents

1. Introduction

Current research in constructal design is showing that the optimal distribution of flows and services on a populated area consists of balances between the sizes of centers of production and the sizes of the distribution networks that connect the centers with every inhabitant of the area [1–3]. The balances result form an important trade-off, which is fundamental, universally applicable, and worth exploring.

The trade-off is a consequence of an essential characteristic of all flow systems: the larger flow systems are more efficient thermodynamically [4,5]. This accounts for the tendency toward the centralization of the generation of power, refrigeration, air conditioning and other useful streams that are required by the population. At the same time, larger centers produce larger streams that must be distributed on larger areas. In this direction, the losses associated with the distribution and collection networks increase because they are proportional to the length scale of the served area. The global flow system consists of production, distribution and collection, and it is most efficient when the size of the production center is properly matched to the size of the networks. From

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Nomenclature

A	area (m^2)
$c_1,\ldots,c_5$	constant factors
C	thermal conductance (W/K)
D	length scale (m)
h	heat transfer coefficient (W/m^2K)
h_{fg}	latent heat (J/kg)
k	exponent
L	length
$\dot{m}$	mass flow rate (kg/s)
$\dot{m}_1$	mass flow rate for one user (kg/s)
q	heat current (W)
S	solar power plant
T	temperature (K)
W	water desalination plant
$\dot{W}$	power (W)

Greek symbols

α	exponent
ΔT	temperature difference (K)

Subscripts

b	boiler
c	condenser
max	maximum
diss	dissipated
s	solar
0	ambient

this balance results the size of the area served by one center, and the sizes of the production center, and distribution networks.

This principle of constructal design underpins the emergence of "distributed energy systems" on the globe, at all scales. These are *tapestries* of nodes and links on area elements. This is the design of the civilized landscape, and by exploring it we shed light on the future of globalization. In engineering science, we construct a basis for the concepts of globalization, limits to growth, sustainability, and evolution.

So far, the application of this principle was demonstrated by considering distributed energy systems permeated by a single kind of flow: hot water for heating [1,2] and refrigeration [3]. In this paper we extend this design principle to the more complicated domain where two or more energy systems are distributed and superimposed on the same populated area. These multiple tapestries are coupled: they feed on each other, and in order to be efficient together (as an ensemble) their sizes must be in balance. The features of multiple distributed-system design are fundamental [1]: here we illustrate them with two coupled systems: solar power generation on an area, and the production and distribution of desalinated water for the inhabitants of the area (Fig. 1).

2. The effect of size on solar power generation

Efficiency data of existing power plants show that larger power plants are more efficient [5]. Additional data are reproduced in Figs. 2 [6] and 3 [7]. Here we show that the same size effect rules the efficiencies of power plants driven by solar energy. We can demonstrate this with simple models and analyses of solar-thermal power plants for example, the model shown in Fig. 4. The solar heat current q_s is collected by a reflector, and it is absorbed in a water heating tank of temperature T. Heat leaks from the tank to the ambient (T_0) at the rate $C(T - T_0)$. The net heat input available for driving the power plant is $q_s - C(T - T_0)$. For simplicity, we assume that the power plant operates reversibly between T and T_0, therefore the power output is

$$\dot{W} = [q_s - C(T - T_0)]\left(1 - \frac{T_0}{T}\right) \quad (1)$$

The power output reaches its maximum when the water heater has the temperature

$$T_{opt} = T_0\left(1 + \frac{q_s}{CT_0}\right)^{1/2} \quad (2)$$

This temperature is situated between the two possible limits of T, namely, the lowest ($T = T_0$) and the highest ($T = T_0 + q_s/C$). The maximum power output per collected heat current is

$$\frac{\dot{W}_{max}}{q_s} = \frac{(1 + \frac{q_s}{CT_0})^{1/2} - 1}{(1 + \frac{q_s}{CT_0})^{1/2} + 1} \quad (3)$$

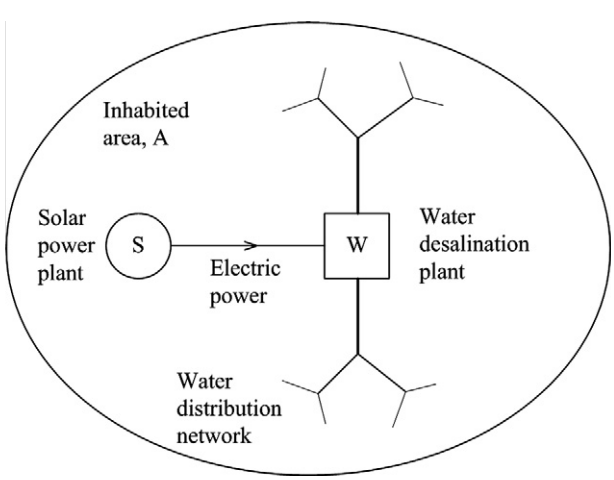

Fig. 1. Two energy systems superimposed on the same area: solar power generation and the delivery of desalinated water.

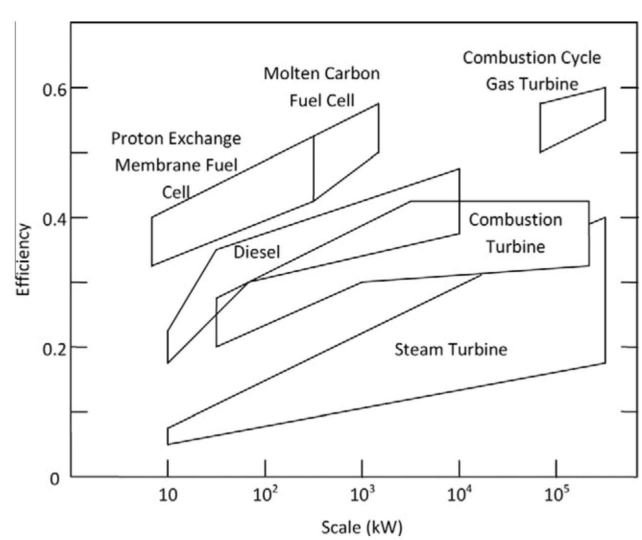

Fig. 2. The effect of size on the efficiency of power plants [6].