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Programme of Research, Development and
Demonstration on District Heating

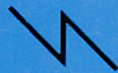
IEA District Heating

ADVANCED DISTRICT HEATING PRODUCTION TECHNOLOGIES

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LOCUS-SYSTEMS AND -PLANTS

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1. Introduction

LOCUS, for Local Cogeneration Utility System, has been adopted in Denmark as the name for energy systems with certain properties with respect to regulation of electricity and heat production from several energy sources, in particular renewable resources and natural gas. The name was originally used to label a computer program designed by the author of this article to compute energy balance accounts and required component capacities for such systems. This LOCUS-program is available at Aalborg University, Institute of Development and Planning.

A distinction is made between LOCUS-plants and LOCUS-systems. A LOCUS-plant is a cogeneration plant that may consist of engines, heatpumps, boilers and heat storage tanks as shown in principle by fig. 1 and in more detail by figs. 2 and 4. A LOCUS-system may consist of several LOCUS-plants, belonging to towns and villages within a certain region. The plants within such a system are assumed to be interconnected through the electric grid and the regulation of the power generation of each plant is assumed to be subject to rules designed to optimize the performance of the system. These rules constitute a hierarchical structure of LOCUS-systems with respect to regulation of electric power generation. Such a hierarchy is shown in principle by figs. 5 and 6.

A LOCUS-plant can, of course, be designed for heat production to a district heating system alone. Because its thermodynamic efficiency with respect to utilization of fuel resources for low-temperature heat production is higher than that of an ordinary boiler, fuel consumption may be reduced by about 50 percent by replacing a boiler with a LOCUS-plant. For environmental and economic reasons improved energy conversion systems should, however, be designed to minimize the overall consumption of fossil fuel for heat and electricity generation

in an economically optimal manner. In order to achieve this aim cogeneration of heat and electric power should be adopted as a general principle for the development of advanced heat production techniques.

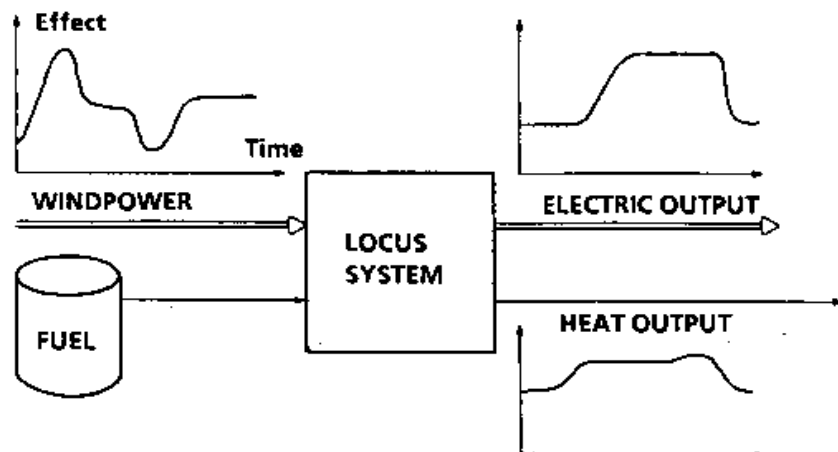
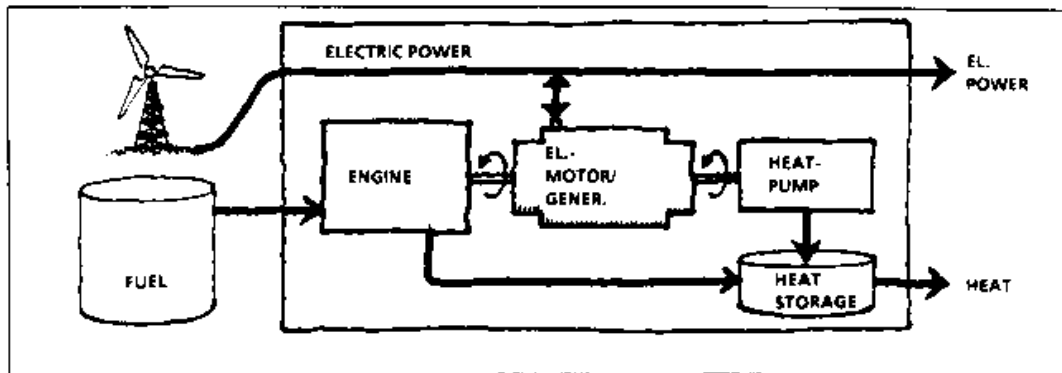


Fig. 1. LOCUS-plant, principle. A LOCUS-plant composed of an engine, an electric motor/generator and a heatpump and equipped with the necessary heat-storage tanks provides enhanced possibilities for regulation of simultaneous thermal and electric output-effects.

The LOCUS-plant concept has primarily been developed to facilitate efficient utilization of windpower in combination with natural gas, biogas and other renewable or non-renewable fuels. The heat-storage tanks required for the regulation of the heat-output effect from a LOCUS-plant do, however, readily enable the integration of solar collectors into a LOCUS-plant as described in section 2.1 below.

2. Technical Description

The technical concept of a LOCUS-plant is shown in principle by fig. 1. The general purpose is to facilitate regulation of the simultaneous electric and thermal outputs according to the actual variations in heat demand and the desired variations in electricity-production from the plant. If the plant is partly driven by windmills it may, therefore, be necessary at times partly to convert the windpower-effect to thermal effect. This is done by increasing the electric power-input to the heatpump-compressor when the electric output-effect from the plant exceeds the desired value w_{prod} . At the same time the engine-load w_{eng} must, of course, be adjusted according to the equation:

$$w_{eng} = w_{prod} - w_{wind} + w_{h.pump}$$

In this equation w_{prod} is the scheduled electric output-effect and w_{wind} is, naturally, exogenously determined. w_{eng} and $w_{h.pump}$ are thus the two effects that may currently be regulated in order to balance the above electric output equation while at the same time ensuring that the required thermal output effect can be delivered.

Because the variations of the input-effects from the energy sources generally will be out of step with the required variations of the output-effects from the plant, a certain energy storage capacity within the plant is required. For the first generation of LOCUS-plants this storage capacity is obtained by water tanks for heat storage only. This is because storage of

electrically transmitted energy at a larger scale is not yet economically feasible.

The thermal energy production from the heatpump over a certain period of time is determined as the total heat demand from the plant over that period minus the thermal output from the engine when both the scheduled electric output and the required heat output is to be delivered. The proportion of the heat production delivered from the heatpump determines the wanted temperature-increase of the district-heating water as it passes through the heatpump-system, see fig. 3. When the steering-program shall also comply with the electric output-regulations it can, however, not be assured that the engine supplies its thermal output-effect in step with the output-effect from the heatpump, although the integrated values of the two thermal output-effects over the considered period of time are in accordance with the heat demand in that period. It is therefore necessary to introduce separate heat storage tanks for the heatpump and the engine respectively as shown by fig. 2.

In most cases the plant will also comprise a boiler to cover peak heat demand and to ensure that the required thermal effect can be delivered even when the scheduled combined production from the engine and the heatpump fails to fulfil the requirements. The boiler may be equipped with a separate heat storage tank, as shown by fig. 2, or it may share the high-temperature storage tank with the engine.

The systems description of a LOCUS-plant naturally appears as two separate descriptions of the thermal energy-transmission system and the electromechanical power-transmission system respectively. The thermal system is shown by fig. 2 and the electromechanical system by fig. 4.

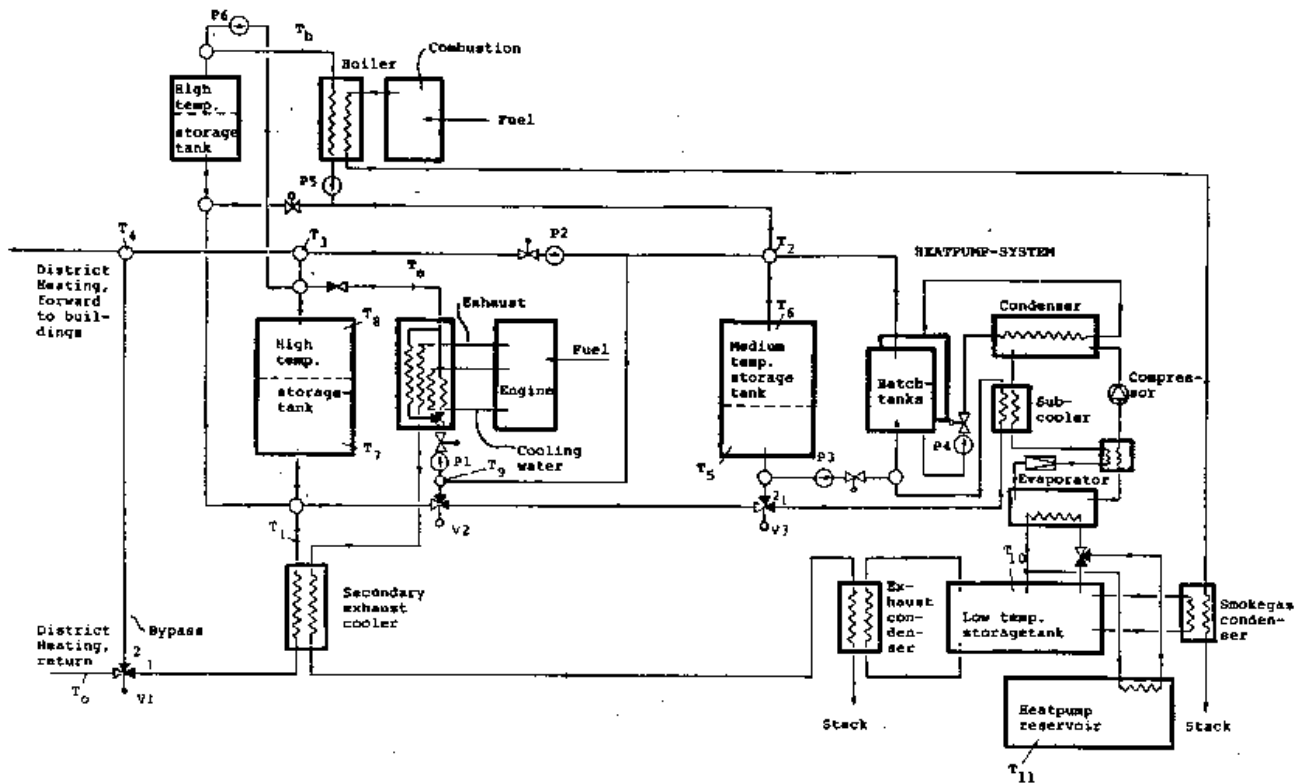


Fig. 2. LOCUS-plant, thermal circuits. The flows through the medium-temperature storage-tank and the heatpump-batchtanks respectively is regulated in such a manner that the temperature T_2 is kept constant at the preset value (see fig. 3). The outlet temperatures T_a and T_b from the engine and the boiler respectively are kept as high as possible (about 90°C) in order to maximize the heat storage capacity of the high-temperature storagetanks. The pump+valve P2 regulates the circulation through the medium- and high-temperature storagetanks so that the outlet-temperature T_3 to the district heating network is kept at the required value.

2.1 The Thermal System

The thermal system consists of three parts:

- a **heatpump-system** (shown to the right in fig. 2) which preheats the water to the appropriate temperature (see fig. 3). The thermal energy from the heatpump-system may partly be stored in the heatpump-storagetank.

- an **engine** with one or more cooling circuits, depending of the type of engine in question (piston-engine, gasturbine, Rankine-type steam-engine, Stirling-engine, fuelcells or a combination of such motors). The thermal energy from the engine may partly be stored in the engine-storagetank.

- a **boiler**, which may either be equipped with its own heat-storagetank or share storagetank with the engine.

In addition to the primary exhaust-gas cooler attached to the engine a secondary exhaust-gas cooler is applied to preheat the return-water from the district heating network. A tertiary cooler may be applied for further cooling of the exhaust-gas by means of water circulated through a low-temperature heat-storagetank. This tank is then used as a reservoir for the heatpump, see fig. 2.

A substantial improvement of the thermodynamic efficiency of the plant can be obtained by replacing the primary exhaust-gas cooler with an **absorption-heatpump**.

Although the LOCUS-plant is not primarily designed for utilization of solar collectors these may readily be integrated in the plant in an efficient manner. When a solar collector is attached to a LOCUS-plant it should be connected through three circuits: one, passing through the low-temperature storagetank, to be activated at low solar influx rates in periods when the heatpump is being used; another, passing first through the heatpump-storagetank and thereupon through the low-temperature storagetank, to be activated at higher solar influx rates in periods when the heatpump is

being used; a third, passing only through the heatpump-storage tank, to be activated in periods when the heatpump is not being used.

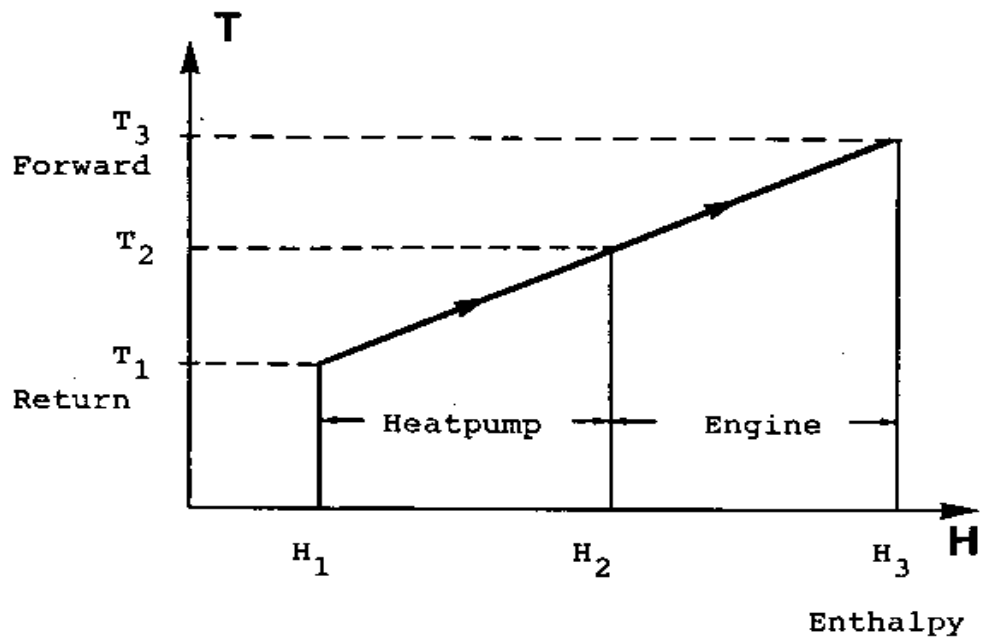


Fig. 3. Distribution of heat-production between heatpump and engine (+boiler). It is important for the efficient operation of a LOCUS-plant, that the outlet-temperature T_2 from the heatpump-system (see fig. 2) over a certain period of time corresponds to the proportion of heat (enthalpy) delivered by the heatpump to heat delivered by the engine (+boiler), i.e.

$$(T_2 - T_1) / (T_3 - T_2) = (H_2 - H_1) / (H_3 - H_2)$$

The appropriate value of T_2 should thus currently be computed from the required outlet-temperature T_3 from the plant (see fig. 2), the expected return-temperature T_1 and the planned production by the engine and the heatpump respectively during the period.

In order to obtain maximum thermodynamic efficiency of the heatpump a batch-heating system with two batch-tanks is applied as indicated in fig. 2. The principle of the batch-system is to let the heatpump-condenser gradually heat one batch of water as it circulates at a high flow-rate in a circuit through the batch-tank and the condenser. In this manner the condenser-temperature increases gradually as the water is heated instead of being constant at the temperature corresponding to the outlet-temperature from the heatpump-system. Whenever the temperature of the one batch-tank which is presently being heated exceeds the temperature at the top of the other tank, which is simultaneously being emptied for heated water, the two tanks are automatically shifted. In this way the outlet-temperature from the heatpump-system is currently determined by the flow through the heatpump-system and the effect from the condenser. The desired outlet-temperature T_2 from the heatpump-system, see fig. 2, can thus be controlled by the valve V_3 and the pump+valve P_3 .

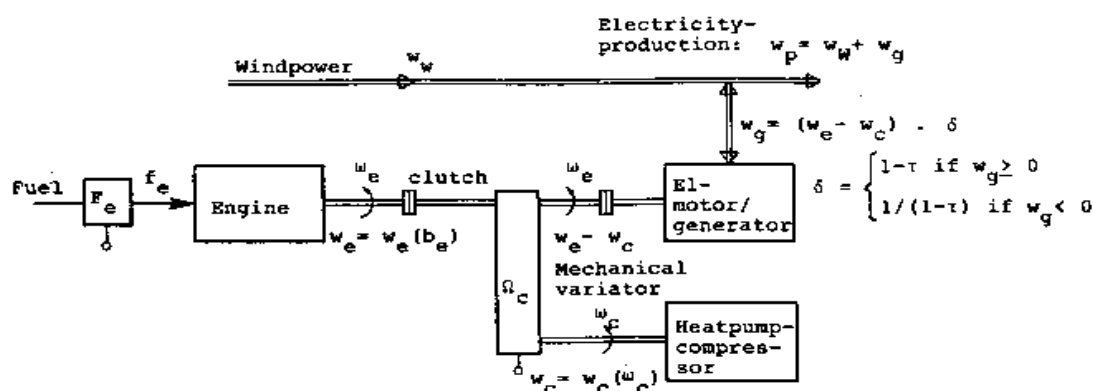


Fig. 4. LOCUS-plant, electromechanical system. The total electricity production w_p from the plant and the attached windmills can be regulated by means of the engine-load regulator F_e , which sets w_e , and the mechanical variator, which allows the rotational speed and thereby the mechanical load w_c on the heatpump-compressor to be varied.

Only when there is no heated water left in the heatpump-storage tank and it therefore cannot be ensured that the desired value of T_1 can be obtained the full flow of water will be directed through the heatpump-system, i.e. the flow through the heatpump storage tank will be zero in that situation.

2.2 The Electromechanical System

The electromechanical system is shown in principle by fig. 4. The heatpump-compressor shaft is connected to the engine-shaft and the electric motor/generator shaft respectively through a mechanical variator in order to enable the regulation of the heatpumps thermal effect by regulating the rotational speed of the compressor. The engine as well as the electric motor/generator may be decoupled by means of the shown electromagnetic clutches.

The shaft-effect from the engine may thus be zero or assume any value between minimum and maximum load effect as regulated by the fuel supply regulator B.

The shaft-effect - positive or negative - to the electric motor/generator is determined by the shaft-effect from the engine and the rotational speed of the compressor which determines the input-effect to the compressor under the actual thermal conditions (condenser-temperature and evaporator-temperature mainly).

Consequently, the electric output-effect from the plant - positive or negative - can be regulated within certain limits by regulating the engine-load and the rotational speed of the compressor.

3. Technological Stage of Development

A LOCUS-plant can be built from component already commercially available. Five similar plants comprising engines and heatpumps have been in operation in Denmark for some years (see section 11 below) and several engine/heat

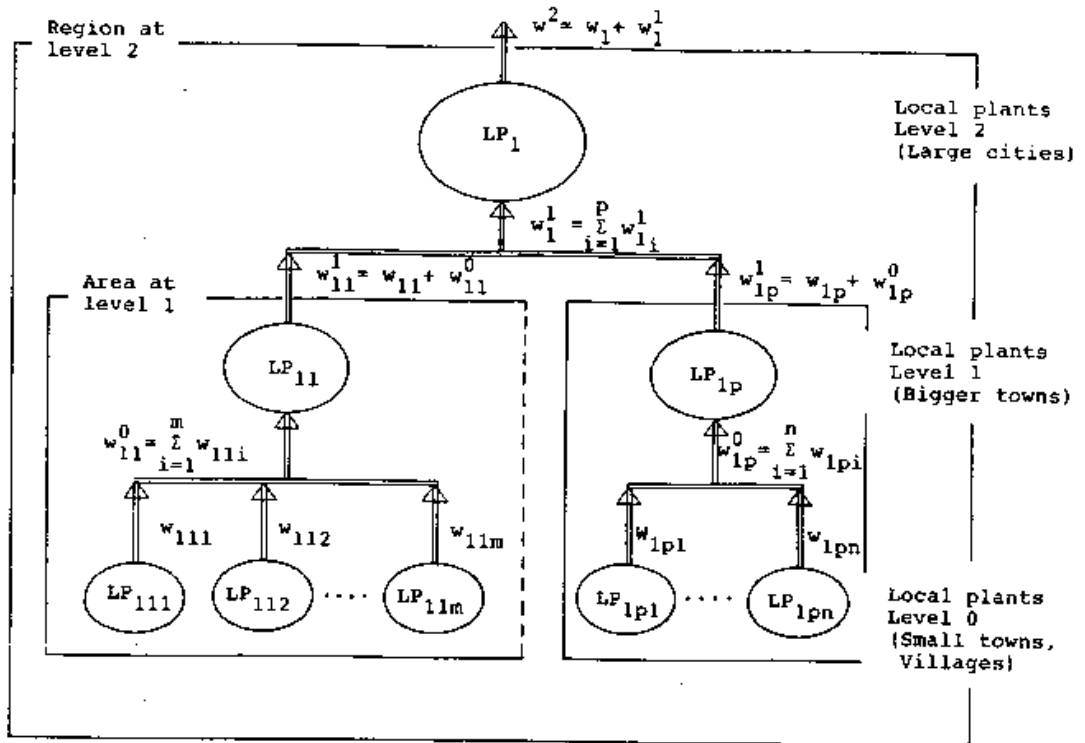


Fig. 5. LOCUS-system. With respect to regulation of electric effects transmitted through a regions common grid the LOCUS-plants in the villages and towns of that region can be organized in a hierarchy that facilitates the efficient operation of the system as a whole. See also fig. 6.

pump-plants are found in other European countries, mainly in the Federal Republic of Germany.

The technical problems still to be solved have to do with technical improvements of some hardware-components and, mainly, with the development of appropriate steering and regulation programs for automatic control of flows and effects. In a broader technological sense the main problem is to develop rational methods for the planning and design of regional LOCUS-systems (see fig. 5) in such a manner the overall efficiency of resource-utilization is optimized with respect to environmental protection, resource-depletion and economy.

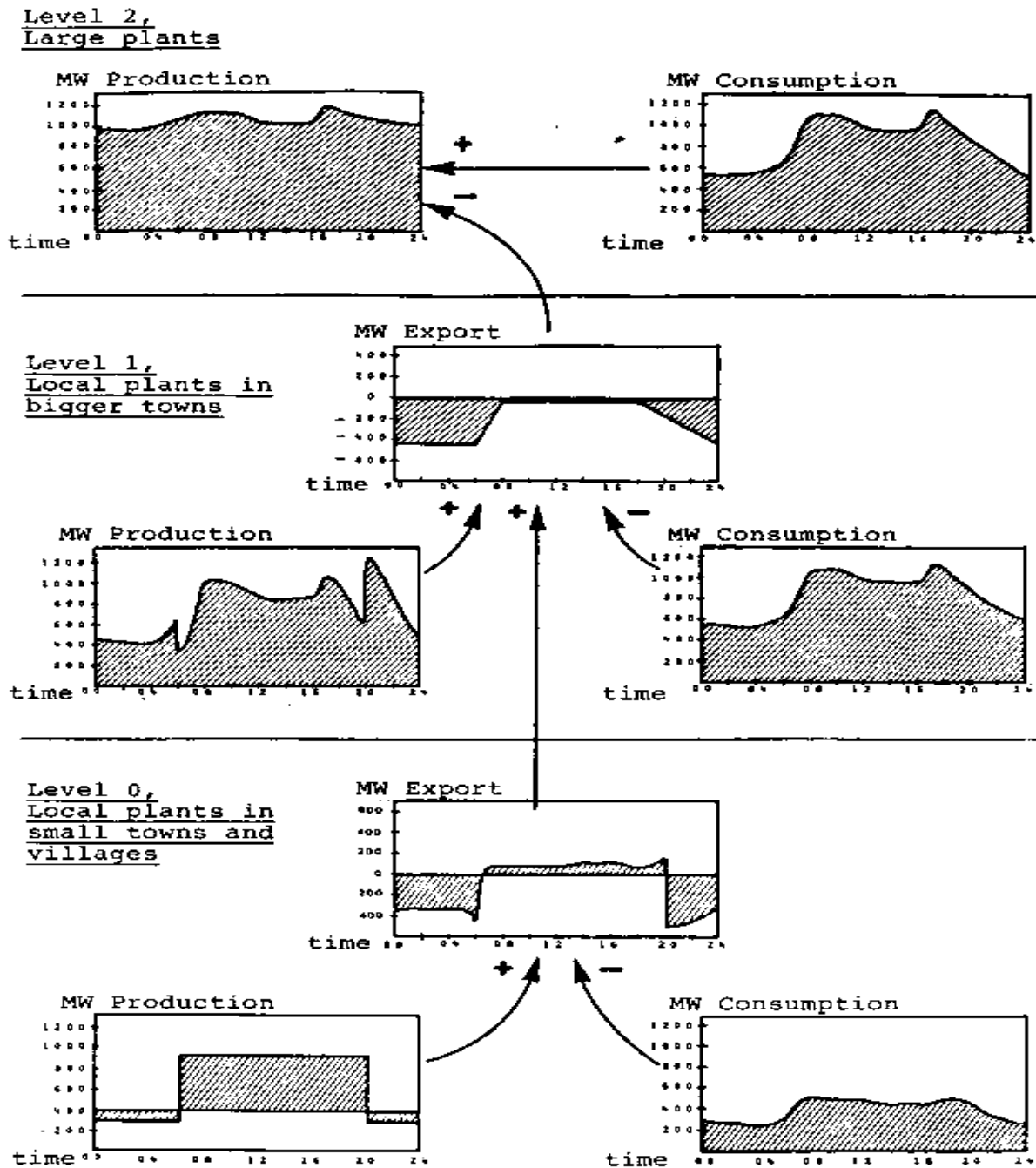


Fig. 6. Hierarchical regulation of power generation. By regulating the local electricity production at level 0 (villages) according to a specified 24-hour distribution and regulating the production at the next level (1, bigger towns) in such a manner that the export (here shown negative) to the top-level (2, large steamturbine-plants) follows an appropriate distribution, an even load can be obtained for the large plants at the top level of the hierarchy.

Concerning hardware-improvements efforts should be made to develop more efficient heatpump-evaporators with the atmosphere as the heat-reservoir. The energy-consumption for ventilation of these evaporators should be reduced by improved aerodynamic design and by taking advantage of the vertical pressure gradient caused by the cooling of the air.

Concerning the development of steering and regulation programs a solution is offered by the LOCUS-computerprogram. This program defines the optimal steering-algorithms for a given plant equipped with thermal and electromechanical regulators as shown by figs. 4 and 6, assuming that the quantity and variations over the considered period of time of the following four variables are given: 1) available fuel resources(if limited), 2) windpower-effect, 3) required thermal output and 4) scheduled electric output are given. If fuel resources are limited the program will determine the electric output according to this limitation. If fuel consumption is unrestricted electric output may be chosen as the free variable which determines fuel consumption for the given windpower input and thermal output. The program does, of course, require data that specify all relevant technical parameters for the components of the plant.

In actual practice the problem is to schedule the electricity production for a certain period, f.ex. the next 24-hours, given a prognosis for windpower, heat demand and - in case of limited fuel-resources - the available engine-fuel. Because of the discrepancies between these forecasts and the real development it may turn out that scheduled electricity production cannot be achieved because the heat-storage-tanks are emptied or storage capacity is exhausted. Therefore the production schedule must currently be revised with respect to the actual state of the system and the newest prognosis for the exogenously determined effects.

In Denmark the solution of this production-scheduling problem is sought through a project carried out by the firm Innosys, Consulting

Engineers, Copenhagen. The project is financed by the Danish Technology Council under the Ministry of Industry.

A different problem is, of course, to decide the capacity of the different components of a LOCUS-plant in such a manner that the plant can perform optimally as cogeneration-production unit in the planned development of an efficient, regional energy-system. The LOCUS-computerprogram also offers a solution to this design problem. The input-data to the program specify for each month of the year the production-schedules, resource-prognosis, temperatures of the district-heating supply and heatpump-reservoirs and values of a number of other exogenously determined variables together with the relevant technical performance-parameters. On the basis of these data the program will compute the required capacities of the engines, heatpumps and heat-storage tanks for each of the LOCUS-plants in a regional LOCUS-system taking the electric power-transmission between the plants into account. The program thus facilitates detailed analysis of the investments required to implement a regional energy-system under certain requirements with respect to utilization of local energy resources and regulation of heat- and electricity-production.

In summary it may be concluded that the hardware-components of LOCUS-plants belong to class A or B, i.e. they are commercially available on the market but further development of the performance and improvements of their longterm durability is expected. Concerning computer-programs for the methodological design, steering and regulation of LOCUS-systems and -plants the LOCUS-program is offered as a design tool while steering-programs for the practical operation of the plants are being developed.

4. Possibilities for placing

As mentioned in the introduction LOCUS-plants should be conceived of as integral components of efficient, regional energy systems based on cogeneration of heat and electric power. LOCUS-

plants should therefore be considered as the presently most efficient, flexible energy supply systems for small and medium sized towns in the temperate climate zones where the heat demand from district heating systems in the cold season is relatively large in proportion to the power demand. Because of their ability to adjust their electric power-output to variations in demand the larger LOCUS-plants located in medium sized towns can, as shown by fig. 6, serve as swiftly adjusting peak-load units to help levelling out the demand from the large, base-load steamturbine plants located at the large cities.

5. Energy relevant conditions

A conventional boiler-plant operates with so large temperature-differences between the combustion chamber and the water to be heated that the thermodynamic efficiency of the district heating system is quite insensitive to the temperature-level of the district heating network. In contrast the efficiency of systems supplied from LOCUS-plants with heatpumps and/or steam-engines that generate heat from condensers are very sensitive to this temperature level. In order to achieve maximum efficiency, i.e. to minimize the resources needed to fulfil the given demands, the temperature level in the district heating system and in particular the return temperature to the LOCUS-plant should be kept as low as possible. There are two ways, mainly, to lower the temperature level: 1) to improve the weathering of the buildings supplied from the district heating system and 2) to increase the areas and/or the heat transmission coefficients of the radiators in these buildings.

It shall also be mentioned that heatpumps should only be applied in a regional energy system at times when the proportion of heat demand to electric power demand is so high that the power production from the engines and steamturbine cogeneration plants that generate heat for district heating plus the wind-generated power exceeds the current power demand. Otherwise the system efficiency will be reduced

because extra electric power is generated to run heatpumps. This excludes heatpumps as a component in energy systems where the power demand is high in proportion to heat demand in all seasons.

6. Financial relations

The price of a LOCUS-plant depends, of course, of its size, composition and the demands for output-regulation capabilities. The economy of such plants can therefore only be evaluated in the context of a comprehensive energy plan designed to help overcome the environmental problems and the resource-depletion problems inherent in the present energy systems. The economic assessment should be made by comparing LOCUS-systems to systems with the same environmental properties concerning air-pollution, CO₂-production and deposition of waste materials.

7. Employment possibilities

Generally speaking construction of more efficient energy systems as LOCUS-systems involves employment of a larger work force than the construction of less efficient systems. This is because the larger investments in the more advanced, efficient systems are substituted for the higher rate of resource depletion in the less advanced and less efficient conventional systems.

8. Environmental conditions

Development of more efficient energy systems is an absolute precondition for the solution of the environmental problems caused by the excessive consumption of non-renewable, fossil fuel resources in the industrialized countries and the global distribution problems connected with energy supply. The development of LOCUS-systems may contribute to enhance energy conversion efficiency in some countries and to facilitate efficient utilization of renewable energy resources at the same time.

9. Combination possibilities

It will already have appeared from the description of LOCUS-systems and -plants that they are designed for combined utilization of several renewable and non-renewable energy sources in an efficient manner: windpower, biogas and other biomass-fuels, natural gas etc., and that also solar collectors may be integrated in LOCUS-plants.

10. Example of calculation

Several calculations of LOCUS-systems and LOCUS-plants designed for different locations in Denmark have been performed by means of the LOCUS-computerprogram. Space does not, however, allow the presentation of results in this article.

The program was developed in 1986 to meet the needs for detailed systems analysis and plant-design in connection with the development of a regional energy plan for the County Council of the Danish island Bornholm in the Baltic Sea. The program has since been used to compute monthly and annual energy balance results and the needed capacities of engines, heatpumps and storagetanks for biogas-and windpower-driven LOCUS-plants required to fulfil certain specifications with respect to regulation of power- and heat-output over 24-hour periods. Further development of the program took place in connection with feasibility studies concerning a proposed LOCUS-plant at Nibe, Northern Jutland, undertaken by the utility companies of Western Denmark (ELSAM).

11. Existing plants

Biogas-driven engine/heatpump-cogeneration plants with attached windmills for district heating and electricity production were built in three villages in Northern Jutland, Denmark, during the years 1984-1987. The plants are owned by the following local energy supply

companies:

V.Hjerimitslev Energiselskab
c/o Ib Telving
V.Hjerimitslev
DK-9700 Brønderslev

Vegger Energiselskab
c/o Orla Christensen
Vegger
DK-9240 Nibe

Skovsgaard Energiselskab
c/o Tage Møller
Skovsgaard
DK-9460 Brovst

The plant in V.Hjerimitslev was redesigned and reconstructed in 1988 to improve its performance. The plant in Vegger has not yet been in regular operation because of insufficient gas-supplies from the biogasplant.

A an engine/heatpump-plant fueled by natural gas has been in operation for a couple of years in the small town Ejby on Funen, Denmark. This plant is operated by

Innosys Aps. Consulting Engineers
Hejmdalsgade 14
DK-2200 Copenhagen

Although these four plants comprise all the components of a LOCUS-plant they have not been designed to comply fully with the presumptions made in the LOCUS-program with respect to effect-control capabilities.

An oil-fueled plant will be built in the town Ærøskøbing on the island Ærø this year. It will be operated by

Ærø Andelsenergi
DK-5970 Ærøskøbing

A biogas-fueled plant has been designed to be

built in Aakirkeby on the island Bornholm by

Aakirkeby Kommune (municipality)
DK-3720 Aakirkeby

but a final decision to build this plant has
not yet been reached.

