

ENERGY SUPPLY MODELLING: THE CASE OF CYCLADES

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1. INTRODUCTION

The Cyclades, a group of over thirty dispersed islands in the middle of the Aegean Sea can become a case study for energy-driven regional development. High cost, low reliability and scarcity of energy have significantly contributed to the underdevelopment of the region. There is a lack of local conventional energy sources, but the potential of renewable energy sources, namely geothermal, wind and solar is many times greater than the region's energy needs.

The Energy Policy Unit has constructed an Energy Plan¹ for Cyclades up to the year 2000 concerning the development of local economic resources in connection with programmes promoting the exploitation of local energy potential. New energy investments, mainly in renewables and energy saving options were examined in detail. For this reason, consistent alternative scenarios of energy supply, energy demand and economic growth were developed and assessed through an integrated modelling system². In this paper, the emphasis will be placed on the energy supply model.

On the other hand, the modelling effort is based upon a systemic approach of energy supply³, which provides an integrated framework for system theory perception, systems analysis and construction of models. The approach of the interrelations within the Energy Supply System (ESS) considers the appropriate homeomorphies⁴ which are innate patterns of structure and offer a generalized possibility of perception. The homeomorphies take into consideration the systemic hierarchy, the flows of energy, money and power, the ESS environment, the information network and the feedback controls.

System Dynamics (SD) is used as a means of translating the systemic perception into graphics or qualitative models⁵ and concurrently to quantitative models by the help of available software packages⁶. The qualitative representation of the Cyclades ESS is based upon relevant generic structures³. The results of the model runs provide evaluations of economic impacts for the region. Additionally, probabilistic simulation is carried out for the most significant uncertain parameters concluding to confidence intervals of the mean values.

2. ENERGY SUPPLY SYSTEM: GENERAL CONCEPT

The analysis is organized in hierarchical levels in such a way that the lowest level contains appropriate detail according to the analyst's judgment^{7,8}. Each level is associated both with the aggregation or

disaggregation of the system's structure and with the institutions concerned. Thus, the hierarchical levels have a substantial and not a formal conception. For the case of Cyclades, it is estimated that three hierarchical levels satisfy the analysis requirements.

The first, or upper hierarchical level represents the regional authorities concerning the specification of the national energy policy within the region. The decisions are related with promotion of local resources, subsidization of energy investments on new or renewable technologies and security problems of energy supply. The discrimination is located among energy subsystems (electricity, oil products, biomass, etc.), from which final or secondary energy forms derive and are fed by primary or secondary energy forms. For example, the electricity subsystem consumes oil products and supplies electricity to consumers.

The second hierarchical level represents the institutions which have undertaken the energy transformation and production sectors, ie. the electric utility, the oil companies, etc. The decisions focus on the satisfaction of energy demand under financial, environmental and other criteria. Alternative energy technologies are assessed aiming at the most efficient and convenient operation. For Cyclades, three subsystems are distinguished: electricity, oil products and other energies.

The third hierarchical level represents the concrete transformation units, like windgenerators, diesel engines for electricity production, solar collectors, oil burners, etc. The main decisions are concentrated on the amelioration of the operation of each unit under the prevailing conditions. The analysis detail comprises the energy flows among the transformation points, as well as the alterations of the capacity stocks. The basic financial flows are represented, but the balances and the regulatory decisions are incorporated in the higher levels.

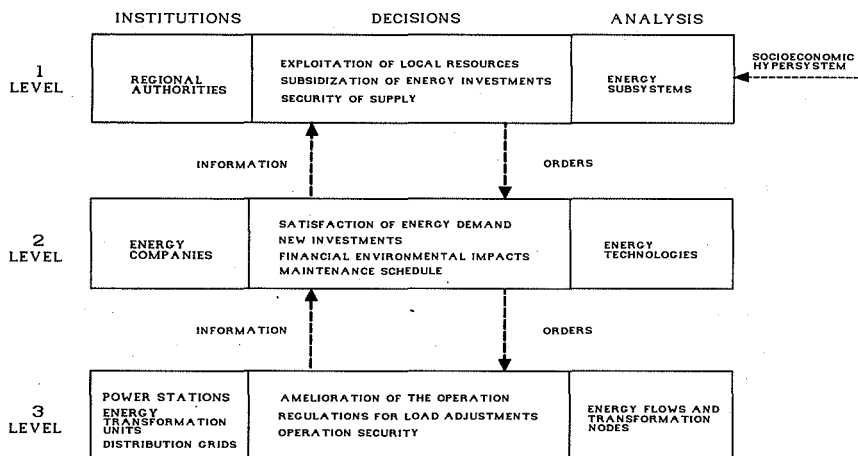


FIGURE 1 THE SCHEME OF ENERGY SUPPLY

The communication between successive levels is achieved by information and order flows, which generate the feedback loops^{9,10}. These contribute to the control of the ESS's behaviour, as it is influenced by the uncertainties, which derive from the broader energy system (eg. prices, availability of fuels) and the socioeconomic hypersystem to the ESS (eg. economic restrictions, national energy

policies). The feedback loops are associated with the major decision points. The latter ones are elements of the feedback procedures aiming at the approach of the system's operation objectives (negative feedback). In general, the most significant feedbacks are integrated within more than one hierarchical levels.

The scheme of Energy Supply presented above is shown in Figure 1.

3. THE SYSTEM DYNAMICS APPROACH AND GENERIC STRUCTURES

The SD approach of ESS modelling lies under a generalized concept, which is based upon a two step procedure.

1. The primary structural elements of the ESS are represented by the symbols of SD.

The types of SD rates and levels, which are compatible with the structural elements of the systemic perception, are determined. Thus, a strong interconnection is created between the systems analysis and the modelling approach. For the ESS, five types of material flows are distinguished, in addition to the flows of information and orders which normally exist. Three of them are mainly used and concern:

- Energy flows, which are analysed at the third level, compose the overall energy network and represent the energy forms (electricity, coal, oil products, etc.). Alternatively, exergy flows can be employed.
- Capacity flows, which concern the new additions and retirements of energy technology capacities.
- Financial flows, concerning money flows at the in microeconomic level.

Two more types of flows are considered:

- Pollution flows, which represent the environmental pollutants deriving from the ESS operation.
- Employment flows, concerning the permanent and temporary employment.

The types of levels which are interrelated with the above flow rates and are compatible to the ESS structure comprise:

- inventory levels, concerning the storage of primary, secondary and final energy forms and following the classical example in SD.
- Financial levels and employment levels, are the typical ones used in the literature and not particular to the ESS.
- Capacity levels, representing the installed capacities as they are already utilized in relevant studies.^{12,13}
- Transformation levels, concerning conversion, transmission and distribution of energy. These are strictly associated with the already mentioned energy flow rates and correspond to the transformation nodes on the energy chains. These latter represent the procedure of successive conversion from primary to final form.

The utilization of transformation levels is rather innovative offers information about cumulative energy losses which are translated to environmental pollution and energy conservation indicators. The relative feedback loop closes by incorporating the social oppositions which act as constraints to given development plans.

2. The generic structures used for model building, are based upon the above determination of flow rates and levels. The identification of generic structures is guided by the objective judgement of the analyst, but, follows the principles posed by Paich.¹⁴ In the case of ESS, the generic structures are distinguished in a combined form for each hierarchical level, as defined in Chapter 2, and for each substantial sector of system modelling. Such sectors are: primary energy supply, transformation of energy forms, financial balances, tariffication and investment procedures.

Thus, a small number of generic structure can be generally used. Their form is rather complicated and too extensive to be presented in this paper. On the other hand, the main feedback loops and decision functions existing in generic structures are compatible with the targets pursued at each hierarchical level. Especially, for the Cyclades case the modelling specifications will be referred in detail.

4. THE MODELLING APPROACH OF THE CYCLADES ESS

The Cyclades region imports oil products which are directed either to local consumption or to electricity production. Concerning the modelling of fuel oil, diesel oil, gasoline and LPG supplies, inventory levels are used. The input energy flows represent fuel imports to the islands and the output energy flows represent the quantities locally consumed. The inventory levels motivate new fuel orders which are subject to delays approached by third order functions. Fuel transportation and distribution is managed by private companies which are adequately subsidized, thus demand satisfaction is secured. Generally, the oil products supply mode is rather simple concerning the operational and decision functions, as they satisfy the part of demand not covered by electricity, traditional and renewable energy forms. The decisions at the upper hierarchical level influence indirectly the dependence on oil products, since the penetration rates of renewables are regulated.

The electricity supply modelling is more complicated, as each island or small groups of own their independent electricity grid. Therefore, the possibilities for electricity production are assessed separately for many quite similar cases and the most characteristic figures are thereafter summed up, so that an immediate perception is obtained for the whole of the region. Two classes of islands are distinguished, the grid-interconnected islands with the mainland electric system and the non-interconnected ones. At present there are no interconnections by undersea cable, but this is a very attractive perspective assessed by the model. Islands that will be interconnected to the mainland are naturally expected to solve automatically the capacity expansion problem. On the other hand, diesel engine capacity can be partially moved from interconnected to non-interconnected islands.

The general profile of electricity flows for each island, associated with the lower hierarchical level, is presented in Figure 2. Diesel engine generators, burning either fuel oil or diesel oil according to each island's demand size, play the main role in the non-interconnected islands. On the contrary, they simple remain as cold reserve on the interconnected islands. Wind generators penetrate better in the non-interconnected islands producing electricity at a cost competitive to the corresponding one of diesel generators. However, the small size of local grids poses technical restrictions on the development possibilities. For interconnected islands there are no such restrictions, but the profitability is doubtful, since wind electricity must compete with electricity produced from lignite and fuel oil at major power stations on the mainland. Thus, the criterion of wind energy penetration in interconnected islands is associated with oil substitution rather than with comparative benefit. Significant high enthalpy geothermal potential exists only at the island of Milos, but the process for equivalent electric capacity

identification is still in evolution. Two main options are examined: either the installed capacity will cover only part of Milos demand, then a station of 2-10 MW is adequate, either capacity of over 20 MW will be established and excess electricity will be transmitted to other areas. For the latter case, the cable interconnection of Milos is a prerequisite. Last, the import of electricity from the mainland is associated with the undersea cable interconnection. The possibility of exports concerns the extensive exploitation of geothermal and wind energy potential.

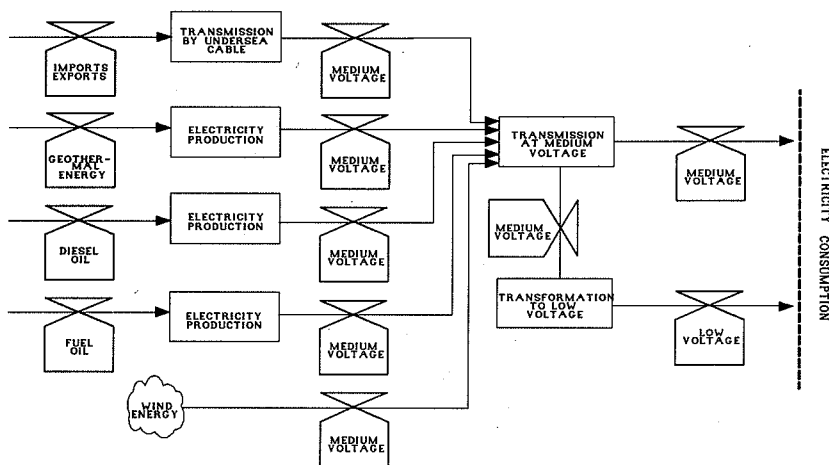


FIGURE 2 ENERGY FLOW DIAGRAM FOR ELECTRICITY SUPPLY

The decisions on electricity investment programmes are taken at the second hierarchical level, taking into account the existing policies on local resources development, subsidization of energy investments and increase of security. A microeconomic analysis for each investment option provides the profitability ranges. Moreover, specific technical, environmental and technological problems are considered together with the forecasts for energy demand and prices evolution. Therefore, the investment schedules for wind, geothermal and interconnection investments are launched in a dynamic process, which comprises both discrete and continuous steps. However, the related decision for diesel engine development follows, as it should safeguard demand coverage. The decision function is rather complicated including information for the alternative investment programmes. In Figure 3, the influence diagram for the diesel engine installation process is presented. Two main feedback loops are activated towards the determination of new installations. The interior positive loop concerns the process of estimating the future requirements of new capacity, whereas the exterior negative loop indicates appropriate regulations considering the prevailing current conditions of reliability. The decision function for new capacity requirements takes into account the installed capacity, the demand forecasts, the foreseen installation of alternative capacities (wind, geothermal, cable) and the transfer of diesel engines due to cable interconnections. Naturally, this decision is influenced by the uncertainty of future events. A reserve margin defined within a given interval of values safeguards reliability in the dynamic evolution of the electricity system. Postponement or acceleration of orders is pursued, if the initially calculated new capacity requirements are proved overestimated or underestimated, by a certain margin.

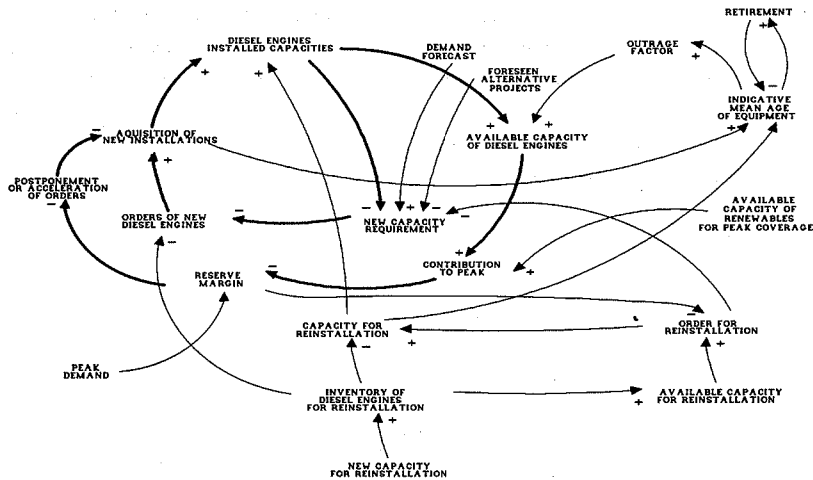


FIGURE 3. INFLUENCE DIAGRAM FOR DIESEL ENGINE INVESTMENTS

Other feedbacks of minor importance concerning the retirement rate and the maintenance programme are also taken into account but will not be presented here. At the upper hierarchical level, three feedback loops ensure the three mentioned policies.

5. SCENARIOS AND RESULTS

The effect of uncertainty is studied both by sensitivity analysis and by scenario construction. Three main scenarios treating different options of electricity supply were run and evaluated:

- the **SI** (Short Interconnection) scenario anticipates the interconnection of four islands till 1992, which correspond to about half of the region electricity consumption, a geothermal power station 2X2 MW for the local demand, penetration of windgenerators up to the technical limits till 2000 for the non-interconnected islands and only a small penetration for the interconnected islands.
- The **LI** (Long Interconnection) scenario anticipates intensive exploitation of geothermal based electricity (2X60 MW) and extended interconnection investments covering 85% of present regional electricity consumption, whereas the aeolic programme is reduced.
- the **HA** (High Aeolic) scenario anticipates short interconnection, geothermal development 2+10 MW for local consumption and extensive promotion of about 35 MW wind energy exploitation.

The model can support both deterministic and probabilistic sensitivity analysis. Variables that include uncertainty and could be approached by probabilistic curves are: energy demand by energy form, fuel prices, capacity retirement, wind energy investments by individuals and other variables of minor importance.

Detailed and comparative presentation of the three scenario results is included in Vol. 3 of the Energy Plan¹. In this paper, only the most characteristic results will be presented. In fact, none of the three scenarios ensures energy independence for Cyclades, as energy imports from the mainland sound indispensable. As shown in Figure 4, the increase of imports is significant in SI, whereas LI displays lower dependency, because of intensive geothermal development. HA displays a range at around the

present situation. It is evident that the energy supply alternative options are considered to take place after 1990. Average annual energy demand growth is expected to range from 3% to 4% within 1986-2000.

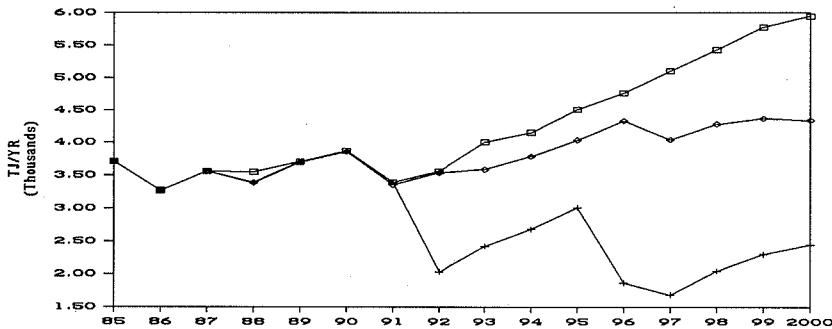


FIGURE 4 EXPECTED ANNUAL ENERGY IMPORTS FROM THE MAINLAND

Figure 5 presents the evolution of annual energy cost (KDr/TJ) in constant 1986 prices for the national economy. The major decrease occurs in LI, amounting to -30% in 2000 in comparison to the present figure. HA displays a little higher costs than SI, respectively -10% in 2000, due to the significant investments of windgenerators. If these investments stop, the cost of HA is expected to fall rapidly. Generally, the involvement of renewables in the Cyclades ESS improves more or less the energy economics.

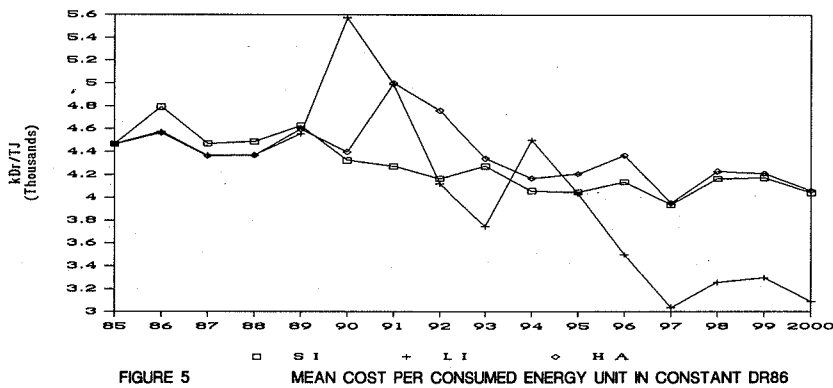


FIGURE 5 MEAN COST PER CONSUMED ENERGY UNIT IN CONSTANT DR86

Tolerance intervals and confidence levels were defined for the mean values of the variables most influenced by uncertainty, like the reserve margin. Satisfactory tolerance intervals were achieved for confidence levels 80% and 95% following the simplest method¹⁵, namely the repeating random number process. Practically, 25-30 runs of the model under probabilistic simulation proved adequate.

6. CONCLUDING REMARKS

In brief, the utilization of SD in a generalized and systemic approach of energy supply problems sounds attractive and facilitates relevant model construction. The identified homeomorphies and generic structures within ESS are specified and translated, through the SD tools, to qualitative and quantitative representations. The case of Cyclades ESS, which is subject to very complicated future perspectives, is modelled adequately and with clarity, thus confirming the potential applicability of the approach.

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