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## ► To cite this version:

Fouzia Ounnar, Aziz Naamane, Patrick Pujo, Nacer Kouider M'Sirdi. Multicriteria control strategies of Holonic Energy Systems. International journal of research and reviews in mechatronic design and simulation., 2013, 2 (4). hal-01212623

**HAL Id: hal-01212623**

**<https://hal.science/hal-01212623>**

Submitted on 31 Oct 2015

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# Multicriteria control strategies of Holonic Energy Systems

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**Abstract** – The renewable energy sources are, and will be more and more, brought to cohabit on the same site. However, they have not yet the subject of a real overall energy management strategy. As several systems rely on multiple energy sources, power distribution strategy must be implemented by matching the supply and the demand. The balance between production and consumption must be carefully conducted to ensure the availability of power. This paper addresses decentralized control strategies of multi-sources and multi-users energy systems. The objective is to describe, by using the recursion principle of the holonic paradigm, a decentralized multi-sources, multi-users energy system. The bases of multicriteria decision aid method are presented to ensure, in an adequate and automated way, the several possible switchings between the various energy sources of the system.

**Keywords** – Control, Multi-energy sources, Multi-users, Overall energy management, Multicriteria decision aid, AHP

## 1. Introduction

Nowadays, new forms of energy management, both in terms of its production than consumption, should emerge. The established model of an unbounded consumer and inexhaustible sources of production, all centrally managed, has become obsolete. Indeed, the significant sources of energy production, of nuclear or fossil fuel type, which can assume all the needs of a country or region, are more strongly contested, either due to accidents of natural origin [1] or following the observation of the dangerousness of the human effect on the global climate balance [2]. Meanwhile, governments are encouraging in recent years the development of green energy [3].

Any centralized control approach will be obsolete regarding, on one hand, the powers concerned and on another hand, the wide dispersion of these production sources: an irreversible movement to locally produce what is locally consumed is being developed. This raises the problem of balancing between production and consumption, with the need of controlling the electrical network in a decentralized manner, taking into consideration technical, economic and natural constraints, while maintaining a good service quality. For example, [4] proposes a paradigm shift for urban energy systems, setting out the principles of local and multicriteria energy management system, optimizing the provision of energy services and its distributed production. Another example is the European project MESSIB ([www.messib.eu](http://www.messib.eu)) that concerns positive energy buildings, i.e. self-sufficient, and provides them with two systems of electrical and thermal storage, integrated with building facilities and with a control system to manage energy demand. Outside of urban space, energy autonomy experiments are conducted (e.g. [www.urd.org](http://www.urd.org)).

These observations may seem punctual. However, it must be considered at the countries or regions scale. [5] addresses the optimization of decentralized energy systems by integrating technical, economic, environmental and social criteria analysis and applies this multicriteria analysis to the study of implementation of renewable energy sources in a Greek archipelago. The prospect of such decentralized energy systems encouraged to refer for their management to the holonic and multi-agent paradigms. [6] proposes and tests a simulated multi-agent system, where there is an agent to control each converter. [7] also describes a multi-agent system for planning of distributed energy resources for electric supply of an island and shows the obtained energy autonomy.

This trend toward distributed control strategies of multi-sources energy systems actually looks interesting. Our aim in this study is in a similar way: the objective is to describe in its whole, using the principle of holonic paradigm recursion, a decentralized energy system multi-sources and multi-users and to show the basics of using the multicriteria decision implemented to ensure adequate and automatic switching between the different system components.

After presenting briefly the different types of energy sources that can constitutes the energy system with variable structure, difficulties arise to manage the system will be highlighted. Then, will be presented, the use of the holonic paradigm to build recursive models of energy entities, sometimes productive, sometimes consumers, whose operation can be managed by a multicriteria analysis. After recalling the fundamentals of the latter, the basics of the multicriteria control of multi-sources and multi-users energy system will be formulated.

## 2. Multi-sources and multi-users system

Renewable energy is as a potential solution for reducing greenhouse gas emissions and protecting the environment. To meet the demand for energy, one of the main solutions to retain is certainly the diversification of resources and the coupling between multiple sources.

### 2.1. Presentation of multi-sources and multi-users system

A multi-energy system is a hybrid system, for example formed of three sources: solar, wind and a storage battery (Figure 1).

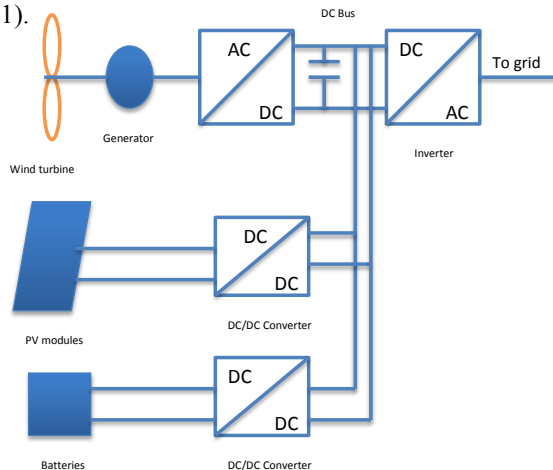


Figure 1: Configuration of multi-sources hybrid energy systems.

The amount of energy produced depends mainly on weather conditions, hence the importance of a hybrid system to maximize the amount of energy produced. For example, in winter the wind is almost permanent. There is so much wind power. In summer, it is the light which is very abundant, and photovoltaic production is high.

Sensors are useful for monitoring the operation of the energy system, but they are not always available. We then use observers, estimators and predictors. The synthesis of these elements will complement the instrumentation system to improve the management and optimize the operation. Robust observers and an online prediction system have been developed for real-time information needs of both energy and operating mode [8]. Indeed, several data must be observed: the interfaces variables regarding the exchange of energy between the system and its environment and the state variables of different parts of the system. The measuring and evaluation step is followed by the system control and optimization.

Knowledge of user behavior is also fundamental to adapt production and consumption. We describe here briefly a consumption model consists of various elements type, corresponding to patterns of use and can be easily parameterized. We find first 'Housekeeping' profile, where consumption can be easily modeled by a curve corresponding to the habits (consumption level during the day, peak consumption at the end of the day, standby consumption at night), to be modulated according to outside temperature (heater), the period of the year (time of sunrise and sunset), the day of the week ... Concerning the 'Enterprise' profile, the consumption curve is generally stable, but must also be adjusted according to the same elements, which can be added for example periods of annual closure. Finally, we can consider a 'Public Use' profile, for example taking into account the illumination of the road. Again, consumption is

perfectly predictable, depending on time of year and especially adjustable according to the available energy.

### 2.2. Holonic approach of a multi-sources and multi-users system

#### 2.2.1. Application of holonic paradigm to a distributed energy system

The holonic paradigm was proposed by [9], for modeling complex social systems. This approach marks a rupture with former hierarchical models. According to [10], the Holon is defined as a conceptual entity based on the association of a material structure (the M\_Holon) that represent the physical part (individual to supervise, gate..) and an informational structure (the I\_Holon) providing the whole thing with a decisional intelligence giving the capability to operate in interaction with other holons. All interacting holonic entities in the system are at the same decision level that corresponds to isoarchic concept: the system architecture is completely decentralized and its components are not of 'master-slave' type, but have a same decision power.

A holonic representation of an energy system can naturally be realized around the concept of Resource Holon (RH). This is equivalent to define a complex mechatronic system, as defined in [11]: holonic approach allows to describe decentralized and recursive complex system. Each RH can only be producer or consumer of energy, or alternatively can play both roles (case of an energy storage system). Beyond this first approach, two other types of Holons must be used: the Energy Holon (EH) and Service Holon (SH). The EH corresponds to the produced or consumed energy by a RH with different electrical characteristics (power, voltage, current, form factor ...). It is linked to a RH by a numerical model of instantaneous production / consumption, which is relative to the energy chain processes. The SH relates more particularly to the temporal description of this consumption: this is related to the fact that the energy system provides a service to users, and this service is broken down by user ... The link EH-SH can assess the users' quality service. The RH-SH relationships are used to organize the control of the energy system, by organizing the switching of RH producers to RH consumers based on SH validated by the links RH-SH-HS and EH-SH. Before describing this switching system, let's look at the concept of recursion in holonic systems and that we find in complex mechatronic systems. Energy system can be considered as a triplet {RH, EH, SH}. This set constitutes Holonic Energy System (HES). It may belong to an interconnected set of more global level, where it can take the role of producer, consumer or alternatively two roles. It may itself be composed of energy systems at a lower level, the lowest being that of the basic equipment that constitute a basic wind, a solar panel...

So we can see that with the holonic paradigm applied to distributed energy systems, an HEQ (High Environmental Quality) building should be considered as a holon composed of holons, as well as a farm or a self-autonomous installation. These holons fit into neighborhood holons, themselves being components of a larger scale (city, district, region ...), where these different holonic entities exchange their needs and their excess energy... Thus, we find here all the characteristics of a

mechatronic approach of complex systems [11], applied to HES: composed of mechatronic components that can be themselves mechatronic systems and that are associated to a decisional intelligence allowing to ensure individual and collective operation.

### 2.2.2. Switching problem in a HES

The main difficulty of such a distributed management of the energy problem is to use the most possible appropriate way all the possible sources of production in relation to all identified needs. For this, it should switch on an ad hoc manner some sources to some users, depending on the state's energy system at time  $t$  and on the forecasts of its operation in the near future.

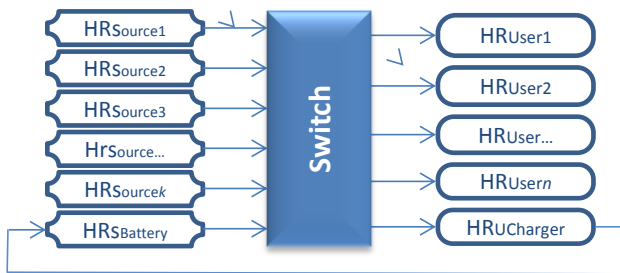


Figure 2: Switching of multi-sources and multi-users energy system.

The switch is then a connection function between some RHUser and some RHSource. The various connection configurations constitute solutions of such a multi-sources and multi-users energy system. Thus the control of an energy system consists in choosing among these connection configurations that will be the most appropriate at a given time, and this according to the actual and estimates state of the different Holons (composing the HES). This will be done through a multicriteria decision aid method.

## 3. Presentation of the multicriteria decision aid method

Each decision-making control is inherently multicriteria: allocation of a task, for example, is a decision process that results from a study based on production cost, change series time, conveying time, waiting time in the upstream stock, production quality, etc.. The use of multicriteria methods can integrate all these constraints [12] and will allow to seek a solution that seems the best in terms of a set of criteria. In this section, it will define the multicriteria decision aid and its use in the context of energy system. Three classes of multicriteria methods can distinguish: decision aid methods, elementary methods and mathematical optimization methods. The choice of one class of methods can depend either on the data available to treat the multicriteria problem, or on the way the decision maker models his preferences [13]. As we described earlier, the classification process of switching possible solutions proposed in this study is based on the knowledge of various alternatives. Therefore, the use of mathematical optimization methods is not possible. In addition, the elementary methods are not considered, because the decision maker can be indifferent between two alternatives. Thus, multicriteria decision aid methods can help the decision maker during the refinement of his decision process related to the choice of an alternative among a set of potential alternatives.

### 3.1. Use of multicriteria decision aid for energy system

According to [14], multicriteria decision aid becomes a technique increasingly used for the management of sustainable energy. Indeed, the aim is to provide solutions to problems expressed in terms of multiple and conflicting objectives. This study concerns more than 90 published articles can analyze the applicability of different methods discussed, with a classification of application fields. For multi-energy sources based on more conventional technologies (gas turbine, internal combustion engine with fuel ...), the need for optimization is proved [15], [16] and multicriteria analysis is of great interest [17], [18].

Regarding the rise of the problem of buildings HEQ, new work emerged. This is mainly related to feasibility studies and design of buildings, like [19]. They consist in validating the adequacy production / consumption, taking into account the annual variations and / or seasonal demand and different sources. Such approaches allow a preliminary design, but there are many uncertainties, such as the choice of efficiencies, and the result is based on the experience of experts designing the multi-energy feeding the HQE building [20]. [21] assesses the design of an optimized energy system for residential buildings in Japan, using a multicriteria decision support integrating economic criteria, energy and environment. [22] describes an autonomous system combining photovoltaic, wind, diesel and battery storage, including a multi-objective optimization using a genetic algorithm. The objectives are to minimize the levelised cost of energy and equivalent carbon dioxide ( $\text{CO}_2$ ) of life cycle. [23] used multicriteria analysis to define the most appropriate configuration of energy sources to meet local rural poor demand in developing countries. Closer to our problem, [24] uses a decision aid method to select as connection configuration one of a possible switching between sources and users. However, this correspond to the choice of the configuration of a multi-sources system, and it is not possible to directly use this approach to change in real time switching mode: the use of the chosen multicriteria decision aid method (Electra III in this case), is very sensitive and is not suitable for automated use.

### 3.2. Choice of a multicriteria decision aid method

The multicriteria decision aid methods include four stages, the first three (List of potential actions to study; List the criteria to take into account; Establish the performance table (consisting of all shares valued according to each criterion)) are common to all methods and show only slight variations, unlike the fourth step (Aggregate the performance) can be defined using three different approaches. The aggregation of preferences consists in the exploitation of the shares valued on the various criteria defined in the previous step to generate an overall assessment. According to [25], in some decision contexts, a modeling of the decision maker's preferences is required. Modeling of preferences consists in the development of a formalized representation of preferences in relation to potential actions. As required by the decision maker, it is possible to distinguish three operational approaches for the aggregation of preferences: Complete, Partial and Local aggregation. In our case, the used multicriteria method must

be the result of interaction of all considered criteria. No criteria may be ostracized, which is why we focused on multicriteria decision aid methods using complete aggregation method. There are several methods related to complete aggregation [26], [27]. Contrary to these multicriteria decision aid methods, the AHP method, developed by T-L. Saaty [28] is the only method that allows one hand the measure of the consistency of the decision maker's preferences and also the consideration of both independence and interdependence of considered criteria. Therefore, this method allows the use of complete lists of criteria without excluding any one. The taking into account of the interdependence results in the construction of a hierarchical structure. Note also that the AHP method allows the consideration of qualitative and quantitative criteria. All these features are the highlights of the AHP method.

### 3.3. The Analytic Hierarchy Process (AHP)

AHP method is a measurement process within hierarchical structures or networks [29], to express preferences and choices among multiple criteria and alternatives and then to obtain a classification of all alternatives using the criteria weights. AHP is a process of decision making that directly interprets data and information and which can be automated. AHP involves two main phases [13]: Configuration phase and Exploitation phase.

#### 3.3.1. AHP Configuration phase

In order to use the AHP algorithm, it is necessary to set the parameters of the relative importance of criteria and their indicators. This configures the pairwise comparison between the different criteria regarding to their importance in the decision. This 'static' phase of the algorithm must be validated by a mathematical verification of consistency. Having identified the decision structure (Overall Goal, Criteria, Indicators, Alternatives), the first step corresponds to rank the criteria regarding the overall objective. To this end, a preference matrix [PC] is built where each element  $pc_{ij}$  is a judgment or a pairwise comparison of  $C_i$  and  $C_j$  criteria, according to a scale 1-9 [28], where  $pc_{ij} = 1 / pc_{ji}$  &  $pc_{ii} = 1$ . A consistency check of established preferences is conducted before determining the relative importance vector of criteria regarding the overall goal [WCO]. The importance vector [W] is calculated by:

$$[W] = [W]_j \text{ where: } j = \text{Inf}(k) \text{ tel que : } [W]_k - [W]_{k-1} = [0]$$

with  $[W]_j = [P^j e^T / e P^j e^T]$  ;  $e = [1, 1, \dots, 1]$  and  $P$  : preference matrix.

The second step corresponds, regarding all criteria  $C_k$ , to establish a classification of each of the indicators  $I_{k,i}$  regarding its criterion  $C_k$ . To do this, preference matrix  $[P_{Ik}]$  is built with consistency checking of judgments. Each element  $pi_{kij}$  of  $[P_{Ik}]$  is a judgment or a pairwise comparison of indicators  $I_{k,i}$  and  $I_{k,j}$ . The relative importance vector  $[W_{Ick}]$  of indicators regarding its criterion is then calculated  $[W_{Ick}] = f([P_{Ik}])$ .

#### 3.3.2. AHP Exploitation phase

The exploitation phase (dynamic phase) of the AHP algorithm allows to classify the possible solutions. A

classification of the solutions (alternatives) regarding each indicator  $I_{kx}$  of each criterion  $C_k$  is established.

For each indicator, the indicator values of alternatives are compared in pairs. A preference matrix is determined  $[P_{Ak,l}]$  ('k' is the criterion number k and 'l' being the indicator number l of the criterion 'k'), where:  $pa_{k,l}(i,j) = pa_{k,l}(j) / pa_{k,l}(i)$  to minimize the criterion and  $pa_{k,l}(i,j) = pa_{k,l}(i) / pa_{k,l}(j)$  to maximize it. The relative importance vector of alternative regarding the indicators of each criterion is then calculated  $[W_{Aik,l}] = f([P_{Ak,l}])$ . An aggregation matrix representing the relative importance of alternatives regarding the indicators is then constructed:  $[W_{Aik}] = [[W_{Aik,1}], [W_{Aik,2}], \dots, [W_{Aik,l}]]$ . Then, it is necessary to move up in the hierarchy of relative choices, because the goal is to determine the relative importance of alternatives regarding the overall goal  $[W_{AO}] = [W_{AC}] * [W_{CO}]$  with:  $[W_{CO}] = f([P_C])$  the relative importance vector of criteria regarding the overall objective and  $[W_{AC}] = [[W_{AC1}], [W_{AC2}], \dots, [W_{ACnc}]]$  the aggregation matrix representing the relative importance of alternatives regarding the criteria ( $n_c$  being the number of criteria). Each relative importance vector  $[W_{Ack}]$  is calculated by:  $[W_{Ack}] = [W_{Aik}] * [W_{Ick}]$  for  $k = 1, n_c$ .

## 4. Control of HES by the AHP method

### 4.1. Implementation of the AHP method

As mentioned above, the AHP method is studied to allow classification of possible switching between different energy sources with different characteristics (storage at short or medium term, production of energy sources (wind and solar)), with an output (production) which varies randomly (depending on the climate), and intended to be exploited by several users. It will be necessary to consider the constraint related to users who have a quasi-periodic regular consumption but also a random consumption (a part of the latter is 'detectable' in time or expected by adaptive predictors).

In order to rank the alternatives (switching solutions between sources and users) using the AHP method, it is essential that during the configuration phase, to identify at first a decision structure (overall objective, criteria, indicators (from the information system's sensors), and alternatives (all direct switching and combined switching)). In a second step, it will be necessary to identify the setting of the relative importance of criteria and their indicators. This phase of the algorithm must be validated by a mathematical verification of consistency. Under the second phase (Exploitation), allowing to rank the alternatives regarding the overall goal, it will be necessary to define the sources of information (electrical parameters) allowing to identify the indicator values (by adaptive observers) for each alternative.

As an illustration of a multicriteria rule that can be implemented, in the case if production exceeds demand, it must be necessary to store the excess energy. In this case, among all possible sources, it is the source(s) which is the most stable(s) that is directed to the battery charger. It should be noted that besides the choice of the switching mode, multicriteria analysis may identify where energy needs are higher than the production capacity and destocking, which would trigger eco-consumption modes: for example, sending



alert messages among users of 'household' type or reducing the supply of users of 'Public use: roads' type. Finally, indicators coming from forecasts, either from outside agencies (eg, weather forecasts), or obtained by predictors relating to the characteristics of the energy system, can be easily incorporated in the decision-making mechanism.

#### 4.2. Predictive indicators obtained by the ARMA method

Given an observable characteristic of an energy system holon, represented by a time series  $X_t$ , the ARMA model is a tool allowing to understand and predict, possibly, future values of this series [30]. The model consists of two parts: an autoregressive part (AR) and a moving average part (MA). The notation ARMA (p, q) is related to the model with p: autoregressive terms AR(p) and q: moving average terms MA(q) [31]:

$$X_t = e_t + \sum_{i=1}^p a_i X_{t-i} + \sum_{i=1}^q c_i e_{t-i}$$

The ARMA(p, q) model associated to each size requiring a predictive view should be adapted to ensure the stability of the model [32]. An illustration of such an interest is the ability to choose where to store excess production: in a battery or in a supercapacitor?

## 5. Conclusion

Holonic Energy Systems based on three type of holons (RH, EH, SH) has been described. Then, the multicriteria decision aid method (AHP) has been presented and its choice was justified. The exploitation of this method in the context of multi-sources and multi-energies systems has been explained. A work is currently underway to define in detail the decision structure to be use and then to test the proposals on a case study. An analysis of the obtained results will be conducted using various performance indicators.

From this work, a medium-term prospect corresponds to provide plug-and-run recursive architecture for multi-sources and multi-users system, based on the holonic paradigm, incorporating intelligent and communicators' components, and taking its decisions on the AHP multicriteria analysis.

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