Alternative Robust Energy Technologies for Environmental Sustainability (ARETES)

Research proposal for the ARISTEIA grant
Principal Investigator: Demetris Koutsoyiannis
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Extended Synopsis

Introduction

In the 20th century, Western civilization became dependent on the intense use of fossil fuels, which gave the luxury of a controllable and deterministically manageable energy production, with the flip of a switch. However, their use is unsustainable and short-lived. Industry and economic growth are intimately connected to energy production and within the current paradigm, ultimately bound by the quantity of (limited) fossil fuels. There is hence a growing realization that the use of renewable energy sources needs to be drastically increased to avoid severe socioeconomic crisis in the not-too-distant future. However, although technology has increased the efficiency and lowered the cost of renewable sources of usable energy, a drastic change from fossil fuels to renewable sources is still difficult to implement: Renewable sources of energy, such as wind and solar, are highly variable, and their efficient use implies an energy management paradigm that recognizes and exploits the intrinsic uncertainty of natural processes. The radically different nature of renewables as compared to fossil fuels calls for a paradigm shift in energy technology and management, which embraces uncertainty as a dominant natural characteristic and converts it into an element boosting, rather than hindering, sustainable development and evolution.

Managing uncertain resources requires regulation through storage. For example, exploitation of wind and solar energy, which are highly variable, dependent on atmospheric conditions (wind speed, sunshine), irregularly varying and unavailable at the time of demand, should be necessarily combined with technologies for energy storage. Despite recent claims that cost-effective storage of electricity is beyond present technology, the proven method of pumped storage (pumping of water to an upstream location consuming available energy, to be retrieved later as hydropower) is an efficient method, representing the best available technology since: (1) it does not emit any by-products to the environment, (2) it is cost efficient, with efficiency ratios exceeding 90% (in large scale projects) and (3) hydroelectric energy production does not consume water (only converts its dynamic energy), and thus can be combined with other water uses: domestic, agricultural and industrial. To this extent, a technological paradigm where natural elements such as water, wind and sunshine are the sources of energy, with water in an additional integrative and regulating role, becomes plausible and desirable. Hydrology, the science of water on the Earth, and its interface with atmospheric sciences and energy technologies, have thus a prominent role to play in this new paradigm.

We propose the development of a consistent mathematical and methodological framework for the description and management of randomness and uncertainty in natural systems and the investigation of its implications for integrated management of renewable and, hence, variable resources with an emphasis on the role of water in sustainable energy production and management under uncertainty. The project duration will be 3 years and will comprise 5 work packages (WP) as specified below.

Towards a novel mathematical framework to quantify uncertainty in nature (WP1)

During the last two decades, hydrology invested in deterministic descriptions and models, harmonizing itself with a more general trend in geophysical disciplines and particularly in climatology. The trend towards the so-called “physically based models” signifies this change of perspective. The concept behind these models is that modern computational means would allow the full description of the physics of the hydrological cycle using mechanistic model structures and “first principles” such as Newton’s laws and their particular formulations in fluid mechanics (i.e. Navier-Stokes equations). From the first steps of these modelling attempts, it was argued that there are fundamental problems in their application for practical prediction in hydrology, which result from limitations of the model equations relative to a heterogeneous reality. There are arguments that this pure deterministic modelling may be infeasible and that research targets to reduce predictive uncertainty within a deterministic context may be misleading.

Our initial research activities intend to develop a new mathematical framework to quantify and model uncertainty in natural processes. This package includes:

1. the study of entropy as a concept for understanding and quantifying uncertainty with respect to hydro-climatic processes and as a driving mechanism of these processes;
2. the study of the nature of geophysical processes based on observed long time series, with particular emphasis on extremes and time dependence structure; and
3. the streamlining of a stochastic theory of hydroclimatic processes.

WP1 will provide the foundation for further scientific progress, including rigorous definitions of concepts and useful interpretations of behaviours. Currently the emphasis has been given on the construction of algorithms and models and the concepts themselves have been left unclear. Therefore the proposed scientific framework, which will provide clear definitions of concepts, is a breakthrough that will boost future research. The notion of entropy and the principle of maximum entropy as a tool for logical inference, understanding of natural phenomena and effective modelling thereof, can be implemented to hydroclimatic systems to provide a sound theoretical basis for hydroclimatology, which is currently missing.

Knowledge discovery from past information on water, climate, energy and socio-economic development (WP2)

Recent advances in dynamical systems and chaos have highlighted the importance of quantified historical information for prediction: the method of analogues has proved efficient in analyzing, learning and predicting from similar system states in the recorded past.

To assist the development of a consistent and concrete mathematical framework for hydroclimatic processes, WP2 will focus on organizing historical information on climate, water, energy, their interconnections and their relationship to socioeconomic development. Specifically, we plan to:

1. process documented historical and paleoclimatic (proxy data) information as a means of (a) understanding historical climatic changes, (b) constructing quantified time series for statistical analysis; and (c) testing the theory constructed in WP1.
2. relate past socio-economic development with (a) the extent of the climatic variation at specific locations, (b) the prevailing practices in society related to resources use (water consumption, exploitation of solar and wind energy), and (c) the ability of different societies to manage natural sources (construction of works, management practices, etc.) in an unstable environment; and
3. investigate the different conditions and models of energy use in developed and developing countries, with respect to interactions with population growth, agriculture and food production, transportation, water use and lifestyle.

WP2 will provide invaluable insights on both historical factors relevant to the understanding of future uncertainty and the interplay between resource consumption, energy and sustainable development.

Decision support for renewable energy management (WP3)

The new approach towards understanding, analysis and modelling of water and climate, developed in WP1 and supported by the historical evidence and socio-economic implications examined in WP2, will give rise to a new framework for describing, quantifying and ultimately managing renewable water and energy resources. WP3 focuses on developing a decision support system for long-term water-energy planning and management, comprising two components:

1. a stochastic simulation model, for the generation of synthetic time series of hydrometeorological processes, related to renewable energy production and hydropower, and energy demand;
2. a parameterization-simulation-optimization framework, for the optimal planning and management of renewable energy systems;.

The above research will explore the key role of water in sustainable energy management and develop strategic planning and long-term management methodologies for exploitation of renewable energies.

Proof of concept (WP4)

The potential of the developed theoretical and technological framework for renewable energy management will be tested in real-world conditions. A unique large-scale hydrosystem extended in two major river basins (Acheloos and Peneios) interconnected through diversion projects will be explored. Importantly, the chosen sensitive socio-economic area lacks fossil fuels and is strongly dependent on external energy sources, despite its substantial hydropower potential. Hence, its sustainable development requires drastic change of the present over-consumptive socio-economical model and the development of local renewable energy resources. In this, it presents an ideal case, highly transferable to other areas of Greece and the world.

The proposed case study, which will test the applicability of the developed framework and also investigate the sustainable development potential of the study area, includes:

1. analysis of the current energy use and management;
2. investigation of the potential for sustainable energy development;
3. development of future energy scenarios;
4. long-term simulations for the development of a strategic renewable energy plan;

An open knowledge approach for disseminating information (WP5)

Science requires verifiability and falsifiability, which, in turn, imply ease of access to all underlying information. To enable the scientific community to reproduce experiments and the public to monitor the progress of publicly funded research, WP5 (which will run in parallel to all the others) aims at:

1. organizing all hydrometeorological and energy data using our existing public database *opemeteo.org*;
2. improving and extending the existing free software of *openmeteo.org*, which will also become the platform for disseminating all models developed within the project;
3. developing a project-oriented web site that will provide news and documentation and point to all sources of relevant information.

Structure, outcomes and indicators of progress

Outcomes of this research are envisaged to include:

1. an open access historical knowledge base related to climate, water and energy use;
2. a new scientific framework for understanding natural behaviours recognizing their inherent uncertainty;
3. an entropic-stochastic theory of uncertainty and risk;
4. a novel tested methodology for modelling hydroclimatic processes;
5. a new methodological approach for the sustainable coupling of water and renewable energy;
6. a proof of concept of integrated renewable resource management in the form of a case study;
7. a set of recommendations and transferable lessons learned, as a basis for innovative applications;
8. a structuring of knowledge gained, for incorporation into educational processes.

We anticipate the following measurable indicators of progress of the research:

- 5 reports, each one documenting in detail the research and results of each work package
- 10+ publications in peer-reviewed journals, in the form of research and opinion papers, and commentaries;
- 12+ presentations in widely respected international conferences;
- an open access database with long-term hydroclimatic information and energy data;
- a toolkit with software implementation of all models developed, provided as free software;
- a web site with all information related to the project;
- 1 workshop designed to bring together experts on relevant fields to foster further discussion;
- 2 short visits of international experts;
- 2 PhD and 4+ MSc and diploma theses produced within the research programme