Design of an Integrated Wind-based Energy Storage and Desalination Solution for the Island of Amorgos

Dimitrios Zafirakis, Cleopatra Ntourou, Christiana Papapostolou, Georgios Nomikos, Emilia Kondili, and John K. Kaldellis

Abstract-- The present work is devoted to the development of an integrated methodology for the design of optimum wind-based energy storage and desalination configurations, used to encounter both electricity and water problems under the prerequisites of cost-effectiveness and minimum fuel consumption for the operation of the local thermal power station. In this context, the developed methodology is accordingly applied to a representative, medium-scale island of the Aegean Sea, i.e. the island of Amorgos. According to the results obtained, the proposed solution achieves increased levels of energy and water autonomy.

***Index Terms*--Wind energy, energy storage, desalination, remote islands**

I. Introduction

According to the Amsterdam Treaty, declaration No. 30, "…insular regions suffer from structural handicaps linked to their island status, the permanence of which impairs their economic and social development". In this regard, satisfaction of vital needs for most of these regions relies on strong dependence bonds with supply networks (normally being mainland-based) of questionable efficiency, both in terms of supply security and costs. Of major significance in this debate, energy and water resources undergoing severe stresses on and off in many island regions, produces volatile conditions in all aspects of every day life, damaging the local economy and development prospects of these communities. At the same time, vulnerability of the local landscape and the cultural heritage in many of these areas dictates investigation of minimum impact and low-intensity solutions that may adapt to the local environment distinct characteristics.

Application of renewable energy sources (RES) to a certain, sustainable extent may align with both these ends; i.e. satisfaction of local habitants' energy and water needs under more secure terms on the one hand and preservation of the local environment on the other. In this context, although there are certain island areas that have already adopted some aspects of the proposed solution, progress met in the field is yet discouraging. In fact, current patterns of energy and water supply in most island regions largely restrict or almost eliminate contribution of RES [1], [2], despite the medium-high quality of RES potential met across several areas. The result of this strategy is the implementation of short-sighted solutions, based almost exclusively on fuel imports for covering energy needs (mainly electricity) [3] and the operation of unorthodox water supply networks [4], [5] so as to cover existing water deficits that may even reach 100% of the local water demand for certain dry island regions.

II. Data and Methodology

Considering the above, the present work is dedicated to the development of an integrated methodology for the design of optimum wind-based energy storage and desalination configurations, used to encounter both electricity and water problems under the prerequisites of cost-effectiveness and minimum fuel consumption for the operation of the local thermal power station. In this context, the developed methodology is accordingly applied to a representative, medium-scale island of the Aegean Sea, i.e. the island of Amorgos. Amorgos is a remote island region found at the south side of the Aegean Sea, belonging to the island complex of Cyclades. The local population of the island reaches almost 2,000 habitants, although during the summer period it may increase to reach even triple figures.

At the moment, the electrical needs of the islanders, i.e. almost 10GWh per annum with a peak load demand of approximately 3MW (see Fig. 1), are mainly covered by the operation of the local autonomous thermal power station. To this end, owed to the increased cost of oil imports required to operate the local thermal power station, the respective electricity production cost well exceeds 300€/MWh, having also reached in the past approximately 380€/MWh. At the same time, the island also encounters water supply stresses,

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This study was supported by the European Union and the Greek Ministry of Education through the Excellence II research framework

European Union European Social Fund — OPERATIONAL PROGRAMME EDUCATION AND LIFELONG LEARNING investing in knowledge society — MINISTRY OF EDUCATION, LIFELONG LEARNING AND RELIGIOUS AFFAIRS MANAGING AUTHORITY — NSRF 2007-2013 EUROPEAN SOCIAL FUND — Co- financed by Greece and the European Union

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especially during the summer period, with the total water consumption reaching approximately 140,000m^3 per year (Fig. 2). In the same context, if also including the small Cyclades islands (i.e. Koufonisia, Schinoussa, Donoussa and Iraklia) the water demand rises to ~260,000m^3.

What is interesting to note is that for Amorgos and other arid island areas found in Cyclades and Dodecanese complexes, water consumption is mainly satisfied through water shipments from the mainland, at an increased cost that may even exceed 9€/m^3. In fact, it is almost 2/3 of the aforementioned water demand that is covered through water transfers.

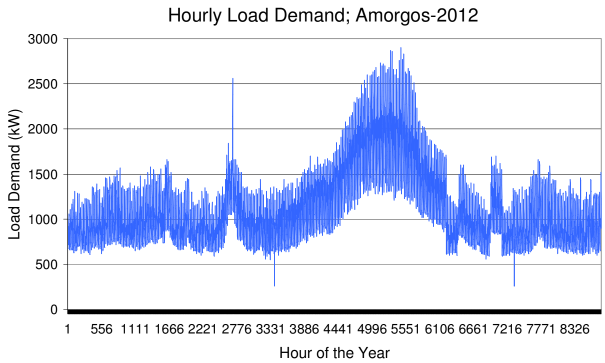

Figure 1. Variation in hourly electricity load demand for Amorgos Island during the year 2012

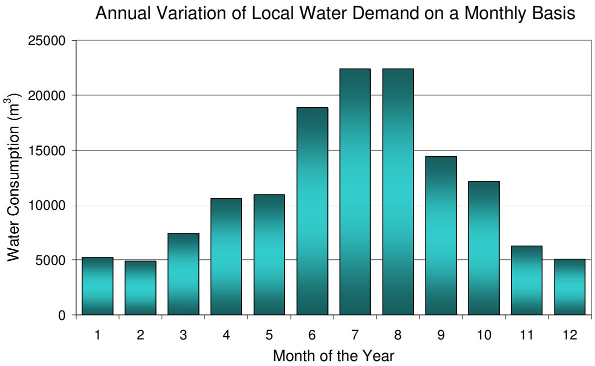

Figure 2. Variation of the monthly local water demand for Amorgos and Small Cyclades islands during the year 2012

On the other hand, current use of renewable energy on the island is rather limited, despite the fact that the entire region appreciates considerable wind and solar potential. In fact, the local wind potential quality is determined by a mean annual wind speed in the order of 10m/sec (see also Fig. 3) which encourages investigation of wind-based energy solutions.

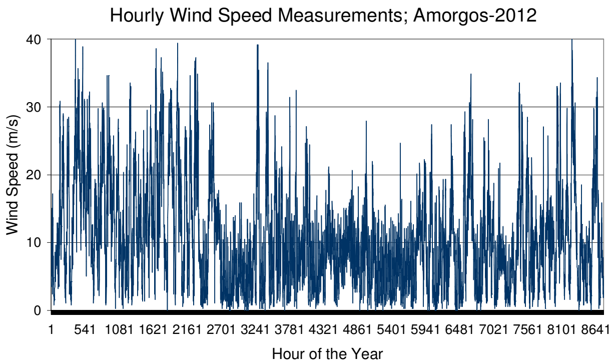

Figure 3. Hourly wind speed for Amorgos island - year 2012

In this context, based on the above described situation, the idea of applying a wind-based battery storage solution [6], [7]. [8] coupled with a desalination facility is currently elaborated (Fig. 4), in order to cover both electricity and water demand of the islanders.

At the same time, the local thermal-based power station is considered only as back-up and is used to cover any energy deficits not satisfied by the operation of the proposed wind-based solution. For this purpose, an integrated computational algorithm is developed which simulates the hourly operation of the system during an entire year (Fig. 5), followed by an extensive parametrical analysis considering the problem main parameters, e.g. installed wind capacity, energy storage capacity, desalination capacity, water tank size, etc.

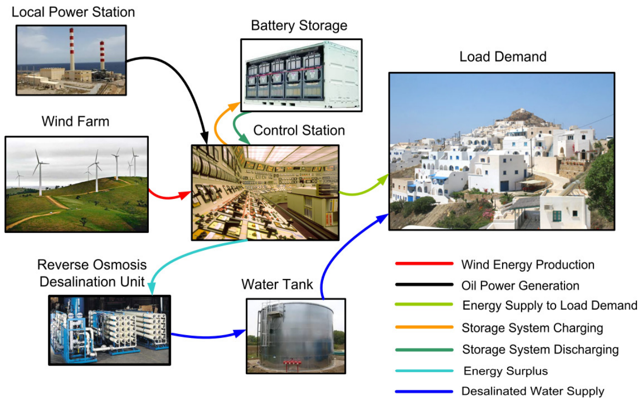

Figure 4. The proposed wind-based energy and water supply configuration

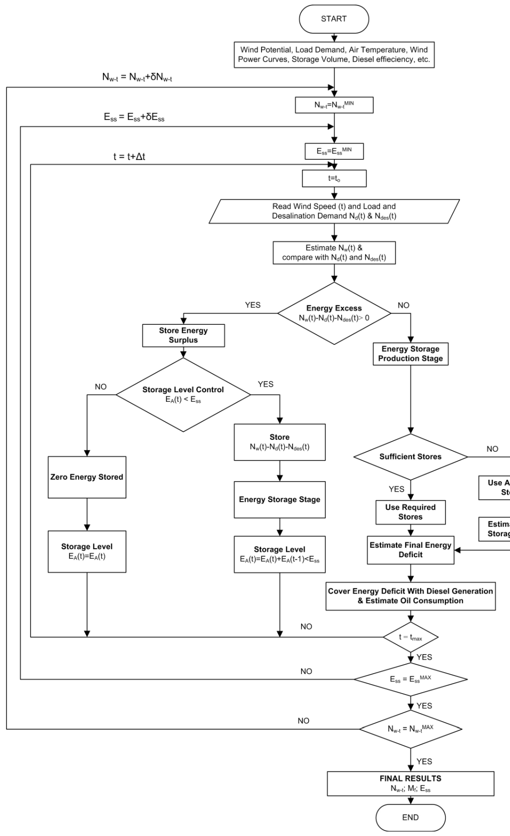

Figure 5. The developed simulation algorithm

As far as the proposed configuration is considered, this comprises of a wind park coupled with battery storage (lead-acid batteries are currently considered), supported also by the minimum contribution of the local autonomous power station of Amorgos.

At the same time, the proposed configuration also employs a reverse osmosis desalination unit [9], [10] and the appropriate water storage tanks, destined to cover the local water demand of the islanders, including costly water transfers. With regards to the simulation algorithm, it gives priority to the satisfaction first of electricity load demand and then of sufficient energy stores, and then allows the operation of the desalination plant as a secondary load. In this context, by examining several configurations of different size, their performance is accordingly evaluated based on the energy and water autonomy results obtained. Furthermore, each of the examined configurations is also economically evaluated, through the estimation of the respective life-cycle production cost. During this effort, both the energy and water production costs are provided, while a weighted, overall production cost is also estimated considering energy and water satisfaction levels (€/kWh).

III. Results and Discussion

Using the developed simulation algorithm, the proposed methodology is accordingly applied for the island Amorgos, considering additionally satisfaction of water demand for the complex of Small Cyclades as well. To this end, problem input parameters are gathered in Table I, while in Table II the respective cost parameters of the problem investigated are given.

TABLE I
Problem Input Parameters

Parameter	Assigned Values
Wind park peak power	2 to 16MW
Energy storage system capacity	0 to 250MWh
Desalination max capacity	137m^3/hour
Water reservoir	1,000 to 10,000m^3
Initial water level	1,000m^3
Minimum water level	200m^3
Battery round trip efficiency	75%
Battery max depth of discharge	60%
Desalination energy consumption	5kWh/m^3

TABLE II
Problem Cost Parameters

Cost Parameter	Assigned Values
Wind park installation cost (€/ kW)	1,100
RO desalination plant cost (€/m^3/day)	940
Battery specific cost (€/kWh)	200
Electronic equipment cost coefficient	10% x total initial cost
Water reservoir cost (€/ m^3)	70
Annual maintenance and operation cost	3% x total initial cost

Furthermore, representative energy and water autonomy related results are accordingly presented in Figs. 6 and 7, for two different energy storage cases, i.e. 50MWh and 250MWh respectively. As one may see, the parallel increase of wind power and available water tank volume maximizes both energy and water autonomy. In fact, increase of energy storage from 50 to 250MWh does not suggest as considerable autonomy benefits, while use of 1000m^3 of water storage already achieves water autonomy at the levels of 90%. The inverse behavior is as expected presented by the required diesel-based power generation contribution, which drops to less than 100t of diesel oil per year even for the 50MWh case (Figs. 8 and 9).

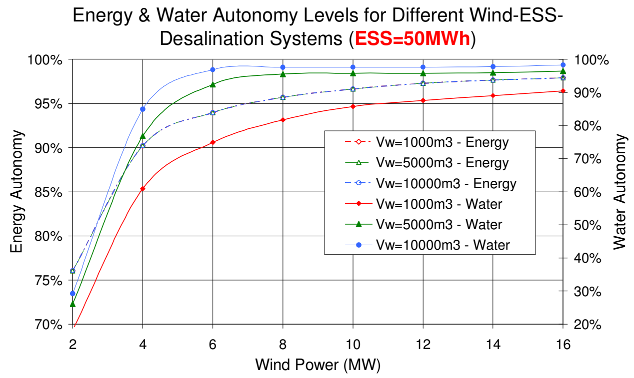

Figure 6. Energy and water autonomy results – 50MWh energy storage

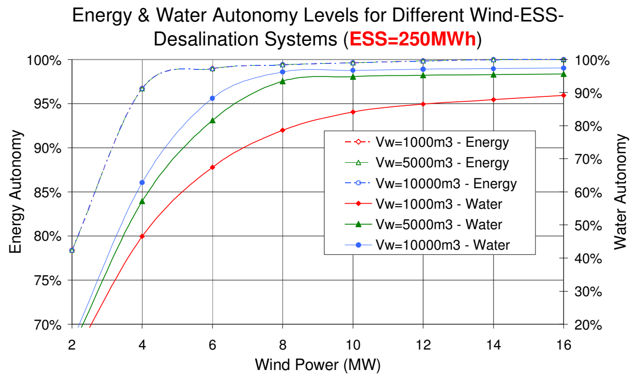

Figure 7. Energy and water autonomy results – 250MWh energy storage

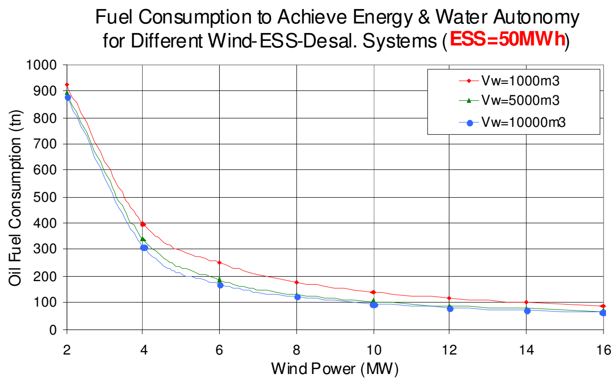

Figure 8. Diesel oil consumption results – 50MWh energy storage

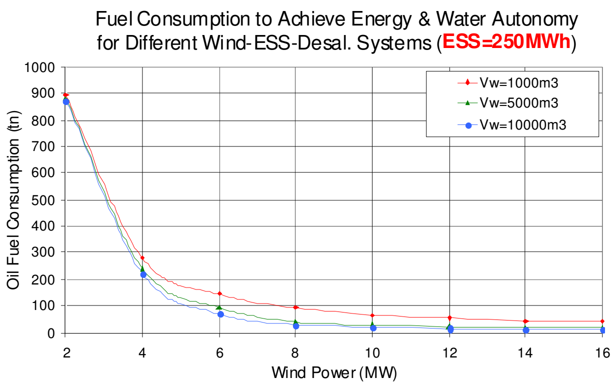

Figure 9. Diesel oil consumption results – 250MWh energy storage

Following the energy and water autonomy results, in Figs. 10-13, the corresponding economic results are given for the same two energy storage cases examined. More precisely, in Figs. 10-11 the electricity and water production costs are presented separately, so as to obtain a direct comparison with current costs.

According to the results, an area of minimum electricity production costs appears for wind power in the order of 6MW, which is found to be comparable with current electricity costs, only in the case of 50MWh. On the other hand, the production cost of water is significantly lower when compared to the current water transfer cost.

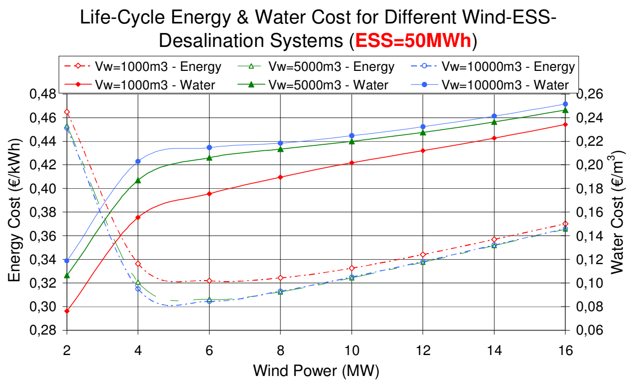

Figure 10. Energy and water cost results – 50MWh energy storage

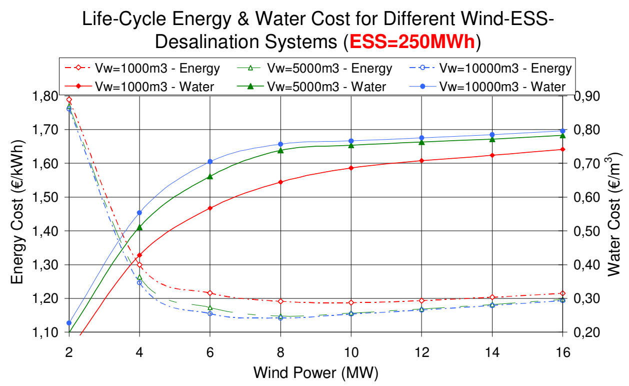

Figure 11. Energy and water cost results – 250MWh energy storage

Finally, in Figs. 12 and 13, the overall, weighted energy and water cost is presented, validating the results of the previous figures. To this end, the overall production cost is found to minimize in the area of 4-6MW, reaching approximately 350€/MWh and favorably comparing with the current value of around 450€/MWh.

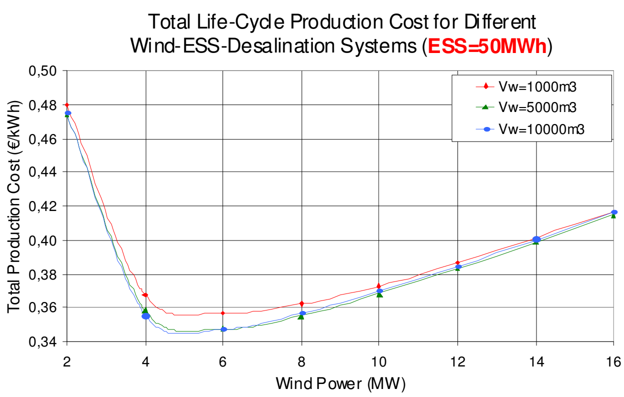

Figure 12. Total production cost results – 50MWh energy storage

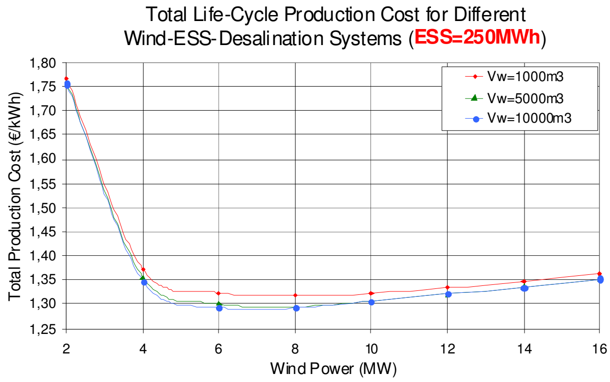

Figure 13. Total production cost results – 250MWh energy storage

IV. Conclusions

In the present work, development of an integrated methodology for the design of optimum wind-based energy storage and desalination configurations was achieved, used to encounter both electricity and water problems under the prerequisites of cost-effectiveness and minimum fuel consumption for the operation of the local thermal power station. In this context, the developed methodology was accordingly applied to a representative, medium-scale island of the Aegean Sea, i.e. the island of Amorgos, considering also additional water demand of the Small Cyclades island complex. According to the results obtained, the proposed solution achieves increased levels of energy and water autonomy while also presenting comparable and even lower production costs to the current ones. As a result, the proposed combined configuration is found to provide energy and water autonomy even for medium scale size islands such as Amorgos, where the cost of energy is not as high (e.g. >1€/kWh) as in smaller scale ones.

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VI. Biographies

Dimitrios Zafirakis holds a Mechanical Engineering Degree from the Technological Education Institute of Piraeus and an MSc in Energy Degree from the University of Heriot Watt, while he is a member of the research team of the Laboratory of Soft Energy Applications & Environmental Protection and belongs to the academic staff of TEI of Piraeus. His research interests include energy storage systems and applications, RES-based hybrid systems, RES integration and island grids/microgrids' energy planning. His up to now research experience is validated by participation in numerous research projects and the publication of 32 papers peer reviewed Journal papers and over 45 conference papers. He is finally the author of a contributing chapter in the "Stand-alone and hybrid wind energy systems: Technology, energy storage and applications" book and co-author of two contributing chapters in the "Comprehensive Renewable Energy" Encyclopedia of Elsevier, preparing also a contributing chapter on energy storage for the forthcoming (2014-15) "Handbook of Clean Energy Systems" by Wiley. He has approximately 470 citations in his research work, while his current h-index (Scopus) is 12.

Kleopatra Ntourou was awarded her Diploma in Mechanical Engineering (TEI of Athens, Greece) in 1989 and a M.Sc. of Science in Manufacturing Management & Technology - Open University in 2003. Currently, she is attending the Graduate Program "Waste Management" of the Faculty of Science and Technology of Greek Open University. She has been teaching in the Technological Education Institute of Piraeus from 1996 until now; as member of temporary staff in the Laboratory of Hydraulics and Flow Mechanics (1996 to 2004) and as Permanent Specialised Technical Staff (2004-2014). Last year she was appointed as Executive Didactic Personnel at the Department of Engineering.

Christiana Papapostolou holds a Mechanical Engineering Degree from the Technological Educational Institute (TEI) of Piraeus, from which she graduated in 2004. She obtained her Master Diploma in the field of Energy from the Heriot-Watt University of Scotland (2008). Since 2005 she works as a research member of the Optimization of Production Systems Lab of the TEI of Piraeus and also belongs to the adjunct academic staff of the Mechanical Engineering Department, assigned with teaching tasks in the courses of Production Management, Project Management, Wastes' Management and Energy Audit and Management. Her research activities are mainly focused on sustainable development and policy related issues and more specifically on the optimization of energy systems and alternative fuels' logistics. Her research experience may be validated by participation in research projects such as FP7_CRISP (2011-2014) "CReating Innovative Sustainability Pathways", "Optimization of Water Systems in Islands with Limited Water Resources" (ARCHIMEDES II, TEI of Piraeus, Greece, 2005-2007) and "PREMIA R&D, demonstration and incentive programmes effectiveness to facilitate and secure market introduction of alternative motor fuels" (European Commission – Directorate-General Energy & Transport (DG TREN) under the 6th Framework Programme, 2005-2006) and co-authorship of several research papers.

Georgios Nomikos holds a Mechanical Engineering Degree from the Technological Educational Institute (TEI) of Piraeus. His research interests include the integration of RES systems in island environments and the use of desalination for the optimum exploitation of RES power generation together with the satisfaction of water demand in arid island areas of the Aegean Sea. His is also studying the potential for the introduction of novel marine technologies in the Mediterranean region.

Emilia Kondili holds a Chemical Engineering degree from the Aristotle University of Thessalonica (1983), an MSc (1985) and a PhD (1988) degree from the Chemical Engineering Department of Imperial College, UK. She belongs to the academic staff of the Mechanical Engineering Department, TEI of Piraeus, holding the position of a Professor. Her expertise focuses on optimization tools (Mathematical Programming) in energy, environmental and production systems and energy systems planning. She has participated in several R&D projects funded by the EU, European/Greek industries and the Greek State. She is the author of more than 20 papers in international journals and more than 50 papers in international conferences, with more than 400 citations. She has contributed in international book editions concerning energy and the environment and she is reviewer in several international journals in the fields of Energy and Environment.

John K. Kaldellis received his Diploma in Mechanical Engineering (National Technical University of Athens, Greece) in 1983, his Diploma in Business Administration (University of Piraeus, Greece) in 1988 and his Ph.D. at the National Technical University of Athens, Department of Mechanical Engineering, Fluid Sector, in collaboration with Ecole Centrale de Lyon, in 1988. Nowadays, he is Professor at the Department of Mechanical Engineering of the Technological Education Institute (TEI) of Piraeus, Greece. Concretely, he is the Director of the Soft Energy Applications and Environmental Protection Laboratory of the TEI of Piraeus. He is also the Scientific Director of the MSc in Energy program organized by Heriot Watt University and TEI of Piraeus. Professor Kaldellis scientific expertise is in the fields of energy and environment. His research interests include feasibility analysis of energy sector applications, technological progress in wind, hydro and solar energy market, hybrid energy systems, energy storage issues, social attitude towards renewable energy applications and environmental technology-atmospheric pollution.

Kleopatra Ntourou was awarded her Diploma in Mechanical Engineering (TEI of Athens, Greece) in 1989 and a M.Sc. of Science in Manufacturing Management & Technology - Open University in 2003. Currently, she is attending the Graduate Program "Waste Management" of the Faculty of Science and Technology of Greek Open University. She has been teaching in the Technological Education Institute of Piraeus from 1996 until now; as member of temporary staff in the Laboratory of Hydraulics and Flow Mechanics (1996 to 2004) and as Permanent Specialised Technical Staff (2004-2014). Last year she was appointed as Executive Didactic Personnel at the Department of Engineering.