Convocatorias 2014
Proyectos de I+D “EXCELENCIA” y Proyectos de I+D+I “RETOS INVESTIGACIÓN”
Dirección General de Investigación Científica y Técnica
Subdirección General de Proyectos de Investigación

AVISO IMPORTANTE

En virtud del artículo 11 de la convocatoria **NO SE ACEPTARÁN NI SERÁN SUBSANABLES MEMORIAS CIENTÍFICO-TÉCNICAS** que no se presenten en este formato.

Lea detenidamente las instrucciones que figuran al final de este documento para rellenar correctamente la memoria científico-técnica.

Parte A: RESUMEN DE LA PROPUESTA/SUMMARY OF THE PROPOSAL

A.1. DATOS DEL PROYECTO COORDINADO

INVESTIGADOR/ES COORDINADOR/ES

INVESTIGADOR COORDINADOR PRINCIPAL 1 (Nombre y apellidos)**:**
MANUEL BERENGUEL SORIA

INVESTIGADOR COORDINADOR PRINCIPAL 2 (Nombre y apellidos)**:**
MANUEL PÉREZ GARCÍA

TÍTULO GENERAL DEL PROYECTO COORDINADO: Estrategias de control y gestión energética en entornos productivos con apoyo de energías renovables

ACRÓNIMO DEL PROYECTO COORDINADO: ENERPRO

RESUMEN DEL PROYECTO COORDINADO Máximo 3500 caracteres (incluyendo espacios en blanco):

Este proyecto trata sobre el análisis, diseño y aplicación de técnicas de modelado, control y optimización (en el ámbito del control jerárquico y control predictivo basado en modelo MPC) para conseguir una gestión eficiente de energía (electricidad y calor/frío de proceso), agua y CO_2, en sistemas productivos apoyados en energías renovables y sistemas de almacenamiento. Mediante una gestión óptima de estos recursos y la adaptación de la generación a la demanda, se pretende demostrar que el control automático permite conseguir ahorros económicos y reducir el impacto medioambiental en la explotación de procesos complejos.

En esta temática han surgido conceptos como el de micro-grids (MG), relacionados con el uso eficiente de la energía eléctrica, renewable heating and cooling (RHC), en el ámbito del aporte de energía primaria basada en fuentes renovables y water efficiency (WE), en torno al manejo del agua. El paradigma tratado en este proyecto va más allá, pues tratará de forma integral y coordinada el manejo de los citados recursos heterogéneos con un enfoque basado en la eficiencia y la economía. El problema se compone de diferentes niveles de control y decisión sobre el uso final de la energía disponible en base a distintos objetivos (minimizar el uso de combustibles, aspectos económicos, medioambientales o de calidad, etc.) Esto da lugar a un problema de control jerárquico que requiere coordinación y cooperación entre diferentes sistemas y que será abordado incluyendo técnicas de control predictivo jerárquico e híbrido, en versiones centralizadas y distribuidas. También será

necesario desarrollar modelos, estimadores y predictores para las etapas de generación y demanda de energía y agua.

Un elemento diferenciador del proyecto es que se dispondrá de un sistema productivo real como planta demostrativa (incluyendo un edificio bioclimático, un invernadero, un vehículo eléctrico y una desaladora solar), sobre el que se validarán las técnicas de modelado y control desarrolladas.

Los tres objetivos básicos del proyecto coordinado son:

1. Desarrollo de metodologías para la obtención de modelos de procesos que contengan fuentes de energías renovables para producir/consumir calor y frío de proceso, electricidad, agua y CO2. Desarrollo de estimadores y predictores de las etapas de generación y demanda.

2. Desarrollo de estrategias de gestión y control jerárquico, híbrido y predictivo para conseguir optimizar la producción desde los puntos de vista económico, de seguridad y de uso de energía y agua en sistemas heterogéneos, con un enfoque coordinado e integral.

3. Implementación y validación de las estrategias en el sistema productivo de demostración. Esto facilitará el desarrollo de las diferentes tareas del proyecto sobre situaciones realistas. Se demostrarán las posibilidades de extensión a entornos más complejos tipo campus o cluster industrial.

El cumplimiento de estos objetivos representa una contribución significativa con impacto real en esta clase de procesos, como demuestra el interés que ha despertado en diferentes empresas tales como Fundación Cajamar, Unica Group SCA, Wagner Solar, Solar Jiennense, entre otras. La propuesta es una continuación natural de actividades conjuntas de los dos centros, que poseen una considerable experiencia en control de sistemas energéticos, soportada por los numerosos artículos publicados en revistas de prestigio y relaciones con grupos de investigación internacionales.

PALABRAS CLAVE DEL PROYECTO COORDINADO: Control y gestión de energía y otros recursos, optimización, control predictivo, sistemas termosolares, energías renovables

TITLE OF THE COORDINATED PROJECT: Control and energy management strategies in production environments with support of renewable energy

ACRONYM OF THE COORDINATED PROJECT: ENERPRO

SUMMARY OF THE COORDINATED PROJECT Maximum 3500 characters (including spaces):

This project deals with the analysis, design and application of modeling, control and optimization techniques (in the framework of hierarchical and model-based predictive control, MPC) to achieve an efficient energy (electricity and process heat/water), water and CO2 management in production environments with support of renewable energy and storage systems. Through optimal management of these resources and by adapting generation to demand, it should be demonstrated how automatic control allows to achieve cost savings and reduce the environmental impact on the operation of complex processes.

Around this theme, concepts like micro-grids (MG), related to the efficient use of electricity, renewable heat and cooling (RHC), in the area of primary energy supply from renewable sources and water efficiency (WE), around adequate use of water have arisen. The paradigm treated in this project goes beyond, since it treats comprehensive and coordinated management of those heterogeneous resources focusing on efficiency and economics. The problem is composed by different control and decision levels about the final use of the available energy based on different objectives (minimizing the use of conventional fossil energy sources, economic, environmental and quality aspects, etc.) This gives rise to a hierarchical control problem that requires coordination and cooperation between systems and that will be addressed using hierarchical and hybrid predictive control techniques, both in

centralized and distributed versions. It will be also necessary to develop models, estimators and predictors of the energy generation and demand stages.

A key element of the project is that a real production system will be use as test-bed plant (including a bioclimatic building, a greenhouse, an electric vehicle and a solar desalination plant), on which the developed modeling and control techniques will be validated.

The three basic objectives of the coordinated project are:

1. Development of methodologies for obtaining models of processes that contain renewable energy sources to produce/consume process heat, electricity, water and CO2. Development of estimators and predictors of generation and demand stages.

2. Development of hierarchical, hybrid and, in general, MPC control and management strategies to optimize production from the economic, security and energy and water use points of view in heterogeneous systems, using a coordinated and comprehensive approach.

3. Implementation and validation of the strategies in the production environment selected as test-bed plant. This will facilitate the development of the different tasks of the project over realistic conditions. Possible extensions to more complex environments like campus or industrial clusters will be demonstrated.

The fulfilment of the preceding goals represents a significant contribution with real impact in this class of processes as evidenced by the interest shown by firms like Fundación Cajamar, Unica Group SCA, Wagner Solar, Solar Jiennense, naming only a few. The proposal is also a natural continuation follow-up of previous work carried out the research groups integrating the project. The team has a remarkable experience in control systems backed by many papers published in some of the most cited scientific journals and relationships with international research teams.

KEY WORDS OF THE COORDINATED PROJECT: Control and management of energy and other resources, optimization, predictive control, solar power systems, renewable energy

A.2. DATOS DE LOS SUBPROYECTOS

SUBPROYECTO 1 *(el investigador o investigadores principales del subproyecto 1 son los coordinadores del proyecto coordinado)***:**

TÍTULO: Estrategias de control y gestión energética en entornos productivos con apoyo de energías renovables (*Control and energy management strategies in production environments with support of renewable energy*)

SUBPROYECTO 2:

INVESTIGADOR PRINCIPAL 1 (Nombre y apellidos)**:**

DIEGO CÉSAR ALARCÓN PADILLA

INVESTIGADOR PRINCIPAL 2 (Nombre y apellidos)**:**

TÍTULO: Control y gestión energética eficiente de sistemas termosolares de desalación (*Efficient energy control and management of solar thermal desalination systems*)

Parte B: INFORMACIÓN ESPECÍFICA DEL EQUIPO

B.2. FINANCIACIÓN PÚBLICA Y PRIVADA (PROYECTOS Y/O CONTRATOS DE I+D+I) DEL EQUIPO DE INVESTIGACIÓN (repita la secuencia tantas veces como se precise en cada uno de los subproyectos participantes hasta un máximo de 5 proyectos y/o contratos por cada subproyecto)

SUBPROYECTO 1:

1. Investigador del equipo de investigación que participa en el proyecto/contrato: Francisco Rodríguez Díaz, Manuel Berenguel Soria, Manuel Pérez García
   Referencia del proyecto: DPI2010-21589-C05-04
   Título: Estrategias de control y supervisión para la gestión integrada de instalaciones en entornos energéticos energéticamente eficientes.
   Investigador principal: Francisco Rodríguez Díaz
   Entidad financiadora: Plan Nacional. Ministerio de Ciencia e Innovación
   Duración: 01/01/2011-31/12/2013
   Financiación recibida (en euros): 114.670
   Relación con el proyecto que se presenta: mismo tema
   Estado del proyecto o contrato: concedido

2. Investigador del equipo de investigación que participa en el proyecto/contrato: Francisco Rodríguez Díaz, Manuel Berenguel Soria, Manuel Pérez García, Antonio Giménez Fernández, Esteban José Baeza Romera
   Referencia del proyecto: TEP 06174
   Título: Control del crecimiento de cultivos bajo invernadero optimizando criterios de sostenibilidad, económicos y de eficiencia energética.
   Investigador principal: Francisco Rodríguez Díaz
   Entidad financiadora: Proyectos de Excelencia. Junta de Andalucía
   Duración: 01/03/2011-31/03/2015
   Financiación recibida (en euros): 215.000
   Relación con el proyecto que se presenta: mismo tema
   Estado del proyecto o contrato: concedido

3. Investigador del equipo de investigación que participa en el proyecto/contrato: Manuel Berenguel Soria, Francisco Rodríguez Díaz
   Referencia del proyecto: PHB2009-0008-PC
   Título: Estrategias de control no lineal con compensación del retardo en plantas de generación de energía solar.
   Investigador principal: Manuel Berenguel Soria
   Entidad financiadora: Ministerio de Educación, Cultura y Deporte (Proyecto de Cooperación Bilateral – convenio Hispano-Brasileño)
   Duración: 01/01/2007-31/12/2013
   Financiación recibida (en euros): 65.000
   Relación con el proyecto que se presenta: está muy relacionado
   Estado del proyecto o contrato: concedido

4. Investigador del equipo de investigación que participa en el proyecto/contrato: Manuel Berenguel Soria, Francisco Rodríguez Díaz
   Referencia del proyecto: DPI2007-66718-C04-04
   Título: Control jerárquico de procesos con conmutación en el modo de operación: aplicaciones a plantas solares e invernaderos.
   Investigador principal: Manuel Berenguel Soria
   Entidad financiadora: Plan Nacional. Ministerio de Ciencia e Innovación.
   Duración: 01/10/2007-31/09/2010
   Financiación recibida (en euros): 145.805
   Relación con el proyecto que se presenta: está muy relacionado
   Estado del proyecto o contrato: concedido

5. Investigador del equipo de investigación que participa en el proyecto/contrato: Manuel Berenguel Soria, Manuel Pérez García, Francisco Rodríguez Díaz
   Referencia del proyecto: PS-120000-2005-1
   Título ARFRISOL: Arquitectura bioclimática y frío solar.
   Investigador principal: María del Rosario Heras Celemín
   Entidad financiadora: Ministerio de Educación, Cultura y Deporte y Ministerio de Ciencia e Innovación. Proyecto Singular Estratégico.
   Duración: 01/05/2005-30/04/2012
   Financiación recibida (en euros): 25.000.000 (Universidad de Almería 1.100.000)
   Relación con el proyecto que se presenta: está muy relacionado
   Estado del proyecto o contrato: concedido

SUBPROYECTO 2:

1. Investigador del equipo de investigación que participa en el proyecto: Julián Blanco Gálvez, Diego César Alarcón Padilla, Patricia Palenzuela Ardila
   Referencia del proyecto: EC–FP7-ENERGY-2013-IRP. Contrato 609.837
   Título:Scientific and Technological Alliance for Guaranteeing the European Excellence in Concentrating Solar Thermal Energy (STAGE-STE)
   Investigador principal: Julián Blanco Gálvez
   Entidad financiadora: EU
   Duración :01.02.2014 - 31.01.2018
   Financiación recibida :9.997.207 Euros
   Relación con el proyecto que se presenta: algo relacionado
   Estado del proyecto o contrato: concedido

2. Investigador del equipo de investigación que participa en el proyecto: Julián Blanco Gálvez, Diego César Alarcón Padilla
   Referencia del proyecto: Contrato EVK1-CT-2001-00102
   Título: Enhanced Zero Dischage Seawater Desalination using Hybrid Solar Technology (AQUASOL)
   Investigador principal:Julián Blanco Gálvez
   Entidad financiadora: EU
   Duración :2002-2006
   Financiación recibida :1.500.000 Euros
   Relación con el proyecto que se presenta: muy relacionado
   Estado del proyecto o contrato: concedido

3. Investigador del equipo de investigación que participa en el proyecto: Luis José Yebra Muñoz, Javier Bonilla Cruz
   Referencia del proyecto: FP7-ENERGY-2012-1.CP, Grant agreement 308912
   Título: Innovative Configuration of a Fully Renewable Hybrid CSP Plant (HYSOL)
   Investigador principal:Miguel Lasheras
   Entidad financiadora: European Comission. 7th Framework Programme (FP7)
   Duración: 01/05/2013-30/04/2016
   Financiación recibida:6.165.254 €
   Relación con el proyecto que se presenta: está algo relacionado
   Estado del proyecto o contrato: concedido

4. Investigador del equipo de investigación que participa en el proyecto: Julián Blanco Gálvez, Diego César Alarcón Padilla, Patricia Palenzuela Ardila
   Referencia del proyecto: CENIT program. Ref. 2006/304
   Título: Desarrollo de Desalación con Energías Renovables (TECOAGUA)
   Investigador principal: Arturo Buenaventura
   Entidad financiadora: Ministerio de Ciencia e Innovación
   Duración: 01/09/2009-01/12/2012
   Financiación recibida: 180.000 €
   Relación con el proyecto que se presenta: muy relacionado
   Estado del proyecto o contrato: concedido

5. Investigador del equipo de investigación que participa en el proyecto: Diego César Alarcón Padilla, Luis José Yebra Muñoz, Javier Bonilla Cruz
   Referencia del proyecto: DPI2010-21589-C05-02
   Título: Estrategias de modelado y control para una desaladora solar híbrida
   Investigador principal: Luis José Yebra Muñoz
   Entidad financiadora: Ministerio de Ciencia e Innovación
   Duración: 01/01/2011-31/12/2014
   Financiación recibida: 105.270,00 €
   Relación con el proyecto que se presenta: muy relacionado
   Estado del proyecto o contrato: concedido

Parte C: DOCUMENTO CIENTÍFICO

C.1. JUSTIFICACIÓN DE LA COORDINACIÓN/JUSTIFICATION OF THE COORDINATION

In the official announcement, it is stressed that the Call tries to encourage the funding of coordinated projects and the association of emerging research groups and experienced groups. Also, the multidisciplinary research that is able to integrate complementary knowledge of several scientific fields is encouraged. This proposal is oriented by these principles and therefore we present an ambitious project involving researchers both from emerging and experienced groups.

This is really a single project (instead of two separate projects) in which two groups belonging to different agencies but placed in the same province collaborate. Physical closeness is also reflected in research collaboration, as both groups have been working together since 2002 on the development of projects funded by the National R+D+i Plan and other institutions. In fact, both groups collaborate within the Joint Research Center of Solar Energy (CIESOL) between the University of Almería (from now on UAL) and the Research Centre for Energy, Environment and Technology-Solar Platform of Almería (Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas-Plataforma Solar de Almería, from now on CIEMAT-PSA). The different challenges of the project justify its coordinated and interdisciplinary nature. The objectives of the project are the natural continuation of those planned in previous projects in which the researchers integrating this proposal were involved; in particular the projects POWER "Predictive control techniques for efficient management of renewable energy micro-grids" DPI2010-21589-C05-04/05 (UAL/PSA-CIEMAT, subprojects "Monitoring and control strategies for integrated management of installations in energy efficient environments" and "Modeling and control strategies for a hybrid solar desalination plant"), PRINMODI DPI2007-66718-C04-03/04 (UAL+PSA-CIEMAT, subproject "Hierarchical control of processes with switched operation modes: applications to thermosolar plants and greenhouses"), CPROS DPI2004-07444-C04-04 (UAL+PSA-CIEMAT subproject "Hierarchical predictive control of processes in semi-continuous operation") and others. This collaboration has produced many publications with authors from both groups, as can be seen in the list of references. One of the benefits of this new project is that it will make it possible to follow the join work. The main objectives of this project can be summarized in three large blocks dealing with modeling and forecasting, control and management and implementation and validation tasks applied to heterogeneous renewable energy based production environments, with applications in a test-bed plant. The coordination in this case is necessary due to the multidisciplinary character of the project, requiring experts in energy and other resources, control and management in buildings, greenhouses, electric cars and solar desalination plants (see corresponding curricula). There is a clear interaction between the objectives of both groups. The CIEMAT-PSA group (subproject 2) is expert on **design, modeling and control of solar desalination plants**, that will act in this project as a generation system providing process heat and water to the other elements forming the test-bed production system (building and greenhouse). On the other hand, the UAL group (subproject 1) is expert on the **design of hierarchical model predictive control strategies** for processes subject to nonlinear dynamics and measurable disturbances, with applications to buildings, electric cars, agriculture and thermosolar systems. According to our experience, cooperation between both groups is essential to reach the objectives.

Interaction among goals, activities, and subprojects: The chronogram in section C.2.6 shows the interaction among the two subprojects. Each task is leaded by the group with an, a priori, greater experience in the subject, but in most tasks personnel of both groups is involved. This results in a significant interaction and therefore, it allows a good exchange of knowledge and experience.

Coordination procedures needed to the efficient management of the project: As the groups are placed in the same province (40 km distance), coordination and management is easy. The lead researchers of both subprojects that apply to this call will guarantee that all the tasks in each subproject will be carried out as expected. They will maintain regular meetings to guarantee that all the results are met within the specified deadlines. The meetings will be:

- Coordination between subprojects meetings: one kick-off meeting and then one each semester.
- Subgroups meetings to develop tasks: as often as needed.
- There will also flow of information via e-mail. Sharing files technologies (such as Dropbox) will be also used and a website that will be used to disseminate the results not only between the project members, but also between other research groups, nation, or worldwide. Interaction with the companies and research centers supporting this project will be fostered.

C.2. PROPUESTA CIENTÍFICA / SCIENTIFIC PROPOSAL

C.2.1. Antecedentes y estado actual / Background and current status

Nowadays, most countries are promoting the efficient use of energy and water (with focus on industrial, transport and building sectors) due to increasing demand and fostering the use of renewable energy to reduce costs and increase sustainability. Generally, energy efficiency is not only associated with technological improvements, but also with the **improvement of control and energy management**. This is the main framework of this research project **ENERPRO**. This project is a natural evolution of a previous project POWER already mentioned in section C.1, where both UAL and CIEMAT-PSA subprojects focused on heat/cooling and water management and the other components of the coordinated project (Universities of Seville and Valladolid) mainly focused on research lines related to hybrid vehicles, fuel cells and micro-grids. In order to have time to discuss in detail the results and challenges to be addressed, this project was not presented in the call 2013, as one of the subprojects had also requested extension. The main results obtained in the previous project have been published in 35 international journals (ratio JCR/EDP=5.4), 24 international conferences and 8 national conferences and collected in the books "Comfort Control in buildings" (Castilla et al., 2014a), "Modeling and Control of greenhouse crop growth" (Rodríguez et al, 2014) and "Evaluación del acoplamiento de plantas de destilación multiefecto a plantas termosolares" (Palenzuela, 2013b). From the analysis done in the preparation of these works, the new research challenges have been determined. In the previous project, the main objective was to develop modeling and control strategies for the different elements comprising the test-bed plant used in this project. As noted in the final report of that project, the summary of the main fulfilled tasks is:

Modeling methodologies: The UAL team focused on issues related to modeling of a building, a greenhouse and electric vehicles. The CIEMAT-PSA team was responsible for the methodology and the definition of the library in Modelica, focusing on the desalination plant. As summary of the relevant achievements: In (Silva et al., 2014), thermosolar plants design and modeling through themo-economic optimization approaches was carried out, useful to maximize theoretical plant efficiency and saving costs. Hybrid models of thermosolar plants have also been developed (Pasamontes et al, 2013). Preliminary models based on neural networks and polynomial approaches have been validated for climate variables and energy consumption (Castilla, 2013; Mena et al., 2014). The model of illuminance has to be developed in this new project, as well as improvements in the previous models. Models of rooms and enclosures based on first principles were also developed (Castilla et al., 2014b). A similar approach was followed in the greenhouse case, where the development of virtual sensors was also accomplished (Sánchez et al., 2012). Nevertheless, many of the results have to be highly improved to be used in the new project. Preliminary models a muti-effect distillation plant were developed (Roca et al., 2012; De la Calle et al., 2014). Problems arose regarding the heat pump coupled to the desalination plant, which have been already solved so that it will be fully used in the next project (Palenzuela et al., 2013a, 2013c). Regarding the electric vehicle, some basic models (kinematics, dynamics) and energy consumption estimation were developed (Torres et al., 2014). For the next project, a photovoltaic (PV) system will be installed in the vehicle to improve its autonomy. Preliminary climate disturbance forecasting methods were developed using time series approaches (Pawlowski et al., 2011). This is a task that requires more effort because the final results are very sensible to the estimation of these factors. All these models and new ideas that have emerged will be very useful in the new project as will be integrated together for comprehensive energy, water and CO_2 management, as detailed in objective 1 in section C.2.3 (Task 1).

Development of MPC control for optimal management: In this objective, the previous project concentrated on the development of MPC-based control strategies for the individual subsystems: Solar cooling system with basic MPC techniques (Camacho et al., 2012), Building, through Practical Nonlinear Model Predictive Control (PNMPC) of thermal comfort (Álvarez et al., 2013, Scherer et al., 2014). A promising first approach (that will be further studied in the new project is the application of repetitive control to this kind of systems (Álvarez et al., 2013b). In the greenhouse, a multiobjective control approach was developed to optimize benefits, quality and water use efficiency (Ramírez et al., 2012). This approach has been tackled as a possible architecture to control the complete system. A receding horizon optimal control approach was also developed to cope with optimal greenhouse crop growth taking explicitly into account different time scales (González et al., 2014). Some schemes for controlling the electrical vehicle were also developed aimed at attaining autonomous energy-efficient navigation (Torres et al., 2014, González et al., 2013), although there is much work to do in this field, because it is a complex goal that will be treated in the next project. Control works on the desalination plant were poor and concentrated on the solar field (Roca et al., 2011), because of the mentioned problems with the equipment of the installation that have been already solved. It is expected that the new project will provide different solutions to the problem of energy-efficient water consumption and coupling to greenhouses and buildings. Work is continuing in the development of efficient comfort control techniques in buildings extending a hierarchical MPC-based control architecture for controlling the **thermal comfort, air quality and illuminance**, that is one of the objectives of the new project. The same approach will be adopted in the greenhouse. Most effort will be devoted to a global view of the control problem, by developing hierarchical MPC formulations for the optimal economic and energy efficiency management of heterogeneous energy systems considered in the proposal. In 2013 the initial hierarchical control problem was reformulated to account for the prediction of energy prices. New concepts of productivity and utility were defined (Agüero et al., 2013). New ideas have arosen, which are linked to objective 2 in this new proposal (see section C2.3).

The group of the University of Almería (UAL) has participated in more than 20 R+D projects related to this proposal, where the design of robust, hybrid and hierarchical model predictive control for processes subject to measurable disturbances was carried out. The previous projects DPI2002-04375-C03-03, DPI2004-07444-C04-04, DPI2007-66718-C04-04 and DPI2010-21589-C05-04 have been basic and fundamental to propose this new project, which is a natural evolution of these. They have given rise upon the publication of more than 75 papers in journals and more than 100 articles in Symposia, as well as 17 Ph. D. Thesis. The Group has participated in the Proyecto Singular Estratégico ARFRISOL (PS-120000-2005-1), leaded by the Energy Efficiency in Buildings Unit, UiE3 of CIEMAT, dealing with Bioclimatic Architecture and Solar Cooling, as well as in the European project FutureFarm, where the goal is to provide solutions to energy efficiency, reducing environmental impacts and improve benefits in farming, producing many publications in journals and books. The project coordinator has recently been Guest Editor of the Special Issue on “Optimal control of solar systems” in the journal Optimal Control Applications and Methods (Wiley, 2014).

The previous background and results of the CIEMAT-PSA group comes from some projects, mainly the AQUASOL research project, funded by EU (Contract nº: EVK1-CT2001-00102), and performed at CIEMAT. In addition, the collaboration with other groups inside CIEMAT with several projects, in the modeling and control design activities of different solar thermal and chemical processes, has contributed to the background of this group. In addition, the collaborations of some members of CIEMAT-PSA with the research groups of Prof. Sebastián Dormido (UNED) and Prof. Eduardo F. Camacho (US) have enhanced greatly the knowledge of this group.

Aim of the project

In the last decades, the search of efficient and renewable energies to compensate for the fuel dependence as main energy source and the mitigation of industrial flue gases to reduce the greenhouse gases emission have been two of the most important concerns of the scientific community and the society. Taking into account the strategic research lines of EU and Spain explained in section C.2.2, this project deals with the analysis, design and application of modeling, forecasting, control and optimization techniques (in the framework of hierarchical and model-based predictive control, MPC) to achieve an efficient energy (electricity and process heat/water), water and CO_2 management in production environments with support of renewable energy and storage systems. Through optimal management of these resources and by adapting generation to demand, it should be demonstrated how automatic control allows to achieve cost savings and reduce the environmental impact on the operation of complex processes.

Around this theme, concepts like micro-grids (MG), related to the efficient use of electricity, renewable heat and cooling (RHC), in the area of primary energy supply from renewable sources and water efficiency (WE), around adequate use of water have arisen. The paradigm treated in this project goes beyond, since it treats comprehensive and coordinated management of those heterogeneous resources focusing on efficiency and economics. The problem is composed by different control and decision levels about the final use of the available energy based on different objectives (minimizing the use of conventional fossil energy sources, economic, environmental and quality aspects, etc.) This gives rise to a hierarchical control problem that requires coordination and cooperation between systems and that will be addressed using hierarchical and hybrid predictive control techniques, both in centralized and distributed versions. It will be also necessary to develop models, estimators and predictors of the energy generation and demand stages. A key element of the project is that a real production system will be use as test-bed plant (including a bioclimatic building, a greenhouse with biomass boiler, an electric vehicle and a solar desalination plant), on which the developed modeling and control techniques will be validated. Figure 1 shows a schematic view of the approach followed in the project. Section C.2.5 provides a detailed description of the constitutive elements. On one hand, the CIESOL building provides electricity and process heat using solar collectors and a photovoltaic installation for feeding the building, greenhouse and electric car demand, storing the exceeding one. On the other hand, the desalination plant supplies drinkable water and process heat to the systems using solar energy. Moreover, through biomass combustion, both process heat and CO_2 is generated within the greenhouse. In all cases energy has another auxiliary uses. A key factor is to try to adapt the demand to the production of energy (and vice-versa), where modeling, predictive control and supervision techniques play an important role. Thus, both low-level (systems and equipment level) and high-level (setpoint optimization, process coordination, dynamic real-time optimization) modeling and control objectives arise in this scope.

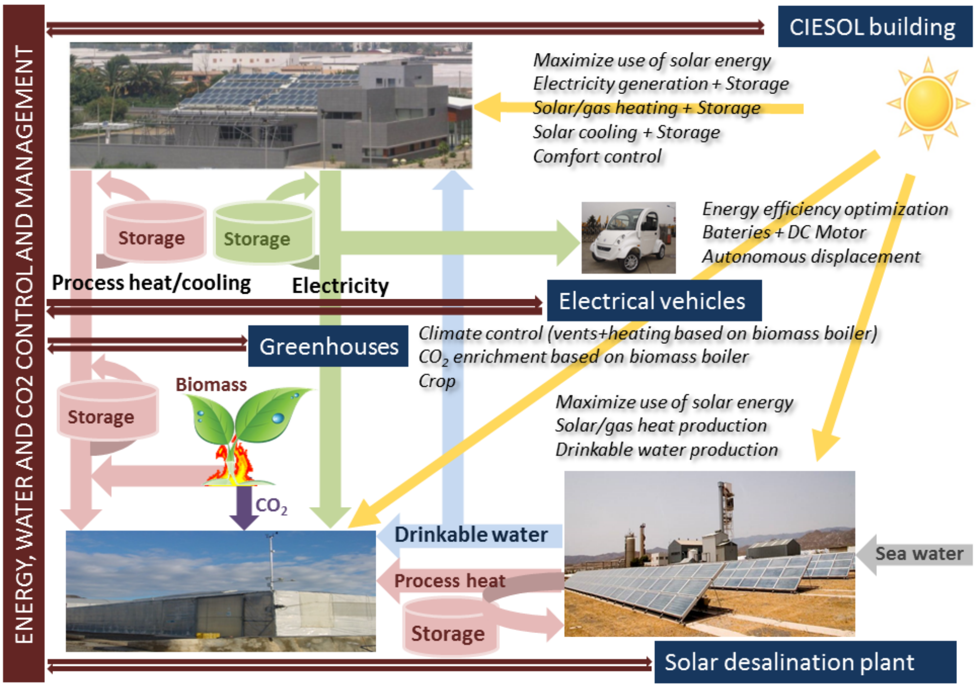

Figure 1. Research approach and functional diagram of the test-bed plant.

The project aims to **develop hierarchical MPC formulations for the optimal energy efficient and economic management of heterogeneous energy systems integrated in a production system**. Since MPC is capable of providing optimal control strategies that guarantee the fulfilment of the operating constraints in spite of the incomplete information on future supplies and demands, it is considered here as the keystone for the enhanced management of production systems supported by renewable energies.

The project will try to fulfil three main objectives (references are given in the state-of-the art section, except in particular cases in which their introduction helps understanding the objectives). The first one is the development of **methodologies for obtaining models of processes that contain renewable energy sources to produce/consume process heat, electricity, water and CO_2.** Also development of **estimators and predictors of generation and demand stages** will be fundamental (there are still many open issues in this area from the conclusions obtained in the previous project). The main issues in this objective will be related to: **Development of prediction models for environmental variables, disturbances, sources and loads** (modeling and prediction of water, electricity and heat/cooling production and demand). The research group already has models for environmental variables and disturbances (that will be improved), so that, the main focus will be on predicting resources production and consumption patterns in heterogeneous production system (and even user's behavior models). System identification will play a very relevant role in this case. Different approaches will be used: first principles models, time series models, autoregressive linear models, neural network models,… **Extension of climate models to the management of air quality and lighting**. Models for these variables will be developed and the general models will be adapted to different enclosures trying to adopt a modular approach. **Dynamic modeling of solar-gas hybrid desalination plants**. The preliminary models will be adapted (dynamical behavior and energy/generation demand) to a new layout, where the collector field, thermal storage and heat pump have been recently changed. **Modeling of storage systems** (electricity, heat and CO_2), as the production in renewable energy-based systems is not usually coupled to the demand. So, new thermal storage systems will be studied, simulated and tested. **Modeling of auxiliary equipment for energy cost reduction**. For the development of the project, it will be necessary to model and characterize auxiliary equipment to try to minimize energy consumption and maximize efficiency. **Adaptation of the developed models for control purposes** and **Integration and scaling of the developed models**, to scale the models to industrial cluster level, that is another important objective of this project.

The second overall objective is the **Development of hierarchical, hybrid and, in general, MPC control and management strategies to optimize production from the economic, security and energy and water use points of view in heterogeneous systems,** using a coordinated and comprehensive approach. This general objective comprises different tasks: **Design of hierarchical multiobjective controllers of climate, air quality and lighting**, to allow trying a tradeoff between these competing objectives while accounting for patterns of behavior of users, the profile of typical disturbances, the accommodation of the generation to the demand and the existence of different time scales. In the lower level of the hierarchical architecture, both **centralized and distributed MPC controllers** will be developed to manage energy generation and demand in several subsystems. In this context, several strategies based on **receding economic optimal control and MPC** will be developed in this project. **Economic optimal controllers** and **Rule-based controllers** will be also developed and compared to typical MPC ones, as well as **repetitive control approaches**. The objective also comprises the development of a **multiobjective hierarchical control system for electric vehicle trajectory generation and tracking using energy savings criteria**. Also, autonomous navigation of the vehicle within the production environment will be treated, trying to optimize energy management and batteries charging and assuring reliable and safe autonomous navigation.

The third global objective is the **Implementation and validation of the strategies in the production environment selected as test-bed plant.** This will facilitate the development of the different tasks of the project over realistic conditions. Possible extensions to more complex environments like industrial clusters will be demonstrated. A complete description of the installations is provided in section C.2.5.

<u>Brief State of the art</u>

The topics addressed by this project are very broad and are of great interest from both scientific and technological points of view nowadays. For example, taking a look at the latest publications in related magazines, it is possible to see that in each issue several articles on this topic are published. Therefore, the following literature review has not been exhaustive and only the most important references have been included for lack of space.

Solar energy in industries and buildings: In (Mekhilef et al., 2011), a review of applications of solar energy in industry is performed. In (Wang et al., 2015), a comprehensive critical review towards the solar water heating technology in terms of its theory, application, market potential and research questions is developed. In (Ürge-Vorsatz et al., 2015) the thermal energy use in buildings is summarized, including its drivers, past, present and future trends.

Lighting and air quality: In (Dounis and Caraiscos, 2009), a review of control systems used within the comfort control in buildings is performed (including lighting and air quality). Regarding MPC techniques, the work by (Kolokotsa et al., 2009) can be highlighted and taken as a basic example of the algorithms that are going to be developed in this project. In (Sun et al., 2013) an integrated control of active and passive heating, cooling, lighting, shading, and ventilation systems is carried out.

Models and forecasting for energy efficiency: For an efficient energy management, accurate information of energy generation and consumption is needed in order to know how it behaves in short and medium-term. The literature on this subject is extensive. In (Jebaraj and Iniyan, 2006) different energy models are summarized: energy planning models, energy supply-demand models, forecasting models, commercial energy models, renewable energy models, optimization models, energy models based on neural networks and emission reduction models. From the publication of that paper different approaches in each one of these issues have appear, but are not included here for the sake of space. In (Suganthi and Samuel, 2012), a review of the various energy demand existing forecasting methods is performed, including methods like time series, regression, econometric, ARIMA, neural networks, SVR, …, some of which will be used in this project. In (Pawloski et al., 2011) forecasting methods were used within an MPC framework.

Storage: Storage devices play an important role in energy systems to balance the system following disturbances and/or significant load changes. Residential PV systems are dealt with in (Hoppmann et al., 2014). Regarding electrical energy storage for vehicular applications, in (Ren et al., 2015) a recent review can be found. Different ways for energy storage can be found in (Mahlia et al., 2014). Thermal storage in the range of 60-250ºC is an important issue for optimizing heating and cooling processes using solar energy. In (Pintaldi et al., 2015), a review of thermal storage media is done. In (Chatzivasileiadi et al., 2013), a discussion of energy storage in the design of future built environments where renewable energy systems will play a significant role is performed. Regarding CO_2 storage, in (Leung et al., 2014) an overview of current status of CO_2 capture and storage technologies is performed, including adsorption systems as the one that will be used in this project.

Micro-grids and control for energy efficiency: Nowadays, the concept of MG mainly focuses on the integration of distributed renewable energy sources, stationary storage batteries and methodologies for management and control of MGs. In (Planas et al., 2013) a complete description of the main features of MG and related control systems are presented. A very interesting work is that of (Palizban et al., 2014), which describes the principles of micro-grid design, considering de operational concepts and requirements arising from participation in active network management. The underlying problem has been traditionally handled through an agent-based approach (Wang et al., 2012). Nevertheless, MPC approaches are being widely used nowadays. In (Geidl et al., 2007) the *energy hub* concept is defined as a general interface among energy producers, consumers and the transportation infrastructure. Such general formulation allows high flexibility. Moreover, the energy hub concept has also been recently adapted in other research fields (Arnold et al., 2010; Del Real et al., 2014; Camacho et al, 2011) as coupled electricity and gas networks. This concept will be dealt with in this project as a framework for coordinated and comprehensive management approach.

The role of automatic control on the efficient management of energy has been widely recognized from different points of view. Classical MPC has been applied to energy control (Camacho and Bordóns, 2004; Oldewurtel et al., 2012; Qi et al., 2012; Castilla et al., 2014a, 2014c) in the framework of this project. As both energy efficiency and economy are of interest, one of the control techniques which has attracted the attention of process industry to satisfy the increasing need for improving systems economics, efficiency and quality under globalized market environment is the so-called real-time optimization (RTO) (Engell 2007). The objective of the RTO is to maintain the plant operation near economic optimum. In (Zavala et al., 2009), an on-line optimization framework to exploit weather forecast information in the operation of energy systems is proposed. On the other hand, economic MPC (EMPC) is capable to cope with economic performance index in the derivation of the control (Rawlings and Amrit, 2009; Ellis et al., 2014). In this EMPC, the cost function to optimize is directly the economic performance index, not the tracking error to the set-points. This new framework will be used in this project to study predictive control techniques to integrate both real time optimization and economic criterion. Very recently (2014-2015), several papers have been published closely related to the approach faced in this project (Special issue on Energy Efficient Buildings in Journal of Process Control, 24(5), 2014). In (Touretzky and Baldea, 2014) EMPC is applied in the context of buildings with active energy storage. In (Ma et al., 2014), an application is presented using EMPC for optimizing the building demand and energy cost under the time-of-use price policy. In (Mendoza and Chmielewski, 2014) EMPC is used in conjunction with thermal energy storage to time-shift power consumption away from periods of high demand to periods of low energy cost. In (Domahidi et al., 2014) automated rule based synthesis is proposed and compared with hybrid MPC. In (Vana et al., 2014), hierarchical MPC is applied to a building for saving energy, while in (Chandan and Alleyne, 2014) the problem of decentralized control design for thermal control in buildings is studied. In close relation with this project, in (Yu et al., 2013), the problem of modeling and MPC stochastic optimization for home energy management is considered. Several different types of load classes are discussed, including heating, ventilation, and air conditioning unit, plug-in hybrid electric vehicle, and deferrable loads such as washer and dryer. Distributed predictive techniques (Venkat et al., 2008; Scattolini, 2009) seem appealing control techniques for solving such problems. However economic optimality, integration of the RTO, etc. have still open problems. As can be seen, the project theme is of much interest nowadays.

Energy management in electric vehicles: Energy storage charging poses a new challenge to the utility grid interconnection. Renewable energy can help to reduce the peak load during peak hours of power consumption, as well as favor the supply-side management due to electric vehicles charging requirements. From the other perspective, the idea of vehicle-to-grid (V2G) system, which is the reverse activity of charging the vehicle, has been proposed recently. Naturally, exploiting such opportunity requires exploring cooperative and distributed MPC algorithms (Venkat et al., 2008). An interesting niche for such power transfer between micro-grids are *autonomous* electric vehicles, since they are subject to central or distributed planning as indicated by the output of optimization algorithms. In (Di Giorgio et al., 2014) an event driven MPC framework for managing charging operations of electric vehicles in a smart grid is presented. For the sake of space, we also mention here the review in (Tie and Tan, 2013) and references therein, where a review of the state-of-the-art of the energy sources, storage devices, power converters, low-level control energy management strategies and high supervisor control algorithms used in electric vehicles are explained.

Modeling and control of solar desalination plants: A number of solar energy-based seawater desalination technologies have been developed during the last several decades to augment the supply of water in arid regions of the world (Qiblawey and Banat, 2008; Eltawil et al., 2009; Deng et al., 2010). Recently, both static (Palenzuela et al., 2014) and dynamic (De la Calle et al., 2014) models based on first principles have been developed. In the last decades, automatic controllers applied to water desalination have been developed to solve mainly operational goals (i.e. maintaining a given setpoint, tracking a desired reference, etc.) (Torrico et al., 2011). In addition, optimization algorithms have been employed to design cogeneration plants with desalination processes (Wu et al., 2013).

Related research groups

Naming only a few, the group of Goran Andersson (ETH, Zurich) has a wide expertise in the mathematical formulation of these systems. De Schutter‘s group at TU Delft (Netherlands) is focusing its research on hierarchical and decentralized model predictive control of large-scale systems. The Systems Dynamics and Control group of Manfred Morari is very active in energy and comfort control in buildings (M. Castilla from the UAL group did a 3-month research stay with him). In the same line, the group of Tomas Matuska in the CTU in Prague (University Centre for Energy Efficient Buildings) focusses on energy-efficient buildings. The UAL group is participating in an EU proposal leaded by him entitled HOME-STORE: Building integrated, energy efficient and Highly Optimized Multiple Energy STOrage systems for increased use of REnewables and advanced grid interaction through smart heat pumps and control (Horizon 2020, call H2020-LCE-2014-3, Topic LCE-08-2014, SEP-210162338) with the participation of other groups from the TU Kaierslautern (Germany, Conrad Voelker and Matthias Pahn), KU Leuven (Belgium, Lieve Helsen), Innsbruck University (Austria, Worlfgang Streicher) and some companies. The group of CIEMAT-PSA has also strong relationships with other European partners due to the participation in STAGE-STE, POWERSOL, MEDESOL, AQUASOL and SOLWATER EU projects, with a very long list of participants. As an example, it is worth noting that Julián Blanco, from the CIEMAT-PSA group, is actually **leader and coordinator** of the Scientific and Technological Alliance for Guaranteeing the European Excellence in Concentrating Solar Thermal Energy (STAGE-STE), EC – FP7-ENERGY-2013-IRP, with a budget of more than 9 million euros and the participation of more than 50 partners (http://www.stage-ste.eu/). Regarding autonomous electrical vehicles, we can cite the group of Paul Newman and Ingmar Posner within the Oxford Mobile Robotics group (UK). Among non-European groups, we mention here the USA groups of James B. Rawlings (University of Wisconsin-Madison), Panagiotis Christofides‘s group (UCLA) and finally Julio Normey’s group (UFSC, Brazil), who participates in the proposal as recognized researcher in control of renewable energy systems.

In Spain, the group of Eduardo F. Camacho and Carlos Bordóns are very recognized experts in MPC and they are working in predictive control and applications to energy systems. Both the UAL and CIEMAT-PSA groups have a strong collaboration with them in many projects and publications. The same applies to the group of Sebastián Dormido (UNED). The Solar Desalination unit at PSA takes part actively in the Solar Desalination research group (TEP026) of University of Seville. In addition, this unit collaborates with the department of Mechanical Engineering of University of Zaragoza and the Research Center for Energy Resources and Consumption (CIRCE) in thermodynamic studies of renewable desalination processes and heat pumps.

Main references

Agüero, J., F. Rodríguez, A. Giménez. Energy management based on productiveness concept. Renew Sust Energ Rev, 22:92–100, 2013.

Álvarez, J.D., J.L. Redondo, E. Camponogara, J. Normey-Rico, M. Berenguel, P.M. Ortigosa. Optimizing building comfort temperature regulation via model predictive control. Energ Buildings, 57:361–372, 2013a.

Álvarez, J.D., R. Costa, M. Castilla, E.F. Camacho. Repetitive control to counteract the effect of people on thermal comfort control, ECC2013, Zurich, Switzerland, 2013b.

Arnold, M., R.R. Negenborn, G. Andersson, B. De Schutter. Distributed predictive control for energy hub coordination in coupled electricity and gas networks. “Intelligent Infrastructures”, R.R. Negenborn, et al. Eds. Dordrecht, The Netherlands, Springer, 2010, 235-273.
Camacho, E.F. and C. Bordons. Model Predictive Control. Springer, 2004.
Camacho, E.F., A. Del Real, C. Bordóns, A. Arce. Thermal plants integration in Smart grids. 18th IFAC World Congress, Milan, 2011.
Camacho, E.F. M. Berenguel, F.R. Rubio, D. Martínez. Control of solar energy systems. Advances in Industrial Control Series; Springer, 2012.
Castilla, M., J.D. Álvarez, M.G. Ortega, M.R. Arahal. Neural network and polynomial approximated thermal comfort models for HVAC systems. Build Environ, 59:107–115, 2013.
Castilla, M., J.D. Álvarez, F. Rodríguez, M. Berenguel. Comfort control in buildings. Advances in Industrial Control Series, Springer, 2014a.
Castilla, M., J. Bonilla, J.D. Álvarez, F. Rodríguez. A room simulation tool for thermal comfort control in a bioclimatic building. A real example of use with an optimal controller. Optim Contr Appl Met, 2014b (in press).
Castilla, M., J.D. Álvarez, J.E. Normey-Rico, F. Rodríguez. Thermal comfort control using a non-linear MPC strategy: A real case of study in a bioclimatic building. J Process Contr. 24(6):703-713, 2014c.
Chandan, V, A.G. Alleyne. Decentralized predictive thermal control for buildings. J Process Contr, 24:820-835, 2014.
Chatzivasileiadi, A., E. Ampatzi, I. Knight. Characteristics of electrical energy storage technologies and their applications in buildigs. Renew Sust Energ Rev, 25:814-830, 2013.
De la Calle, A., J. Bonilla, L. Roca, P. Palenzuela. Dynamic modeling and performance of the first cell of a multi-effect distillation plant. Appl Therm Eng, 70:410–420, 2014.
Del Real, A., A. Arce, C. Bordons. An integrated framework for distributed model predictive control of large-scale power networks. IEEE T Ind Inform, 10(1):197-209, 2014.
Deng, R., L. Xie, H. Lin, J. Liu, W. Han. Integration of thermal energy and seawater desalination. Energy, 35:4368-4374, 2010.
Di Giorgio, A., F. Liberati, S. Canale. Electric vehicles charging control in a smart grid: A model predictive control approach. Control Eng Pract, 22:147-162, 2014.
Domahidi, A., F. Ullmann, M. Morari, C.N. Jones. Learning decision rules for energy efficient building control. J Process Contr, 24:763-772, 2014.
Dounis, A.I., C. Caraiscos. Advanced control systems engineering for energy and comfort management in a building environment – A review. Renew Sust Energ Rev, 13:1246-1261, 2009.
Ellis, M., H. Durand, P.D.Christofides. A tutorial review of economic model predictive control methods. J Process Contr, 24:1156-1178, 2014.
Eltawil, M.A., Z. Zhengming, L. Yuan. A review of renewable energy technologies integrated with desalination systems. Renew Sust Energ Rev, 13:2245-2262, 2009.
Engell, S. Feedback control for optimal process operation. J Process Contr 17:203-209, 2007.
Geidl, M., G. Koeppel, P. Favre–Perrod, B. Klöckl, G. Andersson, and K. Fröhlich. Energy hubs for the future. IEEE Power Energy M, 5(1):24–30, 2007.
González, R., F. Rodríguez, J.L. Guzmán, C. Pradalier, R. Siegwart. Control of off-road mobile robots using visual odometry and slip compensation. Adv Robotics 27(11):893–906, 2013.
González, R., F. Rodríguez, J.L. Guzmán, M. Berenguel. Robust constrained economic receding horizon control applied to the two time-scale dynamics problem of a greenhouse. Optim Contr Appl Met, 35:435-453, 2014.
Hoppmann, J., J. Volland, T.S. Schmidt, V.H. Hoffmann. The economic viability of battery storage for residential solar photovoltaic systems – A review and simulation model. Renew Sust Energ Rev, 39:1101-1118, 2014.
Jebaraj, S., S. Iniyan. A review of energy models. Renew Sust Energ Rev, 10:281-311, 2006.
Kolokotsa, D., A. Pouliezos, G. Stavrakakis, C. Lazos. Predictive control techniques for energy and indoor environmental quality management in buildings. Build Environ, 44:1850-1863, 2009.
Leung, D.Y.C, G. Caramanna, M.M. Maroto-Valer. An overview of current status of carbon dioxide capture and storage technologies. Renew Sust Energ Rev, 39:426-443, 2014.
Ma, J. S. Joe Qin, T. Salsbury. Application of economic MPC to the energy demand minimization of a commercial building. J Process Contr 24:1282-1291, 2014.
Mahlia, T.M.I., T.J. Saktisahdan, A. Jannifar, M.H. Hasan. A review of available methods and development on energy storage; technology update. Renew Sust Energ Rev, 33:532-545, 2014.

Mekhilef, S., R. Saidur, A. Safari. A review on solar energy use in industries. Renew Sust Energ Rev, 15(4):1777-1790, 2011.

Mena, R., F. Rodríguez, M. Castilla, M.R. Arahal. A prediction model based on neural networks for the energy consumption of a bioclimatic building. Energ Buildings, 82:142-155, 2014.

Mendoza, D.I., D.J. Chmielewski. Smart grid coordination in building HVAC systems: EMPC and the impact of forecasting. J Process Contr, 24:1301-1310, 2014.

Oldewurtel, F., A. Parisio, C.N. Jones, D. Gyalistras, M. Gwerder, V. Stauch, B. Lehmann, M. Morari. Use of model predictive control and weather forecasts for energy efficient building climate control. Energ Buildings, 45:15-27, 2012.

Palenzuela, P., L. Roca, G. Zaragoza, D.C. Alarcón, L. García, A. de la Calle. Operational improvements to increase the efficiency of an absorption heat pump connected to a Multi-Effect Distillation unit. Appl Therm Eng, 63(1):84–96, 2013a.

Palenzuela, P., D.C. Alarcón, G. Zaragoza, J. Blanco. Evaluación del acoplamiento de plantas de destilación multiefecto a plantas termosolares. Ed. CIEMAT, Madrid, 2013b.

Palenzuela, P., A.S. Hassan, G. Zaragoza, D.C. Alarcón. Steady state model for multi-effect distillation. Case study: Plataforma Solar de Almería. Desalination, 337:31-42, 2014c.

Palizban, O., K. Kauhaniemi, J.M. Guerrero. Microgrids in active network management – Part I: Hierarchical control, energy storage, virtual power plants and market participation. Renew Sust Energ Rev, 36:428-439, 2014.

Pasamontes, M., J.D. Álvarez, J.L. Guzmán, M. Berenguel, E.F. Camacho. Hybrid modeling of a solar-thermal heating facility, Sol Energy, 97:577-590, 2013.

Pawlowski, A., Guzman, J. L., Rodríguez-Díaz, F., Berenguel, M., Normey-Rico, J. E., 2011. Predictive Control with Disturbance Forecasting for Greenhouse Diurnal Temperature Control, 18 IFAC World Congress, Milan, Italy, 1779-1784, 2011.

Pintaldi, S., C. Perfumo, S. Sethuvenkatraman, S. White. A review of thermal energy storage technologies and control approaches for solar cooling. Renew Sust Energ Rev, 41:975-995, 2015.

Planas, E. A. Gil-de Muro, J. Andreu, I. Kortabarria, I. Martínez de Alegría. General aspects, hierarchical controls and droop methods in microgrids: A review. Renew Sust Energ Rev, 17:147–159, 2013.

Qi, W. J. Liu, P.D. Christofides. Supervisory predictive control for long-term scheduling of an integrated wind/solar energy generation and water desalination system. IEEE T Contr Syst T,20(2):504–512, 2012.

Qiblawey, H.M., F. Banat. Solar thermal desalination technologies. Desalination, 220:633-644, 2008.

Ramírez, F. Rodríguez, J.L. Guzmán, M. Berenguel. Multiobjective hierarchical control architecture for greenhouse crop growth. Automatica, 48:490–498, 2012.

Rawlings J.B. and Amrit, R. Optimizing process economic performance using model predictive control. In Nonlinear Model Predictive Control, 384, LN in Control and Information Sciences, 2009. Springer.

Ren, G., G. Ma, N. Cong. Review of electrical energy storage system for vehicular applications. Renew Sust Energ Rev, 41:225-236, 2015.

Roca, L., L.J. Yebra, M. Berenguel. A. de la Calle. Dynamic modeling and simulation of a muti-effect distillation plant. 9th MODELICA Conf, Munich, Germany, 2012.

Rodríguez, F., M. Berenguel, J.L. Guzmán, A. Ramírez. Modeling and control of greenhouse crop grow, Springer, 2014.

Sánchez, J.A., F. Rodríguez, J.L. Guzmán, M.R. Arahal. Virtual sensors for designing irrigation controllers in greenhouses. Sensors, 12:15244-15266, 2012.

Scattolini, R. Architectures for distributed and hierarchical model predictive control–a review. J Process Contr, 19(5):723–731, 2009.

Scherer, H.F., M. Pasamontes, J.L. Guzmán, J.D. Álvarez, E. Camponogara, J.E. Normey-Rico. Efficient building energy management using distributed model predictive control. J Process Contr, 24(6):740-749, 2014.

Silva, R. M. Berenguel, M. Pérez, A. Fernández-García. Thermo-economic design optimization of parabolic trough solar plants for industrial process heat applications with memetic algorithms, Appl Ener, 113:603–614, 2014.

Suganthi, L., A.A. Samuel. Energy models for demand forecasting – A review. Renew Sust Energ Rev, 16:1223-1240, 2012.

Sun, B., P.B. Luh, Q-S. Jia, Z. Jiang, F. Wang, C. Song. Building energy management: Integrated control fo active and passive heating, cooling, lighting, shading and ventilation systems. IEEE T Autom Sci Eng, 10(3):588-602, 2013.

Tie, S.F., C.W. Tan. A review of energy sources and energy management in electric vehicles. Renew Sust Energ Rev, 20:82-102, 2013.
Torres, J.L., R. González, A. Giménez, J. López. Energy management strategy for plug-in hybrid electric vehicles. A comparative study. Appl Energ, 113:816–824, 2014.
Torrico, B., L. Roca, J.E. Normey-Rico, J.L. Guzmán, and L.J. Yebra, Robust nonlinear predictive control applied to a solar collector field in a solar desalination plant, IEEE T Contr Syst T, 18(6):1430 – 1439, 2010.
Touretzky, C.R., M. Baldea. Integrating scheduling and control for economic MPC of builidngs with energy storage. J Process Contr, 24:1292-1300, 2014.
Ürge-Vorsatz, D. L.F. Cabeza, S. Serrano, C. Barreneche, K. Petrichenco. Heating and cooling energy trends and drivers in buildings. Renew Sust Energ Rev, 41:85-98, 2015.
Venkat A.N., Hiskens I.A., Rawlings J.B. and Wright S.J. Distributed MPC strategies with application to power system automatic generation control. IEEE T Contr Sys T, 16(6):1192-1206, 2008.
Vana, Z., J. Cigler, J. Siroky, E. Zacekova, L. Ferkl. Model-based energy efficient control applied to an office building. J Process Contr, 24:190-797, 2014.
Wang, L, Z. Wang, R. Yang. Intelligent multiagent control system for energy and comfort management in smart and sustainable buildings. IEEE T Smart Grid, 3(2):605-617, 2012.
Wang, Z., W. Yang, F. Qiu, X. Zhang, X. Zhao. Solar water heating: From theory, application, marketing and research. Renew Sust Energ Rev, 41:68-84, 2015.
Wu, L., Y. Hu, and C. Gao, Optimum design of cogeneration for power and desalination to satisfy the demand of water and power, Desalination 324:111–117, 2013.
Yu, Z., L. Jia, M.C. Murphy-Hoye, A. Pratt, L. Tong. Modeling and stochastic control for home energy management. IEEE T Smart Grid, 4(4):2244-2255, 2013.
Zavala, V.M., E.M. Constantinescu, T. Krause, M. Anitescu. On-line economic optimization of energy systems using weather forecast information. J Process Contr, 19:1725-1736, 2009.

C.2.2. Hipótesis de partida y objetivos generales / Hypothesis and general objectives

Efficient energy generation and consumption is a key factor to achieve ambitious goals for sustainable development and activities related to air pollution and climate shifting. Since efficient and safe power distribution along with minimized and balanced power consumption is an important part of the economic activity, the development of new techniques for energy management is fully justified. This project deals with the analysis, design and application of modeling, forecasting, control and optimization techniques (in the framework of hierarchical and model-based predictive control, MPC) to achieve an efficient energy (electricity and process heat/water), water and CO_2 management in production environments with support of renewable energy and storage systems. Through optimal management of these resources and by adapting generation to demand, it should be demonstrated how automatic control allows to achieve cost savings and reduce the environmental impact on the operation of complex processes. The problem is composed by different control and decision levels about the final use of the available energy based on different objectives (minimizing the use of conventional fossil energy sources, economic, environmental and quality aspects, etc.) This gives rise to a hierarchical control problem that requires coordination and cooperation between systems and that will be addressed using hierarchical and hybrid predictive control techniques, both in centralized and distributed versions. It will be also necessary to develop models, estimators and predictors of the energy generation and demand stages.

The three basic objectives of the coordinated project are:

1. Development of methodologies for obtaining models of processes that contain renewable energy sources to produce/consume process heat, electricity, water and CO_2. Development of estimators and predictors of generation and demand stages.
2. Development of hierarchical, hybrid and, in general, MPC control and management strategies to optimize production from the economic, security and energy and water use points of view in heterogeneous systems, using a coordinated and comprehensive approach.
3. Implementation and validation of the strategies in the production environment selected as test-bed plant. This will facilitate the development of the different tasks of the project over realistic conditions. Possible extensions to more complex environments will be demonstrated.

The fulfilment of the preceding goals represents a significant contribution with real impact in this class of processes as evidenced by the interest shown by firms like Fundación Cajamar, UNICA Group SCA, Wagner Solar, Solar Jiennense, naming only a few. The proposal is also a natural continuation follow-up of previous work carried out the research groups integrating the project. The team has a remarkable experience in control systems backed by many papers published in some of the most cited scientific journals and relationships with international research teams.

Notice that the topic of this project belongs to the strategic research lines of the European Union and the National Research Plan (Spanish Strategy for Science, Technology and Innovation 2013-2020). Twelve areas were identified in the first **Horizon 2020** Work Programme. Among them, **smart cities and communities, competitive low-carbon energy, mobility for growth, energy efficiency and water innovation: boosting its value for Europe** (http://europa.eu/rapid/press-release_MEMO-13-1122_en.htm) are the areas with a stronger relation with this proposal. The EU aims to reduce greenhouse gas emissions by 20% below 1990 levels by 2020, with a further reduction to 80-95% by 2050. One of the challenges addressed under this focus area is the integration of next-generation renewable energy technologies into the future energy system. The current **National Research Plan 2013-2016** proposes also a challenge on this topic under the name of "**Secure, Efficient and Clean Enegy**". Moreover, in Spain, the called "**Estrategia Española de Cambio Climático y Energía Limpia Horizonte 2007-2012-2020**", expresses the necessity to create campaigns to make people more aware about the economic and environmental costs of the energy, to develop new technologies with less CO_2 emissions and/or based on renewable resources, and to finance processes allowing to mitigate or store the CO_2 from the combustion gases. Moreover, the proposal fits the recommendations provided by the World Energy Council (http://www.worldenergy.org/publications/) and the EU Strategic Research and Innovation Agenda for Renewable Heating and Cooling Technologies (http://www.rhc-platform.org/fileadmin/Publications/RHC_Common_Roadmap.pdf). Thus, the objectives proposed in this project attempt to highly contribute in these EU and National energy-based demands under the optimal management of energy (process heat and electricity), water and CO_2. Furthermore, contributions to the mitigation of the environment pollution can be also achieved.

C.2.3. Objectives of each subproject:

Subproject 1: Universidad de Almería (UAL)

1. Development of methodologies for obtaining models of processes that contain renewable energy sources to produce/consume process heat, electricity, water and CO_2. [Manuel Pérez].
2. Development of prediction models for environmental variables, disturbances, sources and loads. [Manuel Pérez].
3. Modeling of energy storage and auxiliary systems for energy cost reduction [Manuel Pérez].
4. Obtaining of simplified models for control purposes [Manuel Berenguel].
5. Design of hierarchical multiobjective controllers of climate, air quality and lighting [Manuel Berenguel].
6. Development of hierarchical MPC formulations for the optimal economic and energy efficiency management of heterogeneous energy systems considered in the proposal, where different hierarchical levels will be considered, characterized by the existence of different dynamical time scales and changing operation modes, where renewable energy generation and consumption must be coordinated [Manuel Berenguel].
7. Implementation and validation of the different strategies the test-bed plant with clear industrial relevance and coordination requirements, with different demands in generation, distribution and use of electricity, process heat and water [Manuel Pérez].
8. Analysis of the possibilities of extending the obtained results to industrial clusters [Manuel Berenguel].
9. Technology transfer to the companies and institutions interested in the project [Manuel Pérez].
10. Dissemination of the results in different national and international forums at different levels (educational, research, industry) [Manuel Berenguel].

Subproject 2: Plataforma Solar de Almería (CIEMAT-PSA)

1. Dynamic modeling of solar-gas hybrid desalination plants supplied with novel industrial solar collectors.
2. Development of prediction models for environmental variables, disturbances, sources and loads.
3. Analysis and modeling of energy storage systems and other auxiliary systems for energy cost reduction.
4. Obtaining of simplified models for control purposes.

5. Development of MPC strategies (hierarchical, hybrid and economic) for desalination plants.
6. Coupling of solar desalination plants as a water and energy supply to greenhouses and buildings.
7. Testing of the selected algorithms both in simulation and in the real installations.
8. Technology transfer to the companies and institutions interested in the project.
9. Dissemination of the results in different national and international forums at different levels (educational, research, industry).

C.2.4. Methodology

As shown in the task schedule in section C2.6, the project is composed by different tasks. From a methodological point of view, these could be classified as follows:

- **Bibliographical searching and analysis:** Scientific literature should be evaluated and articles and research works related with the project tasks must be studied and analyzed. This searching task will be carried out mainly during the first stage of the project and will be continued in a faded way throughout its duration. The main sources to be analyzed will be international journals, conferences and workshops preprints, combined with periodic searching in the web by means of recent specialized tools, and visiting the web pages of the main research groups related to the project objectives.
- **Modeling of the experimental plants**: Applied research must be based on the experimental demonstration of the obtained results on a study case. In this project, this is carried out in two different stages related with its two main parts: the determination of the model and the analysis and design of the controlled system. The success and utility of the experimentation depends on a good selection of the experiments, that is, the plants and processes to be analyzed and controlled. Each sub-process will be modeled in two different ways: a) models for control and b) models for simulation. In the first case, different dynamics and uncertainty models will be developed with diverse degree of complexity to be used in the algorithms produced in tasks 2 and used in task 3. Simulation allows one to use more complex models considering a large number of states and operating constraints. The dynamics of these models should be similar to the real dynamics of the plant in order to be used for testing the developed controllers before their implementation on the real plant. This will reduce the cost of the experiments to be executed. Dynamical models developed in previous projects will be used as support for the proposed modeling objectives.
- **Development of algorithms and novel results:** This task is the proper research activity and due to its creative nature, it is quite difficult to be described. The task will be based on the bibliographical searching, the own knowledge of the groups and the addition of new ideas from both research groups. Each research group must discuss together all the ideas and decide the most promising ones to be expanded, programmed, and implemented.
- **Development of programs to implement the obtained algorithms and models**: It is worth noting that the algorithms associated to the proposed control techniques are quite more demanding than the ones used in classic control techniques and therefore, it is expected that this task will require a significant time burden (help of the employed engineer will be necessary).
- **Simulation tests:** Once simulation models are ready to be used, and as a previous stage to the implementation of the controllers on the experimental plants, preliminary tests will be executed in simulation. These will allow us to verify if the performance and control objectives are satisfactory.
- **Experimental tests:** Throughout the project it is necessary to produce ad-hoc tests for the identification of the processes, uncertainty bounding and validation of the designed algorithms. These tests will be decided in meetings of the groups involved in the experiments. The tests will be executed according to the decided protocol and the obtained results will be analyzed in later meetings. All the obtained results must be stored in such a way that all the experiments could be replicated and that all the involved researchers are able to access the data. It is worth noting that several tasks as setting up of the plants, instruments and sensors installation, preparation of the environment for the execution of the experiments, etc. must be considered. The employed engineer will be in charge of this task.

The leader of each group is responsible for the appropriate evolution and fulfilment of the expected tasks at each stage. Moreover, the researchers from both institutions involved in each task will have frequent meetings and will attend coordination meetings where the results and stages of the project will be analyzed. Information sharing between the different groups will be done by means of the electronic mail, a web-server and sharing files technologies (such as Dropbox). Dissemination of the obtained results can be enhanced by means of the web page. During the development of these tasks, it will be interesting to involve companies that have shown interest in the project.

- Fundación CAJAMAR – Estación Experimental Las Palmerillas will play a very important role, as will take part of the tests performed in the greenhouse located in its installations, devoting own personnel, installations and consumables to this task (a provision has been included in the budget that covers only part of the associated cost). They are very interested in the energy efficiency view of the climate and fertigation control.
- UNICA Group will act as a supervisor of the project, providing useful information related to energy demand, economic and environmental sustainability of the processes that constitute its productivity activity (in greenhouse, buildings and industrial clusters). They are interested in innovations achieved during the development of the project.
- Wagner Solar and Solar Jiennense are interested in keeping track of the progress of the project throughout the implementation period to analyze how the obtained results may improve actual industrial practices to incorportate them in their productive processes.
- Centro de Experiencias Michelin Almería (CEMA) is interested in the results on energy efficiency in vehicles and the influence the tires have on energy consumption and vehicle autonomy.

In the description of the task (not in the work program) we have also highlighted those tasks in which the requested research fellows (FPI) could develop their Ph. D. thesis.

Task T0. Coordination and project management.

Task leader: UAL

This task is active all the project life. As the groups are placed in the same province (40 km distance), coordination and management is easy. The lead researchers of both subprojects that apply to this call will guarantee that all the tasks in each subproject will be carried out as expected. They will maintain regular meetings to guarantee that all the results are met within the specified deadlines. The meetings will be:

- Coordination between subprojects meetings: one kick-off meeting and then one each semester.
- Subgroups meetings to develop tasks: as often as needed.
- There will also be personal exchanges between researchers of each subproject and a flow of information via e-mail. There will be also a ftp server to be set-up and a website that will be used to disseminate the results not only between the project members, but also between other research groups, nation, or worldwide. Interaction with the companies and research centers supporting this project will be fostered.

Groups involved: All of them.
Task life: 36 months.
Deliverables: D0.1: First annual Report (M12); D0.2: Second annual Report (M24); D0.3: Third annual Report (M36)
Milestones: M0.1: Kick-off meeting (M1); M0.2: 1st semester meeting (M6); M0.3: 2nd semester meeting (M12); M0.4: 3th semester meeting (M18); M0.5: 4st semester meeting (M24); M0.6: 5st semester meeting (M30)

Objective 1 / Task T1. Development of methodologies for obtaining models of processes that contain renewable energy sources to produce/consume process heat, electricity, water and CO_2. Development of estimators and predictors of generation and demand stages.

Task Leader: CIEMAT-PSA (Diego César Alarcón Padilla)

The objective of this task is to develop an adequate framework for the modelling and simulation of heterogeneous energy systems. This task will formalize a hierarchical structure of models oriented to the different tasks considered in the project: identification, estimation, analysis, synthesis and coordination/cooperation

Task T1.1. Development of prediction models for environmental variables, disturbances, sources and loads. As one of the main objectives of this research project focuses on the efficient management of energy, a thorough analysis of the energy requirements of each process and the estimated energy sources available to meet energy demands is necessary. The result of this work will be of particular interest for the development of tasks related to aspects of control, as the basis for determining the cost functions that can be used in multi-objective control problems (including terms for revenues from energy sales, penalties, production costs and plant aging, between others). This is of special interest in

the framework of MPC algorithms, where future values of disturbances are required for optimization purposes (these values are usually set to the actual value). The availability of at least approximated future estimations in different time scales could considerably improve the control results. Renewable energy plants are characterized by the fact that the primary energy source cannot be manipulated and it varies during the day. In that sense, renewable energy plants have to be started each day and usually depend on auxiliary conventional energy sources. Thus, the identification and prediction of these primary energy sources (that also act as disturbances from the control point of view) is of particular interest to optimize the process performance, minimize the use of auxiliary energy sources and planning to optimize the electrical grid based on the requested demand. Moreover, in order to maximize the use of renewable resources, it is necessary to estimate the energy demands within the production system to help taking decisions about energy storage and final use of energy. The idea is to obtain models and predictors of production and demand of water, electricity, heat/cooling and CO_2. Models or user's behavior models will be also studied to analyze their feasibility to be used within a control scheme. Different approaches will be used: first-principles models, time series models, autoregressive linear models, neural network models, ...
Groups involved (task leader): UAL (Manuel Pérez García), CIEMAT-PSA.
The EPOs UNICA Group and CAJAMAR will collaborate by providing useful information related to energy demand, climate variables and economic and environmental sustainability of the processes that constitute its productivity activity (in greenhouses, buildings and industrial clusters).
Task life: 18 months.
Deliverables: D1.1.1. Report on requirements, methodologies, paradigms, and tools for the modeling and simulation of the systems treated in the project (M18); D1.1.2. Report on models and predictors of water and energy (electricity and process heat) production and demand in CIESOL building and the electric car powered by renewable energy (M15); D1.1.3. Report on models and predictors of water, energy (electricity and process heat) and CO_2 production and demand in greenhouses powered by renewable energy (M15); D1.1.4. Report on models and predictors of water and energy (electricity and process heat) production and demand in solar desalination plants (M15).
Milestones: M1.1.1: Libraries of models and predictors of production and demand of water, electricity, heat/cooling and CO_2 (M18).

Task T1.2. Extension of climate models to the management of air quality and lighting. Models developed in previous projects cope with temperature and humidity (or thermal comfort). In this project, focus is being placed on air quality (related to CO_2 concentration) and lighting. General models for these variables will be developed and adapted to different enclosures trying to adopt a modular approach. The same modeling approaches commented in the previous sub-task will be applied here. Extension of room models and simulators to a complete building will be accomplished.
Groups involved (task leader): UAL (Francisco Rodríguez Díaz).
For the development of this task the UAL employed engineer will be necessary as much experimental work has to be carried out.
Task life: 18 months.
Deliverables: D1.2.1: Report on modeling approaches of air quality (M18); D1.2.2. Report on modeling approaches for lighting (M18); D1.2.3. Report on the integration of air quality and lighting in a general model of an enclosure. Application to buildings and greenhouses (M18).
Milestones: M1.2.1: Libraries of models of air quality and lighting (M18). M1.2.2: Simulators or different enclosures (M18).

Task T1.3. Modeling of auxiliary equipment for energy cost reduction. For the development of the project, it will be necessary to model and characterize auxiliary equipment to try to minimize energy consumption and maximize efficiency. Among the new equipment that is going to be used in the installations, we can highlight dehumidification systems, new solar collectors, heat pumps, and those related to the electric car (mechanics, main propulsion motor, auxiliary steering motor, onboard computer power load …) Some of these systems have not been modeled yet (only input-output data is allowable). So, it will be necessary to characterize and model (both from the dynamical and energy points of view) all these elements.
Groups involved (task leader): CIEMAT-PSA (Patricia Palenzuela Ardila), UAL.
For the development of this task the UAL employed engineer will be necessary.
Task life: 15 months.
Deliverables: D1.3.1: Report on static and dynamic models of auxiliary equipment (M15).
Milestones: M1.3.1: Libraries of auxiliary equipment components (M15).

Task T1.4. Modeling of storage systems (electricity, heat and CO_2). To implement the hierarchical coordinated control architecture, it is necessary to have the possibility of energy storage, as the production in renewable energy-based systems is not usually coupled to the demand. So, thermal low-medium temperature storage systems will be studied, as well as systems for CO_2 storage and electricity storage (including electric car from network and on-board PV system) in production systems.
Groups involved (task leader): CIEMAT-PSA (Julián Blanco Gálvez), UAL.
Task life: 15 months.
Deliverables: D1.4.1: Report on models of thermal storage systems (M15); D1.4.2. Report on models of CO_2 storage systems (M15); D1.4.3. Report on models of electricity storage systems (M15);
Milestones: M1.4.1: Libraries of models of storage systems (M15).

Task T1.5. Dynamic modeling of solar-gas hybrid desalination plants. The preliminary models will be adapted to a new layout, where the collector field, thermal storage and heat pump have recently been changed and thus, it is mandatory the characterization of the new plant (dynamical behavior and energy generation/demand).
Groups involved (task leader): CIEMAT-PSA (Diego César Alarcón Padilla)
Task life: 18 months.
Deliverables: D1.5.1: Report on modeling approaches of solar desalination plants (M18).
Milestones: M1.5.1: Libraries of models of hybrid desalination plants (M18).

Task T1.6. Adaptation of the developed models for control purposes. Many of the models to be developed (or already available) are sometimes complex to be used for control purposes. So, these models will be adapted and simplified to be used within MPC control strategies.
Groups involved (task leader): UAL (Manuel Berenguel Soria), CIEMAT-PSA
Task life: 24 months.
Deliverables: D1.6.1: Report on the adaptation of building subsystems models (solar field, PV plant, absorption machine, storage tanks, distribution pipes, rooms, …) into models for control (M24); D1.6.2: Report on the adaptation of greenhouse subsystems models (biomass boiler, storage tanks, distribution pipes, greenhouse environment,…) into models for control (M24); D1.6.3: Report on the adaptation of electric vehicles models (kinematic, dynamic, electrical, power consumption and battery status) into models for control (M24); D1.6.4: Report on the adaptation of solar desalination plant models (solar field, heat pump, distillation column, … into models for control (M24).
Milestones: M1.6.1: Libraries of simplified models for control purposes (M24).

Task T1.7. Integration and scaling of the developed models. The models implemented with different tools (Simulink, Ecosim-Pro, Modelica, etc.) will be integrated. This will also help to scale the models to industrial cluster level. We will analyze the possibility of using new energy management paradigms commented on in the literature review.
Groups involved (task leader): CIEMAT-PSA (Javier Bonilla Cruz), UAL
For the development of this task the UAL employed engineer will be necessary as much experimental work has to be carried out (see comments on task 1.2).
Task life: 24 months.
Deliverables: D1.7.1. Report on the integration of models implemented in different tools (M24); D1.7.2. Report on the analysis of other paradigms for scaling the developed models to industrial clusters (M24).
Milestones: M1.7.1. Definition of a modeling framework for integrating models of heterogeneous renewable energy based systems (M24).

Objective 2 / Task T2. Development of hierarchical, hybrid and, in general, MPC control and management strategies to optimize production from the economic, security and energy and water use points of view in heterogeneous systems, using a coordinated and comprehensive approach.

Task Leader: UAL (Manuel Berenguel Soria)

This task will develop algorithms based on adapting energy demand to energy production through the use of mainly MPC algorithms and the models developed in Task T1. Economic performance and optimal energy management will be taken explicitly into account in the derivation of the proposed predictive control techniques.

Task T2.1. Design of hierarchical multiobjective controllers of climate, air quality and lighting, to allow finding a tradeoff between these competing objectives, while accounting for patterns of behavior of users, the profile of typical disturbances, the accommodation of the generation to the demand and the existence of different time scales. Variable tariffs will be contemplated. These approaches will be mainly applied to buildings and greenhouses. The combination of natural light with artificual light through installed actuators (powered by a PV plant) will be studied.
Groups involved (task leader): UAL (Francisco Rodríguez Díaz)
Task life: 24 months.
Deliverables: D2.1.1. Report on hierarchical multiobjective controllers (updates at M24, M30, M36 according to partial validation results).
Milestones: M2.1.1. Methods developed for hierarchical multiobjective controllers (M36).

Task T2.2. Design of centralized and distributed MPC controllers, will be developed to manage energy generation and demand in several subsystems. Notice that few contributions have tackled an economic objective in the daily operation of the desalination processes. In this context, several strategies based on **economic receding optimal control and MPC** will be developed in this project, using as cost function the economic profit of the plant, taking into account the fresh water produced at the end of the considered period, the involved electricity consumption, market and disturbances variations. This problem is typically addressed by a hierarchical structure as that studied in Task T2.1, incorporating RTO merging the standard two-level structure in only one providing optimal energy management. Another interesting aspect is the coupling of biomass boiler and solar desalination plant to a greenhouse and a building to control users' comfort (humans, crop) while using energy and water storage systems. Simultaneous control of CO_2 injection and heating/ventilation will be carried out in the greenhouse, as well irrigation linked to the solar desalination plant. Also, MPC controllers for the electric vehicle and its coupling with the PV generator will be included in this task.
Groups involved (task leader): CIEMAT-PSA (Diego César Alarcón Padilla), UAL
Task life: 24 months.
Deliverables: D2.2.1. Report on centralized and distributed MPC and economic optimal controllers (updates at M24, M30, M36 according to partial validation results).
Milestones: M2.2.1. Methods developed for centralized and distributed MPC and economic optimal controllers (M36).

Task T2.3. Other control strategies. The objective of this task is to develop and implement different control strategies that have been found in the literature to be competing alternatives to MPC ones within the framework of the kind of production systems studied in this project. **Rule-based controllers**, as well as **repetitive control approaches**, among others, will be estudied.
Groups involved (task leader): UAL (Manuel Pérez García), CIEMAT-PSA
Task life: 18 months.
Deliverables: D2.3.1. Report on rule-based controllers and potential applications (updates at M30, M36 according to partial validation results). D2.3.2. Report on repetitive controllers and potential applications (updates at M30, M36 according to partial validation results).
Milestones: M2.3.1. Rule-based control algorithms (M36). M2.3.2. Repetitive control algorithms (M36).

Task T2.4. Control of the electric vehicle. The objective comprises the development of a **hierarchical control system for electric vehicle trajectory generation and tracking using energy savings criteria**. Control of the storage management and PV power module will be necessary as well as development of a Hardware-in-the-Loop (HIL) simulation platform aimed at testing the behavior of the batteries and powertrain system of electric vehicles under real-world conditions. Also, autonomous navigation of the vehicle within the production environment will be treated, trying to optimize energy management and batteries charging and assuring reliable and safe navigation. One of the research fellows (FPI) requested can work in this problem in both the design of energy management strategies and those related to autonomous navigation optimizing energy consumption.
Groups involved (task leader): UAL (Antonio Giménez Fernández)
The EPO CEMA will collaborate in supervising the works.
Task life: 24 months.
Deliverables: D2.4.1. Report on the energy control and navigation of electrical vehicles (updates at M24, M30, M36 according to partial validation results).

Milestones: M2.4.1. Library of control algorithms for energy control and navigation of electrical vehicles (M36).

Task T2.5. Integration and coordination. This task will cover the overall objective of the project, by developing global and coordinated multilevel multiobjective hierarchical MPC formulations for the optimal economic and energy efficiency management of heterogeneous energy systems considered in the proposal, where different hierarchical levels will be considered, characterized by the existence of different dynamical time scales, changing market prices, renewable energy sources (adaptation of the generation to the demand), hybrid nature and changing operation modes. From an economic point of view, the whole system should be globally controlled to provide the optimal energy management. However, each energy subsystem is typically controlled locally, leading to a loss of optimality even in the case that each one is optimally operated. In order to reduce this loss and enhance the efficiency of the whole system, information of all subsystems must be shared (in a centralized or cooperative way). Particular interest deserves the economic criterion of the whole plant which will be the real measure of the goodness of the control technique. Possible extension to industrial clusters will be analyzed. One of the research fellows (FPI) requested can work in this complex problem where many recent contributions and interest have been placed. He/she will be in charge of studying algorithms for optimal coordination and recent energy management paradigms.
Groups involved (task leader): UAL (Manuel Berenguel Soria), CIEMAT-PSA
Task life: 30 months.
Deliverables: D2.5.1. Report on cost functions and control architectures for integrated control and optimal energy management (updates at M30, M36 according to partial validation results).
Milestones: M2.5.2: Economic performance indexes and control algorithms for integrated control and optimal energy management (M36).

Objective 3/ Task T3. Implementation and validation of the strategies in the production environment.

Task Leader: UAL (Manuel Pérez García)

The objective of this task is the implementation and validation of the different strategies in the test-bed plant with clear industrial relevance and coordination requirements, with different demands in generation, distribution and use of electricity, process heat and water. This task will facilitate the development of the different tasks of the project over realistic conditions and the analysis of possible extensions to more complex environments. Modifications to the test-bed plant have to be carried out in order to improve its demonstrative capabilities:

- Integration of new sensors and improvements on auxiliary systems that allow a better estimation of states, disturbances and consumption in buildings, greenhouses and desalination plants to improve the prediction of the load.
- Improved capacity energy storage based on the limitations noted in the previous project.
- Integration of biomass boiler as an alternative energy source for generating process heat and CO_2 in physiological processes necessary for greenhouse cultivation, based on a recent patent.

For the development of this task the UAL employed engineer will be necessary.

Task T3.1. Validation of the proposed methodologies for modeling, identification and prediction. The proposed procedures and tools for modeling, identification, forecasting and prediction have to be tested on the test-bed plant in order to demonstrate their results and efficiency. For the achievement of the proposed goal, the following steps should be considered: Development or conditioning of the different plants, modeling of each plant based on first principles (or prior knowledge) according to the proposed modeling methodology (related to task 1), analysis of the software tools to be used in the identification and validation of the model (related to task 1), definition of the tests to be executed in each plant for validation of the model, estimation and diagnosis, analysis of the obtained results and validation the obtained model.
Groups involved (task leader): CIEMAT-PSA (Luis José Yebra Muñoz), UAL
UNICA Group and CAJAMAR will supervise the results obtained in prediction generation and loads in productive environments.
Task life: 24 months.
Deliverables: D3.1.1. Report on conditioning, validation and analysis of results of models developed in task 1 (M24).
Milestones: M3.1.1: Experimental plants validated (M24).

Task T3.2. Validation of the proposed control strategies on the test-bed plant. The obtained analysis tools and algorithms will be validated over the experimental plants in order to demonstrate their properties and benefits, following five steps: 1. Design the test to be executed in the plant and its validation protocol. It is important to define the main parameters to evaluate the role of different considered operational criteria: technical, economic, energy efficiency, security of supply, etc.; 2. Implementation of the controller; 3. Re-configuration of the plant and preparation of the test, 4. Execution of the test, 5. Analysis of the obtained results. This step consists of analyzing the results of the experiments and producing the appropriate reports. The data will be made available to all members of the group and the analysis will be examined at the task leaders meetings.
Groups involved (task leader): UAL (Antonio Giménez Fernández), CIEMAT-PSA
All EPOs will supervise this task.
Task life: 24 months.
Deliverables: D3.2.1. Report on experimental results when testing control strategies (M36).
Milestones: M3.2.1. Experimental results analyzed by all the groups (M36).

Task T4. Dissemination of the results

Task leader: CIEMAT-PSA (Julián Blanco Gálvez)

This task is devoted to the diffusion of results, either final ones that can be useful to the rest of the scientific community or for interchange of partial results of the project between their members. This will mainly cover the creation of a web page of the coordinate project and a sharing space for data exchange of the different test plants involved in the project. The project’s web-site will contain all public information. The web-site will be continuously maintained and updated throughout the project’s lifecycle. Furthermore, the public information portal will serve as a basis and starting point for the information portal for the permanent interest group to be established towards the end of the project. A workshop is planned towards the end of the project. The workshop is planned to take place in the Technology Park of Almería (PITA), and will target individuals both from industry and the university at several levels. The task considers the writing of papers to be submitted to the main control conferences (IEEE CDC, IFAC World Congress, ACC, ECC) and journals (Automatica, Control Engineering Practice, IEEE Trans. On Control Systems Technology, Journal of Process Control, IEEE Transactions on Industrial Electronics, IEE Transactions on Industrial Informatics, Solar Energy, Desalination, …) The main objetives of this taks can be summarized as follows:

- To effectively disseminate information about the progress and results of the project both to the stakeholders, target groups and to the potential users and customers.
- To prove the usefulness and appropriateness of the results to potential users and interest parties.
- To make easier the exploitation of the project results obtanied.
- To establish a permanent and sustainable user community and interest group on energy and water optimal management.

Groups involved: All
Task life: 36 months.
Deliverables: D4.1. Dissemination plan (updates at M6, M12, M18, M24, M30 and M36); D4.2. Public information portal (to be continuously updated); D4.3. Mininum of 15 international conferences and 6 journal papers of high impact factor.
Milestones and expected results: M4.1. Dissemination plan v1.0 (M2); M4.2 Opening of the project website (M6); M4.3 All publication goals achieved (M36).

C.2.5. Recursos materiales, infraestructura y equipos singulares / Material resources, infrastructure and singular equipment

The global layout of the system has been shown in Figure 1 and includes:

Bioclimatic building: CIESOL is a bioclimatic building where active control of inside comfort can be carried out by means of a solar cooling and heating system, automated windows and blinds. More than 300 sensors are installed to allow estimation of inside variables and comfort control. The roof of the building is composed by both PV cells (for producing electricity for lighting and other uses of the building) and solar collectors (for producing process heat). The solar cooling system consists in a field of solar flat collectors which supply hot water to an absorption machine generating chilled water for air conditioning.

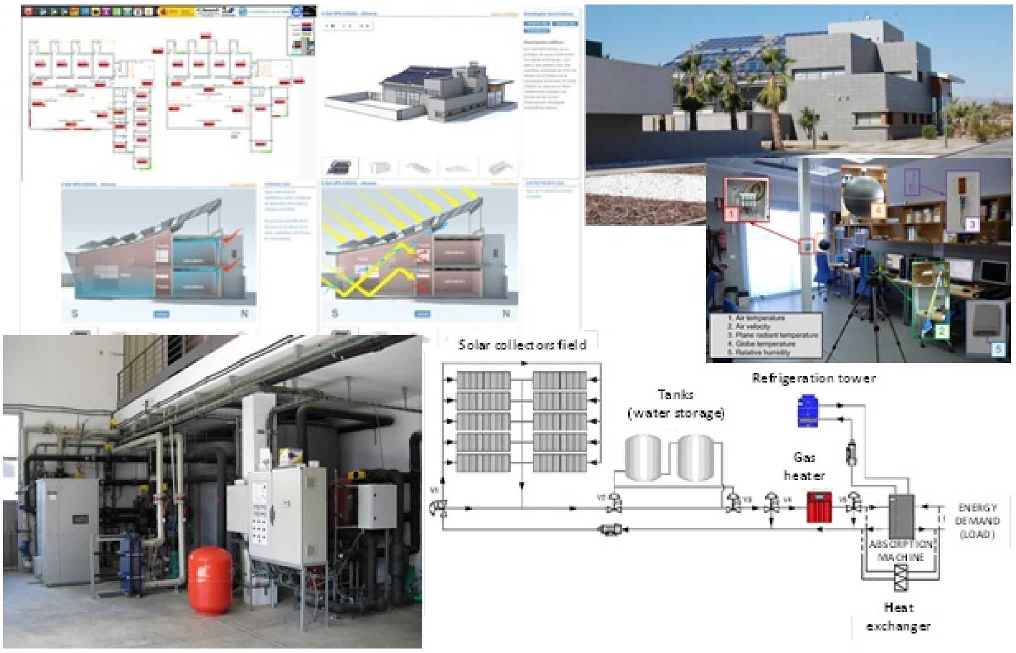

Figure 3. CIESOL bioclimatic building

Greenhouse:

"Parral" type greenhouse (877 m^2 total soil surface). The control actuators installed are automated flap roof and rolling lateral continuous ventilators. For heating purposes a petrol heater is used as well as aerial tubes with hot water that can come from a conventional boiler, a biomass boiler or from a solar collector. A complete fertigation system has been installed. Sensors (outside and inside climate, and others) and actuators (ventilation and heating) helps monitoring and control.

Figure 5. Greenhouse of the E.E. Las Palmerillas – CAJAMAR

Autonomous electric vehicle: The electric vehicle of the UAL group (eCARM) consists of an urban electric car that has been adapted for automated control. The prototype features a 48 volt DC-motor and 8 gel-batteries. Its batteries system ensures autonomy of 90 km at a maximum travel speed of about 45 km/h. In its current form, the prototype features full manual control and semi-autonomous mode (only autonomous thrust control is fully implemented). It has two embedded computers. Regarding power consumption, basic sensors are installed.

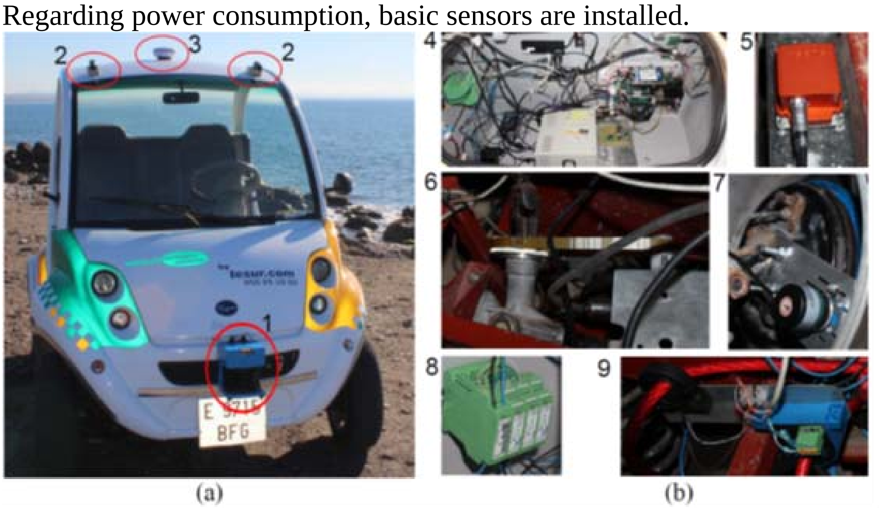

Figure 6 (a) Autonomous car prototype

(a) Visible sensors marked in red, and (b) close-ups of the rest of sensors. Labeled devices are: (1) Sick LMS-200, (2) PGR Flea3 USB3 monocular cameras, (3) GPS antenna, (4) embedded computers in the car trunk, (5) IMU system, (6) steering-wheel encoder, (7) rear wheels encoders, (8) voltage and (9) current sensors.

The eCARM can be considered as a good test-bed for the study of a hierarchical predictive control as it involves i) Different time scales: integration of typical process of ms inherent to the communications with sensors and actuators and also to the variables related to models of demand of mobility or load which need of wider scales of time. ii) Constraints: The battery capacity, the acceleration required, or the priority of the use for mobility needed. iii) Predictions: forecasting methods for the prediction of the renewable generation, for the load or the prediction of mobility patterns.

Solar desalination plant: The AQUASOL system (Figure 4) basically consists of a CPC solar collector field, two water storage tanks, a multi-effect distillation plant (MED) and a double effect absorption heat pump (DEAHP) coupled to a gas boiler. The MED plant consists of 14 effects at decreasing temperatures from cell 1 to 14 and. Seawater is pumped to the first cell where first evaporation is produced at the same time that the rest of seawater goes to the following cells by gravity. To get the first seawater evaporation, in the first cell there is a heat exchanger working with water from primary tank. Specifically, for the optimal MED operation, it is necessary an inlet heat exchanger water temperature of 66.5ºC.

This temperature is possible to reach with heat from the solar field and also with the absorption heat pump. Energy supplied by the collectors and DEAHP is transferred to the primary tank using water as the heat transfer fluid. To reduce the overall fossil energy expenditure, the low-pressure steam from the last cell is used in the DEAHP, which decreases consumption from 200 kW to 90 kW. The AQUASOL plant can operate in three modes; solar, fossil and hybrid.

Figure 4. AQUASOL Solar desalination plant: (a) Solar field, (b) storage tanks and building of the solar desalination plant at PSA and (c) double effect heat pump (d) SCADA of the DEHP (e) MED desalination plant.

C.2.6. Cronograma / Schedule and tasks

Participants

UAL (Subproject 1)		**CIEMAT-PSA (Subproject 2)**	
Name	*Acronym*	*Name*	*Acronym*
Research team			
Manuel Berenguel Soria	MBS	Diego César Alarcón Padilla	DCAP
Manuel Pérez García	MPG	Julián Blanco Gálvez	JBG
Antonio Giménez Fernández	AGF	Patricia Palenzuela Ardila	PPA
Francisco Rodríguez Díaz	FRD	Luis José Yebra Muñoz	LJYM
Work team			
Julio Elías Normey Rico	JENR	Lidia Roca Sobrino	LRS
José Luis Blanco Claraco	JLBC	Javier Bonilla Cruz	JBC
María del Mar Castilla Nieto	MMCN		
José Luis Torres Moreno	JLTM		
Javier López Martínez	JLM		
Contracted that is asked for in subproject 1*	CON1		

* Notice that we have asked for a two years contract because the first year (2015) will be covered by an engineer that actually is hired for that purpose, but that finishes his contract by the end of 2015.

The following table shows the work schedule with the different tasks, personnel involved, deliverables (■) and milestones (■) for the three years of the project.

Objective/Task	Firs Year	Second Year	Third Year	Center	Person
T0. Coordination				Leader: UAL	**MBS**
	M0.1 M0.2 D0.1 M0.3	M0.4 D0.2 M0.5	M0.6 D0.3	PSA-CIEMAT	DCAP
T1. Development of modeling and simulation framework				Leader: PSA-CIEMAT	**DCAP**
T1.1. Development of prediction models for environmental variables, disturbances, sources and loads		D1.1.2 D1.1.1 D1.1.3 D1.1.4 D1.1.5 **M1.1.1**		PSA-CIEMAT	LJYM, JBG
				UAL EPO UNICA, CAJAMAR	**MPG**, MBS, FRD, MMCN, JLBC, JLM, AGF, JLTM
T1.2. Extension of climate models to the management of air quality and lighting		D1.2.1-D1.2.3 **M1.2.1-M1.2.2**		UAL	**FRD**, MPG, MMCN, MBS, CON1
T1.3. Modeling of auxiliary equipment for energy cost reduction		D1.3.1 **M1.3.1**		PSA-CIEMAT	**PPA**, DCAP, JBG, LRS, JBC
				UAL	MPG, MMCN, AGF, JLBC, JLTM, JLM, CON1
T1.4. Modeling of storage systems		D1.4.1-D1.4.3 **M1.4.1**		PSA-CIEMAT	**JBG**, DCAP, PPA, LRS
				UAL	MPG, FRD, MBS, MMCN, JLTM
T1.5. Dynamic modeling of solar-gas hybrid desalination plants		D1.5.1 **M1.5.1**		PSA-CIEMAT	**DCAP**, JBG, PPA, JBC, LRS
T1.6. Adaptation of the developed models for control purposes		D1.6.1-D1.6.4 **M1.6.1**		PSA-CIEMAT	LRS, PPA, LJYM
				UAL	**MBS**, JENR,FRD, JLBC, MMCN, JLTM, JLM
T1.7. Integration and scaling of the developed models		D1.7.1-D1.7.2 **M1.7.1**		PSA-CIEMAT	JBC, LRS, PPA
				UAL	**MBS**, MMCN, FRD, CON1

Objective/Task	Firs Year	Second Year	Third Year	Center	Person
T2. Development of control and management strategies				Leader: UAL	**MBS**
T2.1. Design of hierarchical multiobjective controllers of climate, air quality and lighting		D2.1.1	D2.1.1 D2.1.1 **M2.1.1**	UAL	**FRD**, JENR, MPG, MMCN, MBS
T2.2. Design of centralized and distributed MPC controllers		D2.2.1	D2.2.1 D2.2.1 **M2.2.1**	UAL CIEMAT-PSA	MBS, JENR, MMCN, FRD, MPG, JLBC **DCAP**, LRS, JBC, PPA,
T2.3. Other control strategies			D2.3.1-D2.3.2 D2.2.1-D2.3.2 **M2.3.1-M2.3.2**	UAL CIEMAT-PSA	**MPG**, JENR, MMCN, MBS, FRD, JLBC LRS, JBC, PPA, DCAP
T2.4. Control of the electric vehicle		D2.4.1	D2.4.1 D2.4.1 **M2.4.1**	UAL	**AGF**, JENR, JLBC, JLTM, FRD, JLM
T2.5. Integration and coordination			D2.5.1 D2.5.1 **M2.5.1**	UAL CIEMAT-PSA	**MBS**, everyone everyone
T3. Implementation and validation of the strategies				Leader: UAL	**MPG.** Supervision of EPOs
T3.1. Validation of the proposed methodologies for modeling, identification and prediction		D3.1.1 **M3.1.1**		UAL EPO UNICA, CAJAMAR CIEMAT-PSA	MPG, MBS, FRD, MMCN, JLBC, JLM, AGF, JLTM **LJYM**, JBG, DCAP
T3.2. Validation of the proposed control strategies on the test-bed plant			D3.2.1 **M3.2.1**	UAL CIEMAT-PSA ALL EPOS	**AGF**, MBS, JLTM, JLBC, FRD, MPG, MMCN, JENR, JLM, CON1 LRS, JBC, PPA, JBG, DCAP
T4. Dissemination of the results	**M4.1** D4.1 **M4.2**	D4.1 D4.1	D4.1 D4.1 **M4.3**	Leader: PSA-CIEMAT UAL	**JBG** Everyone Everyone

C.2.7. Contratación de personal / Hiring of personnel

The development of the proposed tests for modeling and control approaches and the setting up of the installations composing the productive system test-bed require the help of an employed engineer to work in these activities for the whole duration of the project. Notice that several tasks as setting up of the plants, instruments and sensors installation, preparation of the environment for the execution of the experiments, etc. must be performed, as well as to produce multiple tests for the process identification, modeling objectives and validation of the designed algorithms (related with Tasks 1, 2, and 3 of the project). These real plants require continuous maintenance and help in programming algorithms. Hence, according to the previous requirements, a full-time engineer is requested to work during the last 2 years of this project at the CIESOL center and the E. E. "Las Palmerillas" (CAJAMAR Foundation). For this contract, an estimation of 37 hours/week during 36 months is considered. Notice that we have asked for a two years contract because the first year (2015) will be covered by an engineer that actually is hired for that purpose, but that finishes his contract by the end of 2015.

C.3. IMPACTO ESPERADO DE LOS RESULTADOS/EXPECTED IMPACT OF RESULTS

The main contribution of this project is to create an experimental cooperative framework of renewable energy-based production systems as a concept beyond that of district heating, micro-grid or water efficiency, where to demonstrate how efficient and coordinated energy and water management (by means of hierarchical control) can impact within the challenge of "Safe, Efficient and Clean Energy". Scenarios where the impact resulting from the research is clear:

a) Scientific-technical: By providing novel results in control and management of energy and water as a fundamental problem in Spain.
b) Economical: By developing control and novel forecasting techniques which allow a flexible and efficient operation of the processes enhancing the economic operation of this class of systems that are subject to a great variability in both generation and demand. Moreover, by achieving technology transfer to potentiate the involved industries that have shown their interest in the development and outputs of this project.
c) Environmental ones: By the development of optimal control and management techniques of different energy resources involving energy efficiency with intensive use of renewable energy, as well as by coupling solar desalination systems to greenhouses.
d) Internationalization: The problem tacked in this project it is an opportunity for both academia and companies to try to stand out and differentiate from the technological development in other advanced countries, as Spain is leader in renewable energy technology development.
e) Social: The efficient use of energy and water is also a social problem and people have to be aware that not only technology is able to overcome the problems tackled in this project, but can help, in combination with good practices.

Dissemination plan: As usual, by papers or technical communications in books, book chapters, journals and international conferences and workshops. By looking at the groups trajectories, it is expected to publish the results in the most relevant international journals (category Q1), as well as international conferences such as IFAC World Congress, CDC, ACC, ECC. During the last three years the members of the proposal have published 4 international books and more than 40 papers and 35 contributions in international journals and conferences, respectively. The results will also be available through the web page, giving seminars to transfer knowledge and by the publication of doctoral theses. Direct promotion of the project will be performed: 1) by internal diffusion within the companies involved, 2) through the contacts the groups have with other centers.

Exploitation of the results: This is a fundamental pillar. The team is experienced in R&D related to technology transfer and several companies are interested in the results. The protection of results will be conducted, when appropriate, by the corresponding patents, considering the associated rights, if any, and the maintenance of rights intellectual property of the participating members. In the previous project the UAL group performed a patent on a combined heating and carbon enrichment from biomass combustion. Potential results of this project to be patented or transferred to industry are: new technologies for solar desalination plants, scalable model for energy and water management in industrial clusters, new control system for energy-based climate control in greenhouse, new control system of an autonomous electrical vehicle.

C.4. CAPACIDAD FORMATIVA DEL EQUIPO SOLICITANTE / TRAINING CAPACITY

Subproject 1 will ask for FPI fellow grants ("Contratos predoctorales para la formación de doctores"). The applicant group has 8 doctors, 4 doctors in the research team (3.5 EDPs) and 4 in the working team. They teach in two master programs at UAL. The project leader, Manuel Berenguel, is actually responsible of the Doctorate Program in Informatics (RD99/11) of UAL, adaptation of a previous one with Mention of Excellence. He also belongs to the Steering Committee of the International Doctoral School of UAL (EIDUAL). He has directed or codirected 14 Ph. D. theses. Francisco Rodríguez has been coordinator of the inter-departmental Master on Industrial Computing (2010-2012), while

Manuel Berenguel was coordinator of the Master on Advanced Computing Techniques during the biennium 2002-2004. Both masters actually have been merged into the Master in Advanced and Industrial Computing, providing access to the mentioned Doctorate Program. The two groups have also supported the Master on Solar Energy at UAL. The UAL group is able to supervise at least 2 Ph. D. theses related to this project. Most project members belong to the research group "Automatic Control, Robotics and Mechatronics" TEP-197 of the Andalusian R&D Plan, which has been within the 2nd-3rd absolute position in score and funding at UAL (1st in Production Technologies) and around 8th of 105 groups in Production Technologies in Andalusia during the last years.

The training plan for the FPI fellows will be the following:

1. Completing the Master on Advanced and Industrial Computing of the University of Almería.
2. Completing the Doctorate Programme on Informatics of the University of Almería.
3. Stays at prestigious foreign research centers. The stays performed during the last years have been:
   - Prof. Tore Hägglund, Lund University (Sweden): 3-months stay of fellow A. Pawlowski (2011).
   - Prof. Julio Normey, Federal University of Santa Catarina (UFSC, Brazil): 6-months stay of fellows J.D. Álvarez (2011), M. Castilla (2011), A. Castro (2011), C. Rodríguez (2012).
   - Prof. Daniel Pagano, UFSC (Brazil): 6-months stay of fellow I. Fernández (2012).
   - Profs. Manfred Morari and Roy Smith, ETH Zurich (Switzerland): 3-months stay of fellow M. Castilla (2012).
   - Prof. Roland Siegwart, ETH Zurich (Switzerland): 3-months stay of fellow R. González (2010), who is actually a postdoc fellow at MIT under the supervision of Prof. Karl Iagnemm.
   - Prof. Javier Cuadrado, Universidad de La Coruña (Spain): 1-month stay of fellows J.L. Blanco (2013) and J.L. Torres (2013).

The group also attracts researchers from other countries, that have performed one year stays at UAL (M. Americano, H. Scherer, G. Andrade, from UFSC, Brazil, M. Beschi, from U. Brescia, Italy and M. Bellone, U. Salento, Italy) and even the full Ph. D. thesis with our group (R. Silva from Portugal, A. Pawlowski from Poland and A. Ramírez from México). The group also receives researchers through the UE Sfera 2 programme (http://sfera2.sollab.eu/access, D. Gorni from U. Brescia on 2014). Several members of the group are coordinators of Erasmus and Leonardo Programs at UAL. During the last ten years, 21 Ph. D. theses have been defended and directed by members of the group (17 of them in the scope of the project), having established collaborations with renowned researchers (some of them participating in the Doctorate Programme), like Profs. Karl J. Aström and Tore Hägglund from the Lund Institute of Technology (Sweden), Robin de Keyser from U. Gent (Belgium), Daniel Rivera of the Arizona State University (USA), Joao Lemos from the Higher Technical Institute of Lisbon (Portugal), Antonio Visioli from U. Brescia (Italy), Ryszard Klempous from the Wroclaw Polytechnic University (Poland), Antonio Ruano from U. Algarve (Portugal) and Julio Normey from the UFSC (Brazil), who is participating in the working group in this proposal. From Spain, Eduardo F. Camacho (U. Seville), Sebastián Dormido (UNED) and Carlos Balaguer (U. Carlos III de Madrid). Moreover, some of the members of this proposal (M. Berenguel, F. Rodríguez) have participated as teachers in "quality mention" doctorate programs: Computer Science and Automatic Control of UNED, Automatic Control, Telematics and Robotics of the University of Seville and Automatic Control, Robotics and Industrial Computing of the Polytechnic University of Valencia.

Ph. D. thesis during the last 10 years in subproject 1:

1. Torres, J.L. Análisis multidominio de vehículos eléctricos. *Cum laude*. Advisors: A. Giménez, J.L. Blanco. Univ. Almería, Spain, 28/07/2014.
2. Silva, R. Modeling and optimization of parabolic trough solar plants for industrial applications. *Cum laude*. Advisors: M. Pérez, M. Berenguel. Univ. of Almería, Spain, 14/07/2014.
3. Fernández, I. Modelling and control strategies for the microalgal production in industrial photobioreactors. International Ph. D. Thesis. *Cum laude*. Advisors: M. Berenguel, J.L. Guzmán. Univ. Almería, Spain, 16/06/2014.
4. Rodríguez, C. Advanced control strategies for efficient disturbance compensation. International Ph. D. Thesis. *Cum laude*. Advisors: J.L. Guzmán, M. Berenguel. Univ. Almería, Spain, 16/06/2014.
5. López, J. Modelado dinámico del impacto hombre-robot. Aplicación al diseño de actuadores de rigidez variable para robots de servicio. *Cum laude*. Advisors: A. Giménez, D. García-Vallejo, A. Jardón. Univ. Almería, 13/06/2014.
6. Beschi, M. Event-based and model-based control strategies with applications to solar energy systems. Thesis in international co-tutela. *Cum laude*. Advisors: A. Visioli, M. Berenguel. Università degli Studi di Brescia, Italy, 10/04/2014.

7. Hernández, D. Contribución al modelado termo-hidráulico de captadores solares cilindroparabólicos. *Cum laude*. Advisors: L. Valenzuela, M. Pérez. Univ. Almería, Spain, 24/04/2014.
8. Fernández, A. Optimización de herramientas para el diseño y evaluación de captadores solares cilindroparabólicos para el suministro de energía térmica a temperaturas inferiores a 250ºC. Aplicación al prototipo CAPSOL. *Cum laude*. Advisors: M. Pérez, E. Rojas, F. Manzano. Univ. Almería, 23/04/2013.
9. Castilla, M. Advanced comfort control techniques for energy efficient buildings. International Ph. D. Thesis. *Cum laude*. Advisors: F. Rodríguez, J.D. Álvarez. Univ. Almería, Spain, 10/10/2013.
10. Morales, L. Improvement of compacted soils by biotechnological tools. *Cum laude*. Advisors: E. Garzón, A. Giménez, E. Romero. University of Almería, Spain, 18/11/2013.
11. Pawlowski, A. Predictive control strategies for disturbance compensation. International Ph. D. Thesis. *Cum laude*. Advisors: J.L. Guzmán, M. Berenguel. Univ. Almería, Spain, 08/06/2012.
12. González, R. Contributions to modelling and control of mobile robots in off-road conditions. *Cum laude*. European Ph. D. Thesis. Advisors: F. Rodríguez, J.L. Guzmán. Univ. Almería, Spain, 2011.
13. Roca, L. Contribuciones al modelado y control de una planta de desalación solar. *Cum laude*. Advisors: M. Berenguel, L.J. Yebra. Univ. Almería, 2009.
14. Álvarez, J.D. Estrategias de control de intercambiadores de calor en plantas termosolares. *Cum laude*. Advisors: M. Berenguel, L.J. Yebra. Univ. Almería, 17/06/2008.
15. Martínez, C. Control jerárquico de la producción de energía mediante plantas de colectores solares distribuidos. *Cum laude*. Advisors: M. Berenguel, M.R. Arahal. Univ. Almería, 2007.
16. Valenzuela, L. Control automático de plantas de generación directa de vapor con colectores solares cilindro-parabólicos. *Cum laude*. Advisors: M. Berenguel, E.F. Camacho. Univ. Almería, 2007.
17. Guzmán, J.L. Interactive control system design. European Ph. D. *Cum laude*. Advisors: S. Dormido, M. Berenguel. Univ. Almería, 16/06/2006.
18. Jardón, A. Metodología de diseño de robots. Aplicación al robot ASIBOT. *Cum laude*. Advisors: A. Giménez, C. Balaguer. University Carlos III de Madrid, 03/11/2006.
19. Yebra, L.J. Modelado orientado a objetos de colectores solares con Modelica. *Cum laude*. Advisors: S. Dormido, M. Berenguel. UNED, 12/05/2006.
20. Jiménez, M.J. Determinación de propiedades térmicas de cerramientos constructivos mediante el uso de células de ensayo de intemperie. Aplicación del cálculo de incertidumbres a la optimización de los ensayos. *Cum laude*. Advisors: M. Pérez, R. Heras. Univ. Almería, Spain, 19/07/2005.
21. Ramírez, A. Control jerárquico multiobjetivo de crecimiento de cultivos bajo invernadero. *Cum laude*. Advisors: F. Rodríguez, M. Berenguel, D. Valera. University of Almería, 18/07/2005.
22. de Luis, F.J. Ganancias solares sobre soluciones constructivas horizontales con geometría compleja. *Cum laude*. Advisor: M. Pérez. Univ. Almería, Spain, 07/05/2004.

The scientific or professional development of the previous graduated doctors is the following: 1 and 9 have a Postdoc contract at the University of Almería; 2, 3, 4, 9 and 10 are applying for a Postdoc (Marie Sklodowska-Curie grant) while they have a bridge grant; 5 is working in a spin-off of the University of Almería; 6 works actually for Consiglio Nazionale delle Ricerche (CNR, Italy); 7, 8, 13, 16, 19 and 20 now belong to the staff of CIEMAT; 11 has a Postdoc grant at UNED; 12 has a Postdoc position in MIT (USA); 14 has a Ramón y Cajal grant; 15 works in the company Abengoa Solar; 17 is associate prof. (accredited to full prof.) at the University of Almería; 18 is associate prof. at the University Carlos III de Madrid; 21 is professor at Chapingo University (Mexico) and 22 works in a private company. All of them are still working in the scope of their Ph. D. theses.

It has been thus considered convenient to apply for two FPI fellows (research contracts) because there exist some research lines with great interest to develop a Ph. D. Thesis, related with the coordinated and hierarchical architecture for energy, water and CO_2 management and with the control of energy and autonomy in electric cars. In the case of being assigned, the new fellows would be located in one of the new Labs of the research group, having access to all the computing facilities, equipment and high technology related with the project. They would obtain and excellent experience in the collaboration with Fundación CAJAMAR- E.E. Las Palmerillas and with the CIEMAT-PSA, within the framework of the CIESOL Center (which actual Director is Dr. Manuel Pérez, one of the co-directors of this project) and of course the accomplishment of stays in other international centers of prestige would be stimulated, as has been done in the case of FPI scholarship holders in previous projects, already mentioned.