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SPACE AND ENERGY - AT THE SERVICE OF ENERGY ON EARTH

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Abstract

Following preparatory activities, ESA has proposed in 2012 a dedicated and structured approach for its activities in the field of space and energy. Space contributions to transformi the current terrestrial energy system into a more sustainable, ultimately carbon-neutral system are considered as much an imperative for a responsible public organisation with the capacity to do so as an attractive opportunity to widen the scope of the space sector and thus allow space industry to benefit from new markets for space technology and space-based applications and services.

Those contributions cover the whole range of energy, from identification of where renewable energy can be harvested best, to production, transport, distribution, efficiency, safety of operations, access. They include technology (spin-in, spin out as well as co-development), applications and services. Some of these contributions from the space sector are already taking place naturally. These show the much larger potential of a dedicated initiative towards this goal.

The present paper presents the updated activities, main milestones and mid-term planning for these activities, with a special focus on synergetic technology developments for space and terrestrial applications and on the identification of future needs not yet covered by the existing space systems.

Keywords: energy systems, sustainability, space and energy

1. INTRODUCTION

The space and energy sectors show several interesting commonalities and have shared some technology developments, though for most of the ‘space age’, the sectors evolved in relative independence. We refer to chapter 2 of a previous paper for a more in depth analysis of this situation [1].

ESA has proposed in 2012 a dedicated and structured approach for its activities in the field of space and energy [1]. Space contributions to supporting the transformation of the current terrestrial energy system into a more sustainable, ultimately carbon-neutral system are considered as much an imperative for a responsible public organisation with the capacity to do so as an attractive opportunity to widen the scope of the space sector and thus allow space industry to benefit from new markets for space technology and space-based applications and services.

In [1] we have analysed the two sectors and then presented some ESA activities in the field of ‘space & energy’. These were categorised to a) technologies, including

1. PV Technology and power management design
2. Energy storage
3. hydrogen production and storage
4. thermal control
5. robotics and remote control
6. life support and recycling technology
7. space weather effects
8. remote sensing instruments

b) institutional cooperation, and c) infrastructure and equipment for new services.

It concluded with a generic outlook on potential space contributions to a more sustainable 21st century energy system.

The present paper builds up on this work by providing information on the steps taken during 2012 and 2013 to identify the most promising technology R&D and programme areas. The description of the different technology areas with the associated analysis is intended to generate critical review and scholarly feedback.

2. SPACE & ENERGY INITIATIVE

Barrett [2] argues that emissions of CO_2 and other greenhouse gases can be reduced significantly using existing technologies, but stabilising concentrations will require nothing less than a technological revolution, because it will require fundamental change, achieved within a relatively short period of time.

Along the same lines and based on the insight of the International Energy Agency, Dordain [3] emphasises in “Agenda

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2015", the most recent strategy document for ESA, the importance of the energy sector and its potential for space:

> "According to the OECD, achieving global energy security, climate change and energy access goals will require nothing short of an energy revolution, implying major improvements in the full set of low-carbon energy technologies, as well as unprecedented intervention by governments in developing policies that work with and influence energy and consumer markets. In all energy scenarios, the world primary energy demand increases until 2025, mainly driven by developing countries, reflecting their faster rates of growth of economic activity, industrial production, population and urbanisation. Renewable energy sources (solar energy, wind etc.) will have to play a central role in moving the world onto a more secure, reliable and sustainable energy path, especially for electricity demand, which is expected to grow more strongly than any other final form of energy, however with fossil fuels still providing the majority of our energy. Around 2025 the energy question is expected to remain also a source of major tension (economic and geopolitical)". [3]

At least for what concerns technologies, the energy sector is unlikely to seek potential space solutions of its own initiative. Applications might be better known in the energy sector but still a lot more can be done for an efficient and wide use of space programmes and data. The two sectors have too few traditional links and connections. It is therefore necessary for the space sector to take the first steps. First promising applications and technologies are most likely small niche applications for the energy sector but at the same time potentially large for the much smaller space sector.

ESA has therefore started in 2012 a new initiative targeting specifically the energy sector. This initiative builds upon recent and ongoing activities performed across ESA since many years. A first step, initiated in 2008, consisted of an analysis of those activities, leading to the internal coordination of those efforts.[4] This further allowed to increase their visibility outside and, through their coordination, the formulation of new, more ambitious overall goals.

ESA has been contributing since years to the energy sector in various domains, mainly via its General Studies programme [5, 6], the Earth Observation programmes [7] and Integrated Applications programmes [8], but also with activities in the Human Spaceflight [9] and Technology directorates [10]. The ongoing activities have established initial working links with the European Commission on the topic [4]. Even before, already several projects were funded by the European Commission. [9].

2.1. Objectives

So far, activities were mostly targeting the development of applications based on existing means. The objective of the new cross-cutting initiative is to develop or spin-in the necessary technologies and identify infrastructure and equipment that would be needed to expand further the support of the space sector to the energy sector.

This initiative is made of two components

1. "Space and energy technologies", exploiting the technological synergies between the two sectors;
2. "Infrastructures and equipment for new services", corresponding to a dedicated energy-related space programme, which involves specific and new space infrastructures.

2.2. Structure and Method

Unlike traditional ESA projects, the potentially wide range of different competences, technologies and service applications concerned, the initiative required a flexible, interdirectorate structure that allows drawing relevant resources and expertise on a per-need basis. Similarly, the diversity of projects also requires benefitting from the flexibility offered by the diverse ESA funding and programme schemes. The main challenge therefore lies in putting these into a frame that allows to benefit from this flexibility while also providing the added value of creating a critical mass and cross-fertilisation among the different activities.

These activities include internal and external studies and research work in order to:

- analyse and perform research on future trends in energy matters and energy from space.
- identify the policies and regulations existing that concern the energy sector and where space programmes can help.
- perform a survey of existing and planned applications and services (involving both space and terrestrial solutions) that help or will help address those policies and regulations e.g. monitoring systems, detectors, infrastructure etc.
- identify user requirements in consultation with stakeholders (Member States, local and regional authorities, space and non-space industries, operators) to better understand the needs, inform on the potentialities of space programmes and define priorities.
- identify the elements that are not yet supported by a space programme or application
- perform internal or industrial feasibility studies for potential programmes or application.
- prepare a coherent programme proposal (or elements within programmes) for the ESA Council at Ministerial level.

These activities are performed in coordination and with the support of the Directorates at ESA potentially concerned. The initiative thus also puts an emphasis on the involvement of participants from all Member States, taking benefits of the wide range of energy-related competences available across ESA Member States.

2.3. Goal

The goal is to identify by 2015 if such a programme is technically and financially viable for a short/medium term implementation and to develop the key technologies to enable the new services. These could be:

1. Space means supporting energy-related regulations; e.g. in support of energy efficiency management, independent verification of energy related regulations (international/legal) agreements; space-based tools might include high-resolution thermal infrared instruments for energy demand and efficiency observation.
2. Space means supporting the currently developed renewable energy infrastructure, including energy grids, increased efficiency and safety of infrastructure, building upon activities performed within GSP, EOP and TIA (IAP) on this topic.
3. Space in support and complement of terrestrial very large-scale solar power infrastructure (of the Desertec type). Ambitious terrestrial solar power plant activities in the EUMENA region were proposed a few years ago with the first plants now being built. Space contributions are already made on an ad-hoc basis e.g. for plant siting, solar irradiation measurements. Many more substantial contributions can be elaborated in the area of wind and hydro-electric power generation.

3. SPACE & ENERGY TECHNOLOGY ROADMAPS

A public workshop on the "Space & Energy Technology" initiative was organised at ESA/ESTEC to present the relevant ESA technology roadmaps to interested industry and academia. The goal of this meeting was to provide an overview of current space activities, get feedback, encourage discussion and obtain valuable recommendations. The outcome of this meeting subsequently marked the start of the next phase in early 2013. In this phase, an industrial activity was initiated aimed at identifying adaptations to the technology R&D roadmaps.

By analysing these roadmaps from a terrestrial energy point-of-view, new opportunities could be identified. These opportunities would potentially benefit not only the space industry by supporting terrestrial applications with space technology, but also allow the development of new synergies between terrestrial and space applications. The remainder of this section outlines the approach taken during this activity, followed by the preliminary results in each of the considered domains.

The study is structured into two main phases. The first phase compares the current ESA technology roadmaps with possible relevant terrestrial energy roadmaps in various domains to identify any areas of common interests. These are subsequently analysed against a set of criteria in order to downselect the most promising technologies. Some of the criteria considered are,

- technical differences and commonalities,
- current and planned R&D budgets,
- development times,
- application domains.

The first phase ends with a classification of all the technologies in each of the common technology areas. From this list, a subselection is then made to form the basis of an in-depth analysis to be performed in the second phase. These technologies are then studied in detail on how the technology developments fit within both the terrestrial and space R&D programs. In addition, the most relevant key actors in the selected technology sectors are identified. Finally, extensive in-depth technical discussions between the key actors in the terrestrial and space sectors elaborate on the improvements and modifications to the existing roadmaps.

The following sections focus on the preliminary results of the above investigation on each of the technology domains. A downselection was made after the first phase with five of the domains proceeding to the second phase. The domains considered are: hydrogen production & storage, thermal control, life support & recycling, robotics & remote control and space weather. The remaining domains were not considered as they are already covered by other programmes within ESA.

3.1. Hydrogen production & storage

Major current use of commercially produced hydrogen can be found in the oil refining, food production, material treatment, fertiliser production and various other industria. However, there is a growing use of hydrogen for electricity production and/or energy storage. Within the space industry, hydrogen is widely used for propulsion purposes and has developed to a mature technology state. Current space research is focused on the production and storage of hydrogen. Hydrogen storage is therefore considered as one of the technologies of interest for synergetic development in both markets. In this field, the study has identified two areas of particular interest; liquid and slush hydrogen (see also table 1).

Liquid hydrogen storage tanks offer an advantage over compressed hydrogen due to the higher mass density, allowing smaller volumetric containers. However, the cooling and compression requirements result in a net loss of about 30% of the stored energy. Storage tanks for space applications are designed for short operating times (minutes) and fueled once. One of the major challenges is minimizing the weight of the required insulation and reinforcement structure. Due to the short operating time, boil-off losses are less of an issue in space applications. However, to achieve long-term storage for terrestrial applications, it is essential to reduce boil-off effects as losses can consume up to 40% of the available energy. Due to these boil-off effects, the most likely terrestrial application in the near-term is the development of large-scale storage (> 20000m^3) while further efficiency improvements will be required to develop liquid hydrogen as a fuel in transport application.

Slush hydrogen is a mixture of liquid and frozen hydrogen in equilibium at the triple point (13.8K). The mass density is thus

Table 1: Table of considered technology domains and activities

Technology domain	Technology	Space R&D	Terrestrial R&D
Hydrogen production & storage	Liquid	Light-weight materials	Boil-off Light-weight materials
	Slush	Thermal insulation Thermal control Boil-off capture & liquification	Slush-LNG
Robotics & remote control	Decommissioning	Operations in remote, complex & hazardous spaces	Teleoperation Navigation Robotic manipulation haptic rendering
	ROV	Autonomy Light-weight Flexibility	Vision systems Human-robot interaction Cooperative systems Confined & complex spaces
Thermal control	Heatpipes (LHP/HP)	Weight-reduction Reliability & Safety	Cost-reduction High temperature
	Aerogel	Material properties	Mass-production Environmental costs Mechanical properties
Life support & recycling	Volatile fatty acids	-	Membrane technology
	algae based biofuels	Microbial fuel cells Weight reduction	Test-bed facilities Life cycle analysis Temperature control
Space weather effects	Magnetic measurements	Earth obervation Climate models Protection	Surge protection
	Ground conductivity		Grid safety
	GIC monitors		Powerline transmission Pipeline corresion
	Forecasting & Models		Prediction

higher than liquid hydrogen, thereby allowing for a more compact tank design which further reduces the mass of major stage components. Furthermore, there is the advantage that varying the solid mass fraction in the tank can be used to counter heat leaks without the need for venting. This is of particular interest to the automotive and aeronautical industry. In addition, slush technology could also be used to produce slush-LNG with the added benefit of enhanced (cryogen) density and avoiding the boil-off of methan greenhouse gases. Current research activities are focused on achieving high quality insulation, precise temperature control and capture and reliquification of boil-off gases.

3.2. Thermal control

Heat pipes (HP) are extensive used in spacecraft to control internal temperature conditions which are required for optimal operation. The space industry has developed over the years various types of HP for a large variery of instruments. In particular, the effort has focused on weight reduction, but also on improving thermal management for safe and efficient operation. Both HP and loop HP (LHP) devices are passive thermal control devices, requiring no external power supply. LHP are more tolerant to non-condensable gases and their main advantage is that they operate gravity independent. This is both a major benefit in space as well as in terrestrial systems for use in adverse elevation situations.

The development of solar dynamic systems, e.g. concentrated solar power (CSP), is a technology area expected to benefit from the development of HP/LHP. In this application, high temperature loop heat pipes can provide efficient means to transport the heat from the concentrator to the conversion engine. Current LHP however operate at a relatively low temperature range and high temperature cycles requires the use liquid metals as working fluid. Further research should aim at increasing the operating temperature and reduce costs, which currently are about two orders of magnitude higher than conventional mass produced HP.

Finally, the development of smaller scale HP, which could be integrated into fuel cells and batteries, is of interest as these systems already have very similar characteristics to what is used in current space counterparts.

A second technology of interest in the field of thermal management is the use of advanced materials like aerogel as insulation materials. Aerogels have been used in space applications to provide insulation of space suits and cryogenic tanks due to the superior thermal properties compared to existing materials. An additional advantage is that the use of aerogel beads does not restrict mechanical movement of parts. Although research is required to further improve some material properties, like mechanical stress, the extreme light weight makes them ideal materials for space applications. In the terrestrial industry however, the high manufacturing costs limit the application to a few niche markets (building insulation, biomedical, luxury sport goods). The research efforts are therefore mainly focused on improving both the economic and environmental costs.

3.3. Robotics & remote control

An earlier study performed in the context of the ESA Technology Transfer Program (TTP) [11] has identified future opportunities in the synergies between automation and robotics in the space and oil&gas industry. In this study, this field has been extended to also include decommisioning activities which are applicable to both the oil&gas industry as well as the nuclear industry. In this area, the advantage of enhanced remote operations is expected not only to be beneficial in an economical sense, but also by the extended capabilities in order to provide improved safety for the workers involved.

The markets for remote inspection in both the nuclear and oil&gas industry are expected to show an increase in activity in the upcoming years driven by a growing investment in offshore and powerplant decommisioning services. In many cases these installations will contain unknown challenges. It will therefore become even more critical to improve the maturity of technology to provide accurate assessment and monitoring in order to provide timely action when needed. This requires enhanced robotic and autonomy capabilities. Especially in the area of nuclear decommisioning in which robotic devices may not be retrievable once deployed, robotic experiences from space exploration could provide valuable insights into developing such new capabilities. Of particular interest for example would be the capability of exploring complex spaces, to perform remote handling operations in confined and possibly hazardous spaces. Furthermore, research fields of common interest in the development of space and terrestrial applications are,

- Enhanced human capabilities using robotics
- Vision systems and real-time inspection
- Autonomous 3D sensing and interpretation
- Cooperative and distributed planning
- Haptic telemodeling
- Navigation and accurate area assessment

3.4. Life support & recycling

Advanced recycling technology is increasingly becoming more attractive in both the terrestrial and space industry to reduce the footprint on the mass, volume and energy consumption. This study has identified two technologies of interest; volatile fatty acid product

Among many other uses, volatile fatty acids (VFA) have been attracting great attention in recent years as potential candidates for the fabrication of biodegradable polymers in plastics production. These plastics could directly replace counterparts derived from petrochemical processing. Key research is focused on the separation processes using membranes (e.g. nanofiltration). The main disadvantage of current membrane systems is the required frequent cleaning due to fouling, placing a higher requirement on pre-processing.

The potential advantages of algae-based biofuels over other biofuel pathways include higher biomass yield per area, use of a wide variety of water sources, the opportunity to reuse carbon dioxide and the potential to relatively easily replace existing fuels in todays infrastructure. Potential drawbacks include the anticipated cost of production [12]. However, the experience gained in space in the development of microbial processes in fuel cells can support the development of biofuel production. Photo-bioreactors for high cell density raises however several challenges such as light energy transfer, bio-compatible materials and hydrodynamics. In addition, detailed modeling is performed to better understand and ultimately control the processes involved. In the case of space applications, this modelling has so far focused on mass aspects. For terrestrial applications, aspects related to temperature control and life cycle analysis are of particular interest in order to increase the efficiency and, possibly more importantly, the scale of production.

3.5. Space weather effects

Time variation of the Earth magnetic field can have possibly catastrophic effects on the global electrical and communication infrastructure. Such large-scale disturbances are induced by the interaction between the Earth magnetic field with geomagnetic storms originating from extreme solar activity. In particular, electric power systems are vulnerable due to geomagnetically induced currents (GIC's) that are easily picked up by transmission grids causing voltage regulation problems, overheating and in extreme cases permanent damage. As the terrestrial grid becomes more interconnected, especially with the growth of distributed renewable energy sources, the impact of space weather induced effects increases. Furthemore, ionospheric fluctuations can also have an impact on the operation of earth and space systems which rely on GPS/GLONASS signals (eg magnetic surveying and directional drilling activities).

The main research activities in this area are focused on improving forecasting models and obtaining more accurate measurements of space weather induced effects.

The ultimate goal is to provide real-time forecasting of GIC's using accurate real-time measurements of geomagnetic activity and solar wind in combination with earth observation. The terrestrial industry is improving and expanding the network of sensors to monitor critical grid infrastructure on the presence of GIC's and develop new control techniques to counteract its effect.

4. EARTH OBSERVATION AND ENERGY

In addition to the synergies mentioned above, Earth Observation applications are a major sector of interaction between the two domains [13]. ESA is involved both in developing current applications using existing infrastructure, and also in considering future EO missions and techniques in support of the energy sector.

4.1. Current applications

ESA via its ESRIN centre is already heavily involved in supporting the energy generation industry. For the last 15 years support has been provided to go from R&D efforts towards more and more industrial and operational applications [13]. As an overview the following applications are currently being exploited:

Renewable Energy Resources assessment (Solar, Wind, Snow),

On-Shore Operations Seismic Quality Mapping and Precision Land Motion

Off-Shore Operations Wind/wave/tide/current climatologies, SAR based Bathymetry Mapping, Iceberg detection and tracking, Sea ice analysis

Environmental Impact Land (Oil Sands - Shell), Marine (Gulf of Mexico - BP)

Sustainable Development Reporting Population dynamics in line with Global Reporting Initiative, (GRI) guidelines (Dam construction, Brazil - Suez)

More and more of these applications are integrated into GIS where data from space seamlessly integrates in other data sets. For instance, the figure below shows a composite assessment of site suitability for renewable power plants using both terrestrial and remote sensing data for insolation and wind profiles.

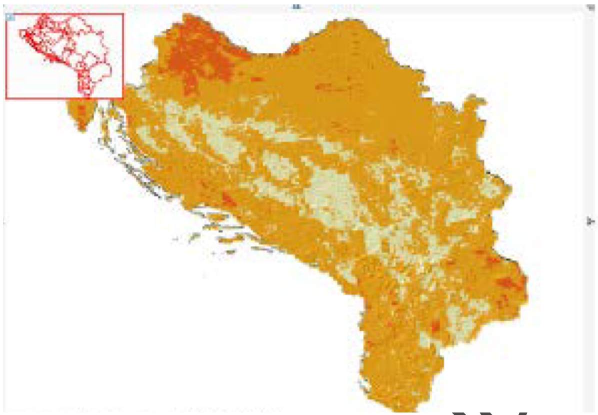

Figure 1: Composite Assessment of site suitability for Renewable power plants, based on a multi-parameter GIS including terrestrial (population . . .) and remote sensing data (Insolation, wind level) - Test site in the West Balkans. From [13]

In general the oil & gas industries are very well advanced in the use of remote sensing data, with renewables progressing in their use of it, in terms of exploring resource location and site suitability. Further applications in the short term will extend these and related in particular to environmental damage assessment, such as detection of flaring in platforms, assessment of land changes on shale oil extraction sites, or suitability assessment of Carbon Capture and Storage underground sites.

4.2. Future EO missions and applications for Energy

Beyond the short-term developments of further applications to existing data sources, ESA is exploring the potential of future missions. Activities are on-going in this area. Their aim is first, to explore what short-term and medium-term activities can be developed in addition to the existing ones that will specifically benefit energy. In particular, an interesting finding of this will be to find out which new applications will be enabled by the advent of the Sentinel satellites as part of the GMES Space component.

Looking further, the ongoing activities will also consider novel observation and mission concepts to explore dedicated EO missions. Ideally new concepts for which a strong user case is made in terms of interest, technical and programmatic feasibility may be proposed for further study and eventual implementation. Several ideas are being considered across the energy sector, i.e. not only generation but also energy users and energy transport and storage. For instance, a potential application to be considered would be systematic monitoring in the thermal infrared wavelength of all urban areas in Europe to address issues of energy efficiencies of building, which could come in complement or in replacement of partial and irregular aerial surveys. Fig. 2 shows a potential result of such a mission.

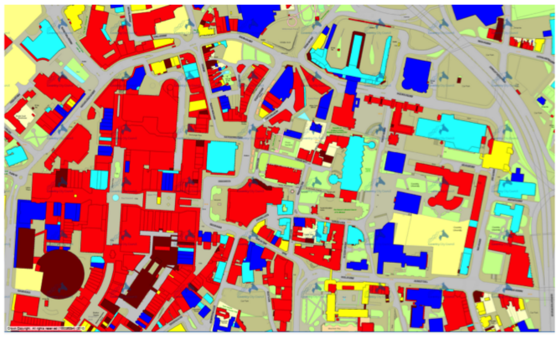

Figure 2: Illustration of potential assessment of thermal characteristics of buildings as could be obtained from remote sensing in the infrared.

With this and other activities ESA expects it will both improve the development of current activities and provide interesting concepts for new ones.

5. OTHER SPACE & ENERGY RELATED ACTIVITIES

5.1. Opportunities for satcom actors

A study will start in late 2013 on the ‘Identification of opportunities for satcom actors in a low-carbon society’.

It is recognised that the following emerging technologies and markets show a significant potential in the satellite communication sector in particular:

Smart grids the SET-plan forecasts that the evolution towards smart grids will require a more integrated usage of communication systems. Satellite connectivity presents a cost-effective solution for utility companies to establish connectivity in remote geographies, becoming even more attractive considering the expected massive deployment of small scale power plants.

Renewable energies in particular

1. Wind power: the trend to increase the number of offshore wind parks and the distance from the shore makes impractical and expensive fibre optic utilisation
2. Concentrating solar power: the DESERTEC Concept [14] envisages clean power generation in the deserts and will have specific communication/control needs.

The aim of this study will be to explore the opportunities that will open-up for space actors following the on-going changes in the energy sector with a particular focus on the down-stream space applications segment, provide a cost-benefit assessment and a competitive analysis, and define for each opportunity the requirements of the main users/customers and suitable system concepts/architectures.

The key energy domains which are already using or may benefit from exploiting satellite based communication systems and space based applications include smart grids, wind energy and solar energy power.

The detailed objectives of this activity are the following:

1. to identify the key opportunities for the space industry that may arise from on-going and planned energy initiatives/projects1 in the next five years;
2. to identify the key requirements associated to the services and infrastructure planned in the above identified energy initiatives/projects, assess which requirements may be met by satellite communication solutions and / or space based applications;
3. to perform a cost/benefit analysis to position the above identified satellite communication solutions and / or space based applications against competitor space and non-space solutions;
4. to define the overall architecture for the most promising satellite communication solutions and space based applications, together with their required developments (if any), and propose a roadmap for their implementation and commercial roll-out.

5.2. Call for ideas within the GSTP technology synergies initiative

Within the overall *Space & Energy* initiative, the General Support Technology Programme (GSTP) has initiated in 2011 a dedicated theme on energy in its Terrestrial and Space Technology Synergy activities. In January 2013, the second call for proposals for studies was released with a volume of €1M, and a per-study cap of €100k.

The purpose of the GSTP "Terrestrial and Space Technology Synergy Initiative" in general is a better exploitation of the convergences between terrestrial and space technology needs and the development of the synergies between terrestrial cutting-edge technologies and ESA space enabling technologies. For most high-technology, R&T intensive sectors, the overall trend displays increasing R&T financial needs, whereas resources, especially public funding, become scarcer. One of the main challenges for R&T programmes, including in the case of the space sector, is their affordability and sustainability in the long run. The intended synergies (or common R&T) promise to be beneficial both in terms of reduced technology R&T funding as well as innovation and technology cross-fertilisation.

The call specifically targets the industries of these two sectors, which are different and have little tradition of working together. They do not share an industrial base as is largely the case between space and aeronautics, although sharing sometimes identical technologies (e.g. photovoltaics). In some domains, the Energy sector drives technology advances faster than the space sector. This makes such technologies attractive for spin-in, for their performance and also for programmatic considerations. In such cases, the basic research and technology (R&T) is already achieved, resulting products benefit from economies of scale and support in the partner sector contributes to assure the supply chain for space as well. On the other side, the demanding requirements of space missions, e.g. extreme environment, high autonomy, zero maintenance, resources limitations and so on make of space in many areas a lead user, a source of spin-offs and a partner of choice for joint R&T with terrestrial sectors, in particular the Energy sector.

For the purpose of this initiative, the energy industrial cycle was divided in three overarching phases

1. Exploration (i.e. remote sensing, detection),
2. Exploitation/production/maintenance (harsh environment, robotics, remote control, safety, fault detection and correction) and transport,
3. Utilisation at industrial and household levels, distribution.

6. CONCLUSIONS

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