**EU 7th Framework Programme**

Theme: (NMP.2013.4.0-5)

Deployment of societally beneficial nano and/or

materials technologies in ICP countries.

Coordination and Support Action

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| **NMP-DeLA**  **Nanosciences, Nanotechnologies, Materials and**  **New Production Technologies**  **Deployment in Latin American Countries**  FP7-NMP-2013-CSA-7 |

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| **Deliverable D2.6: Roadmap and recommendations for deployment: Focus on nanotechnologies for energy** |



The work leading to these results receives funding from the European Community's

Seventh Framework Programme (FP7/2007-2013) under Grant Agreement n°608740

|  |  |
| --- | --- |
| Work Package: | WP2 Mapping, Strategy Development And Recommendations |
| Task number: | T2.2 |
| Lead beneficiary: | VTT |
| Delivery date: | M24 |
| Version: | M24 |
| Submitted by: | Maria Lima-Toivanen |

|  |  |
| --- | --- |
| **Document Control Page** | |
| **Deliverable Title** | Roadmap and recommendations for deployment of nanotechnologies and nanomaterials for energy in Latin America |
| **Author** (writer/editor and short name of the participant | Luís Carlos Pérez Martínez, VTT |
| **Short Description** (e.g. abstract, summary, table of contents, free text etc.) | This report refers to the roadmap and recommendations for deployment of nanotechnologies and nanomaterials in the field of sustainable energy in Latin American countries. |
| **Publisher** (e.g. journal publisher or the consortium) | N/A |
| **Contributors** (co-authors with participant short name) | Maria Lima-Toivanen, VTT  Martina Lindofer, ZSI  Ineke Malsch, MTV  Heidi Auvinen |
| **Nature** (peer-reviewed article, technical report, table, prototype, demonstrator, etc.) | Technical report |
| **Format** (e.g. MS Word 2003, PDF etc.) | PDF |
| **Language** | English |
| **Creation date** | 2015 |
| **Version number** | 1 |
| **Version date** | August 2015 |
| **Last modified by** (person and organisation name) | Maria Lima-Toivanen, VTT |
| **Rights** (e.g.IPR, copyright, such as copyright “NMP-DeLA consortium”) | Copyright @ NMP-DeLA 2013 |
| **Dissemination level** | PU Public  PP Restricted to other programme participants (including the Commission Services)  RE Restricted to a group specified by the consortium (including the Commission Services)  ⌧ CO Confidential, only for members of the consortium (including the Commission Services) |
| **Review status** | Where applicable:  ⌧ Draft  WP leader accepted  Coordinator accepted  Accepted for publication  Date of publication |
| **Action requested** | to be revised by Partners involved in the preparation of the document  to be revised by all NMP-DeLA partners  for approval by the WP leader  for approval by the IPC  ⌧for approval by the Project Coordinator |
| **Requested deadline**  (dd/mm/yyyy) | 28/08/2015 |

|  |  |  |  |
| --- | --- | --- | --- |
| **Revision history** | | | |
| **Version** | **Date** | **Modified by** | **Comments** |
| V0 | 05-11-2014 | Luis Perez, Maria Lima-Toivanen | First draft of the report |
| V0.1 | 07-11-2014 | Luis Perez | Addition to literature review |
| V0.2 | 14-11-2014 | Luis Perez | Addition to literature review |
| V2 | 06-05-2015 | Luis Perez, Maria Lima-Toivanen, Ineke Malsch, Martina Lindorfer | Included results of focus-group and interviews from Workshops in Monterrey (November 2014) and Santiago (December 2014). |
| V3 | 20-05-2015 | Maria Lima-Toivanen, Luis Perez | Version for presentation in workshop in Curitiba (28-29 May 2015) |
| V4 | 25-05-2015 | Maria Lima-Toivanen, Luis Perez | Update literature review |
| V5 | 25-08-2015 | Maria Lima-Toivanen, Heidi Auvinen, Luis Perez | Final draft for review |
| V6 | 28-08-2015 | Mark Morrison, Maria Lima-Toivanen, Martina Lindorfer | Timeline added, reviewer’s comments and cor-rections to the whole text incorporated. |

Notes:

* Include a comment to all version of the document.
* The initial version must be “v0” and minor changes should be registered as “v0.1, v0.2…”. Major changes should be registered as “v1.0, v2.0…”

**Acknowledgement**

The authors gratefully acknowledge comments and suggestions by reviewer Mark Morrison on the pre-final version of this document. The quality of the contents and analysis remains the sole responsibility of the authors.

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# Abbreviations and acronyms

**Partner Acronyms:**

ASCAMM Fundaciò Privada ASCAMM, Spain

REDINN Rete Europea dell’Innovazione, Italy

ION Institute of Nanotechnology, UK

MTV Malsch TechnoValuation, Netherlands

ZSI Zentrum für Soziale Innovation, Austria

VTT Technology Research Centre of Finland, Finland

RELANS Latin American Nanotechnology and Society Network, Brazil

MINCyT The Ministry of Science, Technology and Productive Innovation, Argentina

CIMAV-CONACYT Centro de Investigación en Materiales Avanzados, S.C, Mexico

MEC Ministry of Education and Culture, Uruguay

EUROCHILE Eurochile Business Foundation, Chile

**Abbreviations and acronyms used in this report**

ANSOLE The African Network for Solar Energy

BRICS Brazil, Russia, India, China and South Africa

CBD Chemical bath deposition

CdTe Cadmium telluride

CELAC Community of Latin American and the Caribbean States

CF Carbon felt

CIGS Copper Indium Gallium Selenide Solar Cell

CIMAV The Center for Research on Advanced Materials

CNEN Comissão Nacional Energia Nuclear

CNF/CNT Carbon nanofibre/nanotube

CNPq The Brazilian National Council for Scientific and Technological Development

CoI Community of Interest

CONACYT The Mexican National Council of Science and Technology

CSIC The Spanish National Research Council

CZTSe Copper zinc tin selenide

CZTSSe Sulfur-selenium alloy

DOD Depth of discharge

DSSC Dye-sensitized solar cells

ECN The energy research centre

EPIA European Photovoltaic Industry Association

FINEP Funder for Studies and Projects

FTO Fluorine-doped tin oxide

IEA International Energy Agency

INCT Brazilian National Institutes of Science and Technology

IPICYT Instituto Potosino de Investigación Científica y Tecnológica

IPT Instituto de Pesquisas Tecnológicas do Estado de Sao Paulo

ITO Indium-tin oxide

JIRI Joint Initiative for Research and Innovation

LA Latin America

LAC Latin America and the Caribbean

Li-ion Lithium-ion Batteries

MCTI Ministry of Science, Technology and Innovation

MJSC Multijunction solar cells

MJSC Multi-junction solar cells

MOF Metal organic framework

NANO-CETENE The Nano-network at the North-East Centre for Strategic Technologies

NanoNextNL The Dutch national nanotechnology programme

NGO Non-governmental organization

NMP Nanosciences, Nanotechnologies, Materials & New Production Technologies

OSC Organic solar cells

PC Photocatalytic

PE Photoelectrochemical

PEMFC Polymer Electrolyte Membrane Fuel Cells

PET Deposited on polyethylene terephthalate

Photo H2 Photocatalytic and photoelectrochemical hydrogen production

PV Photovoltaic

QDSC Quantum dot solar cells

R&D Research and Development

R&D&I Research & Development & Innovation

RFB Redox Flow Batteries

RFBs Redox flow batteries

SCAP Supercapacitors

SENER The Mexican Energy Secretariat

SH2 Solid Hydrogen Storage

SILAR Successive ionic layer adsorption

SOFC Solid Oxide Fuel Cells

SSC Silicon solar cells

STI Science, Technology and Innovation

TCO Transparent Conductive Oxide

TFSC Thin film solar cells

UdelaR University of the Republic

UN MDGs United Nation’s Millennium Development Goals

UNESP University of the State of São Paulo

UNICAMP Universidade Estadual Campinas

USP Universidade de Sao Paulo

YSZ Yttria stabilized zirconia

# Summary

This roadmap shows a way forward for initiatives that stimulate research, development and innovation of nanotechnologies and nanomaterials in Latin America in the field of sustainable energy. It was developed in the context of the project NMP-DeLA (Nanosciences, Nanotechnologies, Materials and New Production Technologies Deployment in Latin American Countries), funded by the European Union. The main objective of the NMP-DeLA project was to develop a series of activities between European and Latin American countries, to strengthen the local research and training potential as a way of facilitating the deployment of nano and advanced materials technologies in areas of major societal challenge in LA: energy, water and health.

This roadmap is addressed to main stakeholders, such as policy-makers, researchers, academics and industrial experts in Latin America and in Europe. It aims to provide information that will help these key stakeholders to utilize opportunities and overcome gaps for the deployment of nanotechnologies for sustainable energy in Latin America.

The report is structured as follows: introduction, methodology, applications of nanotechnologies for the production of sustainable energies, the landscape in terms of research, research groups, research collaboration and policy and funding for nanotechnologies in Latin America, recommendations for deployment, and conclusions.

The main recommendations of this roadmap in the short and medium-term are to focus on the acceleration of research, building up of strategic support for synergetic efforts, building up of a stakeholder support system around the innovations in nanotechnologies for energy, and maintaining focus on local and regional aspects regarding the needs and advantages for the development and production of sustainable energy by deploying nanotechnologies.

# 4. Introduction

The ongoing global discussion on energy matters revolves around the “energy trilemma” of energy security, energy equity and environmental sustainability (WEC 2013). Energy security, which is related to its long-term supply and reliability, is of utmost importance for economic growth; energy equity, which is related to its accessibility and affordability, is of utmost importance for social development; environmental sustainability, which is related to the use of low-carbon energy sources, is of utmost importance to combat climate change (Tol 2013) and preserve public health by reducing greenhouse gas emissions (Haines et al 2009).

The geopolitical complexity and the dependence on fossil fuels are two of the key issues in the energy trilemma. The current system relies on supplying fossil fuels (oil, coal and natural gas) from locations that are at some distance from where they will eventually be used to generate heat and electricity at the lowest price. In 2011, almost 82% of the world´s primary energy demand came from fossil fuels (IEA 2013).

A stepwise change in the energy system is necessary to achieve sustainable development for society as a whole. The use of alternative energy sources, such as solar, wind, biomass, geothermal, hydropower and ocean energy, supported by regional cooperation may contribute to tackle the energy trilemma (Panwar et al 2011).

Developing countries of Latin America and the Caribbean (LAC) region represent approximately 9% of the world’s population, 6.5% of the worldwide Gross Domestic Product (GDP), 6% of the global energy consumption and 5% of the worldwide energy-related CO2 emissions (World Bank 2014, IEA 2013). Sheinbaum-Pardo and Ruiz (2012) highlight the importance of understanding the energy trends in LAC and to visualize the opportunities for a low-carbon future for the region while meeting the energy needs for poverty reduction. The latter is especially true for the 29 million people lacking access to electricity in the region in 2010 (OECD/IEA 2012). Under the most optimistic scenario, the LAC region will have universal access to electricity by 2030 (OECD/IEA 2012). However, other reports indicate that 3 million people may still lack electricity in the region by that time (WEC 2013). Interestingly, a recent report by the World Energy Council (WEC 2014) puts renewable energy and energy efficiency at the top of the list for action on energy at a regional scale, due to their high impact.

The role that modern energy services can have for the LAC region with regard to accomplishing the United Nation’s Millennium Development Goals (UN MDGs) has been documented in two reports (CEPAL 2010; IEA 2010). These reports conclude that: i) a new technological framework is required in order to dramatically scale up the access to modern energy services at the local and regional levels, ii) capacity building activities are required in order to incorporate highly trained and motivated technicians into national planning bodies and agencies, iii) it is important to incorporate integrated planning practices in order to set goals, specify energy sources and technologies to be used and iv) it is necessary to provide funding for research and development (R&D) agencies responsible for new technologies and to supervise results at the design, prototype, test, manufacture stage and actual use by the disadvantaged populations.

In order to generate a new energy technology framework and build technical capacity, it is necessary to use suitable tools to identify the alternative energy technologies that could be deployed in the LAC region. This is especially true for advanced energy technologies with a mid-term implementation time scale. Analyzing the potentialities of nanotechnology for alternative energy applications and developing a technology roadmap will be useful for defining relevant action plans as well as the priorities for interregional (e.g. between the European Union and LAC) and intraregional cooperation.

This document describes a technology roadmap for the LAC region that is focused on the synergies that arise from using nanotechnology in alternative energy applications. The methodology for developing the technology roadmap is described in chapter 5 Chapter 6 provides a brief analysis of the technologies selected for the roadmap, as well as insight to how nanotechnology could contribute to their development. Chapter 7 presents the capabilities in research, education and funding for nanotechnologies, nanosciences and new materials (NMPs) in selected LA countries. Chapter 8 presents recommendations for the deployment of NMPs for energy in LA and chapter 9 presents conclusions of the document.

# Framework for the Roadmap

Here we describe the foundations of the roadmap and the methodology used to develop it, starting by the definition of nanotechnology.

## 5.1 Definition of nanotechnology

Nanotechnology is classified as an emerging, enabling, and disruptive technology that has potential (and confirmed) cross-industrial applications, besides being convergent (Romig Jr. et al 2007). Nanotechnology is an emerging scientific field that has deserved particular attention since the early 1990s, although its foundations were established in the late 1950s. Nanotechnologies are described as a broad-based, multidisciplinary field, projected to reach mass use by 2020 and affecting education, innovation, learning and governance (Roco et al 2011a).

According to the International Standardization Organization (ISO 2010 online) nanotechnology is the application of scientific knowledge to manipulate and control matter at the nanoscale (referring to particles with a size range from approximately 1nm to 100nm) in order to make use of size- and structure-dependent properties and phenomena, as distinct from those associated with individual atoms or molecules or with bulk materials. The deliberate control and manipulation of matter is what differentiates nanotechnology from chemistry, which is the study and manipulation of atoms and molecules. In a more succinct and comprehensive way, nanotechnology is the application of scientific knowledge to measure, create, pattern, manipulate, utilize or incorporate materials and components at the nanoscale (Ramsden 2011).

The possibility of creating materials with novel combinations of properties is at the core of nanotechnology. Examples of physical and chemical properties that may increase or decrease as materials are reduced to the nanoscale include: strength, reflectivity, adsorptivity, crystallinity, porosity, chemical activity, melting point, charge transport, phase transition pressure and solubility (Zhang et al 2013; Balaya 2008; Alivisatos 1996; Guo 2012).

At the nanoscopic, or nanoscale, materials acquire new characteristics that can be used in a wide range of novel applications. They potentially include cheaper and more efficient technologies that can benefit the world’s poor, such as cheap water filters, efficient solar powered electricity, and portable diagnostic tests (Nano-Dev 2010).

## 5.2 Construction of roadmap

Key research questions were used as a tool in the roadmapping process (see next Section 5.3). The roadmap was built upon a needs-based perspective that is of sustainable energy in LA. The adapted capability approach was used as a conceptual framework in the roadmapping to support the needs-based perspective and to bring a multi-dimensional approach to the foresight exercise. The time frame for the roadmap is 10 years, up to year 2025.

The focus of the roadmap is on those technologies/needs that could have an important impact on disadvantaged populations in LA, and more specifically in the ICP countries in LA plus Uruguay. In order to formulate specific conclusions and recommendations, a choice of core topics has been made, meaning that not all technological developments, nor the full range of societal needs can be addressed.

It is important to note that a substantial amount of resources is needed to compile comprehensive roadmaps. The roadmapping exercise within the context of NMP-DeLA is limited in scope as the research relies on (a) a bibliometric analysis, (b) results of two one-day workshops on the topic and (c) expert interviews and focus groups.

The construction of this roadmap included desk research, bibliometric analysis and expert consultation through questionnaires, interviews, focus groups and panel discussions. Desk research was carried out in order to gather information on applications of nanotechnologies in the focus areas (Invernizzi et al 2015). The findings of this review provide information on the state-of-the-art of projects, the most active institutions and researchers, and initiatives and enabling policies in LA.

Firstly, we present an overview on “what is already there?” in terms of applications and developments of nanotechnology in the focus areas. Secondly, we take a more focused look at the societal challenges and realities in LA countries with an emphasis on poor and marginalized populations in the region, and how these relate to the focus areas of the project, with specific data shown for energy in this roadmap. Thirdly, qualitative methods, such as consultation with policy makers and experts from academia and industry, have been applied to analyse which existing technologies could be deployed and what issues still need to be addressed. Interpretation, discussion and validation of the first results was performed with experts and the wider interested/affected community in the framework of NMP-DeLA events (workshops, summer schools) and online consultation. A list of experts consulted for the construction of this roadmap is provided in Annex 1.

## Summary of research questions

The roadmap has been structured along key research questions to be explored by implementing different methodological approaches and participatory assessment methods. This section describes these approaches in more detail. Most of the assessment tools have been applied in the framework of NMP-DeLA events to use synergies and to save costs. Inter-connections between research questions have been exploited by means of joint organization of participatory events and focus groups by project partners, where a set of questions has been discussed with different stakeholder groups.

**Research question 1: What is already there?**

This is to identify the state of the art in terms of research and deployment possibilities.

Assessment method: mapping and deployment of nanotechnologies for energy

* desk research
* bibliometric analysis
* expert consultation

Result: mapping of advanced materials deployment for societal challenges and analysis of the potential for innovations in the areas[[1]](#footnote-2).

**Research question 2: How is NMP deployed (now) in the context of societal challenges in the field of energy?**

This is to analyse to what extent nanotechnology research (and funding programmes) aims to address major societal challenges.

Assessment method: Qualitative analysis

* participatory workshops
* focus groups
* individual expert interviews

Result: “soft” indicators for the social impact of NMP in the focus areas[[2]](#footnote-3)

**Research question 3: How can solutions, technologies and applications be produced in the future?**

This question guides the formulation of the innovation strategy, which aims at supporting the successful commercialization of nanotechnology developments in the field of energy in LA, by looking at the drivers and challenges for commercialization and how infrastructure can assist SMEs and academia in commercialization efforts in LA. In order to achieve this, the innovation strategy is largely based on the results of outreach activities in LAC, i.e. on surveys, interviews and discussions with stakeholders.

Assessment method: Qualitative analysis

* desk research on international roadmaps for the deployment of nanotechnologies
* stakeholder consultation through website
* survey with SMEs and academia in LAC
* participatory workshops

Result: Innovation strategy[[3]](#footnote-4)

**Research question 4: What are good practices and recommendations for deployment of nanotechnologies for energy in LA?**

The purpose of this is to gain an understanding of inspiring cases and derive common conclusions for both EU and LAC.

Assessment method: Qualitative analysis

* participatory workshops
* focus groups
* individual expert interviews

Result: Individual and final summary roadmap on deployment of nanotechnologies in health, water and energy areas in LA.

Linkages to activities that are related to roadmap construction are depicted in Figure 1.

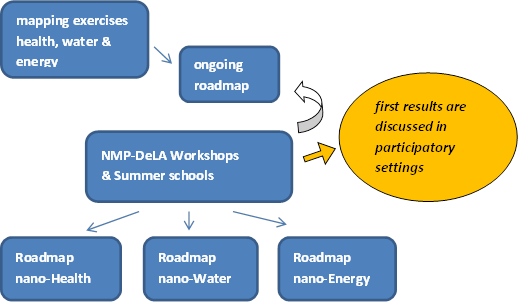


Figure 1. Linkages among supporting activities in roadmap construction

## Addressing energy-related societal Challenges in the roadmap

Science, technology and innovation (STI) play a central role in understanding the phenomena of societal challenges and their interactions, risks and consequences, as well as developing solutions (OECD 2012), although STI alone is not enough, as the development context of the countries in question need to be considered (Salamanca-Buentello *et al* 2005). Nanotechnologies could play an important role in the development of solutions, by having impacts on the welfare of nations, knowledge assets and contributing to achieving and sustaining economic growth. It can, for example, enable many industries to produce goods and services that are cheaper and lighter (Aydogan-Duda 2012a). Salamanca-Buentello *et al* (2005) identified where nanotechnologies could address Millennium Development Goals (MDGs) and thus benefit the populations of developing countries in general terms, and specifically regarding energy (see Table 1).

Table 1. Correlation between the top applications of nanotechnology for developing countries and the UN MDGs – deployment in energy

|  |  |
| --- | --- |
| **Applications of Nanotechnology** | **Examples** |
| *Energy storage,*  *production and*  *conversion* | Novel hydrogen storage systems based on carbon nanotubes and other lightweight nanomaterials  Photovoltaic cells and organic light-emitting devices based on quantum dots  Carbon nanotubes in composite film coatings for solar cells  Nanocatalysts for hydrogen generation  Hybrid protein-polymer biomimetic membranes |

Source: Salamanca-Buentello et al (2005:385)

This roadmap takes into consideration the LA environment, which is configured mostly of developing and emergent countries, for the deployment of nanoenergy solutions. We also bear in mind that governance of nanotechnology has been said to be essential for realizing economic growth and other societal benefits, protecting public health and the environment, and supporting global cooperation and progress (Roco *et al* 2011b). According to Roco *et al* (2011b:3560), nanotechnology governance needs to be:

* *Transformative* – including a results or projects-oriented focus on advancing multi-disciplinary and multisector innovation
* *Responsible* – including environmental, health and safety (EHS) and equitable access and benefits
* *Inclusive* – participation of all agencies and stakeholders
* *Visionary* – including long-term planning and anticipatory, adaptive measures

Roco *et al* (2011b) give examples of applications of nanotechnology governance functions (the ones mentioned above) in the United States. They emphasize that nanotechnology can be used as an example of how an emerging field has evolved in tandem with consideration of EHS aspects as well as ethical, legal and social implications (ELSI) or ethical, legal and social aspects (ELSA). Nanotechnology has been governed by an international community of professionals engaged in research, education, production and societal assessment of nanotechnology, which has the potential to guide its applications for the well-being of populations and environment.

## Addressing Capability Approach in the Roadmaps

Nussbaum’s adapted Capability approach[[4]](#footnote-5) (Malsch and Emond 2013) has also been used for the construction of the roadmap. This is a theory of human rights translated into a limited number of basic capabilities that each person anywhere in the world should be enabled to develop. Some of these capabilities are relevant to international cooperation in STI as well and they are discussed in the context of the deployment of the NMP-DeLA project:

* *Public engagement*: are all stakeholders represented in discussions on the roadmap?
* *National sovereignty*: is national sovereignty of the LA countries where the roadmaps should be deployed respected? What resources do they have and are they willing to invest by themselves? This calls for the suggestion of integrating the roadmaps into existing national plans for STI.
* *Foreign investment*: will the roadmaps fit with the EU strategy for international cooperation under Horizon 2020? What about national strategies of EU Member States?
* *Private investment*: can we convince industrial companies and venture capitalists to invest their own resources in implementing the roadmaps?
* *Access to higher education and research jobs*: in the NMP-DeLA project we should follow an equal opportunity policy for selection of participants in the outreach activities as well as in the stakeholder workshops. In the roadmap we discuss education and training and equal opportunities policies for the organizations involved in implementing the roadmaps.
* *Target research to poverty and health-related problems*: this is the leading force in the development of the roadmaps.
* *Environmental sustainability*: take into account both EHS aspects of nanomaterials and expected environmental benefits (especially in energy and water).

We emphasize both the capabilities approach and the functions of nanotechnology governance as proposed by Roco *et al* (2011b) as foundations for the realization of the roadmap.

The roadmap construction process with research questions and criteria and capabilities is depicted in Figure 2.

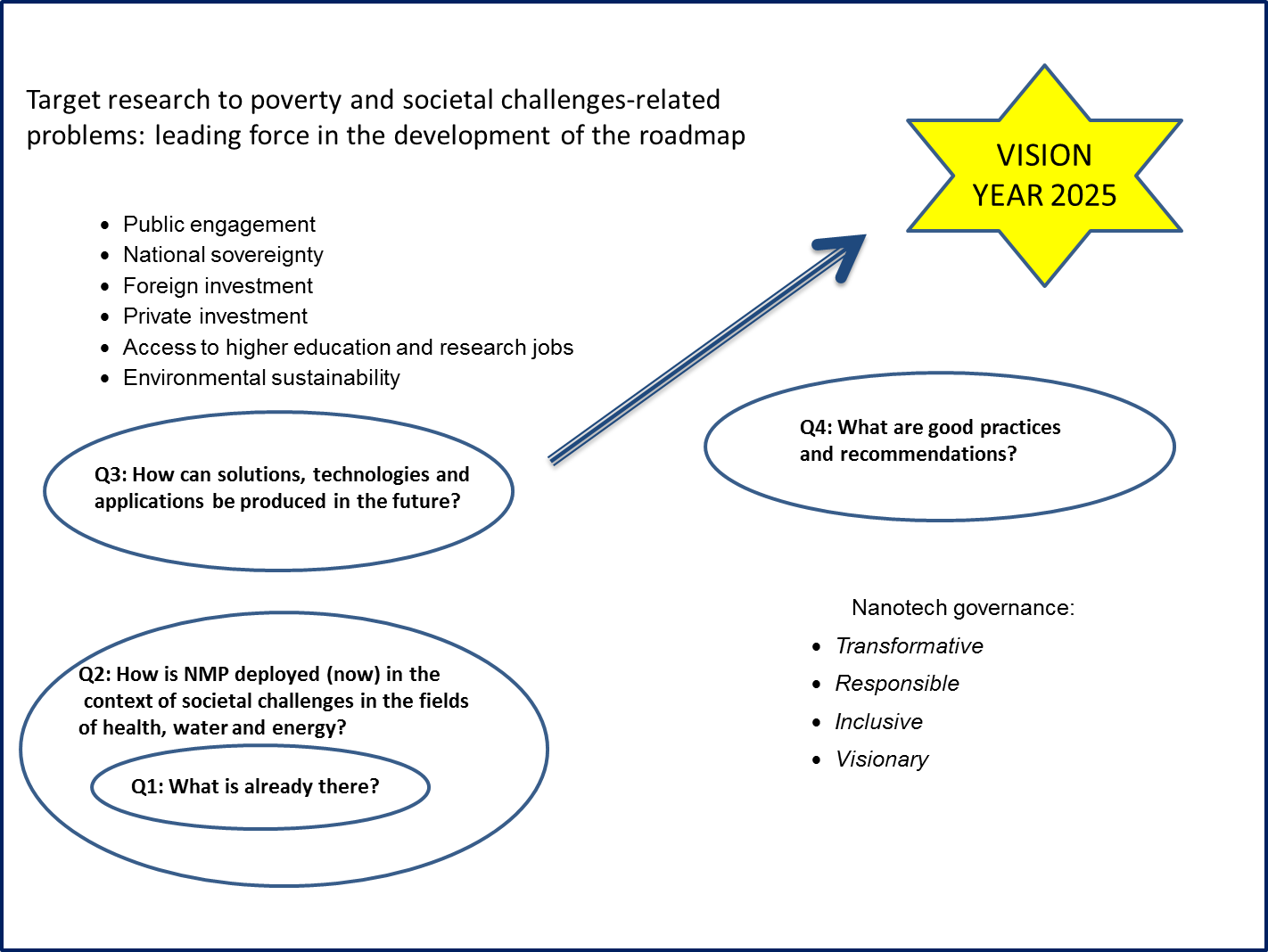


Figure 2. Research questions and criteria for construction of the roadmap

# Nanotechnology and Alternative Energy

With respect to energy applications, the main difference is that energy conversion and charge transport properties of nanomaterials differ significantly from those of bulk materials because of classical and quantum size effects on energy carriers such as photons, phonons, electrons and molecules (Li and Somorjai 2010).

Several review articles dealing with the applications of nanotechnology in the energy field have been consulted for this document (for example, Priolo et al 2014, Guo 2012; Cotal et al 2009 for example). In these review papers, it can be observed that nanotechnology is being applied in many fields of energy conversion and storage including: solar energy, electrochemical energy storage, hydrogen energy, fossil fuels, and biomass (biofuels). Although fossil fuels and biomass are mentioned here, they are not objects of study in this roadmap.

Table 2 summarizes some applications of nanotechnology in the alternative energy field and classifies the review papers by topics covered. The number of occurrences per topic provides an insight on the level of attention from the scientific community and the efforts expended to improve each energy technology using nanotechnology. A deeper analysis of the review papers listed in Table 2 may provide insight on the relative importance of specific nanostructured materials for the improvement of one or more technology subcategories. In this way, carbon based materials emerge as the most important group of nanostructured materials for energy applications. Other important nanostructured materials are Li composites, due to their importance in Li-ion batteries and TiO2, due to its importance in dye sensitized solar cells, quantum dot solar cells and photocatalytic and photoelectrochemical hydrogen production.

All the alternative energy technology subcategories listed in Table 2 are considered in the present work for the technology roadmaps. The research, development and innovation (RD&I) priorities for solar energy and hydrogen energy have been clearly identified elsewhere (ICSU-CONACYT 2010), however, in that report the potential benefits of nanotechnology were not addressed. Energy storage is included in the present work due to its synergies with solar and wind energy. The technologies selected for this roadmap are described in more detail below.

Table 2. Examples of nanotechnology for energy applications and review papers on specific topics

|  |  |  |  |
| --- | --- | --- | --- |
| **Technology** | **Subcategories** | **Applications of nanotechnology** | **Review papers** |
| **Solar Energy** | Silicon solar cells (SSC) | Use of Si nanowires to increase absorption of sunlight. | Priolo et al (2014) |
| Thin film solar cells (TFSC) | Use of nanorods, nanoprisms, nanoplates or nanocrystals to optimize the cell structure. | Ghorpade et al (2014) |
| Multi-junction solar cells (MJSC) | Use of nanoscale fabrication methods based on printing techniques for cell stacking. | Sheng et al (2014) |
| Dye sensitized solar cells (DSSC) | Use of highly efficient dyes, TiO2 and nanocrystallyne films to improve efficiency. | Zhang et al (2013); Balaya (2008); Dai et al (2012); Chen et al (2012); Zhou et al (2011); Li and Somorjai (2010); Serrano et al (2009) ; Chen et al (2013) |
| Quantum dot solar cells (QDSC) | Use of CdS and CdSe quantum dot sensitized, TiO2 nano-crystalline film to improve efficiency. | Zhang et al (2013); Balaya (2008); Dai et al (2012), Li and Somorjai (2010); Serrano et al (2009); Chen et al (2013) and Hu et al (2009) |
| Organic solar cells (OSC) | Develop nanoscale experimental techniques to optimize the charge transport properties of the devices. | Chen et al (2013); Nicholson and Castro (2010) |
| Photocatalytic and photoelectrochemical hydrogen production  (Photo H2) | Use of Mo-based nanowires as catalysts with improved durability. | Chen et al (2012); Li and Somorjai (2010); Serrano et al (2009); Chen et al (2013); Hu et al (2009); Fayette and Robinson (2014); Mao et al (2012) |
| **Electrochemical Energy Storage** | Lithium-ion Batteries  (Li-ion) | Use of Si-C nanocomposites to improve cycling capability. | Zhang et al (2013); Balaya (2008); Dai et al (2012); Chen et al (2012); Zhou et al (2011); Li and Somorjai (2010); Serrano et al (2009); Fayette and Robinson (2014); Arico et al (2005); Kelarakis (2014); Pumera (2011) and Shinde et al (2012) |
| Redox Flow Batteries  (RFB) | Use of carbon nanotubes to increase the reaction kinetics of the redox reactions. | Chakrabarti et al (2014) |
| Supercapacitors  (SCAP) | Use carbon aerogels to improve capacitance and cycling capability. | Zhang et al (2013); Balaya (2008); Dai et al (2012); Serrano et al (2009); Arico et al (2005) and Pumera (2011) |
| **Hydrogen Energy** | Solid Hydrogen Storage  (SH2) | Use of carbon nanotubes and graphitic fibres for improved H2 storage. | Zhang et al (2013); Chen et al (2012); Serrano et al (2009); Mao et al (2012); Pumera (2011); Shinde et al (2012); Niemann et al (2008) |
| Polymer Electrolyte Membrane Fuel Cells  (PEMFC) | Introduce nanoclays in traditional membranes to decrease methanol crossover. | Dai et al (2012); Zhou et al (2011); Li and Somorjai (2010); Serrano et al (2009); Fayette and Robinson (2014); Mao et al (2012); Arico et al (2005); Kelarakis (2014); Shinde et al (2012) |
| Solid Oxide Fuel Cells  (SOFC) | Use of Y2O3-doped ZrO2 nanofilms for improved ionic conductivity in the electrolyte. | Balaya (2008); Dai et al (2012); Li and Somorjai (2010); Serrano et al (2009) |

## 6.1 Solar Energy

The solar energy resource depends on the local solar irradiance, which is related to the amount of power per unit area that is directly exposed to sunlight and perpendicular to it. As a consequence of the earth´s shape, the solar irradiance is different in different locations. Solar irradiance, and consequently the solar energy resource, ranges from good to excellent throughout the entire LAC region. Chile, Mexico, Brazil, Argentina, Colombia, Guatemala, Ecuador and Venezuela are the most attractive countries for solar energy in the LAC region, according to the European Photovoltaic Industry Association (EPIA) (EPIA 2014). Solar irradiance can be transformed either to thermal energy (i.e. heating a fluid) or electrical energy. This roadmap only deals with the latter. The potential for electricity generation from solar energy in the LAC region is approximately 37 500 TWh/year (ECOFYS 2008).

There are three generations of solar energy technologies: first generation (Si-based), second generation thin-film and third generation (emerging technologies) (Razykov et al 2011). Si-based is the dominant technology with almost 80% of the world market followed by thin film with almost 20% (Timilsina et al 2012; Ranjan et al 2011). It is expected that the market share will remain similar in the coming years, however, the global sales for MJSC are expected to grow by 42.8%, and DSSC, QDSC and OSC are together expected to grow by 75.3% by 2018 (BCC Research 2014). Nanotechnology is currently applied mostly in the research and development of DSSC and QDSC, but has potential applications in every solar energy technology subcategory. The efforts made to develop nanomaterials for solar energy has been gathered in several review papers (Oelhafen and Schüler 2005; Tsakalakos 2008; Yu et al 2012; Chen et al 2013 and Wong et al 2013). With regard to DSSC, QDSC and OSC, ongoing efforts are being placed in the design of structured interfaces with tailor made architectures to improve charge management and light absorption within the devices (Graetzel et al 2012). The applications of nanotechnology in the solar energy subcategories considered in this study are described in more detail below.

### 6.1.1 Silicon solar cells

This subcategory of solar cells can be further divided into monocrystalline and polycrystalline Si. The highest efficiency reported for monocrystalline solar cells is 25%, while for polycrystalline it is 20.4%. It is believed that the use of Si nanostructures could boost the efficiency of this type of solar cells by overcoming the theoretical limit of 30% efficiency for first generation solar cells (Shockley and Queisser 1961; Polman and Atwater 2012).

### 6.1.2 Thin film solar cells

This subcategory of solar cells can be further divided in CuInGaSe2 (copper indium gallium selenide solar cell) (CIGS), cadmium telluride (CdTe) and amorphous Si. These cells are made from a sheet of substrate such as glass, plastic or metal on which layers of semiconductor materials are deposited, forming the device structure. The advantage of this approach is the inherently lower cost of manufacturing when compared to Si based solar cells, as considerably less material is required and process temperatures are lower thus saving energy during manufacture. The disadvantage is the slightly lower efficiency and, in some cases, degradation of performance over a number of years.

Nanotechnology could play an important role in optimizing the structure of these devices. Different synthesis methods can be used to grow high quality thin films from copper zinc tin selenide (CZTSe) and the sulfur-selenium alloy (CZTSSe) nanocrystals in order to control the phase, size, shape, composition, and surface ligands (Ghorpade et al 2014; Suryawanshi et al 2013; Zhou et al 2013).

### 6.1.3 Multijunction solar cells

The advantage of Multijunction solar cells (MJSC) is that they can absorb solar photons at a specific wavelength allowing more efficient energy conversion due to exploitation of a broader spectrum of wavelengths. There is a direct relation between the number of junctions and the efficiency of this type of cells. The highest efficiency recorded to date for any type of solar cell is for a MJCS with four or more junctions (38.8%), followed by triple junction (37.9%) and double junction (31.1%). MJSC can be classified according to the number of p-n junctions that they have i.e. double, triple or quadruple junction. There are at least two interesting applications of nanotechnology in this subcategory of solar cells. One was reported by Krogstrup et al (2013) and consists of gallium arsenide nanowires grown on a silicon substrate in order to reduce the cost and increase the light absorption of the cell. The other application has been reported by Sheng et al (2014), who developed a nanoscale fabrication method based on printing techniques that can improve the efficiency of MJSC with four junctions.

### 6.1.4 Dye sensitized solar cells

The heart of a DSSC is a dye bonded to the surface of an inorganic semiconductor, typically nanocrystalline TiO2. The dye captures energy from light and transfers this in the form of electrons to the mesoporous layer of nanocrystalline TiO2. This in turn forms a network for electronic conduction. The layer is deposited on a Transparent Conductive Oxide (TCO) that in turn rests on glass or another substrate for mechanical support. The most commonly used substrate is glass coated with fluorine-doped tin oxide (FTO).

Nanomaterials are widely applied as photoelectrodes for DSSCs due to the following reasons: 1) their high surface area provides a large surface for dye chemisorption, reducing the amount of electrode materials required and 2) their short charge migration length allows effective charge transport from the dye molecules to the electrode. Although other semiconductor materials such as SnO2, ZnO, CdO, and Nb2O5 have been identified as alternatives to TiO2, the latter is still the most efficient photoelectrode for DSSC and because of that, it is important to optimize the methods for synthesizing TiO2 nanocrystals (i.e. mechanical alloying/milling, sol-gel process and co-precipitation) (Prakash 2012). Furthermore, one dimensional TiO2 nanostructures, including nanorods, nanotubes, nanobelts, nanofibres and nanowires have been proposed to improve the electron transport properties over the randomly distributed nanocrystalline TiO2 film (Qu and Lai 2013).

### 6.1.5 Quantum dot solar cells

A quantum dot is a semiconductor with a nanocrystallyne structure that provides the material with distinctive conductive properties that depend on its size and shape. The most common methods for manufacturing quantum dots are successive ionic layer adsorption (SILAR), suitable for covering large surface areas of ordered TiO2 nanostructures, and chemical bath deposition (CBD), which produces the highest efficiency; and can be further improved in order to optimize the photoanode structure and performance (Kouhnavard et al 2014). Health concerns regarding the use of toxic materials, such as Cd, in the photoanode has made it necessary to develop alternatives. In this regard, PbS supported on ZnO nanocrystals is a very promising semiconductor for QDSC (Chuang et al 2014). Other nanostructures of interest for the development of QDSC include ZnO and TiO2 nanowires, TiO2 nanopillars (Lan et al 2014). As a final remark, only a better understanding of the impact of surface chemistry on the electronic properties and stability of quantum dots will enable the design of architectures with enhanced performance and stability (Milliron 2014).

### 6.1.6 Organic solar cells

The cells grouped in the cathegory of organic solar cells (OSC) are fabricated from all-organic solid-state materials. These cells can be further divided into: 1) small molecule, gas phase deposited solar cells and 2) solution processed organic solar cells (Brabec et al 2010). Organic solar cells use a thin film of Π-conjugated semiconducting organic molecules, oligomers or polymers for light absorption and charge transport (Hill et al. 2000; Brédas et al. 2004). The basic structure of OSC consists of a transparent electrode, typically indium-tin oxide (ITO) deposited on polyethylene terephthalate (PET), two organic light-absorbing layers and a second electrode.

Many factors including better understanding of the fundamental mechanism of organic photovoltaic process, introduction of new electron donor/acceptor materials and new device architectures have led to the great progress in OSC in the last few years (Nicholson and Castro 2010; Kaur et al. 2014; Hoppe and Sariciftci 2004; Kippelen and Bredas 2009). This type of cells has achieved a maximum certified efficiency of 11.1%, which is comparable to that of DSSC and higher than that of QDSC. There are many ways in which nanotechnology could contribute to the development of OSC. Nanoprinting techniques provide a way of optimizing the donor-acceptor layer in bulk heterojunction (BHJ) OSC (Heremans 2008). Another field of application is the substitution of the ITO by structures such as carbon nanotubes and graphene, which improve charge transport with little loss (Steim et al 2010). Inorganic nanoparticles can be employed in order to enhance light harvesting at longer wavelengths (Chang et al 2010; You et al 2013). Finally, a major contribution could come from developing methods to precisely manipulate the nanoscale morphology of the cell and tune its electronic properties (Nicholson and Castro 2010; Facchetti 2010; Anthony 2014).

### 6.1.7 Photocatalytic and photoelectrochemical hydrogen production

A shift towards the use of hydrogen as the potential main energy carrier for our society and the consequent implementation of a “hydrogen economy” has attracted the attention of academia, governments and industry in the last few decades (Marbán 2007; Bockris 2013), although there is still a long way to go to reach this state. While there are many ways to produce hydrogen (Wilhelm and Fowler 2006; Holladay et al 2009), the use of photocatalytic (PC) and photoelectrochemical (PE) processes is promising, due to the abundance of both solar and water resources.

Nanotechnology has been used for several years to develop nanostructures for PC hydrogen production, as can be seen from the study by Zhu and Zäch (2009). There are advantages and disadvantages from using nanostructured photocatalysts (Osterloh, 2013). The advantages include improved light capture, and rate of catalysis on surface. Disadvantages include energy losses within the nanostructured material due to defects and slower charge transport between individual nanoparticles.

It should be pointed out that charge separation and migration of the carriers is strongly affected by the crystal structure, crystallinity and particle size of the photocatalyst. In the same way, a smaller number of defects is associated with a higher crystalline quality. The defects can trap photogenerated electrons and holes and allow them to recombine, resulting in a decrease in photocatalytic activity. However, if the particle size becomes small enough, the migration distance to reaction sites on the catalyst surface for photogenerated electrons and holes becomes shorter, decreasing the probability of recombination.

In PE processes, nanotechnology can improve device architectures in several ways to generate hydrogen. The counter electrode in the monolithic semiconductor architecture can be coated with Pt nanoparticles to increase surface area (Jacobsson et al 2013) and Pt itself can be replaced with nanocrystalline MoS2 (Jaramillo et al 2007). As for metal oxide photoelectrodes, nanostuctured materials such as TiO2, ZnO, WO3, BiVO4, VO2, InP and hematite nanocrystalline films can improve performance (Abe 2010; Lin et al 2011). Furthermore, a better understanding of the morphology-dependent properties of different nanostructures (i.e. nanoflakes, nanorods, nanofibres, nanowires, nanonets and nanotubes) and semiconductors with different dopants, will help to optimize efficiency and stability of photoelectrodes (Osterloh 2013; Hisatomi et al 2014; Choi 2010; Li et al 2013; Esposito et al 2013).

## 6.2 Energy storage – batteries and supercapacitors

Energy storage refers to the process of transforming energy from one or several sources into a form of energy that can be stored for later use (usually in the form of electrical energy). There are different ways to store energy nowadays including: pumped hydroelectric storage, compressed air storage, superconducting magnetic storage, hydrogen storage, flywheels, capacitors and batteries (Boicea 2014).

Supercapacitors and batteries have attracted the most attention due to their flexibility in capacity, siting and rapid response to meet application demands over a much wider range of functions than many other types of energy storage (Yang et al 2011; Divya and Østergaard 2009; Lawder et al 2014). The development of energy storage technologies such as supercapacitors, lithium-ion batteries and redox flow batteries is of utmost interest for the LAC region for two main reasons: 1) vast availability of raw materials for their manufacture and 2) to ensure energy security at local or regional level.

The LAC region countries are rich in minerals containing the chemical elements used to manufacture core components of batteries and supercapacitors, such as electrodes and electrolytes. LA mines and processes most of the world’s lithium, with about 50% of the world´s deposits located in Bolivia (Taylor 2010) and with Chile, Argentina and Brazil being the second, fourth and seventh world producers in 2014 (Lithium Investing News 2015). Furthermore, some LAC countries are among the largest producers of different elements used in the most common redox flow systems: Fe, Ti, Cr, Zn, Br, V, S, Ce and Pb (Chakrabarti et al 2013) - see Table 3.

Table 3. Availability of minerals in LAC for manufacturing of batteries and supercapacitors

|  |  |  |
| --- | --- | --- |
| **Mineral** | **Country** | **Position in world output** |
| Iron | Brazil | 3rd |
| Ilmenite\*, \*\* | Brazil | 5th |
| Zinc | Peru | 3rd |
| Mexico | 4th |
| Sulphur | Mexico | 12th |
| Chile | 13th |
| Venezuela | 19th |
| Brazil | 24th |
| Lead | Peru | 4th |
| Mexico | 5th |
| Bolivia | 8th |
| Manganese\*\* | Brazil | 5th |
| Mexico | 11th |
| Nickel\*\* | Brazil | 7th |
| Colombia | 9tn |
| Tungsten\*\* | Bolivia | 5th |

Source: US Geological Survey (2014 – specific reports)

\*The most common mineral concentrate from which Ti is produced.

\*\* With respect to EDLC, transition elements as Mn, Ru, Ni, W and Ti are used when the electrodes are made from metal oxides (Zhang et al 2009).

Deployment of energy storage technologies is also important for the energy security of the LAC region. The current power network of the region is strongly dependent on centralized electricity generation with long distance transmission lines. At the same time the power network is continuously incorporating intermittent and decentralized renewable energy sources (mainly solar and wind). It is estimated that the wind power capacity will grow from 5314 MW in 2013 to 37 667 MW in 2025 for the region (Windpower 2013).

Furthermore, the power network is interconnected between countries e.g. Brazil and Uruguay (Sarmiento and Rosales 2010), Colombia with Venezuela and Ecuador (Molina and Rudnick 2014), Mexico with the United States, Belize and Guatemala (Sarmiento and Rosales 2010) and the Central American countries Guatemala, Honduras, El Salvador, Nicaragua, Costa Rica and Panama (Projeto Mesoamerica 2014). There are at least 12 more projects for interconnection under evaluation in the LAC region (CAF and CIER 2012).

The incorporation of renewable energy sources, and the interconnection between countries, pose many challenges to grid operators and energy utilities: balancing supply and demand, creation of multilateral regulatory frameworks, lower power quality and reliability, increase in start-up costs due to day-ahead solar and wind power forecasting errors. It is believed that deployment of energy storage technologies may help to tackle most of those challenges Beaudin et al (2010).

This section deals with electrochemical energy storage in the form of Lithium ion batteries, Redox flow batteries and supercapacitors.

### 6.2.1 Lithium ion batteries

It is believed that Li-ion batteries will dominate the electric vehicle market in the years to come, reaching revenue of USD 26 billion by 2023 (Alexander and Gartner 2014). It has to be said though that they have no relevance to the grid electricity, as they might be too expensive for such large scale deployment, and will remain for EVs and perhaps small scale off-grid back-up of critical infrastructure.

The advantages of using nanostructured inorganic materials for lithium ion batteries include the following:

* + - * The reduced dimension increases the rate of lithium insertion/removal and electron transport. The small size of nanostructured materials allows shorter transport distances for lithium-ion within the particles. The high surface area of nanostructures permits a high contact area of the electrode with the electrolyte and hence high lithium-ion flux.
      * The chemical potentials for lithium ions and electrons may be modified by tuning the size of the materials at the nanoscale, resulting in a change of electrode potential.
      * Nanostructures can help maintain structural integrity in electrodes which face large volume changes due to the migration of lithium during charge and discharge cycles (Abu-Lebdeh and Davidson 2013).

More specific applications of nanotechnology to Li-ion batteries include: the use of nanoscaled metal alloy composites to increase the life-cycle of composites through the reduction of volume change caused during the formation of the alloy, the nanostructuration of the cathode has been satisfactory explored with transition-metal dioxides, LiFePO4, LiMn2O4 and Vanadium oxide (V2O5), the finding of Li-insertion activities in the lithium titanites inspired interests in titanium oxide-based nanomaterials for anode applications, the use silicon nanowires and nanotubes with high discharge capacities and stable cycling over tens of cycles, with reversible capacities as high as approximately 3400 mA h g-1 (Serrano et al 2011; Hu et al 2009; Szczech et al 2011). These are technical applications that will be contribution to energy security by addressing fluctuations in supply and demand and outings due to grid failure. Large-scale use of Li-ion batteries for EVs will provide independence of fossil fuels.

### 6.2.2 Redox flow batteries

Among electrochemical systems, redox flow batteries (RFBs) represent one of the most recent technologies and a highly promising choice for stationary energy storage. They are electrochemical energy conversion devices, which work in a similar way to other electrochemical cells, by generating electricity from reactions between electrolyte and electrode. However, they differ from conventional batteries and are more alike to fuel cells in that electrolyte can be replenished from external reservoirs or regenerated when external power is applied. The most appealing features of this technology are: scalability and flexibility, independent sizing of power and energy, high round-trip efficiency, high depth of discharge (DOD), long durability, fast responsiveness, and reduced environmental impact. Such features allow for wide ranges of operational powers and discharge times, making them ideal for assisting electricity generation from renewable sources.

Nanotechnology could improve redox flow batteries through enhancing redox reaction rates (via increasing the surface area of the electrodes). A number of materials are being studied includingbismuth (Li et al 2013a), carbon nanofibre/nanotube (CNF/CNT) composites on carbon felt (CF) (Park et al 2013), niobium oxide nanorods (Li et al 2013b), carbon nanowall thin films (González et al 2012), and graphene (Chakrabarti et al 2014).

### 6.2.3 Supercapacitors

Supercapacitors can be used in applications for portable devices and powers components for EVs, not for stationary storage of energy. They offer a number of advantages, such as high power density and long cyclability. The main determining factor for power density and maximum power output is the surface area of each electrode that makes up the capacitor. The use of nanostructured materials dramatically increases this surface area (e.g. up to 1000 m2/g of carbon). The nanomaterials used in supercapacitors are typically metal-based nanocomposites together with conductive polymers, or carbon-based nanostructures together with hybrid inorganic/organic nanocomposites. A transition from activated carbon electrodes to carbon based nanostructures is happening in order to improve the performance of these devices. In this way, carbide-derived carbon nanoparticles, zeolite-templated carbon, multi-layer graphene flakes and carbon onions have been reported as electrode materials in supercapacitors (Choi et al 2012).

Other nanostructured materials are being developed in order to improve the performance of supercapacitors. The combination of pseudo-capacitive nanomaterials, including oxides, nitrides and polymers, with the latest generation of nanostructured lithium electrodes has brought the energy density of electrochemical capacitors closer to that of batteries (Simon and Gogotsi 2008). Molecular modelling has provided further understanding of the physical phenomena taking place in electric double-layer capacitors and could help optimize these electrochemical devices (Burt et al 2014).

## 6.3 Hydrogen Energy

This section describes how nanotechnology could contribute to improving solid state hydrogen storage and its conversion to electrical energy using fuel cells. The main driver for developing H2 technologies in LAC is the amount of human resource and critical mass available in the region (see Chapter 7).

Fuel cells are electrochemical devices that generate electrical energy and heat as long as fuel and oxidant are supplied. A simplified configuration of a fuel cell consists of an electrolyte with a planar structure to which fuel and oxidant are fed in opposite sides. The electrolyte serves as barrier that prevents the direct combustion of the reactants and physically separates the anode and the cathode. The electrons are passed through an external circuit and reach the cathode while the ions migrate through the electrolyte to generate the products of the overall reaction.

Fuel cells have similarities with both batteries and combustion engines. The main similarity between fuel cells and batteries is the direct conversion of chemical into electrical energy. The main difference is that batteries produce electrical energy from the chemical energy stored within them and fuel cells will produce it as long as reactants are fed in. Either primary (disposable) or secondary (rechargeable) batteries are at a disadvantage to fuel cells as a result. Regarding heat engines, the main similarity relies on the possibility of generating electrical energy and heat and as long as reactants are supplied. The main difference is that fuel cells generate electricity without intermediate heat exchange processes, and are more efficient as a result.

Hydrogen and fuel cell technologies have been subject to extensive roadmapping. This could be due to uncertainty regarding deployment of the technologies and/or the magnitude of perceived benefit.

### 6.3.1 Solid hydrogen storage

The lack of a high purity H2 supply infrastructure (Agnolucci and McDowall 2013) along with the challenges posed by the storage of H2, hinders its large scale use. The storage device is a crucial element of hydrogen energy systems since H2 is quite difficult to store or transport with current technology. When compared to hydrocarbons, the energy density of H2 is comparable by mass but poor by volume (Roes and Patel 2011).

There are many ways to store H2: gas storage (compressed), liquid storage, chemical storage (in a metal hydride) and physical storage (in a metal organic framework – MOF). Since compressed and liquid H2 require large containers, these ways to store H2 pose important safety problems for on-board transport applications. In turn, chemical and physical storage could be achieved at near-ambient temperatures and pressures with H2 chemically or physically absorbed to solid-state materials. It is believed that solid H2 storage is potentially the most convenient and the safest method from a technological point of view.

There are several nanomaterials being developed for solid hydrogen storage. These materials include a wide variety of aerogel compositions, including metal oxides, mixed oxides, and other compounds (Mao et al 2012), carbon aerogels (Shinde et al 2012), complex hydrides such as a cubic nanoporous polymorph γ-Mg(BH4)2 (Filinchuk et al 2011), MOFs with nanoparticles of Pt or Pd incorporated (Langmi et al 2014), carbon nanotubes, graphene sheets, graphene nanoribbon and some equivalent nanomaterials such as boron nitrogen nanotubes, hexagonal boron nitrogen sheets and boron nitrogen nanoribbons (Erickson et al 2011).

**6.3.2 Polymer Electrolyte Membrane Fuel Cells**

Polymer Electrolyte Membrane Fuel Cells (PEMFC) are also called Proton Exchange Membrane Fuel Cells (Mench 2008). The main issue with PEMFC is that they are still not competitive in durability and cost, with the exception of some niche market applications (Dicks 2012).

Nanotechnology can be used to improve the performance of the membrane and the electrodes of PEMFC. For the membrane, it is possible to improve hydrogen ion conductivity by using nanoscale hydrophilic inorganic materials such as lithium salts (Serrano et al 2009), titanium and tin dioxide nanoparticles (Abbaraju et al 2008) and depositing silica nanoparticles on sulphonated poly(aryl ether sulphone) (Carvalho et al 2008). Concerning the electrodes, their performance can be improved by nanostructuring the catalysts and the carbon-based supports (Giorgi et al 2011), through incorporating Pt and Pt alloy nanoparticles with tailor-made morphologies (Scibioh and Wiswanathan 2012; Brouzgou 2012), or nanostructures based on non-carbonaceous and inorganic oxide/carbide supports (Sharma and Pollet 2012), or by replacing the precious metal catalysts with alternate nanostructured alloys (Chen et al 2011), or by using carbon nanomaterials instead of metals (Zhang and Dai 2012).

### 6.3.3 Solid Oxide Fuel Cells

Solid oxide fuel cells (SOFC) use yttria stabilized zirconia (YSZ) as an electrolyte. This solid state electrolyte transports O2- ions from the cathode to the anode. The anode is fed with different fuel sources such as hydrogen (H2), reformed hydrocarbons (CHn) or others that can be converted to syngas (an H2-CO mixture) (Adams et al 2012). The cathode is fed with oxygen (O2) from air and the products of the overall reaction are H2O and CO2.

The applications of nanotechnology for this type of fuel cell in the literature are few. One application can be the development of nanocomposite materials with superior ionic conductivity for use as electrolytes (Zhu 2009) and the use of perovskite type nanostructures, including nanoporous materials, nanocomposites, nanotubes, nanoparticles and thin films, as cathode materials in SOFCs (Pinedo et al 2013).

# State of the Art in Nanotechnology for Energy in LA

## 

## 7.1 Research

Here we present a summary of the main findings of the bibliometric mapping study realized by Invernizzi et al (2015), which mapped key scientists, research groups and institutions, research outputs and international collaboration, projects and supporting policies in the field of nanotechnologies for energy in LA. Interviews made during the NMP-DeLA workshops and by electronic means, complement the data.

The four main research areas within the field of nanotechnology and the energy in Latin America are: photovoltaic energy, fossil fuels, energy storage and energy transportation. The most active research institutions are:

* Fossil fuels: Universidade de Sao Paulo (USP) and Universidade Federal de Uberlandia (Brazil), Universidad Nacional de San Luis (Argentina), Instituto Potosino de Investigación Científica y Tecnológica (IPICYT) and Universidad Autonoma de San Luis Potosi (Mexico)
* Photovoltaic energy: Universidade Estadual Campinas (UNICAMP) and USP (Brazil), Universidad de la Republica (Uruguay), Centro de Investigacion y de Estudios Avanzados (Mexico) and Universidad Naciona del Rio Cuarto (Argentina).
* Energy storage: Comissão Nacional Energia Nuclear (CNEN) USP, and Instituto de Pesquisas Tecnológicas do Estado de Sao Paulo (IPT) (Brazil); Centro de Investigacion y de Estudios Avanzados and Centro de Investigación y Desarrollo Tecnológico en Electroquímica (Mexico),
* Energy transport: Universidade de Sao Paulo (Brazil), Universidade Fedederal do Ceara (Brazil), Universidade Estadual de Campinas (Brazil) and Universidad Industrial de Santander (Colombia).

The bibliometric study conducted by Invernizzi et al (2015), mapped key institutions, projects and experts from LA and joint publications between LA and EU experts. They identified 816 articles on nanotechnology for energy by Latin American authors in the period 2003-2012 in the Web of Science. These include 306 articles on photovoltaic energy, 268 on fossil energy, 140 on energy storage and 139 on energy transportation. Thirteen Latin American countries have contributed to at least one article. Eighteen institutions have produced 20 or more publications on nano for energy in this period. Table 4 summarises this data on nanotechnologies and energy in LA.

According to research outputs, the areas are ranked according to number of publication in each during the period 2003-2012, and the number of publications by each country and by institution. The results are shown in Table 4.

Table 4. Key research areas and research output by country and institution in LA

|  |  |  |
| --- | --- | --- |
| **Publications by technology** | **Publications by country** | **Publications by institutions** |
| Photovoltaic energy (306)  Fossil energy (268)  Energy storage (140)  Energy transportation (139) | Brazil (635)  Mexico (430)  Argentina (170)  Chile (92)  Colombia (61)  Cuba (34)  Uruguay (27)  Venezuela (22)  Costa Rica (4)  Barbados (3)  Bolivia and Trinidad and Tobago (1 each) | Brazil: USP (137), UNICAMP(81), UNESP (31), CNEN (31), UFSC (29), UFRGS (28), UFABC (27), UFP (21), UFMG (20)    Mexico: UNAM (99), CINVESTAV (64), IPN (29), UANL (27), CIMAV, (21), UASLP (20)  Cuba: Universidad de Habana (26)  Argentina: CNEA (22), UNC (20) |
| Source: Based on Invernizzi et al (2015) | | |

Research output was also used to map research collaboration between LA and European experts. A search in a combined Scopus-Web of Science database of peer reviewed literature in 2003-2012 resulted in 870 publications on nanotechnology for energy with at least one Latin American and one European co-author. This search added another 54 publications to the original search using Web of Science database. The most frequently involved Latin American countries were Brazil, Mexico and Argentina and the most frequently involved European countries were Spain, Germany and France. The most active institutions were the Spanish National Research Council (CSIC) and the University of Barcelona in Spain, Cumhuriyet University in Turkey, University of Sao Paulo and University of Sao Carlos in Brazil and UNAM in Mexico.

While the University of Sao Paulo (Brazil) and the Universidad Nacional Autonoma de México (México) clearly lead in terms of publications in both the Web of Science and combined Scopus-Web of Science studies, other institutions are following: highlighting the importance of Mexico and Brazil in the Latin-American context and the comparably higher ranked Argentinian institution Universidad de Buenos Aires, the Colombian institution Universidad de Antioqua and the Chilean institution Universidad de Chile within the collaboration with Europe.

Key scientists in nanoenergy were also mapped with the objective to identify research capacity in the different areas as well as the countries where they are located (Figure 4, Figure 5 and Figure 6). This revealed that research and the production of new knowledge is concentrated in Brazil, followed by Mexico.

Figure 4. Percentage of Key scientists in LA by technology subcategories

Source: Based on Invernizzi et al (2015)

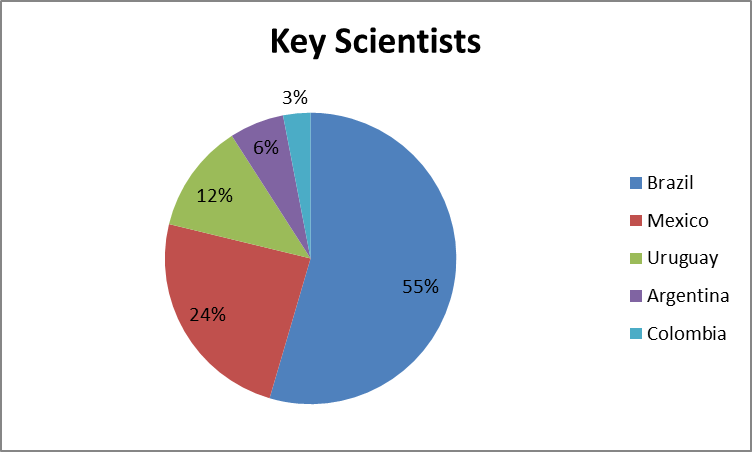


Figure 5 Distribution of nanoenergy scientists in LA per country

Source: Based on Invernizzi et al (2015)

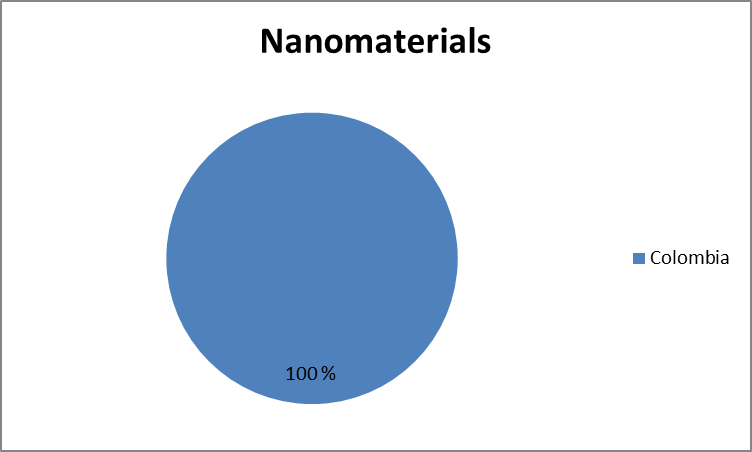
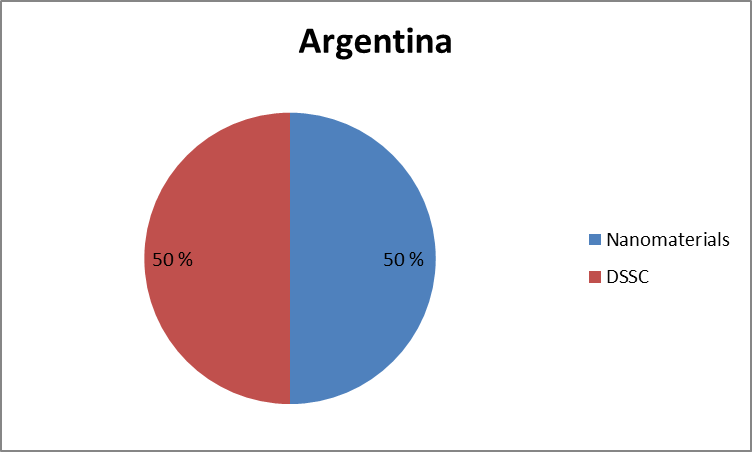
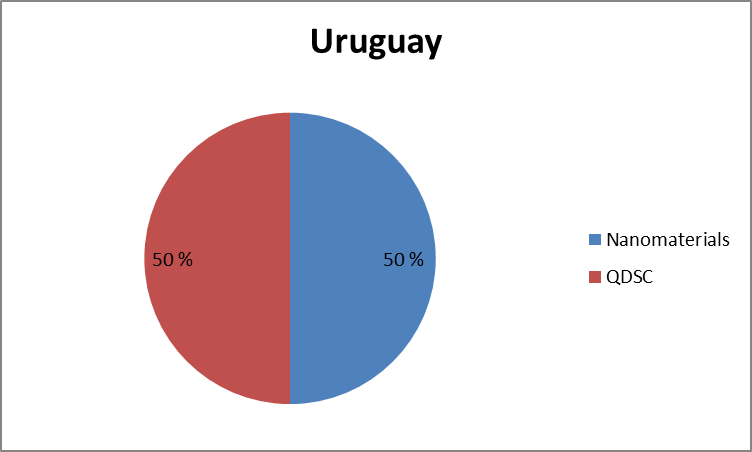
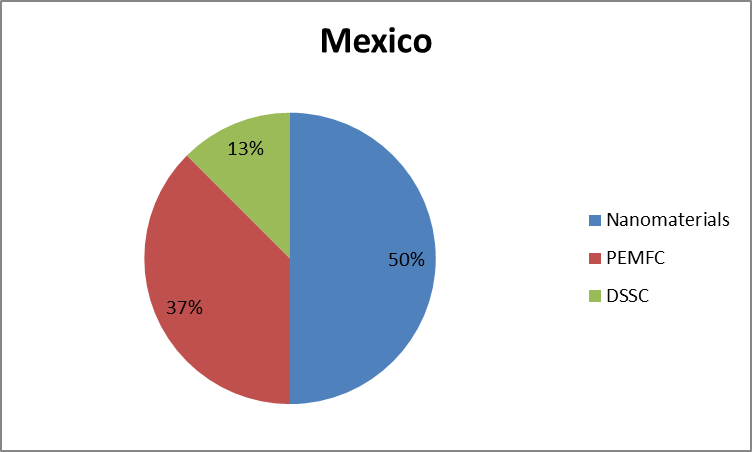
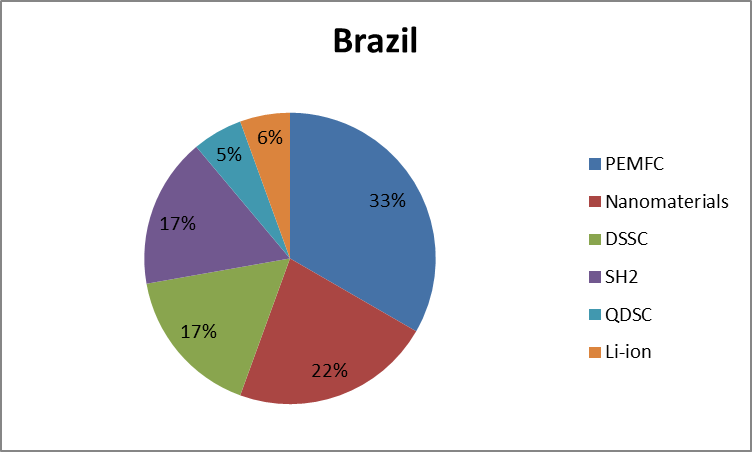


Figure 6. Distribution of Scientists by country and technology category

Source: Based on Invernizzi et al (2015)

### 7.1.1 Projects in Brazil

In the period 2010-2013, eight energy related projects were funded under nanotechnology related calls by the Brazilian National Council for Scientific and Technological Development (CNPq), and 64 nanotechnology related projects under the Energy Sector Fund. The Funder for Studies and Projects (FINEP) funded one project on nanoenergy.

37 Brazilian research groups are working on nanotechnology for energy, including ten that cover more than one kind of application area. In thirteen groups, energy is the main topic. Eighteen groups cover solar energy, nine fuel cells, eight biofuels, five fossil fuels, and seven other topics. Five National Institutes of Science and Technology (INCTs) are spread across the country. Created in 2009, they focus on nanotechnology for energy, mostly on photovoltaic devices and fuel cells. The Nanotechnology and Solar Energy Laboratory of the Chemistry Institute at the Campinas State University (Unicamp), and the Nano-network at the North-East Centre for Strategic Technologies (NANO-CETENE) are particularly important for nanotechnology in the development of solar cells.

According to an interviewed expert, UNESP in Brazil is working on Molecular and Nanomaterials for energy conversion, energy storage and sensors devices, and has applied their materials to solar cells in many international cooperation projects in the past.

### 7.1.2 Projects in Mexico

Nanotechnology for energy applications is carried out in mainly small groups, in 30 centres or institutes, in 21 institutions all over Mexico. The Mexican Energy Secretariat (SENER) and the funding National Council of Science and Technology (CONACYT) together have funded one project on nanoenergy.

According to an interviewed expert, the University of Guanajuato is working on porous materials as a storage media for hydrogen. They cooperate with research groups in Italy and France.

CIMAV, Monterrey, is working on Nanotechnology Enabled Energy Harvesting devices for mobile devices. They are developing integrated solutions for energy harvesting by combining PV, thermoelectrics and radiofrequency. CIMAV has developed several competences for international cooperation including proof of principle and patented applications. On the synthesis of nanomaterials and device fabrication, they are cooperating with others who have these competences. CIMAV works mainly for external industrial clients. The adjacent incubator offers laboratories and pilot scale manufacturing facilities.

### 7.1.3 Projects in other Latin American countries

From the 28 **Argentinean** research groups or projects working on nanotechnology for energy, 21% focus on solar energy, another 21% in catalysis and 19% on storage. Three **Chilean** research groups were identified working on energy storage and solar cells (University of Chile) and renewable energy (University of Santiago), respectively. In **Colombia**, 19 research groups are working on nanoenergy. In Uruguay, 11 groups work on nanotechnology for energy.

According to a participant in the workshop on nano for industry in Chile (Santiago, December 2014), STABLE is an ongoing project on nanotechnology for energy applications in cooperation between the EU and Chile. The project focuses on a Li-air battery based on Chilean innovation. Using an electrospinning technique, they can produce different fibre architectures that are applied in Li-air batteries for electric cars. The project aims to stabilise current materials that can undergo only 100-150 charge/discharge cycles and improve capacity to over 2000 mAh/g.

Another participant in the workshop on nano for industry reported that three groups in Uruguay work on nanoenergy. There are two strategies for solar cells: silica-based and dye sensitized (Grätzel). The two Uruguayan groups are located at Polytecnico Pando/Faculty of Chemistry, and Laboratory of Biomaterials/Faculty of Sciences, both part of UdelaR (University of the Republic). One research line is semiconductor modification and incorporation of TiO2 nanotubes. This improves the surface area of the electrode and contra-electrode. CNT has alos been used to provide different properties. The other research line is modification of the photoelectrode with natural pigments, as in the original design of the Grätzel cell. This is important for reducing production costs and investment required to start a business.

### 7.1.4 Projects in Europe

In Europe, the partnership Solliance brings together R&D organisations from the Netherlands, Belgium and Germany to work on thin film solar PV. Their activities include organic and Perovskite based PV, for which they have the necessary expertise and infrastructure. They are interested in expanding their industrial partnership with companies in other countries.

In the Netherlands, the national programme NanoNextNL[[5]](#footnote-6) includes a thematic programme on energy applications. Several universities are developing innovative concepts for more efficient or cheaper solar cells. The energy research centre ECN[[6]](#footnote-7), translates these academic research results to proof of principle, pilot production or product demonstration for companies. Universities and ECN cooperate with industry in the Netherlands and Europe to apply the results in PV products.

In Germany, the SolarValley Mitte Deutschland is a consortium of universities and companies that could build partnerships with similar organizations in Latin America.

The University of Linz in Austria specialises in designing organic semiconducting materials for photovoltaics in a network of partners from Europe and Africa. They are interested in joining forces with Latin American colleagues.

At Swansea University, UK, researchers are applying nanotechnology to lab scale and pilot scale membrane separation processes for power cells. They work on nanoscale characterization techniques with specialist expertise in SPM technologies, as well as polymer fabrication techniques for modifying surfaces used in energy generation, including nano-electrospinning and nanoparticle functionalization. They apply electrospinning for the production of carbon fibres. They have industrial collaboration with international companies and SMEs.

A list of 65 relevant NMP projects funded by the European 7th Framework Programme was obtained in order to identify possible matches in terms of focus areas, and to identify possibilities for future cooperation with LA. Figure 7 represents the distribution of the projects according to research focus. Projects names and their status are listed in Annex 2, and can be used to identify opportunities for collaboration between LA and EU research organizations.

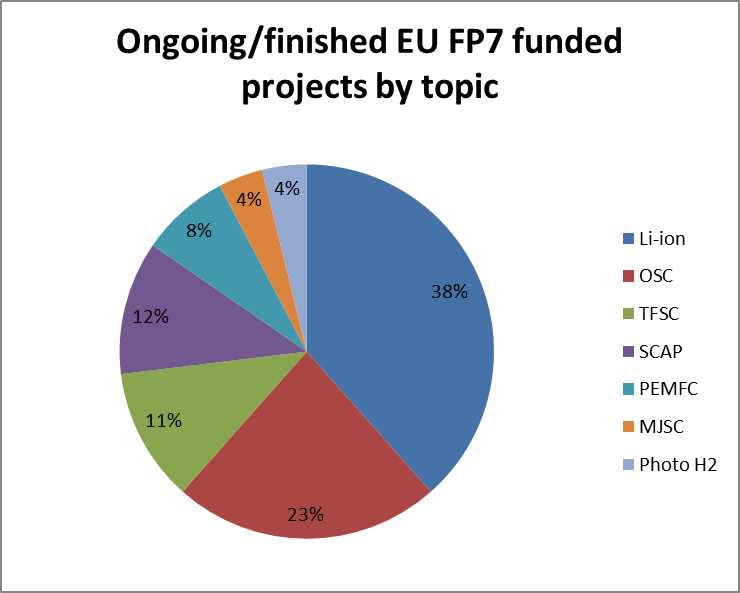


Figure 7. Focus of EU-funded projects with potential use for LA

Source: Communication with European Commission

**7.1.5 International Projects**

The African Network for Solar Energy ANSOLE[[7]](#footnote-8), aims to foster development of solar energy research and applications in Africa through a web platform and research network of African and international research groups. They are interested in South-South collaboration with Latin America.

In the USA, Prof Robert Chang, at NorthWestern University,is developing 3rd generation hybrid solar cells, based on Perovskite-based dye sensitized solar cells, a 2012 breakthrough (Nature, 24 May 2012). He also works on supercapacitor integration and plasmonic sensors. His institute is active in basic research and manufacturing scale-up. The earlier generations of organic dye sensitized solar cells needed a dye and liquid electrolyte. Perovskite has successfully replaced the liquid electrolyte and increased efficiency. This is an environmentally benign, low-cost material that is stable at ambient temperatures and can be processed for large area applications at low temperatures. The facilities currently use roll-to-roll production and are working to lower costs.

## 7.2 Energy Sector Industry and Investment

Invernizzi et al (2015) list eight Brazilian companies developing nanotechnology for energy applications. Zayago et al (2012) have identified one Mexican company in the petrochemical sector that is active in nanotechnology R&D.

According to an interviewed expert, UNESP in Brazil engages in technology transfer of nanomaterials and sensors for solar energy in cooperation with two technology parks in Sao Paulo State, two other universities and start-up companies. In addition, an energy start-up in Campinas, Brazil is developing devices for energy conversion and solar cell devices. They are developing their own technology, supported by Brazilian innovation agencies.

A Chilean consultancy, Nanotec SA, is working on a set of nanotechnology applications based on consumer preferences, such as lighter, more flexible, more tactile, with better resolution, better storage capacity, faster, more environmentally friendly, more durable, more sustainable, more economic and interconnected. Materials that are being used include fine particles, aligned polymers, and coatings. Applications include plastic electronics for sensors in cars, textiles, energy harvesting, collection and storage of energy, batteries and supercapacitors, dancefloor energy.

Another Chilean company, Adrox, has developed transparent self-cleaning coatings for solar panels. This project started 2 years ago in the north of Chile. They are looking for partners that can produce certified TiO2 nanoparticles in high quantities. They have different coatings including PowerSun for solar cells, which reduces water use for cleaning by 80% and increases energy generation of the solar cells by 30%. The coated product is more environmentally sustainable and more profitable than the non-coated product.

In Costa Rica, an expert considers that there is some industrial development in nanotechnology for biofuels and energy, but that they cannot proceed to the next phase by themselves.

In Europe, the ETP Photovoltaics has adapted tools allowing the morphological and opto-electronic nanoscale characterisation of dye-sensitized solar cells. In the ETP Renewable Heating and Cooling most nanotechnology activity is related to energy, according to a participant in the workshop in Monterrey, Mexico.

In the Netherlands, all companies and knowledge institutes engaged in R&D&I in solar PV have formed a network, that is looking for international partners especially in the BRICS countries (Brazil, Russia, India, China and South Africa), but also in other countries. Franken and Meijer (2014) provide an analysis of the Dutch companies’ Unique Selling Point and their positions in the value chain.

## 7.3 Policy and Funding on NMP for Energy

### 7.3.1 Brazil

The Brazilian government is diversifying its energy mix and investing in non-hydro renewables including (since 2014) some centralised solar energy for electricity production. The expected demand for new developments is 1 GW, which opens up opportunities for international cooperation in the next five years, in particular in the form of Joint Ventures with Brazilian-based companies. Foreign partners can contribute applied research, cultural change, education, engineering and logistics, financing, knowledge and technology and policy making (Transfer LBC, 2015).

Invernizzi et al (2015) report that in Brazil, the 2004-2007 Multi-annual Plan of the MCTI (Ministry of Science, Technology and Innovation), identified the following research areas within the Nanoscience and Nanotechnology Development Programme, as relevant for the country’s plan in the field of energy: a) power generation devices; electrodes and membranes for combustible cells; b) storage structures; supercapacitors and new batteries; and c) nano-chemical photovoltaic systems (MCT, 2003, 7). Also in 2008-2011, nanotechnology for the energy sector was a priority in the Multi-Year Plan for STI. The current National Science, Technology and Innovation Strategy 2012-2015 again highlights nanotechnology as a strategic area and places energy among the country’s priority sectors.

The research council CNPq is responsible for awarding Brazilian federal funding for nanotechnology and under the Energy sector funds. In 2013, the CNPq budget for energy was R$83,33 million (around €20.6 million). The FINEP (Funding Authority for Studies and Projects) promotes R&D in business including energy research as well as nanotechnology.

According to an interviewed expert, the Brazilian Ministry of Development and Foreign Commercialization is also involved in nanotechnology policy.

### 7.3.2 Mexico

In CONACYT there was a network and on energy, that has just been restarted. This field is fragmented, according to a participant in the workshop in Monterrey (November 2014).

# Recommendations

## 8.1 Driving forces of nanoenergy technology roadmaps

There are many driving forces for the accurate development of technology roadmaps regarding nanotechnology and alternative energy in the LAC region. As the main objective of this roadmap is to elaborate recommendations that serve as input to policy-making, we list only those driving forces that are applicable to the LA context.

### 8.1.1 Solar energy roadmap

Driving forces:

1) The solar energy resource is vast across the LAC Region (see Section 6.1).

2) The long term forecasts for cost reduction will make the deployment of solar energy technologies very attractive in the coming years in the LAC region. A recent report by the IEA predicts an average cost reduction of 25% by 2020 and 45% by 2030 (IEA 2014).

3) Solar energy is especially suitable for rural or marginalized areas, greatly supporting the accomplishment of the UN MDGs while addressing the energy trilemma at a local level.

4) Approximately 25% of the Key Scientists available in the LAC Region conduct research in solar energy related topics, as highlighted in Section 7.

5) The development of solar energy technologies will necessitate the development of suitable electrochemical energy storage technologies (in order to balance supply and demand).

6) The development of solar energy technologies may contribute to a diversification in the energy sources within the LAC region, by harnessing photoelectrochemical and photocatalytic production of hydrogen.

### 8.1.2 Energy storage roadmap

Driving forces:

1) The possibility of increasing the energy security of the LAC region both at microscale (i.e. in rural or marginalized areas) and macroscale (i.e. supporting the interconnection of the power network between LAC countries and improving the efficiency of the power networks of each LAC country).

2) The vast availability of raw materials for manufacturing core components of energy storage systems across the LAC Region.

3) Energy storage technologies are a key element for the more efficient use of solar and wind energy.

### 8.1.3 Hydrogen energy roadmap

Driving forces:

1) Approximately 35% of the key scientists available in the LAC region conduct research in hydrogen energy related topics, as highlighted in Section 7.

2) The opportunity to diversify energy sources in the LAC region, which is directly related to local and regional energy security, energy equity and environmental sustainability.

3) The knowledge gathered by key scientists could be transferred to other alternative energy technologies.

### 8.1.4 Nanostructured materials

Nanostructured materials based on carbon should be developed for solar energy technologies. These materials could then be adapted for use in other energy technologies. Special attention should be given to graphene, a material for which the European Union has a flagship project (http://graphene-flagship.eu/).

Nanostructured materials based on lithium composites should be developed for Li-ion batteries. The vast reserves of lithium within LAC could contribute to the development of a regional action plan on this topic.

## 8.2 Research in NMP for energy

Most of the recommendations presented here were gathered from experts interviewed during NMP-DeLA workshops and from focus groups.

An interviewed expert recommended that the NMP-DeLA project results be followed up with events where European and LA parties can meet physically, exchange knowledge and learn about each other’s results and vision for applications.

In Costa Rica, an expert recommended building up the human capacity for nanoresearch in the short term, through international cooperation with Europe, in particular Germany and Italy.

In Europe, the EU Photovoltaic Technology Platform organizes research organisations and industry interested in innovation in PV technologies. The latest version of their Strategic Research Agenda aims at considerable cost reduction for solar energy equipment by 2030. Even though nanotechnology for solar energy is not addressed in a separate chapter, several nanomaterials are included as options in the SRA. One of the alternatives being explored is thin film technologies, where processes and equipment for low-cost, large-area plasma deposition of micro/nanocrystalline silicon solar cells are envisaged. Organic PV calls for a fundamental understanding of physical phenomena of the dye, and other materials and components including the effect of nanomorphology and order on charge transport and dissociation. Novel PV technologies may be developed if new methods for nanoparticle synthesis become available (EU PV Platform, 2011).

At a national level, the Dutch national nanotechnology programme, NanoNextNL (2011-2016), includes research that focuses on nanotechnology applications for the efficient generation of sustainable energy, as one of the four key application areas. The Strategic Research Agenda includes an overview of Dutch research organizations and companies active in nanotechnology for energy applications, including solar, wind, biomass, fuel cells, hydrogen storage, energy saving, batteries and fossil energy. It proposes the following research lines:

* + The efficient generation of sustainable (solar) energy
  + Solar energy for generating heat
  + Solar energy production of fuels
  + Wind energy
  + Efficient energy consumption through the secondary conversion of energy and the separation of substances
  + Nanotechnology for energy storage
  + Inorganic and organic LEDs with extremely high efficiency (NanoNed, 2009)

The current NanoNextNL programme includes two thematic programmes related to energy:

* + Efficient generation of sustainable energy
  + Efficient energy utilization by secondary conversion of energy and separation of products

According to an interviewed expert, nanotechnology for solar energy can be applied in more efficient, cheaper solar panels, adapted solar panels such as transparent, lightweight, coloured or flexible solar panels.

International research cooperation including EU-Latin American as well as South-South cooperation in solar energy could be fostered through the existing platform of the African Network for Solar Energy, that already engages African, European, North American and Asian researchers.

## 8.3 Policy and Funding for NMP for Energy

A general, and largely strategic policy recommendation, is the inclusion of nanotechnologies and NMPs addressing sustainable energy production into the policy dialogue that is ongoing between the EU and the Community of Latin American and the Caribbean States (CELAC) under the auspices of the Joint Initiative for Research and Innovation (JIRI). The topics in which collaboration is fostered are developed in bi-regional working groups. Topics can be included either within the thematic areas of the energy working group, or be implemented as a transversal working group specific to nanotechnologies, or in NMPs for societal challenges.

Besides public funding, crowdfunding and sponsorship could also be a solution for investing in practical trainings, as demonstrated by ANSOLE for African students.

Below, we report opinions of experts from Chile and Brazil regarding the topic.

**Chile**

According to a participant in the NMP-DeLA workshop on nanotechnology for industry, Chile could benefit from a Smart Specialization Programme as fostered by the EU, taking into account its modest and limited public funds for innovation at national, meso-regional and regional level. Three national programmes have started in the national interest including one on solar industry, because Chile does not have fossil energy and the desert region in the north is characterized by lots of sunshine.

**Brazil**

According to an interviewed expert, the Brazilian government may foster nano-innovation for energy applications. Self-sustaining, local energy supplies will be required for remote areas and agribusinesses, which might include bioenergy, solar energy and others as well. There are opportunities for joint ventures between foreign companies and Brazilian companies. One way to stimulate local development is to establish projects with local factories or local research council funding.

## 8.4 Energy Sector Industry and Investment

According to an interviewed expert, in the medium term, business formation in LA should be stimulated with new technology. This should be done by starting with an R&D project with European and Latin American partners. Then, existing Latin American and European companies should be engaged with ambitions in the area of nanotechnology for solar energy from an early stage in the development.

Another expert recommended establishing long term, mainly industrial and possibly R&D institutional partnerships with Latin American companies and R&D institutes active in thin film PV that could help in transferring know-how and technologies for future implementation. This would require the identification of and commitment from companies for future production, implementation and commercialization. Complemented with the opinion of another expert, thin film PV is considered to become the successor of classic (mc)Si PV. Thin film PV allows much better integration of PV in buildings, vehicles, urban furniture, etc . However, this will only be realised through further development which could be accelerated by joint EU-LAC collaboration.

Another expert discussed market niches for nanoenergy in Latin America, for example the development of integrated devices for health or water monitoring, that could be based on Li-ion high energy density batteries, which are very light and use Wi-Fi technology.In agriculture, these could be used to power sensor devices for monitoring crop growth, environmental conditions, and water quality. A Costa Rican expert foresees market niches for nanotechnology in energy including hydrogen storage and the modification and enhancement of biofuels for higher efficiency.

According to another interviewed expert, solar energy companies could develop solutions that have adequate energy storage capacity for charging cell phones and other energy needs in remote regions. Their awareness should be raised concerning appropriate technology to address local needs. Brazilian energy companies cooperating with UNESP are interested in developing batteries, energy storage devices, and lithium ion batteries in Brazil. The University of Cornell, USA has developed Li-ion batteries that have a high energy density and can be used for mobile devices. They are interested in starting a subsidiary in Brazil.

According to another interviewed expert, Dutch equipment manufacturing companies are setting up factories and production lines for solar energy. These companies may be interested in applications of nanotechnology if there is a market for these products in LA. Likewise, solar energy companies may be interested in the LA market for solar energy in general if it can be demonstrated to be a growth market.

## Ethical, Legal and Societal Aspects

The study and application of nanotechnology for the energy sector is a new and very broad field, addressed by many scientific disciplines and covering diverse product areas. Nanotechnology applications are present throughout the energy value chain: harvesting (e.g., fuels, solar, wind, nuclear); conversion (e.g., photovoltaic, fuel cells, combustion turbines); storage (e.g., batteries, supercapacitors); distribution (e.g., high temperature superconductors, optimal high voltage alternating current transmission) and usage (e.g., thermal insulation, efficient illumination). Each of these steps is related, in terms of scientific research, to different materials and/or processes, and may be situated within institutions with varied science and technology emphases.

One of the fastest growing application sectors for nanotechnology is energy. Menéndez-Majón et all (2011) showed that while scientific articles on nanotechnology tended to stabilize in the latter years of the first decade in this century, those relating to nano-energy continued to grow. This growth is related to the global concern that fossil fuel resources are running out and to the search for clean and renewable alternatives. In addition, nanotechnology applications also address the need for better storage and distribution alternatives for existing energy sources.

According to interviewed experts, in the long term, nanotechnology could contribute to solutions for climate change, energy for all, including access in remote areas, and improved energy security through reduced dependence on fossil fuel imports.

An expert recommended building capacity through education and training. Academics should be taught in English, but vocational training for technicians and entrepreneurs should be offered in Spanish and Portuguese. Awareness about climate change and energy issues should be raised among the local population using performing art in local languages. For this, it is important to understand the social and cultural aspects of local communities.

Regarding the energy trilemma mentioned in the beginning of the roadmap, experts did not show enough awareness concerning the topic, such the accessibility of the new technologies be accessible to all populations, or more specifically to poor or remote populations; will they lead to energy independence and security (e.g. is developed, manufactured and deployed by LAC) or will developed countries (including China) continue to dominate? These concerns should be brought up to the public arena by policy-makers and other stakeholders (with a bigger role that might be played by NGOs) when implementing actions recommended.

# Conclusions

Along with other nations, Latin American (LA) countries face the globally pressing challenges of energy security, environmental sustainability and energy equity. Climate and health concerns necessitate uptake of renewable energy sources, and depleted fossil fuel resources and related political risks are high on every country’s agenda. Furthermore, there are additional challenges of regional character in LA, e.g. in terms of access to energy that is still lacking because of poverty or distant rural locations.

There are however plentiful opportunities to improve energy systems in LA and to introduce nanotechnologies for energy as an enabler. The LA region is favourable for solar energy production, and it is rich in minerals and other raw materials used in energy applications such as solar cells and batteries. In fact, nanotechnologies could be one of the success factors in bringing improved performance in a multitude of energy applications, in terms of energy conversion efficiency, material efficiency, cost savings, product life cycle, etc. Nanotechnologies are also of great interest in applications related to the shift from centralized energy production towards decentralized and localized energy production. These, together with interconnected grids, may additionally open up larger markets for advanced large-scale energy storage systems. Medium- to long-term aspirations on electromobility and hydrogen economy are also strongly linked to energy storage questions and possible application areas of nanotechnology.

In this report we have surveyed and roadmapped the potential of nanotechnologies for advanced and alternative energy applications, with a focus on solar energy, hydrogen and electrochemical energy storage. Next we present the main conclusions and recommendations for promoting and advancing the development and uptake of nanotechnologies for energy in LA towards 2025. Short-term is up to 5 years, and medium-term is 5 to 10 years.

**Acceleration of research**

Research on nanotechnologies for energy is fairly advanced in LA countries, especially in Brazil and Mexico. Topics involve most importantly nanomaterials and solar energy technologies. Collaboration with e.g. the EU has already been initiated and international research networks are made use of by many research groups. These research and innovation networking activities within the LA research community, as well as with global leading experts should be intensified in the short- to medium-term. Knowledge transfer would be beneficial also with African counterparts, and existing collaboration networks of global research communities should be further developed.

**Strategic support for synergetic efforts**

Energy applications are rather well acknowledged through nanotechnology-related strategies for science, technology and innovation. Similarly, nanotechnology is often highlighted in energy programmes. A systematic understanding of the opportunities for nanotechnologies in energy would be beneficial to foster progress of specific applications in the short- to medium-term and furthermore to encourage synergistic effects between applications in longer term (e.g. synergies between hydrogen energy applications and energy storage applications).

**Innovation ecosystems**

Directly linked to the acceleration of research, the build-up of stakeholder ecosystems around the innovations in nanotechnologies for energy is essential in the medium- to long-term. By this we mean bridging the gap from basic research towards applied research and finally product development and commercialization, as technologies mature. Along this progress a shift from public funding towards industry involvement and investment should take place. It should be noted that some applications of nanotechnology for energy are already market-ready while others are at the early research phase. Appropriate steps of innovation ecosystem building should therefore be promoted.

**Focus on local and regional aspects**

The starting point for promoting nanotechnologies for energy in LA should be to embrace sustainable objectives that support societal, economic and environmental outcomes. The local and regional needs and demand for reliable and affordable energy and electricity supply should be addressed. In addition, fair and sustainable use of renewable energy, mineral and material reserves could strengthen local businesses and economies. International business collaboration and export opportunities should be carefully assessed from an ethical point of view.

In order to summarize the recommendations and conclusions of this roadmap we present some milestones, which stimulate in the short, medium and longer term research, development and in-novation in nanoenergy in Latin America. The presented milestones are no prediction of the fu-ture, but a compilation of recommendations, which resulted from our 2-year multi-stakeholder re-search process where we addressed the question of how nanotechnology-based solutions to soci-etal challenges in the area of energy should be produced in the future. Long term developments shall eventually flow into the achievement of the Sustainable Development Goals related to energy, such as:

Goal 7. “Ensure access to affordable, reliable, sustainable and modern energy for all”

* 7.1 By 2030, ensure universal access to affordable, reliable and modern energy services;
* 7.a By 2030, enhance international cooperation to facilitate access to clean energy research and technology, including renewable energy, energy efficiency and advanced and cleaner fossil-fuel technology, and promote investment in energy infrastructure and clean energy technology
* 7.b By 2030, expand infrastructure and upgrade technology for supplying modern and sustainable energy services for all in developing countries, in particular least developed countries, small island developing States, and land-locked developing countries, in accordance with their respective programmes of support” (UN online)

We focus mostly on milestones at short and medium-term, reaching up to 2025, as this has been the timeframe for the roadmap. The long-term milestones are assumed to be envisioned conse-quences of the implementation of previous activities.

As key actors for the implementation of the milestones we would see policy makers, researchers, pharmaceutical industry, health care personnel, regulatory bodies, non-government organizations, regional, and international organizations. Of utmost importance for the implementation process is the full integration of all stakeholders in deciding priorities in the research agenda, in the transfer of research results into applications and standards and in the evaluation of the progress achieved based on the goals of the regional strategy, as recommended by Savolainen et al (2013).

For the monitoring of progress and impact of defined actions and strategy, we give extensive op-tions of outcome and impact indicators in the general NMP DeLA Roadmap (download from www.nmp-dela.eu). The suggested indicators may be used as a basis for the developing of nanoenergy specific key indicators for impact evaluation.

Table 5. Timeline for implementation of Nanoenergy roadmap recommendations

|  |  |  |  |
| --- | --- | --- | --- |
| **Topic** | **Short term (by 2020)** | **Medium term (2020-2025)** | **Long term (2025-2030)** |
| **Research** | Organization of bi-regional events among researchers and policy makers for knowledge exchange and definition of priorities for cooperation in nanotechnologies for energy. | Priorities for cooperation are implemented through strategic research programs | Results of strategic research programs are evaluated and give rise to new strategic programs. |
| Dialogues for the creation of Nanoenergy research network in LA | Establishment of Nanoenergy Resaerch Network in LA | Nanoenergy research network evolves to Industrial Nanoenergy Platform |
| **Funding** | National, regional, bi-regional funding | Bi-rgional funding; World Bank, Inter-American Devlopment Bank, etc. | Bi-regional funding |
| **Infrastructure** | Realization of feasibility studies for production of nano-based components for batteries and supercapacitors in LA | Establishment of industrial base for the production of nano-based components for batteries and supercapacitors in LA. | Full operation of industrial facilities supplying nano-based components for batteries and supercapacitors and other energy storage solutions. |
| **Technology Transfer** | Study of deployment of energy by European Energy Technology Platforms (photovoltaic, biofuels, electricity networks and wind energy), as possible benchmark for cooperation between EU and LA and among LA countries. | Creation of Energy Platforms in LA with the adoption of nanotechnologies in their strategic research agendas. | EU and LA Energy Technology Platforms launch joint calls for projects related to nanotechnologies for energy. |
| Identification of academic research with potential for commercialization. | Establishment of mechanisms of technology transfer from academia to industry. | Incubators and spin offs are operational. |
| **Policy making** | Inclusion of nanoenergy as a thematic topic for cooperation between EU and LA within the EU-CELAC JIRI | Joint EU-LAC calls for projects on nanoenergy and societal challenges, | Launch of joint bi-lateral (among States) and bi-regional calls for projects. |
| **Capacity building** | Study of common curricula for education on nanoenergy at undergraduate and vocacional levels to be established across LA.  Benchmark of EU curricula for nanoenergy education. | Implementation of common curricula for education on nanoenergy across LA.  Studies for implementation of joint nanoenergy education programs. | Joint issuing of degrees for experts in nanoenergy. |
| **RRI** | Mapping of remote and underserved communities to be attended by research on nanoenergy. | Priorities of research are translated in development projects | Incubators of technologies focusing on social needs related to energy are established at or together with universities and research institutes focusing on nanoenergy. |
| **Cooperation** | Inclusion of nanotechnology as a priority topic in the EU-LA Joint Initiative for Research and Innovation (JIRI). | Bi-regional panel organizes priority topics for long term cooperationand formation of public-private partnerships on nanoenergy. | Joint ventures between EU companies and LA companies. One way to stimulate local development is to establish projects with local factories or local research council funding. |
|  | EU and LA organizations subscribe to the European Latin American Network of Technology Based Business in energy and/or nanotechnology - ELAN | EU nanoenergy-based business and technology transfer are implemented in LA. | Business operate successfully and originate new joint ventures. |

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# Annexes

# Annex 1. List of Experts Interviewed for the Elaboration of the Roadmap on Nanoenergy for LA

**Interviews:**

* Prof Dr Paulo R. Bueno, UNESP, Brazil, http://www.iq.unesp.br/#!/departamentos/fisico-quimica/docentes/paulo-bueno/
* Dr Daniel Egbe, ANSOLE, Germany, www.ansole.org
* Dr Susan Figueroa-Gerstenmaier, University Guanajuato, Mexico
* Prof Dr Wim Sinke, ECN / NanoNextNL, Petten, The Netherlands
* Mr Santiago Nuñez, Director of Technological Development at the Ministry of Science, Technology and Telecommunication of Costa Rica
* Dr Felipe Pacheco, CEO ADROX, http://www.adrox.cl/
* Dr Patricio Jarpa Bisquertt, CEO Nanotec SA, Chile, http://nanotecchile.com/
* Representative Solliance, The Netherlands, Belgium, Germany, [www.solliance.eu](http://www.solliance.eu)

**Participants in the NMP-DeLA workshops covering Nano for Energy (Monterrey, Mexico, November 2014 and Curitiba, Brazil, May 2015**

* Prof Dr Bob Chang, Department of Materials Science and Engineering, and Argonne-Northwestern Solar Energy Research (ANSER) Center, Northwestern University, USA
* Dr Liliana Licea Jimenez (CIMAV, Monterrey, Mexico)
* Prof Dr Miguel José Yacamán (University of Texas at Austin, USA)
* Dr Bertrand Fillon, Laboratory for Innovation in New Energy Technologies and Nanomaterials, CEA, France
* Prof Dr Wim Sinke, Energy Research Center Netherlands and University of Amsterdam, The Netherlands
* Dra. Lucimara Stolz Roman, Universidade Federal do Paraná, Brazil.
* Dr. Ricardo Faccio, Universidad de la República, Uruguay.
* Dr. Pedro Migoski da Silva, Pontifícia Universidade Católica do Rio Grande do Sul, Brazil.
* Dra. Andreia Gerniski Macedo, Universidade Tecnológica Federal do Paraná, Brasil.
* Dr. Daniel Egbe – University Linz and ANSOLE, Austria

# Annex 2. List of projects on topics of possible application in nanoenergy for LA

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| **Project Acronym** | **Status** | **Project Acronym** | **Status** | **Project Acronym** | **Status** |
| BUONAPART-E | Ongoing | BATTERIES2020 | Ongoing | SOLAR DESIGN | Ongoing |
| CHIPCAT | Ongoing | EVOLUTION | Ongoing | MATFLEXEND | Ongoing |
| DECORE | Ongoing | MAT4BAT | Ongoing | NANOCATE | Ongoing |
| SUSFUELCAT | Ongoing | MARS-EV | Ongoing | SPEED | Ongoing |
| CASCATBEL | Ongoing | SAFEJOINT | Ongoing | NANOPV | Finished |
| BIOGO-FOR-PRODUCTION | Ongoing | FREECATS | Finished | THERMOMAG | Finished |
| FASTCARD | Ongoing | NEXT-GEN-CAT | Ongoing | POEMA | Ongoing |
| NEAT | Finished | ARTESUN | Ongoing | OXIGEN | Ongoing |
| NEXTEC | Finished | MESO | Ongoing | CARBOPREC | Ongoing |
| NANOHITEC | Finished | SOLPROCEL | Ongoing | NANOMEND | Finished |
| FAST TRACK | Finished | MATHERO | Ongoing | NANOMAG | Ongoing |
| SCALENANO | Finished | MUJULIMA | Ongoing | LABOHR | Finished |
| STABLE | Finished | OCMOL | Finished | AUTOSUPERCAP | Finished |
| NECOBAUT | Finished | EUROLIION | Finished | LEMSUPER | Finished |
| R2R-CIGS | Ongoing | DEMCAMER | Finished | CRM\_INNONET | Finished |
| SMILEY | Ongoing | CEOPS | Ongoing | MANPOWER | Ongoing |
| SOLAROGENIX | Ongoing | GREENANOFILMS | Ongoing | SINERGY | Ongoing |
| APPLES | Finished | LISSEN | Finished | HYDROBOND | Ongoing |
| ELECTROGRAPH | Finished | EUROLIS | Ongoing | EUROTAPES | Ongoing |
| GECCO | Finished | SMARTONICS | Ongoing | NOVACAM | Ongoing |
| ALIGHT | Finished | PLIANT | Ongoing | CARINHYPH | Ongoing |
| NWS4LIGHT | Finished | INTEC | Finished |

1. This mainly bibliometric study resulted in the mapping of research, institutions and scientific output in the field of nanoenergy in LA. It is published as Invernizzi et al (2015) and available on the NMP-DeLA website. [↑](#footnote-ref-2)
2. These indicators are incorporated into the General Roadmap on nanotechnologies for health, water and energy for Latin America, published by Malsch et al (2015) on the NMP-DeLA website. [↑](#footnote-ref-3)
3. The Innovation Strategy is published as a separate document at NMP-DeLA website. [↑](#footnote-ref-4)
4. Originally published as chapter 5 in Ineke Malsch, Ethics and Nanotechnology [www.nanoarchive.org/11110](http://www.nanoarchive.org/11110) [↑](#footnote-ref-5)
5. [www.nanonextnl.nl](http://www.nanonextnl.nl) [↑](#footnote-ref-6)
6. [www.ecn.nl](http://www.ecn.nl) [↑](#footnote-ref-7)
7. [www.ansole.org](http://www.ansole.org) [↑](#footnote-ref-8)