



CO_2 Capture and Storage in Portugal

A bridge to a low carbon economy

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Acknowledgements and legal disclaimer

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More information on *CCS-PT* is available on http://ccsroadmap.pt

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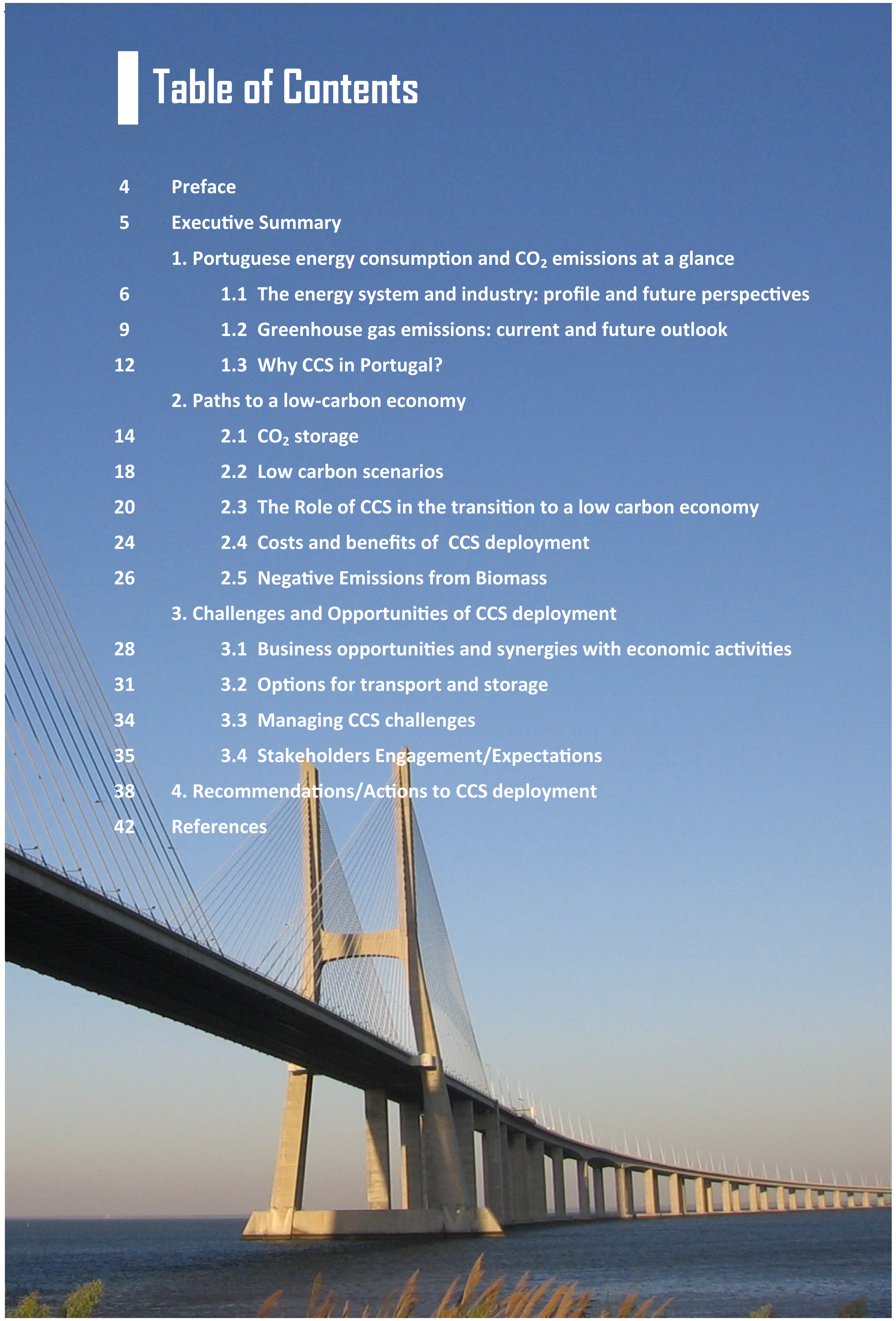


Foreword

Current projections indicate that further efforts are required at national and EU level to keep the EU on track towards its new 2030 targets, and cut EU's greenhouse gas emissions by 80 to 95 % by 2050, as its longer term objectives to decarbonise the European energy and industry system in line with global climate stabilization achievement. This study shows how low carbon technologies interplay up to 2050 to achieve aggressive mitigation targets in Portugal, under diverse scenarios conditions. While power generation appears to become increasingly supported by renewables and energy efficiency, intensive industry should consider CCS for deep CO_2 emissions cuts from industrial processes. As soon as private companies and public policy bodies identify the needs and opportunities from adopting CCS, while taking current uncertainty, the higher the chance to prevent competitive losses while bridge Portugal to a carbon constrained economy.

Júlia Seixas

Lisbon, February 2015

Scientific coordinator of the project CCS-PT

Executive Summary

Aiming to tackle climate change, several countries and regions have been setting mitigation targets, and defining greenhouse gas (GHG) reduction policies and measures, mostly linked with their energy supply, transport and industry. EU vowed to cut 40% its GHG emissions by 2030 relative to 1990 levels, and perspectives to cut 80% by 2050, which requires a diverse portfolio of clean technologies, including carbon capture and storage (CCS). This report evaluates the role the CCS technology may play in the Portuguese energy and industry system as a mitigation option to achieve deep GHG emissions reduction. The cost-effectiveness conditions for its deployment, and the risks and additional benefits it may provide for economic development are also analysed.

Results show that under a high socio-economic development and -80% GHG reduction target, CCS technology is deployed as cost-effective technology from 2030, and by 2050 captures more than 20% of the total GHG emitted in that year compared to a Reference scenario (Figure 11). Power sector and cement production are the only sectors in which CO_2 captured technology is installed and onshore being the primary option for CO_2 storage.

Under all mitigation scenarios modelled, CCS is deployed in significant volumes in the cement sector. Given the availability of renewables generation in Portugal, deployment of CCS in the power sector is relatively low and varies significantly depending on the scenario examined. With high socio-economic development and -80% GHG reduction target, CCS in power sector is only deployed in significant volumes by 2050. With more modest emissions reduction targets (i.e. 60% rather than 80% of emissions reductions by 2050) and with high fossil fuel prices, there are negligible amounts of CO_2 captured in the power sector (e.g. Figure 11).

The difference in the total energy system costs (including supply and demand side, such as industry) between the scenarios with and without CCS, indicate that for all the scenarios, in the long term the earnings surpass the costs. The higher the need for abatement, the more significant are the economic benefits of CCS, revealing that alternative mitigation technologies can be more expensive. Under the same climate change policy mitigation scenario, for example, the price of electricity production in 2050 without the availability of CCS will be significantly higher (more than three times) than a scenario where the technology is available.

1.

Portuguese energy consumption and CO_2 emissions at a glance

The Portuguese final energy demand and greenhouse gas emissions increased around 30% and 15%, respectively, since 1990.

1.1 The energy system and industry: profile and future perspectives

Portugal has undergoing profound social and economic transformations, which have been reflected in its energy system.

Following a period of fast growth in the 1990s, the energy supply has grown more modestly in the 2000s reaching a peak in 2005 (Figure 1), accompanying the economic development. After this period, energy supply has been sharply declining, associated with an increase of energy efficiency and more recently a decrease of consumption.

Portugal is highly dependent on imported energy, which has motivated the diversification of its energy profile. In 2012, Renewable Energy Sources (RES) (mostly biomass, hydro and wind power) accounted for 21% of the primary energy supply (Figure 1), comparing to 18% in 1990. Although this represents one of highest shares of renewable energy supply in EU member states, the Portuguese energy imports dependency (around 79%) is far above the EU28 average (53%), making the country highly exposed to the volatility of the World energy markets. In fact, fossil fuels accounted for 76% of primary energy demand (Figure 1). Oil remains the largest energy source, providing 44% of energy supply, while natural gas and coal represent 18% and 14%, respectively.

The past decade has seen a growing investment in renewable power capacity, mostly wind power, spurred by national support schemes (e.g. feed-in tariff). Currently renewables capacity account for 54% of the total power capacity (Figure 2). This commitment on renewables has been reflected in the national power production (Figure 3). In 2006, an average hydrologic year, the electricity generated from renewable sources was 34% of power generation, while in 2012, a dry year, it represented 44%. Although the diversification of renewable sources has been attenuating this aspect, hydropower plays a crucial role in the Portuguese electricity mix, which is highly dependent on the hydrological conditions (e.g. in 2010 a wet hydrological year, renewables achieved 54% of the total national power generation). Moreover, the climatologic conditions can also affect the electricity market. In a wet hydrological year domestic production can cover around 95% of electricity consumption (e.g. 2010), while in dry years the net imports can achieve almost 20% of demand (e.g. 2012). The availability of the renewable sources and the projections about the impacts of climate change on southern Europe and Mediterranean regions, including Portugal – decrease of annual water flows by 40% (IPPC, 2013) – can make the country's power sector very volatile to weather conditions.

The decommission of the only two coal power plants, reducing the thermal generation and the current constraints regarding the connection between the Iberian electricity market with the rest of Europe, make the planning of the national power supply a very sensitive issue.

In 2012, Portugal's total final energy consumption has gone by 30% from 1990. Figure 4 provides an overview of the national energy system in 2012, and the flows within it. Transport sector was the largest purchaser, accounting for 36% of the total. Industry and other sectors (residential, services and the primary sector) used each 32% of the total. Over the past decade, the share of transport sector has remained fairly stable, while industry has seen its shares decline by 2% per year.

On an energy source basis, oil provided 48% of final energy consumption, followed by electricity (26%) and natural gas, (10%).

FIGURE 1 *Primary energy supply.*
Source: based on (DGEG, 2013)

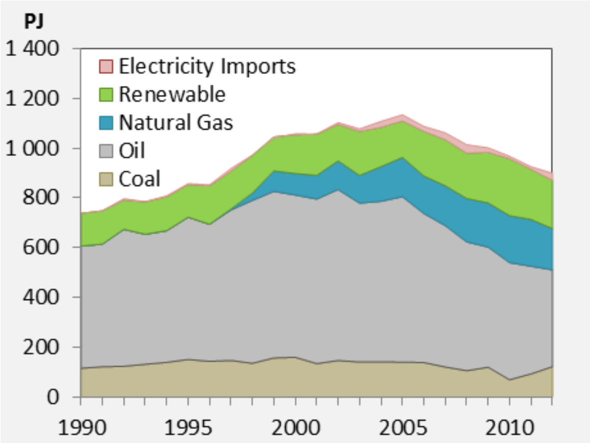


FIGURE 2 *Power Capacity*
Source: based on (IEA, 2013)

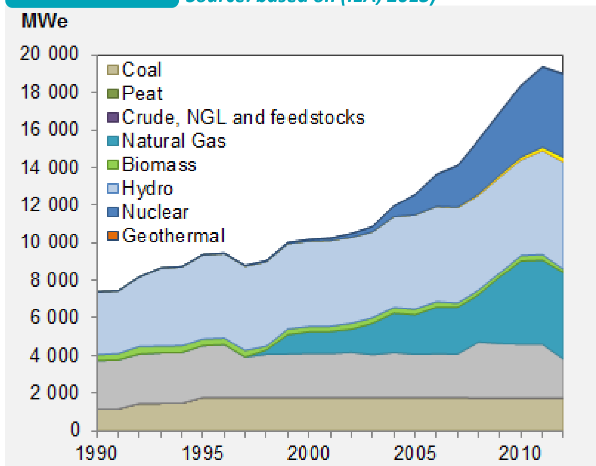
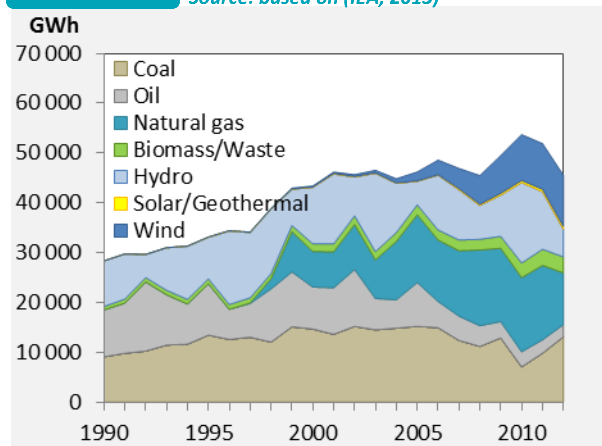


FIGURE 3 *Power generation*
Source: based on (IEA, 2013)



The Portuguese Energy Policy (Presidency of the Council of Ministers, 2011) aims to strengthen the competitiveness of the energy sector, fostering environmental and economic sustainability. In general, Portuguese energy policy targets are sustained by EU policy framework namely in terms of renewable energy consumption (renewable energy directive 2009/28/EC) and energy efficiency (directive 2012/27/EU).

The Portuguese energy policy is currently supported by two main planning documents: i) the Renewable Energy Action Plan (NREAP) and the ii) Energy Efficiency Action Plan (NRAP) (RCM 20/2013), which set a framework of measures, lines of action and national commitments with regard to the use of energy from renewable sources and energy efficiency, respectively.

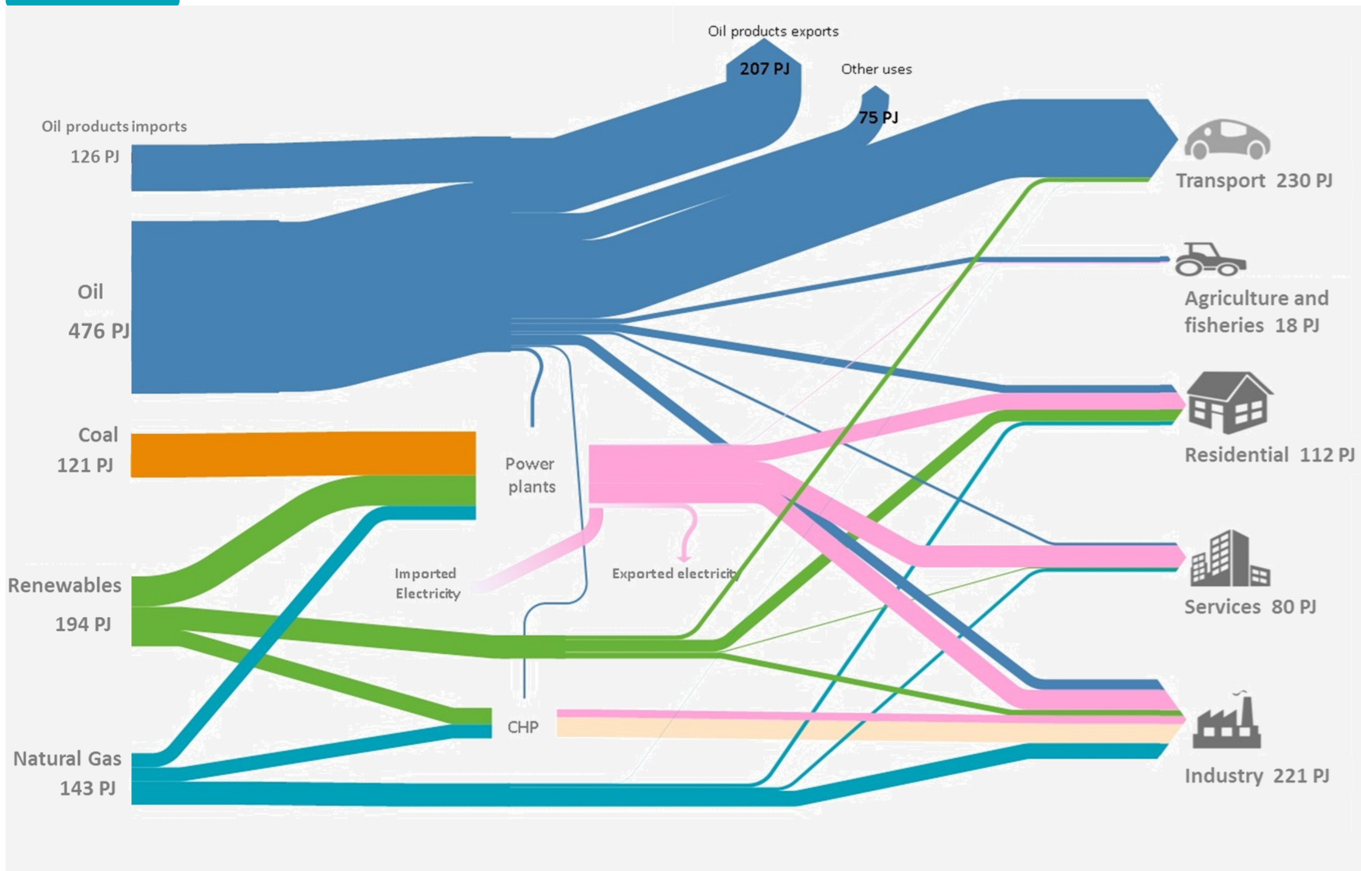
NREAP comprises sectorial annual targets up to 2020, namely: 49.6% of renewable electricity (RES-E), 33.6% of renewable energy consumption in heating and cooling (RES -H&C) and 11.5% share of renewable energy in transport (RES-T), corresponding to a total consumption of gross final energy from RES of 31.7% in a reference scenario. In an additional energy efficiency scenario Portugal defines a more ambitious goal – 34.5%, disaggregated as followed: 59.6% of RES-E, 35.9% of RES-H&C and 11.3% of RES-T. (RCM 20/2013)

In its turn, the NEEAP, embraces two additional goals for 2020: 25% savings of the national primary energy consumption as compared with the projections derived by the EU model PRIMES in 2007 and a specific 30% savings target for the Public Administration, related with current consumption in public buildings and infrastructure.

According to EU renewable energy will play a key role in the transition towards a competitive, secure and sustainable energy system. EU proposed an global objective of increasing the share of renewable energy consumption to 27% by 2030. Considering the high national renewables potential and the ambitious agenda of the current public policy, it is expected that Portugal becomes a EU leader in renewable electricity exports with the increase of electricity interconnections between Iberia and the rest of Europe .

> *“Portugal is highly dependent on imported energy, which has motivated the investment on the diversification of its energy profile.”*

FIGURE 4 *Portuguese energy system 2012*

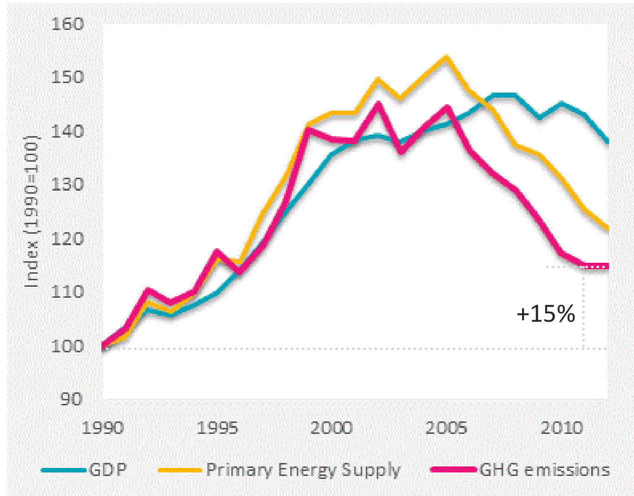


1.2 Greenhouse gas emissions: current and future outlook

The increased consumption of renewable energy sources, the growth of energy efficiency, mainly in sectors covered by EU ETS, and the economic crisis after 2009, have been inducing a decoupling between GHG emissions and GDP. In 2012, the Portuguese GHG emissions represented 115% of the 1990 levels (Figure 5) (excluding the emissions from land use, land-use change and forestry (LULUCF)). The decline registered after 2005 (around 5% per year) was not enough to overcome the marked rise of GHG emissions in the preceding years, especially until the late 1990s. Despite this, in 2012 the Portuguese GHG emissions per capita were below the EU average (6.5 t CO_2e/hab. versus 9.0 t CO_2e/hab. of EU28).

The majority of the national emissions are from energy and industrial processes representing together 77% of the total GHG (excluding LULUCF) in Portugal in 2012.

FIGURE 5 *Portuguese greenhouse emissions (excl. LULUCF), GDP and primary energy supply index. Source: Based on (APA, 2013)*



Energy (i.e., combustion emissions) and industrial process emissions are responsible for almost 100% of the CO_2 emitted. Electricity production and petroleum refining represent 35%, similar to transport sector (34%). Industry represents 22%, and within that 31% are from CO_2 processes emission, essentially from cement production (Figure 6).

The two main point sources of the Portuguese emissions are the two coal power plants Sines and Pego, representing together 22% of the current (2012) national emissions.

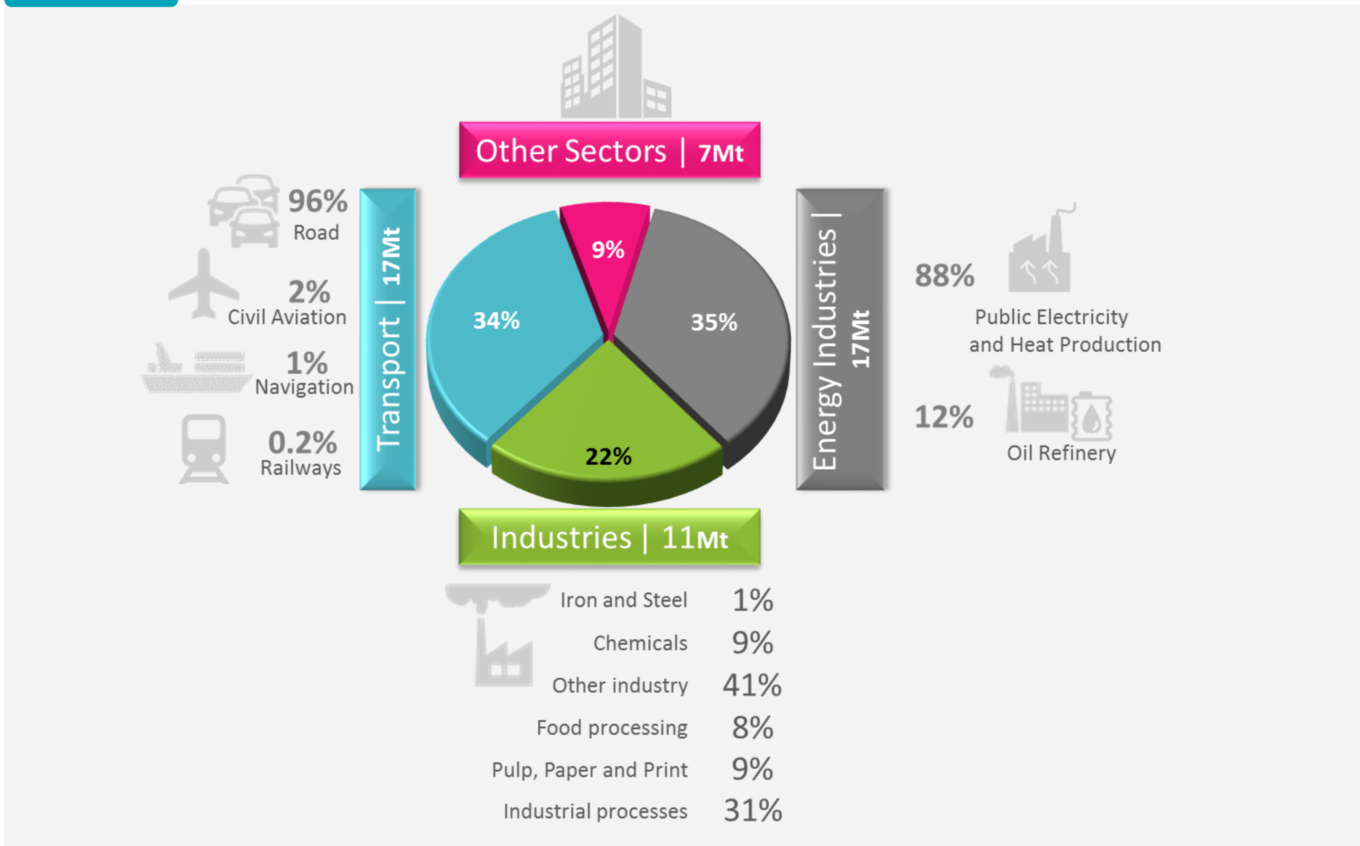
Portugal does not have a significant heavy industry, as a result this industrial emissions are lower than the ones from coal power plants. Industrial emissions are mainly represented by its two oil refineries in Sines and Matosinhos and cement units. The cement sector, with six units from two companies: Secil and Cimpor, has been a crucial sector in the Portuguese economy.

Figure 7 and Table 1 represent the location of the key point sources of the Portuguese GHG emissions and the CO_2 values from selected major sources, respectively.

The Ministry of Environment, Spatial Planning and Energy is responsible for the conception, development and implementation of Portuguese energy and climate change policies. Following the EU climate policy framework, Portugal is currently legally committed to limit the increase of the GHG emissions from the sectors not included in the EU ETS up to +1% through 2020, comparing with 2005 levels (EC, 2009). Energy intensive sectors (e.g. national power sector, refinery, cement emissions) are subject to the EU cap and trade system (EU ETS).

Assuming the continued energy and climate national policies beyond 2020 (e.g. minimum 31% of RES and +1% of non-ETS emissions) and the expected increase for ETS CO_2 price[1], the national GHG emissions are expected to reduce between 37% and 29% (Low and High economic growth) in 2030 and between 41% and 28% in 2050 comparing with 1990 values. These emissions projections, stated as the Reference scenario of the present study, were estimated to assess the energy system pathway, if no additional mitigation policies and measures will occur. That reduction, mostly due to energy efficiency and the decommissioning of the two national coal power plants between 2020-2030 period[2], does not meet the whole EU GHG mitigation goals of -40% for 2030 (EU 2030 framework) and -80% for 2050.

FIGURE 6 *Portuguese energy and industrial CO_2 emission in 2012.* *Source: Based on (APA, 2013)*



[1]According to the Reference scenario of the *EU Energy, Transport and GHG emissions trends to 2050* report (EC, 2014): ETS CO_2 price will range from 5 $€_{2010}$/t currently to 35$€_{2010}$/t in 2030 and 100 $€_{2010}$/t in 2050.

[2]Although the NREAP states the decommission of Sines coal power plant in 2017 and Pego in 2021, in our study, they were postponed to 2020 and 2025 respectively, following recent stakeholders perspectives.

FIGURE 7 *Portugal main GHG emissions point sources (larger squares and blue letters associated to higher emission sources)*

TABLE 1 *CO_2 emissions (Gg) of selected of the Portuguese major emitters in 2010, 2011 and 2012 (EEA, 2014)*

Sector	Unit name	2010	2011	2012
Power sector	Sines coal power plant	4 438.2	6 251.6	7 785.6
Power sector	Pego coal power plant	1 619.5	2 137.0	3 188.2
Power sector	Tapada do Outeiro CCGT	1 886.3	1 735.0	1 007.9
Refinery	Sines refinery	2 050.7	1 769.2	1 899.8
Cement	Cimpor - Centro de Produção de Alhandra	1 321.2	966.9	893.9
Power sector	Ribatejo CCGT	1 167.3	426.6	95.5
Cement	Souselas	1 384.6	1 212.4	1 033.3
Cement	SECIL - Outão	1 296.4	1 209.8	999.0
Refinery	Porto refinery	781.4	843.0	822.2
Cement	Maceira-Liz	628.4	565.2	462.3
Cement	Centro de Produção de Loulé	342.0	169.9	316.7
Cement	Cibra-Pataias	390.8	321.4	271.2
Power sector	Lares CCGT	1 160.4	1 164.9	521.8
Power sector	Pego CCGT	229.4	596.1	567.5

1.3 Why CCS in Portugal?

Global warming threatens the prosperity, health and security of all nations and peoples, and the damaging effects of climate change will affect all future generations. Reducing the impact of climate change requires the implementation of strategies to reduce the GHG that are changing our planet's atmosphere and climate system.

At present, global levels of GHG are increasing. The Intergovernmental Panel on Climate Change (IPCC) has stated that the greenhouse gas emissions must be reduced by 80 to 95 percent by 2050 (IPCC, 2013) in order to stabilize the climate system until the end of 21 century. In order to achieve such ambitious emission reductions, EU defined long term mitigation goals supported by a set of scenarios within Roadmap for moving to a low-carbon economy in 2050 (EC, 2011a) and Energy Roadmap (EC, 2011b).

As shown previously (Section 1.2), the Reference scenario estimated that the expected de-growth of CO_2 emissions will not be enough to decarbonize significantly the Portuguese economy up to 2050, clearly distancing Portugal from the EU goal of 80% GHG reduction.

CCS has already been identified as part of the solution to GHG mitigation at Global and EU level. This technology allows to radically reduce the CO_2 emissions from large point sources such as coal and natural gas power plants and emissions from industrial processes.

The Portuguese National Low Carbon Roadmap 2050 (APA; 2012), launched in July 2012, pointed the adoption of CCS by some power plants and industries as a cost-effective option in Portugal for the mitigation portfolio. More recent findings in the EU-FP7 COMET project highlighted that CCS can play an important role in reducing the national CO_2 emissions even under moderate mitigation targets (40% reduction in 2050, when compared to 1990 emissions level).

Moreover, the Portuguese Implementation Plan of the SET-PLAN (JRC, 2011) defined priority activities including actions to facilitate the implementation of CCS technology in the country. However, basic requirements for discussing the relevance of CCS in the country, such as characterizing the stationary sources, assessing the storage capacity, evaluating the cost-effectiveness of the technology under different conditions and identifying regulatory issues, had to be addressed before developing the roadmap.

The deployment of CCS requires timely and stable action to establish the required infrastructure on time (GCCSI, 2011), namely the installation of capture technologies, the construction and implementation of pipelines network, and the assessment and evaluation of storage reservoirs to eliminate and/or manage the uncertainties and risks demands over time. It is necessary to address the actions required to deal successfully with all aspects of CCS, including stakeholder's engagement, public acceptance, technology development, and finance and organizational issues, in order to overcome barriers and make use of synergies and opportunities to drive the deployment of CCS.

This publication presents relevant aspects of CCS in Portugal, contributing with technical information, to the national debate on CCS deployment and becoming a starting point for setting a Portugal CCS Roadmap.

"CCS — CO_2 Capture and Storage — is a technology designed to reduce CO_2 emissions. It is applicable to large factories and fossil fuel power plants to greatly reduce damaging CO_2 emissions. With CCS the CO_2 is removed from the flue gas coming out of the factories and power plants. The CO_2 is then injected deep below the ground, instead of being dumped into the atmosphere, as is the case today".

2

Paths to a low-carbon economy

Scenarios are alternative visions of how the future may unfold. They help us understand and explore future uncertainties and manage the challenges ahead.

It is increasingly recognized that pathways towards a low carbon economy is vital pillar of sustainability and structural competitiveness. Assuming Portugal aims to be on track toward a low carbon economy, it is crucial to identify the most cost-effective options to reduce national emissions and analyze the role CCS could play in a decarbonized future.

This chapter aims to answer the following questions, using cost-effective optimization modeling tool TIMES_PT (Simões *et al*. 2008) to develop low-carbon scenarios.

- What is the national CO_2 storage capacity and where are the potential storage sites located?

- What economic activities are eligible for CO_2 capture, as a cost-effective mitigation option?

- What is the potential of emission reduction expected from CO_2 capture?

- What are the costs and benefits for the Portuguese energy system if CCS is deployed in the country?

2.1 CO_2 Storage

Rocks are the largest reservoir of carbon on the planet, holding it in the form of coal, hydrocarbons and carbonated rocks. Geological storage of CO_2 aims to mimic that natural process, trapping CO_2 from anthropogenic sources into deep geological formations for long periods of time (Box 1). The operational aspects of storage of CO_2 in geological formations are based on the mechanisms and technologies developed by the oil industry, where injection of CO_2 in geological formations is a common practice since 1972 to enhance oil recovery (EOR). According to the Global Status of CCS (GCCSI, 2014a), as of November 2014, 26.6 Mt of CO_2 were injected, either for EOR purposes or as a climate change mitigation technology.

Deep saline reservoir[4], depleted hydrocarbon reservoirs and the use of CO_2 in EOR are the main scenarios for CO_2 storage, in all cases requiring permeable rocks (sandstones, limestones...) occurring in sedimentary basins. Unminable coal seams have been considered for CO_2 storage, but operational issues and reduced capacity has led to a decline of interest in this type of reservoir. Since exploitable hydrocarbons are yet to be found in Portugal, the storage possibilities are restricted to deep saline reservoirs in sedimentary basins.

Sedimentary basins in Portugal cover less than a third of the onshore territory, and occur along the Atlantic coast and spread offshore, composing most of the Continental Shelf. Three Meso-Cenozoic basins were screened for CO_2 storage capacity: the Porto Basin and Lusitanian Basin, which spread along the west Iberia margin; and the Algarve Basin.

The entirely onshore Tejo/Sado Basin does not meet the basic requirements for CO_2 storage (shallower basin, with important freshwater resources).

BOX 1 ***CO_2 storage operations***

The CO_2 storage operation involves the injection of dense phase CO_2 in reservoirs more than 800 m deep. Although injected with density close to that of a liquid, CO_2 will remain lighter than water and will migrate by buoyancy to the top of the reservoir. Further upward migration is prevented by selecting reservoirs that are overlain by very low permeability rocks, the *seal* or *cap rock*. The requirements for selection of CO_2 storage sites are defined in the EU Directive 2009/31/EC and are translated into the Portuguese decree-law 60/2012.

[4] Deep saline reservoirs, or saline aquifers in the EU Directive terminology, are porous and permeable rocks saturated with non-potable high salinity water or brine, occurring at large depths and without mass transfer with shallower fresh-water aquifers.

The assessment of the CO_2 storage capacity was conducted at regional-scale within the scope of projects COMET (Boavida *et al*., 2013) and KTEJO (Tejo Energia, 2011), and the screening criteria considered several geological constraints (Table 2). Figure 8 depicts the location of the potential storage areas and of the clusters in which they were grouped.

In the fully offshore Porto basin two reservoirs-cap rock pairs were identified as fulfilling the criteria for safe CO_2 storage, namely the Silves Formation reservoir with cap rock from the Dagorda Formation marls and clays, and the Early Cretaceous siliciclastics (hereafter designated as Torres Vedras Formation), sealed by interlayered clays and

FIGURE 8 *Location of potential storage areas and clusters. Also shown the economically viable pipeline routes from and between the main CO_2 source regions..*

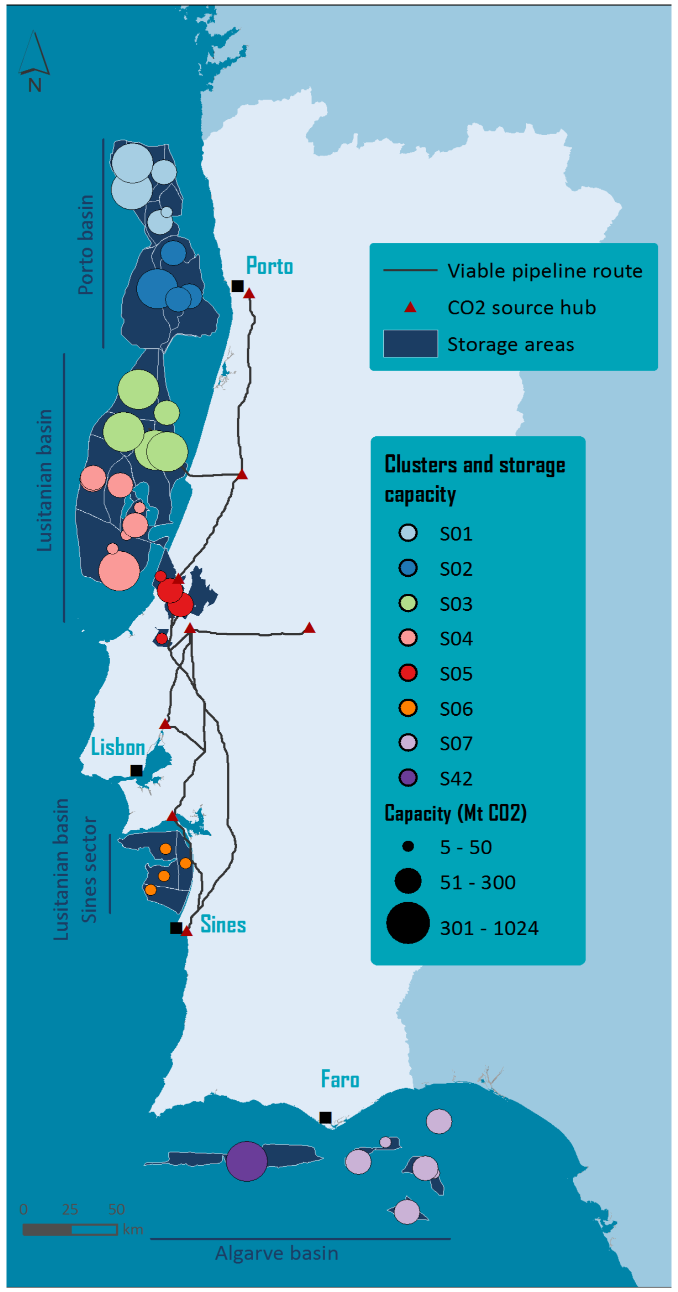


TABLE 2 *Screening criteria. Compiled after Martínez et al., 2010.*

Storage capacity	
Porosity	Preferably> 15%. 6% to 15% - considered depending on other parameters.
Trap type	Traps and regional reservoirs.
Effective pore volume	Storage capacities > 3Mt.
Depth of reservoir	Reservoir top is from 800 m to 2500 m deep .
Injectivity	
Trap type	Open traps/reservoirs to be favoured over closed traps/ reservoirs.
Permeability	Preferably > 200 mD.
Rock mechanics, diffusivity	Take into account geo-mechanical and diffusivity parameters. Maximum pressure - 20% initial pressure
Integrity of seal	
Permeability	Maximum permeability 10^{-2} mD.
Seal thickness	Preferably > 50 metres.
Faulting and tectonic activity	Less faulted formations favoured. Seismo-tectonic behavior to be considered. Discard formations/ traps crossed by active faults.
Homogeneity of seal	Homogeneous and laterally continuous formations to be favoured.

by the Cacém Formation. Several potential storage areas were identified and grouped in two clusters (S01 and S02) according to distance between storage areas.

In the northern and central parts of the Lusitanian basin, where geologic conditions are similar to the Porto Basin, the same reservoirs-cap-rock pairs were identified (Silves Formation and Torres Vedras Formation), and two clusters were defined offshore (S03 and S04) and one cluster was defined onshore (S05), although encompassing only the Silves Formation reservoir since the Early Cretaceous does not comply with the requirements for safe storage.

The onshore sectors of the southern part of the Lusitanian basin (the Sines sector) and of the Algarve basin are not suitable for CO_2 storage, and only the offshore sectors were screened. One offshore cluster, S06, was identified in the Sines sector, encompassing the Silves Formation reservoir. Two offshore clusters were defined in the Algarve Basin, cluster S07, with a Miocene sands reservoir capped by Plio-Miocene shale deposition, and cluster S42, composed by Early Cretaceous carbonated rocks.

[5]The effective storage capacity is obtained by applying a range of technical (geological and engineering) cut-off limits to a storage capacity assessment, including consideration of that part of theoretical storage capacity that can be physically accessed (CSLF, 2007). However, legal and regulatory, infrastructure and general economic barriers are not considered, which will reduce the effective storage capacity.

The effective storage capacity[5] was computed following a volumetric methodology proposed by the EU GEOCAPACITY project (Vangkilde-Pedersen *et al*., 2009). The total CO_2 storage capacity in Portugal[6] is estimated at 7.6 Gt CO_2. The vast majority of the storage capacity is in offshore storage sites, with the onshore capacity being assessed at 340 Mt CO_2 (Table 3). The offshore sites are located in the shallow continental shelf, at very short distance from the coast, a favorable location with respect to the main sources in the country, which are also mostly along coastal regions.

Equally as important as the storage capacity, is the admissible injection rate, that is, the amount of CO_2 that can be injected annually in each storage cluster, which ideally should be above the expected annual captured mass of CO_2. The injection rate in each cluster was estimated taking into account the hydraulic and petrophysic parameters of the reservoir and assuming a maximum pressure increase due to CO_2 injection of 20% of the initial reservoir pressure. The admissible injection rate per cluster varies from 1.7 Mton CO_2/a to 35.7 Mton CO_2/a, with injection rates per well usually less than 0.8 Mt/a in order to avoid fracturing the reservoir and seal, but implying that multiple injection wells are required in each cluster.

A common feature of the reservoirs in the Portuguese sedimentary basins is its tectonised nature, being usually considerably faulted which can impose reservoir compartmentalization. This is a considerable source of uncertainty, since there is scarce information about the hydraulic behavior of those faults. Furthermore, there is a need to reduce uncertainty about the permeability of the Silves Formation reservoir, which occurs in every instance at considerable depths, often more than 2000 m deep. These uncertainties can affect considerably the estimates of the injection rate and storage capacity, but can only be overcome by conducting hydraulic tests or implementing pilot test sites.

> *“Portugal has a total storage capacity of around 7.6 Gt CO_2, more than six times the CO_2 emissions of the last two decades“*

[6]The efficiency factor (S_{eff}), i.e. the proportion of accessible pore space that can filled with CO_2, is site specific and needs to be determined through numerical simulations. The US DOE (U.S. Department of Energy) indicates efficiency factors varying from 0.5% to 5.4% in clastics aquifers, for the P10 and P90 percent probability range, respectively, while the GEOCAPACITY project indicates values from <3% to 5% for closed structures. A value of S_{eff}=2% was applied for the capacity assessment in Portugal, but the methodology is linearly dependent on S_{eff}, so admitting a more conservative scenario, say S_{eff}=1%, would return half the storage capacity reported.

TABEL 3 *Main features of storage clusters in deep saline reservoirs in Portugal*

Cluster	Basin	Setting	Reservoir	Lithology	Areas in cluster	Storage capacity (Mt CO_2)	Injection rate (Mt CO_2/a)	
							Cluster	Well
S01	Porto	Offshore	Torres Vedras Fm.	Sandstones	5	1230	16.1	<0.8
S02	Porto	Offshore	Torres Vedras Fm. and Silves Fm.	Sandstones, conglomerates	4	870	3.8	<0.5
S03	Lusitanian	Offshore	Torres Vedras Fm.	Sandstones	5	2200	11.8	<0.8
S04	Lusitanian	Offshore	Torres Vedras Fm. and Silves Fm.	Sandstones, conglomerates	8	1590	11.4	<0.6
S05	Lusitanian	Onshore	Silves Fm.	Sandstones, conglomerates	4	340	10.7	<0.8
S06	Lusitanian (Sines sector)	Offshore	Silves Fm.	Sandstones, conglomerates	4	80	1.7	<0.4
S07	Algarve	Offshore	Early Cretaceous	Limestones	4	410	35.7	<1.0
S42	Algarve	Offshore	Early Cretaceous and Upper Miocene	Limestones and Sands	2	840	13.0	1.0

2.2 Low Carbon scenarios

To show how a low-carbon Portugal might look up to 2050, and to asses how we might get there, a set of scenarios has been built, focusing on the development of the Portuguese energy system and industrial sectors, including their energy consumption/production, technological choices and respective GHG emissions. The scenarios were generated through the TIMES_PT model (Box 2) with differentiated assumptions (Figure 9), regarding:

Socio-economic

→ **High:** GDP growth of 3.0% pa over the period 2020-2050, associated with an reindustrialization of the economy (industry gross value added growths up to 25% in 2050, as current German economy). Population decrease around 0.2% pa from 2010 to 2050 (*High population scenario* of INE, 2014).

→ **Low:** GDP growth of 1.5% pa over the period 2020-2050 and the preservation of the current importance of services and industry sectors. Population decrease around 0.4% pa between 2010 and 2050 (*Central scenario* of INE,2014).

Climate Mitigation Policy

→ **Reference**: The current Portuguese energy-climate policy within the EU climate-energy package extends beyond 2020 and follows the policy assumptions of the *EU Energy, Transport and GHG emissions trends to 2050* report (EC, 2014). For EU-ETS sectors the CO_2 price ranged from 35€$_{2010}$/t CO_2 in 2030 to 100 €$_{2010}$/t CO_2 in 2050.

→ **-60% reduction** of GHG emissions (energy and industrial processes) in 2050 comparing with 1990 levels: scenario in line to what was set by the Portuguese Low Carbon Roadmap (APA, 2012).

→ **-80% reduction** of GHG emissions (energy and industrial processes) in 2050 comparing with 1990 levels: scenario in line with EU wide level by the EU Energy and Low carbon Roadmaps (EC, 2011a, EC, 2011b).

Energy Import Prices

The present study assumes three fossil fuel prices from Energy Technology Perspectives 2014 (IEA, 2014), considering **medium(4D), low (2D)** and **high (6D)** values, as shown in figure 10.

BOX 2 *TIMES_PT*

TIMES is a linear optimization model generator developed by the International Energy Agency, Energy Technology Systems Analysis Program. The ultimate goal of the model is the satisfaction of the energy services demand at the minimum total energy system cost, subject to technological, physical and policy constraints. TIMES defines an optimal combination of existing and emerging technologies, while respecting the framework of polices and measures imposed and the national potential of endogenous resources (e.g. hydro, wind, solar thermal, biomass). TIMES_PT maps the entire chain of the Portuguese energy system, from the energy supply (fuel mining, production, imports and exports), to energy transformation (including power and heat production) and distribution, to end-use demand in industry, residential, services, agriculture and transport and its respective sub-sectors.

TIMES_PT was the model choose for this study as it allows to explore the CCS competitiveness in Portugal regarding other low carbon technologies, identifying the cost-effectiveness of CCS national deployment.

FIGURE 10 *World fossil energy prices , according to world CO_2 emission reduction pathways (IEA, 2014)*

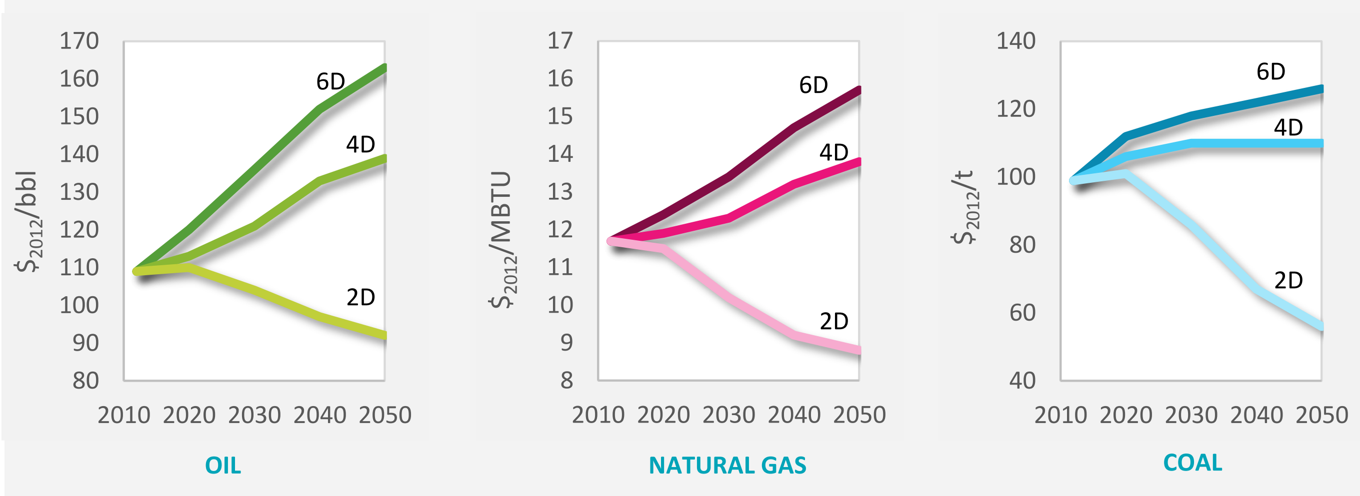


FIGURE 9 *Scenarios matrix*

MODELLING MAIN ASSUMPTIONS

	Scenarios	SOCIO-ECONOMY: Low	High	MITIGATION POLICY: Reference	-60%	-80%	ENERGY PRICES: Low (2D)	Medium (4D)	High (6D)	CCS COSTS AND STORAGE AVAILABILITY – COSTS: Base	-20%	+20%	+50%	STORAGE: Onshore	Offshore	HYDROPOWER – HYDRO CONDITIONS: Average	Dry	Wet	CAPACITY: NREAP	Conserv.
Socio-economic development & Mitigation Policy	Low_Ref	✓		✓				✓		✓				✓		✓			✓	
	High_Ref		✓	✓				✓		✓				✓		✓			✓	
	Low_60	✓			✓			✓		✓				✓		✓			✓	
	High_60		✓		✓			✓		✓				✓		✓			✓	
	Low_80	✓				✓		✓		✓				✓		✓			✓	
	High_80		✓			✓		✓		✓				✓		✓			✓	
Energy Prices	High_60_2D		✓		✓		✓			✓				✓		✓			✓	
	High_80_2D		✓			✓	✓			✓				✓		✓			✓	
	High_60_6D		✓		✓				✓	✓				✓		✓			✓	
	High_80_6D		✓			✓			✓	✓				✓		✓			✓	
CCS costs & Storage availability	High_60_-20		✓		✓			✓			✓			✓		✓			✓	
	High_80_-20		✓			✓		✓			✓			✓		✓			✓	
	High_60_+20		✓		✓			✓				✓		✓		✓			✓	
	High_80_+20		✓			✓		✓				✓		✓		✓			✓	
	High_60_+50		✓		✓			✓					✓	✓		✓			✓	
	High_80_+50		✓			✓		✓					✓	✓		✓			✓	
	High_60_Offshore		✓		✓			✓		✓					✓	✓			✓	
	High_80_Offshore		✓			✓		✓		✓					✓	✓			✓	
	Low_60_Offshore	✓			✓			✓		✓					✓	✓			✓	
	Low_80_Offshore	✓				✓		✓		✓					✓	✓			✓	
Hydropower conditions & capacity	High_60_Dry		✓		✓			✓		✓				✓			✓		✓	
	High_80_Dry		✓			✓		✓		✓				✓			✓		✓	
	High_60_Wet		✓		✓			✓		✓				✓				✓	✓	
	High_80_Wet		✓			✓		✓		✓				✓				✓	✓	
	High_60_Conserv		✓		✓			✓		✓				✓		✓				✓
	High_80_Conserv		✓			✓		✓		✓				✓		✓				✓

CCS technologies

Although CO_2 capture is mostly associated with electricity generation, there are other sectors in which the technology can be applied, namely: iron & steel, ammonia production, petroleum refinery and cement. In Portugal due to the absence of ammonia production and considering the fact that national iron & steel industry is produced from scrap and metallic foils consuming mainly electricity, CO_2 capture can be applied only to power sector, cement, oil refinery industries and the future production of synthetic fuels and gas through fossil fuels gasification.

Due to the uncertainty associated with capture, transport and CO_2 storage costs, four cost scenarios were considered:

→ **Base:** represents the most recent and expected prices forecasts. For the case of cement sector, the investment and O&M prices of capture were validated by national stakeholders based on ECRA, 2009 and ECRA, 2012 reports. Regarding storage and transport, its costs are dependent on site conditions, including aspects such as location, geographical conditions between the capture and storage sites, like topography, crossing of water bodies, among other. Section 3.2. presents the methodology used to define storage and transport costs of Base scenarios. The Appendix shows a summary of the costs and technical data of capture, transport and storage technologies, considered in this study.

→ **Additional CCS costs scenarios**, including investment and O&M costs, for capture, transport and storage, consider higher (+20% and +50%) and lower (-20%) costs comparing with the Base.

A determining factor for the deployment of CCS in a country is related with its storage sites and capacity. Besides considering the possibility of storage CO_2 onshore in Lusitanian Basin, an alternative scenario, assuming mandatory offshore storage for security reasons, was also studied.

Hydropower

Hydropower plays an important role in electricity generation in Portugal. However, its contribution depends on each year's hydrological characteristics, which have high annual oscillations, as illustrated in section 1.1. These conditions can thus influence the competitiveness of CO_2 capture deployment in power sector. Three hydrological scenarios were developed: average, dry and wet, replicating the hydrological conditions of the years 2006, 2005 and 2003, respectively.

The techno-economic potential of new hydro power is a source of uncertainty, as some of the projected capacity set in the NREAP may not have economic reasonableness. Thus, besides a scenario reflecting the NREAP goals, a conservative scenario regarding new hydro capacity was developed, based on stakeholders information. This represents a reduction of the installed capacity in 2050 from 8.8 GW from NREAP scenario to 7.5 GW in the Conservative scenario.

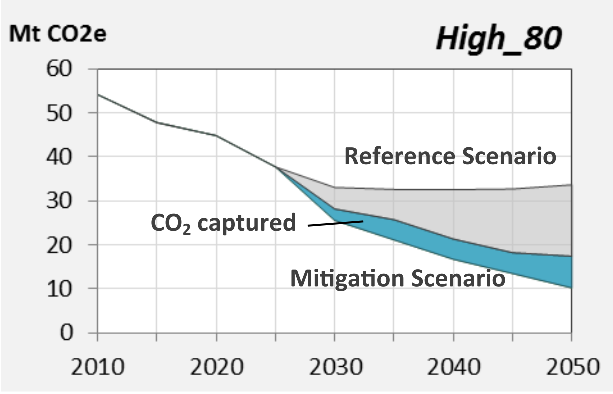
2.3 The Role of CCS in the transition to a low carbon economy

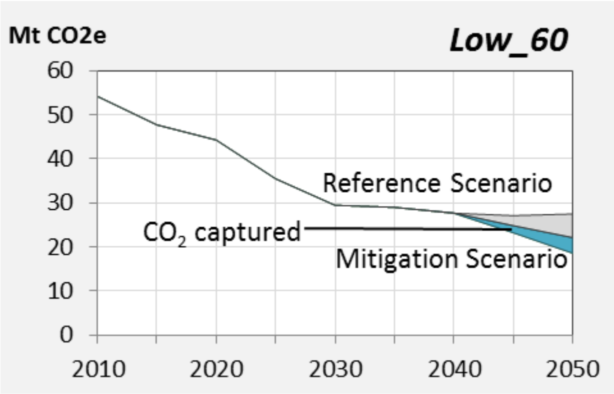
A key condition for CCS deployment is the mitigation policy. The current climate mitigation policy, which reflects a moderate GHG emissions abatement (Reference scenario) is not enough to make CCS a cost-effective option to reduce Portugal GHG emissions. However, more aggressive policies such as the reduction of 60% and 80% of GHG emissions in 2050 comparing to 1990 values, makes CCS a possible economically rentable option beyond 2030. In fact, in 2050, around 21% of the GHG emitted can be captured relative to the reference scenario (Figure 11). The total amount of CO_2 captured up to 2050 does not surpass the onshore storage capacity, which revealed to be the most cost-effective storage solution.

Despite the range of sectors in which CCS can be a mitigation option, due to the Portuguese economic and energy system characteristics, the technology is cost-effective in only two sectors up to 2050: power generation and cement production. For the power sector only under a very restricted set of conditions, such as, meeting the EU's Roadmap GHG emissions and high energy demand, makes the sector a candidate for CO_2 capture in the long term.

Although the high purity of the CO_2 emitted by oil refineries can offer opportunities for low cost demonstration of CCS, if located close to a storage site (Bellona, 2011), according to the scenarios modelled trough TIMES_PT, CO_2 captured is not a cost-effective solution for the Portuguese refineries For the case of Sines for example, it should be underlined that despite located near other possible emitters (substitution of Sines coal power plant by other power units in the long term) and close to a potential storage place offshore (see S06 of Figure 8), this storage site has a very limited capacity and high storage costs (see section 3.2). Thus, the feasibility of CCS in Sines refinery is also conditioned by the development of a transport and storage infrastructure in the area, which was not studied in detail.

FIGURE 11 *CO_2 emitted and CO_2 captured in the mitigation scenarios High_80 and Low_60 comparing with High_Ref and Low_Ref, scenarios respectively*



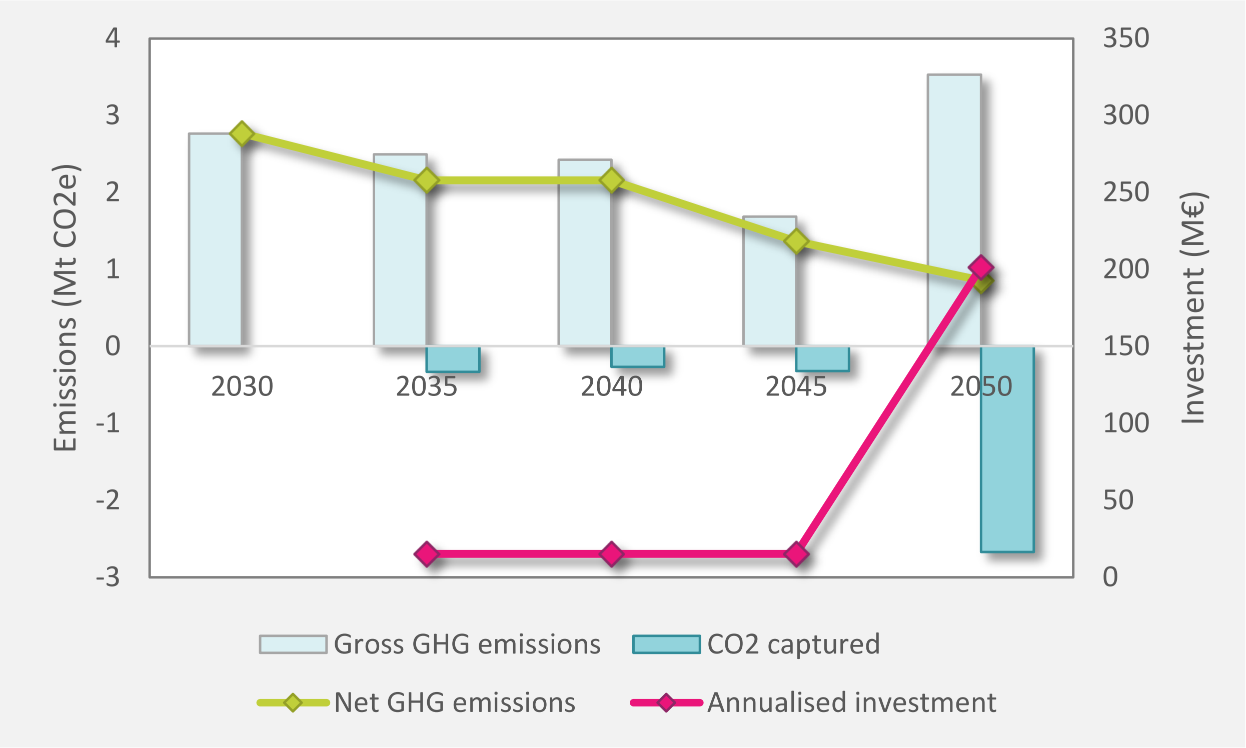


Power Sector

The significant Portuguese renewable potential and the competitiveness of renewable power generation technologies (RES-E), particularly, hydro, wind onshore and solar PV, leave little room for the deployment of CO_2 capture in the sector before 2030 (Figure 12), as most of mature renewable technologies can satisfy electricity demand at lower costs and reduce simultaneously GHG emissions. After 2030, with the decommissioning of the national coal power plants, RES-E generation dominates the Portuguese power production, which can achieve values above 90% in 2050 in the –80% mitigation scenario.

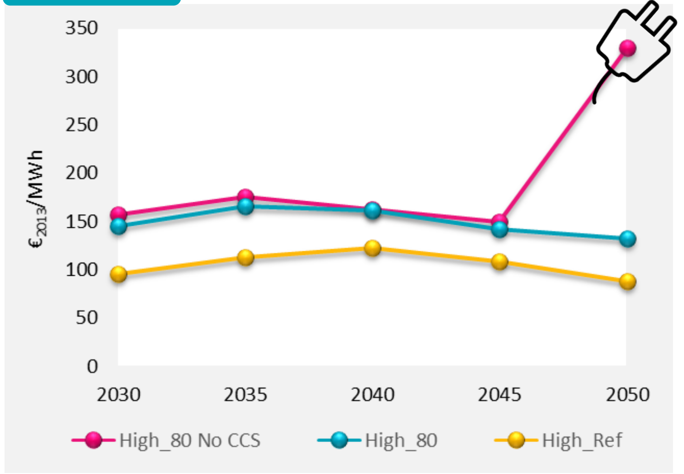
The amount of CO_2 captured becomes material in the power sector only from 2050 (Figure 12), capturing almost 3 Mt of CO_2 emissions with an annualized investment cost for the CO_2 capture technology around 200 million € in that year. The technology is associated to a new natural gas combined cycle power plant, with an installed capacity of 1.7 GW in 2050 for High_80 scenario. Under these conditions, only 8% of the Portuguese power production is associated with CCS, which matches with the high renewable energy deployment scenario of EU roadmap – 7% (EC, 2011b). Given the high levels of renewables generation in Portugal, the amount of emissions captured in 2050 in the *High_80* scenario represents approximately 75% of all power sector emissions.

FIGURE 12 *Power sector GHG emissions, CO_2 captured and investment costs in High_80 scenario*



Although the high renewable potential can preclude large amounts of CCS in the Portuguese power sector, CCS-equipped power plants may increase the competitiveness of the electricity generation system when comparing with a scenario without the availability of the technology, particularly in the long term. Figure 13 shows that, under the same climate mitigation policy scenario, the cost of electricity production in 2050 without the availability of CCS will be significantly higher (more than three times) than in a scenario with the technology made available.

FIGURE 13 *Electricity cost production*



CO_2 capture in the power sector occurs in all scenarios by 2050 however becomes significant only under certain circumstances (Figure 14). High socio-economic development, resulting in high electricity demand, associated with the EU's Roadmap GHG emissions scenario (High_80), as well as lower fossil energy import prices (High_60_2D) and dry conditions (High_60_Dry) make CCS a cost-effective technology even in a moderate mitigation scenario (-60% reduction in 2050 comparing with 1990 values). Low fossil import prices, associated with the EU's mitigation policy results in the most cost-effective combination for CCS deployment, with in the installation of CO_2 capture in the power sector early in 2030. Scenarios with higher CCS costs and hydrological wet conditions results in far less CCS deployment.

Cement sector

Cement is an important industrial sector in the Portuguese economy. Before the current economic crises, Portugal had one of the highest levels of cement production per capita in the EU. Currently the six cement manufacturing units associated with two private companies are exporting a relevant part of its production (almost 50%). According to CCS Status 2014 (GCCSI, 2014a), "CCS is the only technology that can achieve large reductions in CO_2 emissions from industries such as iron, steel and cement", where CO_2 is an unavoidable output. Thus, for all the mitigation scenarios (-60% and -80%) CO_2 captured is deployed in cement sector, although its deployment timeline varies (Figure 15). For a high socio-economic growth and mitigation scenario (-80%) the technology is cost-effective already in 2030, capturing 58% of cement GHG emissions (2.6 Mt), increasing up to 86% in 2050. However, for a low socio-economic growth and a more moderate climate policy mitigation goal (-60%) the technology only becomes a cost-effective option in 2045.

In 2050, all the process emissions are captured under high growth for both mitigation scenarios, and a low growth scenario with 80% reduction. The values of CO_2 captured are related with investment in oxyfuel combustion technology. As shown in Figure 15, the annualized costs for CO_2 capture can achieve a range of 200-340 M€ in the period 2030-2050, for a high mitigation scenario and of 100 -300 M€ for a moderate mitigation.

FIGURE 14 *CO_2 captured in power sector per scenario*

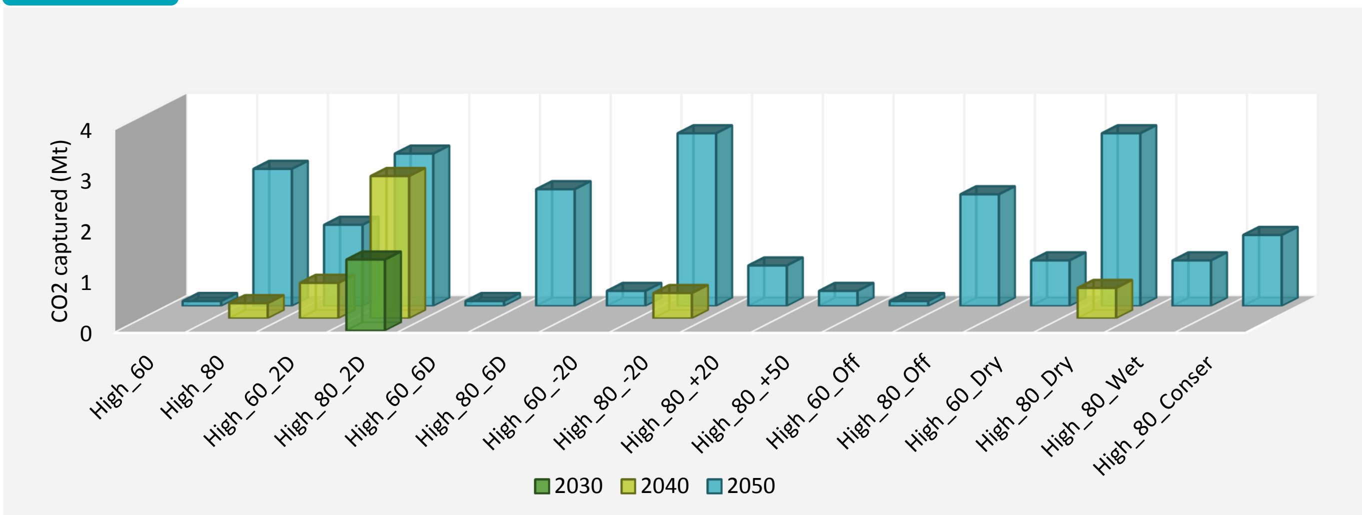
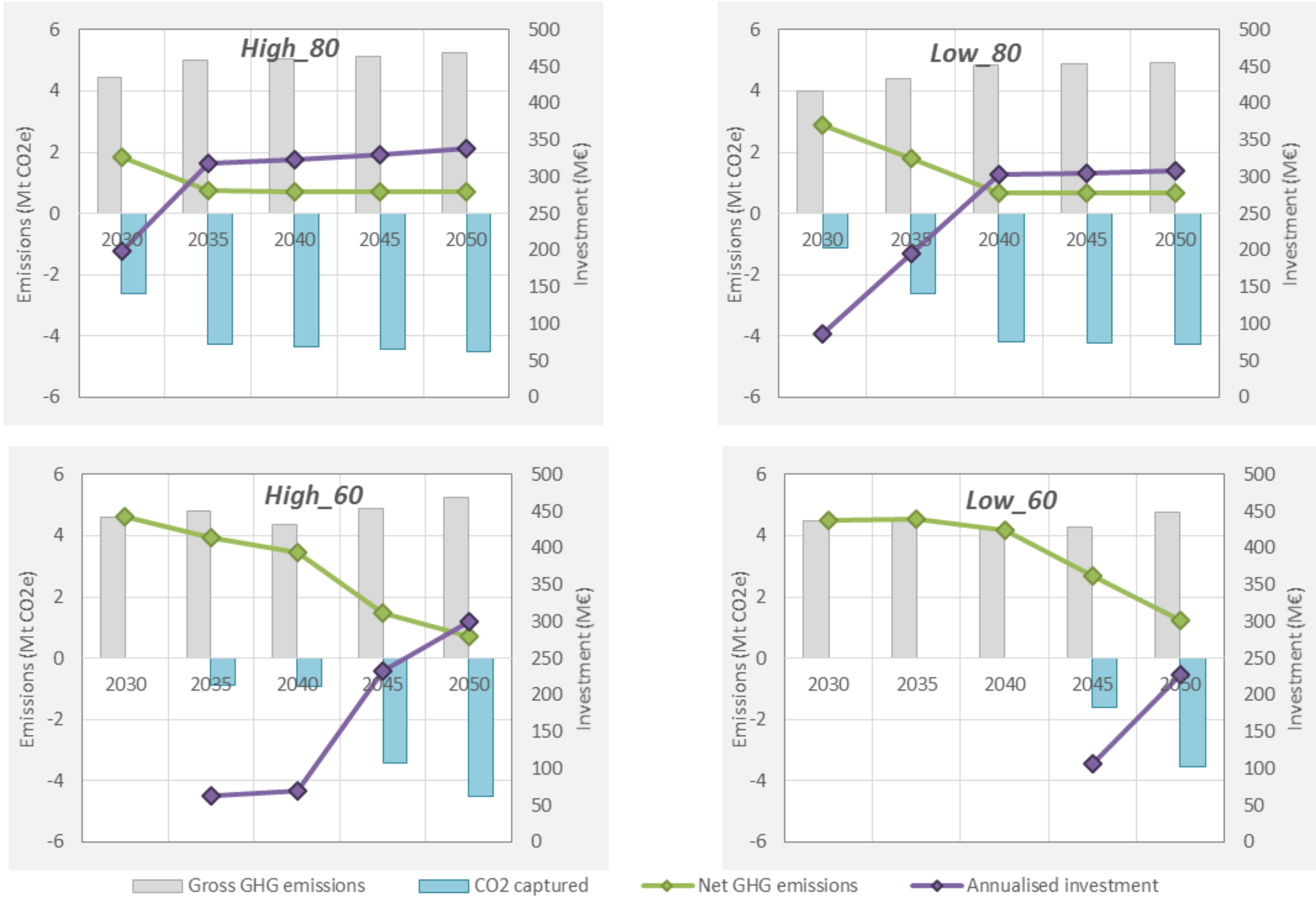


FIGURE 15 *Cement GHG emissions, CO_2 capture and annualized capture investment costs per scenarios*



All the cement production capacity is located in the current locations in the vicinity of the raw materials. Due to the small size of Loulé cement plant, the installation of CAC in this unit is not expected. Also due to the location of Outão plant in the Arrábida Natural Park, it is expected some social barriers due to pipeline transport of CO_2, which may require a more detailed analysis of transport by ship, subject not addressed in this study.

For all mitigation scenarios CO_2 capture is deployed in the cement sector (Figure 16). This corroborates the conclusions of the debate "vision of a low carbon European cement industry" (CEMBUREAU, 2012), which identified CCS as one of critical technologies to maintain a competitive cement industry in a carbon constrained world.

Economic factors like the increase of CCS costs or mandatory offshore can delay the deployment of the technology in time. However, for most of the scenarios, by 2050 more than 85% of the sector emissions are captured. The combination of low economic growth and moderate GHG emissions reduction (-60% in 2050) can be detrimental for the deployment of CO_2 capture in the cement sector, particularly when onshore storage is not allowed (Low_60_Off). In this scenario, CCS is installed later in 2050 and a small amount of CO_2 is captured, less than 1.5 Mt, which limit the competitiveness of the technology.

2.4 Costs and benefits of CCS deployment

The deployment of CCS will require capital investment for capture technologies, transport pipelines and the preparation of storage sites, as well as operation and maintenance costs. Considering base scenario CCS costs and the possibility of storage onshore, total CCS costs can range from 500 million € in 2030 to around 1350 million € in 2050

"CCS represents a cost-effective mitigation option for the Portuguese power sector just after achieving the maximum potential of mature renewable technologies, i.e., hydro, wind onshore and solar PV."

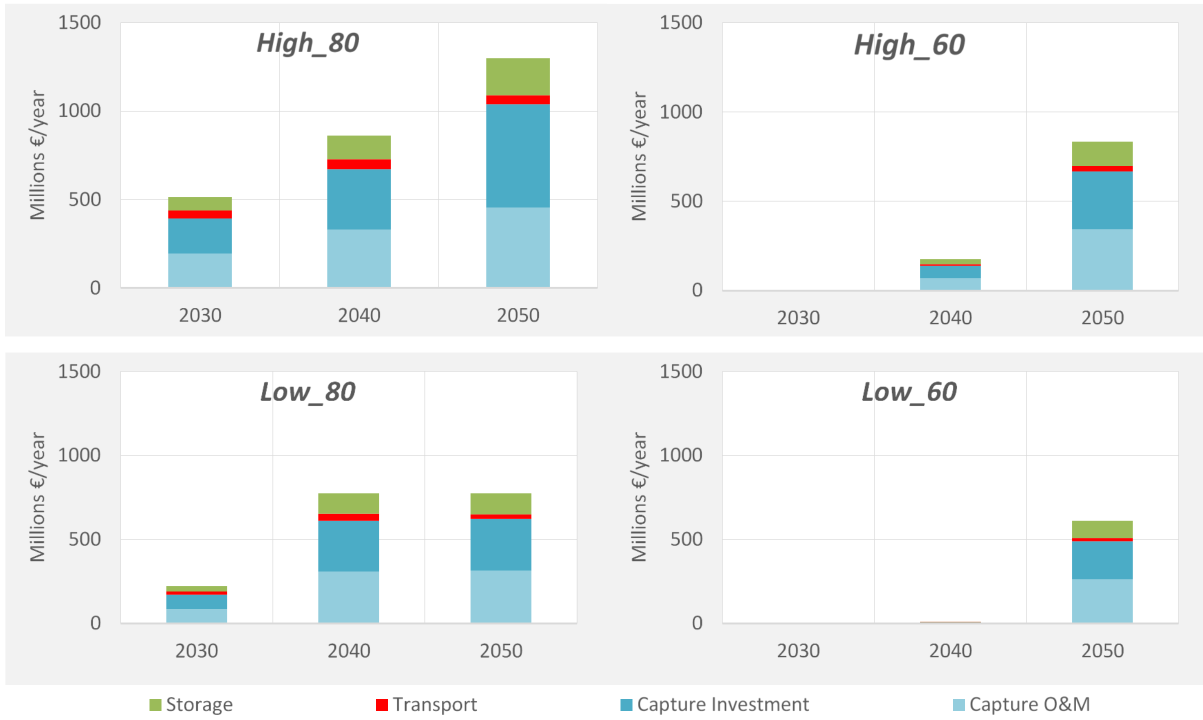
"CCS is a important technology to maintain a competitive national cement industry in a future carbon constrained world"

for High socio-economic scenario associated with the EU's Roadmap reduction of GHG emissions (-80% in 2050) to just nearly 600 million € in 2050 for Low socio-economic scenario linked to less demanding mitigation policy (-60% 2050/1990) (Figure 17), capture costs are the most significant ones, particularly the annualized investment costs, which represent around 39% in average. Transport cost rounds 5% and storage about 15% of total costs (investment and O&M). It should be underlined that, in these scenarios, no EU-ETS CO_2 price is considered, although a shadow price is generated due to the imposition of a CO_2 target.

The total cost of CCS will go around 200 €/tCO_2/a in 2030 to 180 €/tCO_2/a in 2050 (Table 4). Onshore transport will cost around 17 and 7 €/tCO_2/a in 2030 and 2050, respectively, including the investment associated with pipelines building, O&M costs and the cost of electricity consumed in the booster stations. For the case of onshore storage, significant technological learning is not considered, and thus its cost rounds 30€/t/a (28 €/t/a associated with investment and 1.4 €/t/a related to O&M).

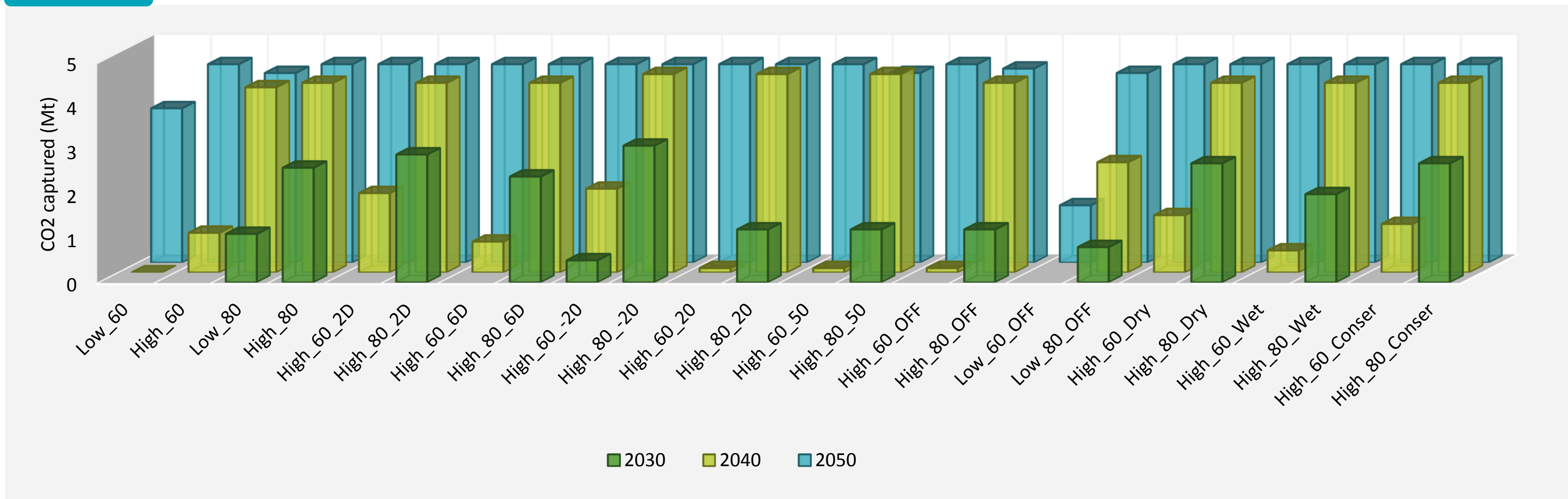
If mandatory offshore storage is set, the total costs of CCS for a High socio-economic development and stringent mitigation policy (-80% reduction) can range from 314 million € in 2030 to around 1 630 million € in 2050. In this scenario the costs of transport and storage cost will be higher, representing together 42% of total annual CCS-chain costs, while CO_2 capture investment costs only represents 28%.

FIGURE 17 *CCS costs per year and scenario (M€) (investment cost are annualized and no mandatory offshore storage)*



"Annualized capture investment costs represent in average 40% of the total annual CCS–chain costs assuming onshore storage"

FIGURE 16 *CO_2 captured in cement sector per scenario*



In fact, mandatory offshore storage will increase significantly CCS costs particularly due to storage which will increase up to 97€/tCO_2/a (Table 4). In these conditions the annualized investment of capture technology represent around 31% of the total CCS annual costs.

It should be underlined that these costs do not include the additional energy consumption associated with CO_2 capture technologies corresponding to the amount of energy efficiency lost in power plant and cement units. Despite this, CCS can have economic advantages compared to a scenario where the technology is not available as a result of the installation of more expensive technologies to decarbonize economy (e.g. wave technology in power sector).

The difference in the whole energy system costs (including supply and demand side, such as industry) between the scenarios with and without CCS, indicate that for all the scenarios, in the long term the earnings surpass the costs, as observed in Figure 18. For example, in 2050 the earnings can range between a minimum of 250 million € to a maximum of 4700 million €. In fact, even the scenario with a 50% increase of CCS costs and mandatory offshore storage associated with higher costs for transport and storage, result in earnings, although less significant particularly for a moderate mitigation scenario and low economic growth. The higher the need for abatement, the more significant are the economic benefits of CCS, revealing that alternative mitigation technologies are more expensive.

These results are aligned with the IPCC WGIII report summary for policymakers (IPCC, 2014), where mitigation cost with no CCS can be from 229 to 297% higher comparing with the scenarios with the availability of the technology from a 450 ppm mitigation policy.

2.5. Negative Emissions from Biomass

Several studies highlighted that negative emissions, namely those associated with bio-CCS, will be indispensable to achieve GHG reductions consistent with limiting average surface temperature increases to 2ºC (e.g. IEA, 2014). Emissions from sustainable biomass combustion are recognized as being neutral as new biomass is grown to replace it and absorb the same amount of CO_2. If the CO_2 emitted by biomass combustion is captured and stored, a carbon-negative value chain is attained which withdraws more CO_2 from the atmosphere than it emits (GCCSI, 2014b). In this study, CCS technologies were associated with biomass just in three main groups of technologies/sectors: i) biomass gasification in power sector; ii) biofuels and gas production through the gasification of black liquors from pulp & paper industry; iii) biofuels production through woody biomass gasification (Fisher-Tropsch with CO_2 capture).

The cost-effective analysis revealed that negative emissions from biomass can be responsible for up to 20% of the emission reduction comparing with the reference scenario in a high mitigation scenario (-80%) and high socio-economic growth (High_80_BIO) (Figure 19). While for a low socio-economic growth and a mitigation policy of -60% (Low_60_Bio), the amount of negative emissions is negligible. The possibility of negative emissions by applying CCS in biomass units induces a reduction of CO_2 captured (2 Mt) from fossil fuel sources, in High_80_BIO by 2050. Second generation biofuels produced by the gasification woody biomass and black liquors associated with CO_2 capture, are the main responsible for these negative emissions. Although other technologies such as the production of methanol through black liquor are also installed the reduced amount produced may not justify the installation of CCS technology. Moreover, it should be underlined that the successful realization of such a carbon negative pathway for Portugal depends on the future development of the global biomass market as in the long term more than half of the biomass would need to be imported.

> *"Despite its costs, the availability of CCS under an ambitious mitigation future can lead to economic benefits comparing with a scenario in which the technology does not exist"*

TABLE 4 *Unit cost of CCS (€/t CO_2 per year)*

Storage	Scenario	CCS chain	2030	2040	2050
Onshore	High_80	Capture	151.3	145.7	144.5
		Transport	17.4	11.8	6.9
		Storage	29.3	29.3	29.3
		Total CCS	197.9	186.8	180.7
	High_60	Capture		149.7	143.2
		Transport		10.1	6.4
		Storage		29.3	29.3
		Total CCS		189.0	179.0
Offshore	High_80_Off	Capture	152.3	146.2	142.7
		Transport	20.3	12.8	8.0
		Storage	97.0	97.0	97.0
		Total CCS	269.6	256.0	247.7
	High_60_Off	Capture		146.2	137.8
		Transport		11.3	7.5
		Storage		97.0	97.0
		Total CCS		254.5	242.3

FIGURE 18 *Earnings with the deployment of CCS technology (negative values represent expenses) comparing with a scenario without the availability of CCS*

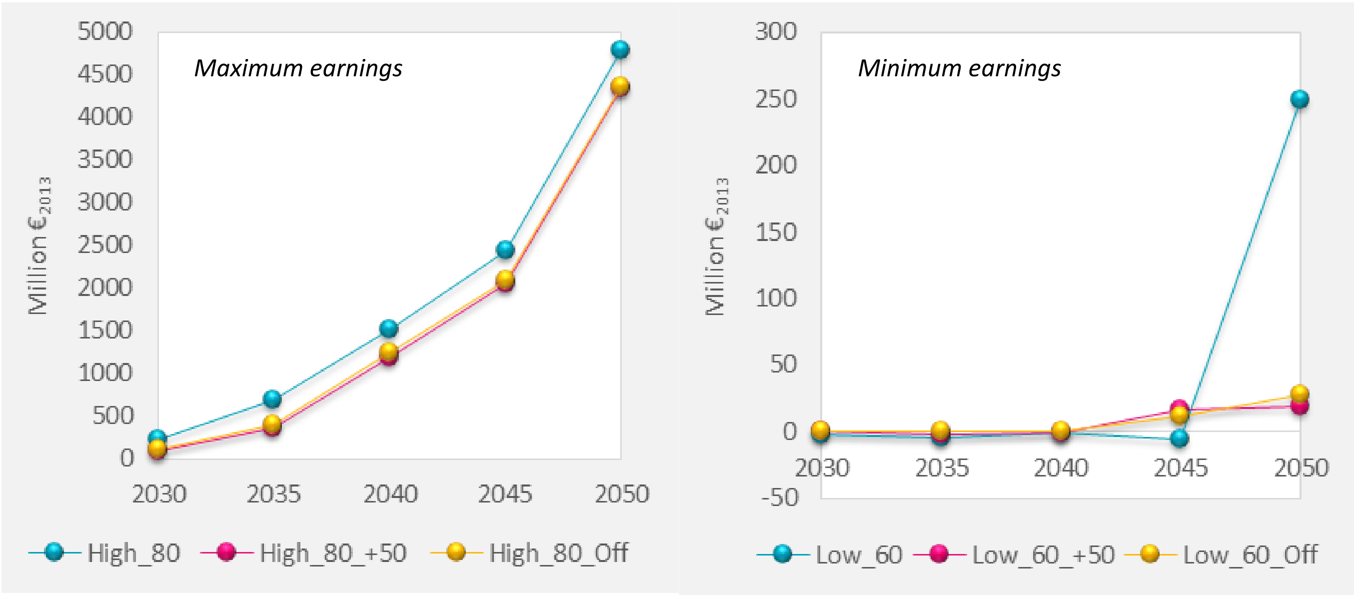
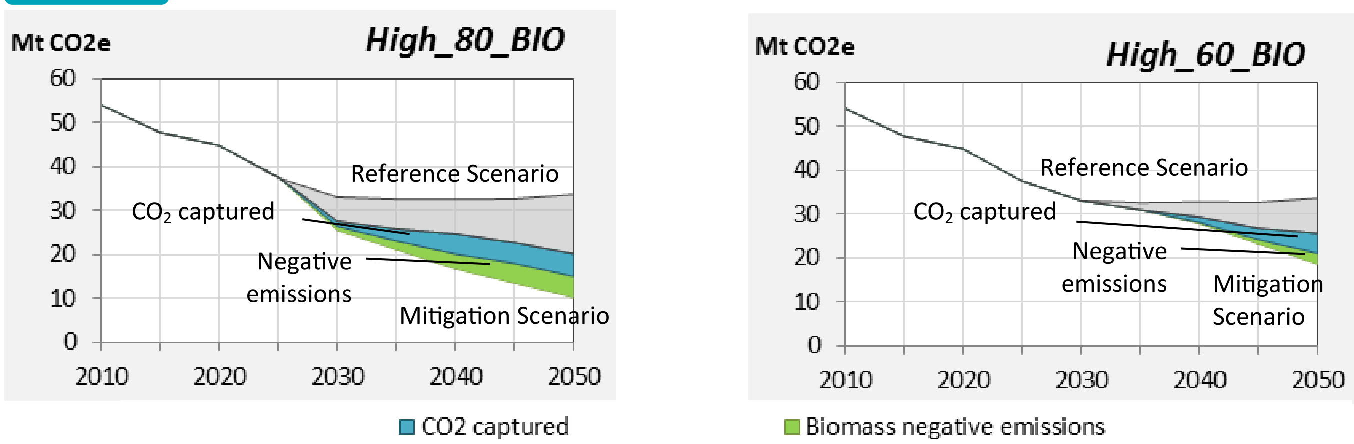


FIGURE 19 *GHG emissions path and CO_2 captured for scenarios considering CCS in bioenergy units*



3

Challenges and Opportunities of CCS deployment

As any new technology, the deployment of CCS faces challenges which need to be managed. Although people are often favorable to low carbon technologies, the social acceptance can hinder the deployment of CCS, if the benefits are not shown.

3.1 Business Opportunities and Synergies with other activities

Low carbon options can offer economic growth and prosperity. The adoption of abatement options for CO_2 emission can protect the companies with its core activity related or dependent on the use of fossil-fuels and even offer business opportunities. However, industries that emit large quantities of CO_2, due to combustion of fossil fuels or inherent to its specific processes, will face a challenge for maintaining its operation at a competitive economic level as the compliance with GHG mitigation targets puts more burdens on its operation cost.

The CCS technology, this instance, will be the last resort to industries that cannot alter its energy portfolio or reduce the CO_2 emission from its processes (such as the CO_2 process emissions from the clinker production sector), although high expectations exist on innovation.

To secure the opportunities that CCS technology offers to the development of the economy is the key strategy to enable it. Interested groups like: Owners of point sources and potential users (oil companies, power companies and other land based industries); Technology suppliers and service providers; Research institutions, can benefit from it and create knowledge-based business and services.

The importance of the CCS technology on empowering competiveness along the path for reduction carbon intensity is particularity high in the national cement production sector since it is the only method that this sector has to reduce its process emissions. The two national cement companies should coordinate efforts and act as a cluster of competences and interest group in order to begin testing scenarios for CCS deployment in (some of) their units across the country.

Moreover, the creation of clusters between industries, power stations and/or refineries (e.g. in Sines region) can contribute to a reduction of costs due to the use of the same transport pipeline and storage hub such as in the UK CCS projects in the North Sea Basin).

Job creation and security

An important impact in the economy from the deployment of CCS technology is related with the preservation of jobs and the creation of new ones.

CCS technology can provide additional jobs across it values chain, although most of existing studies focus in the capture phase and the power sector. The combination of more aggressive GHG emission targets (-80%) with the scenario of lower primary energy prices will induce higher penetration of CCS technologies and therefore higher jobs creation (Table 5) (Wei *et al*., 2010).

Employment at industry sector can also benefits from CCS, as it can deliver the possibility to keep its operation and comply with GHG commitments. The Portuguese cement industry, the two major companies (CIMPOR and SECIL) were responsible for 8573 employees in 2011, which has an important impact in the national industry panorama.

TABLE 5 *Jobs created associated with CCS technology in the power sector in Portugal in the scenarios with the higher CCS deployment.*

Scenario name		2030	2035	2040	2045	2050
GHG mitigation targets	High_60					301
	High_80		221	221	221	2100
Primary energy prices	High_60_2D			443	1051	1541
	High_80_2D	886	1193	1837	1873	3144
	High_80_6D				220	1757
Techno-economic characteristics of CCS	High_60_-20					305
	High_80_-20		275	275	275	2229
	High_80_20				244	1725
	High_80_50				236	1556
Storage sites	High_80_OFF				239	1711
Hydrological conditions	High_60_Dry				292	787
	High_80_Dry		144	408	759	2452
	High_80_Wet					612
Hydro potential	High_80_Conservative					1084
Bioenergy	High_80_BIO			205	241	453

Education and R&D

The CCS technology value chain, from capture to geological storage, requires a multiplicity of specific skills and expertise, on diverse fields like chemical engineering, civil engineering for pipelines construction and management, and geologic and environmental engineering. Other skills also include mechanical engineering, geophysics, electrical and process engineering, reservoir engineering; and specialized crafts (electricians, boilermakers). The needs in terms of R&D could represent an increase in research jobs to meet the needs of pilot projects (Martinez-Fernandez *et al*. 2010) and a way to link academic and industrial research and development activity (CathCart, 2013).

Human resources capacity building and knowledge based jobs related to CCS technology can also provide an opportunity to the national economy, as it can represent a business opportunity and a way to speed the recognition and implementation of the technology. Therefore, CCS deployment should be communicated and translated properly in high-qualification and advanced training at Universities, as well as on R&D research policy and funding, in order to decrease the need for future imports of know-how.

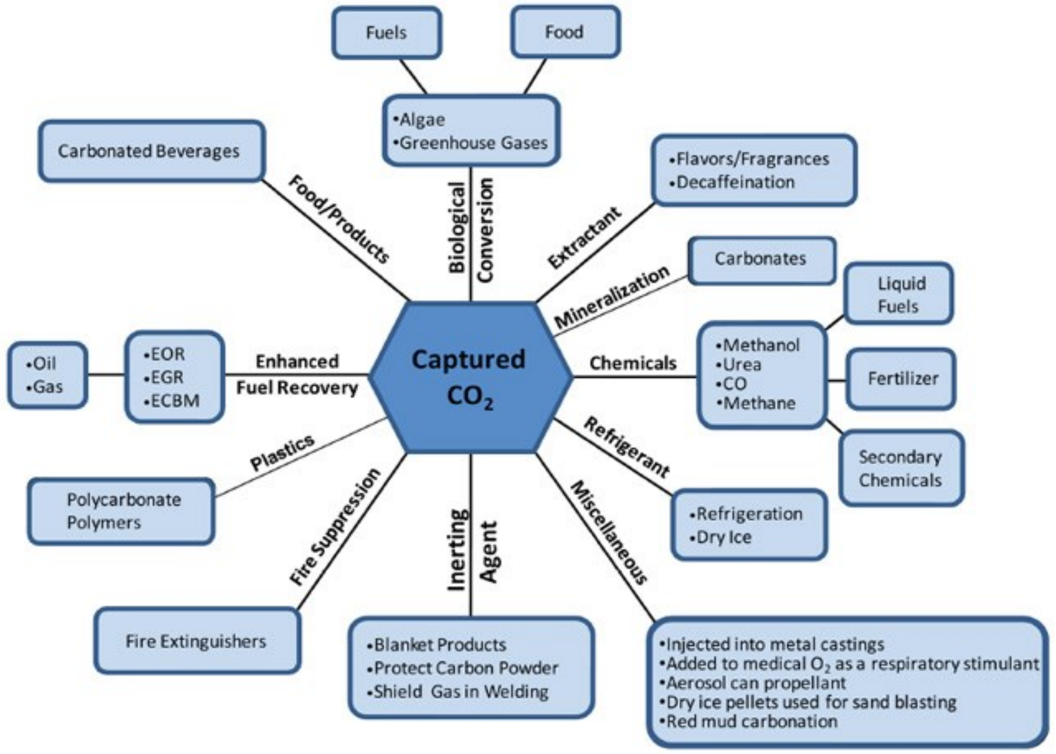
Carbon Capture Use (CCU)

Apart from storage in a geological formation, CO_2 can feed the production of a wide range of carbon-derived products, covering several technologies (Figure 20): CO_2 to fuels; Enhanced commodity production; Enhanced hydrocarbon recovery; CO_2 mineralization; and Chemicals production.

The introduction of CCU technologies in Portugal depends on the specifications of each technology, for example, despite the enormous potential and current maturity, EOR can't be applied for Portugal, as there is no proven oil or gas reservoirs in the national territory. Nevertheless, other CCU options like methanol and microalgae production may be a feasible option for the use of the CO_2 capture in the various industries as required facilities can be located near the CO_2 capture sites and usage can cope with low quantities of CO_2 captured (when comparing with geological storage).

Microalgae systems for carbon dioxide sequestration and production of chemicals is an emergent area, representing a great promise for industrial application. In Portugal there is already a pilot-project that uses the CO_2 captured from the cement industry, located in Cibra-Pataias, to produce microalgae that can be integrated in animal feed – the project A4F – Algafuel. This offers an opportunity to expand this application to other national industries that also have process emission, like the lime sector, reducing GHG emission and gaining additional revenue, making the CO_2 capture a more competitive technology. Nevertheless, the cement industry stakeholders mentioned the small scale of this project in terms of CO_2 captured for this use and even the low quantity of CO_2 that this type of technology can sequestrate.

FIGURE 20 *Diagram of CO_2 utilization options (Source: NETL, 2013)*



3.2 Options for CO_2 transport and storage

The options on storage clusters and/or how to transport the CO_2 is dictated by economic and technical factors, namely by the costs and risks associated to each storage and transport scenario.

Storage costs

The costs for exploration, implementation and operation of the CO_2 storage sites vary strongly depending on the characteristics of the reservoir, its location (onshore, offshore), surface area to characterize/monitor, and the number of injection wells (a function of the injection rate). Table 6 lists the storage costs components and figure 21 illustrates the storage costs estimated for each storage cluster.

Estimated onshore storage costs per injection rate are on average 29 €/tCO_2/a, while offshore costs vary considerably, ranging from 80 €/tCO_2/a in cluster S42 in Algarve to 366 €/tCO_2/a in cluster S06, Sines sector, a function of the large reservoir depth and low injection rate. For comparison with benchmark studies, in scenarios of 30-year injection at the maximum rate, the average onshore storage costs are 4 €/tCO_2, while for offshore storage is 19.7 €/tCO_2. If the prohibitively expensive S06 cluster is not considered, the average offshore storage cost is 15 €/tCO_2. This values compare well with the storage cost benchmark assessment conducted by Zero Emission Platform (ZEP, 2011).

FIGURE 21 *Storage cost estimates*

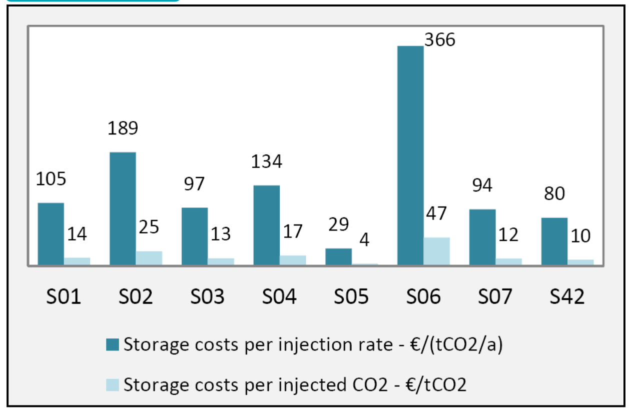


TABLE 6 *Storage cost components (from Boavida et al., 2013)*

Cost component	Onshore	Offshore (WD*<60 m)	Offshore (60m<WD<100m)	Offshore (100m<WD<1000m)
Site development costs (Csd)	24 480 k€	24 097 k€	24 097 k€	24 097 k€
Drilling costs per meter (Cd)	4 k€	10 k€	18 k€	26 k€
Surface facilities (Csf)	1 530 k€	61 200 k€	61 200 k€	61 200 k€
Number of wells per area (W) Reservoir thickness (H)	Site specific			
Monitoring investment	1 530 k€			
OMM	5% of investment costs			
Investment costs	$I = W \cdot C_d \cdot H + C_{sf} + C_{sd}$			
* WD – Water column thickness				

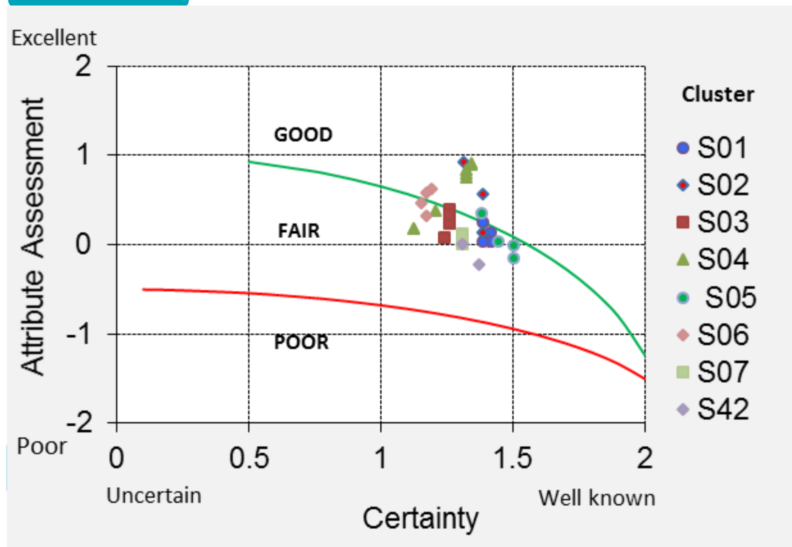
Risks and Site Ranking Qualification

Although CO_2 is characterised as a Category C fluid (Non-flammable fluids which are non-toxic gases at ambient temperature and atmospheric pressure conditions) according to ISO [2000], CO_2 storage is not without risks. Accordingly, a preliminary analysis was conducted of the storage clusters in terms of risks, using the SRF methodology—Box 3.

Figure 22 depicts graphically the results of the SRF methodology. Offshore storage sites in the Porto (S01, S02) and North Lusitanian (S03, S04) basins present the best ranking qualification (Box 3). The onshore cluster S05 is qualified as FAIR quality, but it performs worst than the offshore clusters in terms of the natural attenuation potential of CO_2 leaks. This onshore cluster is within a zone qualified by the Eurocode 8 as with low seismicity for lower magnitude interplate earthquakes and as intermediate seismicity for intraplate earthquakes. These levels of seismicity are probably admissible, but, since active faults occur not very distant from the limits of cluster, careful analysis of the induced seismicity impact should be conducted. In these clusters (S01 to S05) the main sources of risk and uncertainty are the lack of information about the faults that compartmentalize the reservoirs, and unidentified faults that may occur in the secondary containment, near the surface. The characterization stage should address those issues.

The storage sites in the Algarve basin (S07 and S42) present the least favourable conditions mainly due to the poorest quality of the secondary containment and the higher seismicity of the region, a factor which also affects cluster S06, in the Sines sector. These three clusters are located in the south of Portugal and their seismicity risk is a function of the proximity to the interplate boundary between the Eurasia and Nubian tectonic plates. Therefore, CO_2 storage in the clusters S06, S07 and S42, is discouraged.

FIGURE 22 *SRF risk ranking per storage area and cluster*



BOX 3 *SRF—Screening and Ranking Framework*

The SRF approach (Oldenburg, 2008) qualifies and ranks multiple potential CO_2 geological storage sites on the basis of health, safety, and environmental risk arising from CO_2 leakage. It evaluates the 42 properties of the Primary Containment, Secondary Containment, and Attenuation Potential. Output of the method is composed of charts of attribute assessment versus certainty factor allowing to identify POOR, FAIR and GOOD HSE quality ranking of the potential sites.

Transport options

The process of transporting the captured CO_2 depends on the location of emission sources and capture and storage sites. The land transport option is through pipeline, while the maritime transport option can be either by offshore pipelines or by ship.

Figure 8 illustrates the viable and most cost-effective pipeline routes from and between the main CO_2 source regions, defined through least-cost path analysis within the scope of the COMET project (Box 4). The viable corridors develop mainly along the coast, where the main CO_2 sources are located, converging to the cost-effective onshore storage cluster S05. In some scenarios, once the storage capacity or injection rate in S05 becomes exhausted, an offshore pipeline is required to the alternative storage site, in cluster S03. The onshore transport cost per unit of CO_2 ranges from 2.3 €/t to 7.8 €/t depending on the used capacity of the network. The cost increase considering transport to offshore storage is only 28%, since a large part of the network would still be developed onshore.

BOX 4 *Optimizing transport routes*

The definition of the cost effective pipeline routes relies on an accurate, local-scale, description of constraints that affect the cost of building a pipeline, including: i) land use; ii) terrain slope; iii) crossing of existing infrastructures and, iv) the availability of natural gas or oil pipelines corridors. The approach was implemented in a GIS environment and cost factors were applied to decrease the probability of crossing urban areas and environmental protected areas.

The selection of storage sites depends also on the optimization of the whole transport and storage network. In general, the onshore cluster S05 is the cost-effective option to store CO_2, having simultaneously the lowest transport and storage costs, and fair risk ranking qualification. Furthermore, its injection rate is compatible with the expected volume of CO_2 captured in the country. The storage capacity is not very high, but it is probably enough for two to three decades.

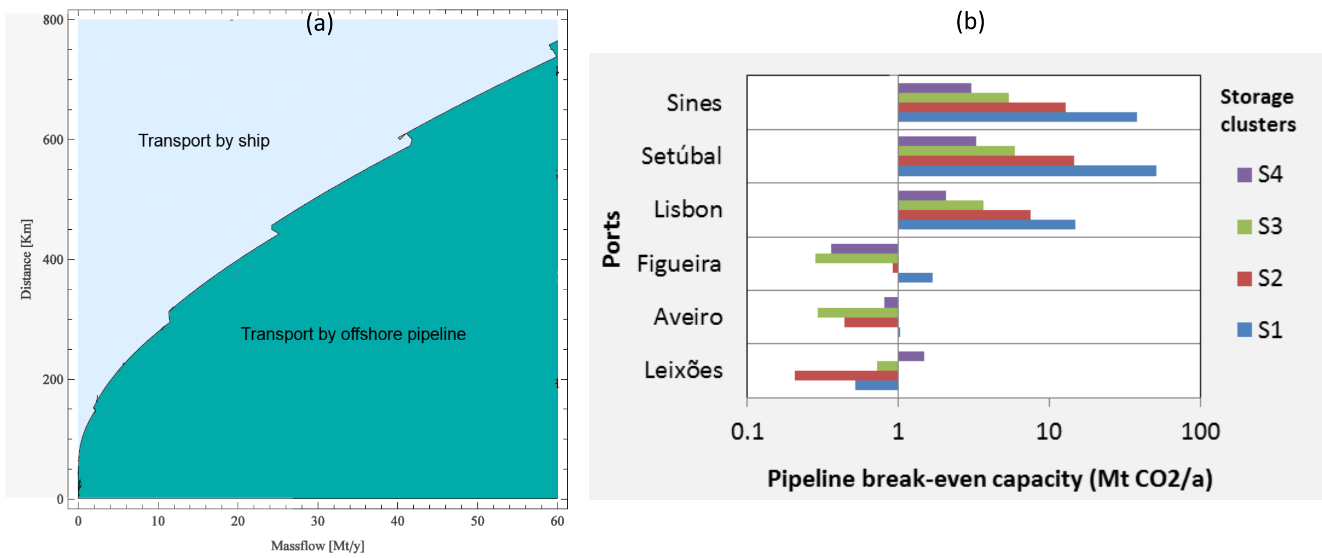
However, in scenarios of offshore only, the most reliable alternative is cluster S03 for sources in the Porto region and in the central and south of Portugal, since the Algarve and Sines clusters are discarded based in its higher risk. Cluster S01 could be interesting also for sources in the northernmost part of the country, but there are few stationary sources in that region. Should the injection rate or capacity in cluster S03 be exhausted, the cost-effective alternative is cluster S04, in the same offshore region of the Lusitanian basin. A similar result is retrieved for a scenario in which the onshore capacity in cluster S05 is exhausted.

In scenarios admitting transboundary transport, storage in Spain (in the Guadalquivir basin) are cost effective options for sources located in the south of Portugal, namely in the Algarve region, but storage in Spain can also be cost-effective for all southern Portugal and sources located closest to the border when the onshore capacity and injection rate in S05 is exhausted, or if onshore storage is not allowed in Portugal.

Unlike transport by pipeline, CO_2 transport by ship is not confined to a spatially prescribed infrastructure network and, thus, it is more flexible to temporal and spatial changes in transport quantities and storage capacities than for pipeline networks, for instance due to: i) capacity development on the capture site; ii) the storage capacity and its development; and iii) re/co-use of the vessel as LNG transporter. Ship transport is advantageous for long distances with low mass flow rates, while pipelines are more cost effective for short distances with high flow rates (Geske and Berghout, 2012) (Figure 23a).

A systematic analysis of the relevance of transport by ship to the whole CCS value chain was not conducted, but a preliminary analysis allows to understand if and which Portuguese ports should be studied in detail. Considering the cost model for transport by ship developed by (Geske and Bergout, 2012). Figure 23b illustrates the break-even capacity for pipeline transport to be the cost-effective option for the CO2 sources located near the main Portuguese ports. The break-even capacity for pipeline transport instead from the Sines, Lisbon and Setubal ports is always very high. Thus, ship transport from these ports may be the best option especially if storage occurs in the Porto Basin clusters (S01 and S02). Even for storage in the nearest S03 and S04 clusters, transport by ship should be carefully studied for those two ports. The Leixões ports may be cost competitive for CO_2 transport to offshore cluster S04.

FIGURE 23 *Comparison of point-to-point ship and pipeline transport alternatives. Based on the cost model by Geske and Berghout, 2012*



A systematic analysis should be conducted to assess the impact of transport by ship in the whole CCS chain, specially in the framework of the Portuguese Strategic Plan for Transport and Infrastructures (PETI3+), which aims to develop infrastructures in several ports.

3.3. Managing CCS challenges

The scenarios presented in the previous chapters are possible outcomes for capture, transport and storage for Portugal, which are dependent on a significant number of factors, particularly the climate mitigation policy and the socio-economic development.

Beside these factors, the deployment of CCS in Portugal is subject to major challenges, which need to be overcome to make the technology an available mitigation option for the future, otherwise, and as seen in chapter 2.4, additional costs may occur with negative impacts on the Portuguese economy. This chapter presents a brief overview of some of the challenges that must be supressed.

Legal aspects

Establishing a robust and clear legal framework for CCS is of utmost importance. This will create transparency and reduce risks for investors and companies, allowing them to consider CCS in their long-term plans. Portugal has transposed to the national law the EU Directive 2009/31/EC, which defines a legal framework for the management of environmental and health risks related to CCS, mostly storage. Accordingly, the *Directorate General for Energy and Geology* (DGEG) is the public body responsible for the legislation in relation to CCS and is also responsible for disseminating information to promote public acceptance. Still, there is a lack of specific legislation for the transport of anthropogenic CO_2 designated for permanent storage in Portugal. The national oil and gas industry has used pipelines in Portugal for transporting chemicals for several decades, their expertise can gather valid and useful lessons for CO_2 transport.

Funding

CCS requires financial support outside of normal commercial patterns to demonstrate the economic feasibility of the technology at commercially scale. Cover the various risks is necessary to enable a flow of capital. The market opportunities are different depending in the potential users of CCS. If for oil companies CCS can enable its production, for power and industry investment in CCS can represent a challenge due to limited financial resources. International financial programs like CLIMIT that gather different stakeholders of the different phases of the supply chain of CCS, provide the opportunity for technology suppliers to contact partners to help bring their innovations to the market and for research institutions to persuade industrial partners to engage in consortia for international research funding and co-finance their research projects (Bekken *et al*. 2013).

For the Portuguese case, the two cement companies should organize themselves and act as a cluster of competences and interest group in order to begin testing scenarios for CCS deployment in (some of) their units across the country.

Moreover, loan guarantees could have a significant cost reducing and minimize the financial barrier of CCS deployment. The effectiveness assessments of the different public support schemes point out that the first CCS demonstration projects may be largely equity-financed as commercial debt is not an option for such first of a kind projects (Al-Juaied, 2010). Due to economic and financial situation of Portugal, public support schemes should be planned with the direct support of European Commission as Portugal will receive up to €25 billion in EU structural funds for the period 2014-2020.

Storage conflicts and synergies

Overall the most important constraint for onshore storage in cluster S05 is the existence of a natural park covering part of the storage cluster, imposing serious limitations to surface activities. Choice of potential injection sites in this onshore cluster needs also to consider the population density and land use distribution, since those vary considerably in potential storage areas composing the onshore cluster, with more favourable conditions found in the S. Pedro de Moel area. Other issues to consider refer to the relevance of shallow aquifers for freshwater supply and the existence of hot springs and mineral groundwater potential. These are, however, issues that should not give rise to conflicts as long as they are properly managed with the regulating authorities and monitoring programs are implemented. Synergies in the onshore cluster are mainly associated with the ongoing hydrocarbon explorations efforts, which could provide invaluable data to characterise the CO_2 storage reservoir and cap-rock.

As for offshore storage, the most relevant constraints are likely to be connected to restriction of fishing activities during drilling stages and seismic surveys, as well as the permanent restriction to bottom trawling fishing practices in the immediate vicinity of the wellheads and along offshore pipelines, if they are necessary. Furthermore, although none of the existing maritime protected areas are affected by offshore clusters, it is inevitable that localised impacts occur for the conservation of biodiversity and nature at the seabed during the drilling stages. These should not be conflicting issues for CO_2 storage activities as long as the proper environmental practices are ensured and regulating authorities are engaged. Interesting synergies with the protection of biodiversity can result if planning is made to manage the wellhead protection areas as an opportunity to protect the seabed ecosystems from the negative effects of excessive bottom trawling fishing, in accordance with recent regulations issued by the Portuguese government.

Public engagement

Public acceptance can have a significant influence on the success or failure of a widespread CCS chain, particularly for CO_2 transport and storage. A sincere and clear dialogue with the national stakeholders, including the ones from society is essential, otherwise CCS runs the risk of being the focus of social protest phenomena. In fact, Portugal has clear examples how the lack of dialogue with population has negative impacts, like the NIMBY (not in my back yard) phenomenon that has caused many delays in the implementation of solutions for waste management in Portugal. The following section describes the engagement and expectations of national stakeholders regarding CCS, representing a first step of the dialogue process.

3.4 Stakeholders Engagement/Expectations

The communication process aimed to extent and involve in active participation three central Portugal stakeholders:

→ Industry, power and respective regulators;

→ Civil society (including NGO's and Regional/local players);

→ Academia and research community.

Two workshops were organized, and feed-back was asked from stakeholders on a range of aspects such as identification of drivers and challenges, implementation scenarios, priorities for public policies. A website (http://ccsroadmap.pt) was implemented where stakeholders could input their views on the matters discussed in the workshops, but a more active consultation was implemented through questionnaires.

All stakeholders considered to have at least a medium level of information on CCS technologies and more than half considered to be well informed (four from the Academy and NGOs, three from the Industry). In fact just two associations (APEA and COGEN Portugal) had not yet been involved in some kind of CCS-related initiative.

Feasibility of CCS as a technological option for climate mitigation

On the feasibility of CCS to become a climate change mitigation option, the opinions of the Academy and NGOs were evenly divided. Those that answered yes, stated that CCS is one more option within a portfolio, available to the largest polluters, in particular the cement industry. In the opposite response, it was pointed out that for Portugal, due to the limited geological conditions for storage and the good availability of renewable energy resources, the development of the latter would be more cost-effective, considering CCS technological option only as a last resort of aggressive transition to an low GHG emission future.

Regarding Industry, the positions are clear. The power sector does not view CCS as an option, basically due to the availability of renewable energies and lower cost of the related technologies. In contrast, the cement sector considered that it must be an option, simply because the emissions related to the industrial process of cement production itself are unavoidable, and no other technology seems to be available (even in concept) to deal with those emissions. It also mentioned reutilization of CO2 as an alternative, or at least a significant complement to CCS, using paths such as synthesis of methanol and microalgae production, especially in a context of contributing (and being rewarded for) smoothing the variability of renewables.

CCS and business

The industry stakeholders were adverse to the possibility of CCS as an option for dealing with the targets and constraints imposed by the EU ETS, as well as any related business opportunities. The reasons cross the existence of other more feasible and cost-effective options the regulatory uncertainties and CO_2 price instability.

Even under this negative view about EU ETS, the stakeholders were inquired further about the possibility of changing the activity and/or price products of the companies so as to include CO_2 capture costs. A bad track record of EU ETS as a way of internalizing CO_2 costs was highlighted for a start. The answers considered that this would require a strong involvement of the governments of both Portugal and Spain: financing infrastructures, pilot and demonstration plants, and proving much higher tariff and subsidy support to conventional fossil fuel power plants. In addition, a fixed, stable, and relatively high price of CO_2 would be required.

Industry stakeholders were also asked about possible business models with CCS, or some of its components (capture, transport, storage). Most did not consider this feasible from the start, favoring other options (renewables, efficiency, recovery) or still to be studied from this point of view considering the added costs for the consumers. Nonetheless, there was an opinion that the transport and storage should be a regulated monopoly type of business, as these facilities would be used by various agents, therefore following e.g. the existing model for the public grid for electricity transmission.

Obstacles to CCS in Portugal

The specific barriers for the installations: the difficulty of obtaining know-how for CO_2 transportation was selected as the most relevant (83% of respondents), followed by know-how for capture and for storage (67% each). Also relevant (50%) were the difficulty to obtain technology for CCS and the capacity/possibility to change processes. Changing existing procedures and obtaining licenses were not seen as important barriers.

As for the priority initiatives to be taken in the country, the Academy and NGOs mentioned more information to the public (raise awareness) and especially, more studies.

Stakeholders from the Industry viewed as priority intersectorial knowledge sharing and governmental support to pilot plants as well as to transport and to storage facilities, and creation of a stable regulatory framework.

The role of the Public Policies in particular, the responses did not depend much on the type of stakeholder, but varied between the extremes of “premature to take action” and “full responsibility of the State”. In-between a wide range of issues were raised, that can be summarized as follows:

→ financial incentives (helping transition)

→ financial support to R&D (initially about geological sites and then about other CCS aspects)

→ creation of a regulatory framework (acceptable also by future Governments)

→ launching land management studies for assuring passage of CO_2 transport infrastructures and avoid future conflicts with the public, land owners, and existing land management instruments (agriculture and ecological reserves, protected natural areas, regional and municipality level plans, etc.).

→ coordination with Public Policies from other EU countries, so that a level playing field for industries exists (CO_2 price, taxes, technical and environmental requisites).

Relationships with the civil society

Public support – or at least no strong opposition – based on correct understanding of CCS, was viewed as fundamental in the workshops, and in the survey.

Providing correct and transparent information was seen as the most important issue. The contents should include basic technical explanation of CCS, effectiveness at reducing GHG emissions for the power and cement sectors, examples of existing working projects, challenges and benefits, economical aspects, and connection to EU targets and legislation.

The audience to be reached, are the general public to raise awareness, and in an initial phase specialized audiences should be targeted, such as R&D teams, university level students, professionals from the energy and cement areas, and technical staff at public bodies.

The mechanisms for information, a wide range was suggested, including improving university and even secondary school curricula, conferences and workshops, interviews, debates and news in the mass media about CCS and related R&D being developed, demonstration days and visits to potential CO_2 capture and CO_2 storage locations.

The public response to CCS, suggested meetings with environmental NGOs and municipalities, and sociological studies.

The engagement of the civil society in a context of implementation of CCS related project, the stakeholders referred that raising public awareness on CCS is a pre-requisite for dealing with specific projects. The existing public engagement mechanisms are enough for the time being (Environmental Impact Evaluation study with mandatory public consultation) but should be complemented with public hearings with promoters, NGOs and municipalities, as well as with news and debates in local mass media.

BOX 5 Stakeholders views on challenges and benefits of CCS in Portugal

The perception of the stakeholders about challenges of CCS in Portugal encompassed a wide variety of issues:

→ from an environmental point of view, seismic risk and impacts on marine biodiversity (for offshore storage),

→ from a social point of view, public opposition, if not well informed,

→ from an implementation point of view, legal conflicts about land management (transport and storage) and high infrastructure costs (too scattered CO_2 sources, long distances to storage sites),

→ from a strategic point of view, danger of relaxing the efforts that continue to be needed at the forefront of renewable energies and energy efficiency.

About benefits, there was also a range of advantages identified:

→ on top, a potentially significant contribution to reducing the country’s current GHG emissions (although not necessarily in the long term),

→ promotes energy security (more diverse energy mix if fossil fuels continue to be used in significant proportion),

→ job creation (building installations and infrastructures, maintenance),

→ possibility of reusing the captured CO_2.

BOX 6 Stakeholders views on the crucial issues for CCS in Portugal

The stakeholders were questioned on what are the three top priorities for CCS within the country context.

→ The Academy and NGOs all identified the following issues: more technical studies on CCS technologies for the case of Portugal, transparence in the decision process about CCS implementation (or not) in the country, and engagement of the civil society organizations in this decision process.

→ For the Industry, the crucial issues for adopting CCS would be a clear, stable regulatory environment (top priority for all stakeholders), economic return on investments in CCS (83% of respondents) and the existence of CO_2 storage facilities (50%). Important, but not on top, remained the issues of financial incentives, access to transport infrastructures, and the transparence of the decision processes.

4.

Recommendations/Actions to CCS deployment

Proactive approach is necessary to make CCS technology go ahead towards the medium term and contribute to decarbonized economy

This study contributes to the clarification of the role that CO_2 capture and storage (CCS) could play in the decarbonisation of the Portuguese economy. It was concluded that CCS technology could represent a mitigation opportunity to domestic industry, namely for the cement production that appear as first movers from 2030. The intensification of policy efforts to reduce drastically the greenhouse gas emissions in the medium to long term (by 2050) is the main driver of CCS cost-effectiveness, determined by integrated modeling of the energy and industrial Portuguese system. To achieve 80% reduction of greenhouse emissions by 2050 compared to 1990 figures, CCS appears as a cost-effective technology, capable of avoiding the emission of 1 to 3 Mt CO_2 to the atmosphere in 2030 and 4 to 7 Mt CO_2 in 2050.

The findings of this study should be framed by a set of uncertainties, in particular, the expected evolution of fossil fuel prices over the next decade, the projections of industrial production, for both domestic consumption and exports, as well as the availability of natural resources such as hydrological conditions, which support a significant part of electricity production. In addition, the uncertainty about the performance and the expected costs for CCS in the future emerges as a major barrier to its deployment.

CO_2 capture is not a competitive option to decarbonize the power sector, mainly due to the cost-effectiveness of renewable technologies and energy efficiency in Portugal. However, CO_2 capture may possibly be equated, providing additional benefits in terms of security of supply by allowing the diversification of energy sources, and of the final cost of electricity production, although under specific conditions.

Currently, the deployment of CCS in Portugal faces a number of obstacles, as identified in the consultation and communication process with the national stakeholders through various workshops. Stakeholders indicated, as a priority, the need for a strong involvement of the Portuguese and Spanish governments to clarify (i) how public policy considers CCS as a tool to achieve high levels of decarbonisation; (ii) whether there is any willingness to promote and support pilot and demonstration units in the country; (iii) how funding and management of transport and storage infrastructure could be approached. It was also recognized that the existence of a fixed, stable and relatively high CO_2 price would be an advantage for the development of CCS technology. From the stakeholders point of view, the clarification of these aspects, or at least the clarification of public policy framework within which they shall be addressed, is essential to further recognize CCS as an effective mitigation technology to be included in the national portfolio. Since CO_2 capture in industrial installations requires the use of transport infrastructures and CO_2 storage, specific regulation is seen as a barrier and a challenge that must be addressed clearly by public policy.

Based on the information and views gathered through this study, including the expected evolution of industrial production like cement, a set of recommendations can be asserted for Portugal, bearing in mind the ambition for a high level of decarbonization of the economy by 2050.

a. Prepare a task-force to explore the best options for CO_2 transport, given the expected amount and the location of CO_2 emission sources. This analysis should considerer both (i) onshore storage solutions, including land management instruments in place and land-use management to ensure the passage of CO_2 transport infrastructure while avoiding potential conflicts with population and landowners, and (ii) offshore storage solutions, including marine areas management and the possibility of transport by ship; for this purpose, the involvement of public policy agents, and communication with local political bodies is highly recommended;

b. Prepare the training and scientific programs on (i) CO_2 capture in partnership with industrial candidates for CCS adoption; (ii) CO_2 storage in close cooperation with geological services and academia; and (iii) CO_2 transport, in partnership with the national transmission system operator, taking advantage of its know-how in natural gas transport by pipeline.

c. Evaluate regulatory models integrating the whole chain of CCS, and possible financing schemes to promote the various components of capture, transport and storage; for this purpose, it is recommended that the key role should be played by public policy agencies in close collaboration with experts from the different components;

d. Implement a pilot site of onshore injection to overcome the uncertainties associated with deep geological environments and consolidate the estimates of storage capacity and costs; this goal should be supported by European funds, in cooperation with industry and R&D organizations, as already happen in the projects in Ketzin in Germany and Hontomin in Spain.

A 80% reduction of greenhouse gas emissions in Portugal in the medium to long term (2050), compared to 1990, as pointed out as a need to stabilize the global climate, will require CO_2 capture as a mitigation option in the industry sector, given that renewable energy continues to prove to be a cost-effective solution for electricity production, together with the high potential for energy efficiency. Assuming the national cement production expectation from this study (i.e. 13% to 20% in 2050 compared to the current production for low and high socio-economic scenarios respectively), it seems reasonable the two cement companies should coordinate their efforts and act together as a cluster of skills and interest group in order to start CCS implementation test scenarios in some units. On the other hand, national public policy bodies cannot ignore this option, because the sooner the country identify their weaknesses and opportunities, the more likely it will avoid competitive losses in the future.

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Appendix

The following tables show some of the techno-economic characteristics of capture, transport and storage technologies considered in the Base scenario of the modelling exercise.

TABLE A1 Techno-economic characteristics of electricity generation technologies with and without CO_2 capture* (Source: JRC, 2014)*

Technology	Average Size	Specific investments costs (overnight)				Fixed operating and maintenance costs				Electric net efficiency (condensing mode)				Tech. Lifetime	Availability	CO_2 capture rate
	Mw	Eur2010/kW				Eur2010/kW				%						
		2010	2020	2030	2050	2010	2020	2030	2050	2010	2020	2030	2050		%	%
Electricity only plants - Coal																
Supercritical	600	1705	1700	1700	1700	34	34	34	33	45	46	49	49	35	80	
Supercritical+post comb capture			2450	2209	2018		43	41	34	30	32	36	39	35	75	88
Supercritical+oxy-fuelling capture			3028	2287	1876		38	37	31	28	31	36	40	35	75	90
IGCC		2758	2489	2247	1830	55	50	45	37	45	46	48	50	30	80	
IGCC pre-comb capture			2689	2447	2030		47	40	38	31	33	39	44	30	75	89
Electricity only plants – Natural Gas																
Combined-cycle	550	855	855	855	855	26	21	20	20	58	60	62	64	25	60	
Combined-cycle+post comb capture			1244	1155	1093		44	41	39	42	44	49	53	25	55	88
Electricity only plants – Natural Gas																
Combined-cycle conventional	50	823	822	816	816	21	21	20	20	45	46	48	48	25	90	
Combined-cycle advanced		1019	980	907	907	26	25	24	24	47	48	51	51	25	90	
Combined-cycle+ post comb capture			1637	1419	1419		35	32	32		44	46	46	25	90	88
Combined-cycle + pre comb capture			1727	1328	1328		31	29	29		43	45	45	25	90	88
Combined-cycle + oxy fuelling capture			1827	1347	1347		32	30	30		41	43	43	25	90	88

*Source: JRC, 2014. The JRC-EU-TIMES model. Assessing the long-term role of the SET Plan Energy technologies. Joint Research Centre. Institute for Energy and Transport. European Commission

TABLE A2 Techno-economic characteristics of cement production with and without CO_2 capture (Source: Validated by national stokeholds based on ECRA, 2009 and ECRA, 2012)*

Technology	Energy consumption	Fuel input level	Output	Starting Year	Tech. Lifetime (years)	Investment Cost		Total operating and maintenance costs		Fixed operating and maintenance costs		Variable O&M Cost		CO_2 capture rate/Where applicable
						€2010/ton clincker		€2010/ton clincker		€2010/ton clincker		€2010/ton clincker		%
	PJ	PJ	Mt			2030	2050	2030	2050	2030	2050	2030	2050	
Dry process with pre-calcining technology - No CO_2 capture	Heat*	3.70	1 Clinker	2010	50	180	180	30	30	22	22	8	8	0
	Electricity	0.29												
Dry process with POST COMBUSTION via Membranes	Heat*	3.70	1 Clinker	2025	25	615	492	51	40	39	31	12	9	95
	Electricity	0.87												
Dry process with POST COMBUSTION via Adsorbents	Heat*	5.95	1 Clinker	2025	25	280	224	66	61	31	30	29	26	95
	Electricity	0.54												
Dry process with OXY FUEL capture	Heat*	3.80	1 Clinker	2030	25	360	288	54	54	26	26	14	14	90
	Electricity	0.71												

*Source: ECRA, 2009. Development of State of the Art-Techniques in Cement Manufacturing: Trying to Look Ahead (CSI/ECRA-technology Papers. Duesseldorf, Geneve, 4 June; ECRA, 2012. Technical Report TR-ECRA-119/2012. ECRA CCS Project – Report on Phase III. European Cement Research Academy

TABLE A3 Average CO_2 storage and transport cost and CO_2 storage capacity

			Onshore	Offshore
Storage	Storage site		Onshore Lusitanian Basin	North Lusitanian 1
	Cumulative capacity (Mt)		331	2 211
	Injection capacity (Mt/pa)		10.7	11.8
	Investment costs (€/t/a)		27.9	92.4
	O& M costs (€/t/a)*		1.4	4.6
Transport	Investment + O&M (€/t/a)*	2030	7.2	9.2
		2040	4.6	5.9
		2050	3.3	3.9

*Fuel costs namely the costs with electricity consumed in the booster stations are not considered in this costs, as electricity price is endogenously calculated by the TIMES_PT model