Long-Term Analysis of the Spanish Environmental Policies using the Life Cycle Assessment Method and Energy Optimisation Modelling

PhD Thesis

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Que la Tesis Doctoral titulada

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Fdo.: Javier Martínez Moguerza

memento mori,

memento vivere

“[…]

I am content to follow to its source
Every event in action or in thought;
Measure the lot; forgive myself the lot!
When such as I cast out remorse
So great a sweetness flows into the breast
We must laugh and we must sing,
We are blest by everything,
Everything we look upon is blest.”

A Dialogue of Self and Soul

W. B. Yeats

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El siguiente trabajo es el fruto de un esfuerzo de años. Lo que en él se incluye no sólo son resultados y conclusiones, son también palabras y números que son enfados, frustraciones, miedos y, también, ahora que el final se acerca, alegrías. Y como no se trata de hacer poesía, allá vamos:

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Dijo con su propia voz: "*I know not what tomorrow will bring*"

Y cerró los ojos, agradecido.

List of acronyms

ACOGEN – Asociación Española de la Cogeneración
ACV – Análisis del Ciclo de Vida
ADP – Abiotic Depletion
AF – Availability Factor
AFA – Annual Availability Factor
AP – Acidification
APPA – Asociación de Productores de Energías Renovables
ATC – Almacén Temporal Centralizado
BAT – Best Available Techniques
BdE – Banco de España
BFS – Blast Furnace Slag
BOA – Boletín Oficial de Aragón
BOE – Boletín Oficial del Estado (Spanish national bulletin)
BOJA – Boletín Oficial de la Junta de Andalucía
BORM – Boletín Oficial de la Región de Murcia
BTEX – Xylene
BWR – Boiling Water Reactors
CASES – Costs Assessment for Sustainable Energy System
CCS – Carbon Capture and Storage
CDM – Clean Development Mechanisms
CEDEX – Centro de Estudios y Experimentación de obras públicas
CEM – Cement
CEMA – Fundación laboral del CEMento y el medio Ambiente
CEMBUREAU – European Cement Association
CFC – Chlorofluorocarbons
CFD – Cumulative Frequency Distribution
CHP – Cogeneration Heat and Power
CML – Chain Management by Life-Cycle Assessment
COD – Chemical Oxygen Demand
CORES – Corporación de Reservas Estratégicas de Productos Petrolíferos
CORINAIR – CORe INventory AIR emissions
CSP – Concentrated Solar Power
CTUe – Comparative Toxic Units environment
CTUh – Comparative Toxic Units human
DALYs – Disability Adjusted Life Years
DECC – UK Department of Energy and Climate Change
Dir – Directives
DME – Dimethyl-ether
EC – European Commission
ECRA – European Cement Research Association
EDIP – Environmental Design of Industrial Products
EEA – European Environmental Agency
EEB – European Environmental Bureau
EFF – Efficiency
EFOM – Energy Flow Optimisation Model
EIA – Energy Information Administration
EIPPCB – European IPCC Bureau

ELC – Electricity
ENCI - Eerste Nederlandse Cement Industrie
EOH – End of Horizon
EPS – Environmental Products Declarations
EREC – European Renewable Energy Council
ETP – Ecotoxicity Potential
ETS – Emission Trading Scheme
ETSAP – Energy Technology Systems Analysis Programme
EU – European Union
ExternE – External costs of Energy
FA – Fly Ashes
FEP – Freshwater eutrophication
FETP – Freshwater ecotoxicity
FGD – Flue Gas Desulphurisation
FIT – Feed-in-Tariff
FIXOM – Fixed operation and maintenance cost
FT - Fischer-Tropsch
FUNCAS – Fundación de las Cajas de Ahorros
FUND – Climate Framework for Uncertainty, Negotiation and Distribution
GAMS – General Algebraic Modelling System
GDP – Gross Domestic Product
GEI – Gases de Efecto Invernadero
GHG – Greenhouse Gases
GNG – Gaseous Natural Gas
GT – Gas Turbine
GWP – Climate change
GWP – Global Warming Potential
HFC – Hydrofluorocarbons
HFO – Heavy Fuel Oil
HTPce – Human toxicity with cancer effects
HTPnce – Human toxicity with non-cancer effects
IBM – International Business Machines
ICM – Acronym for the cement commodity in TIMES
ICMHTH – High Temperature Heat in Cement
ICMPRC – Cement process heat
IDAE – Instituto para la Diversificación y el Ahorro de Energía
IEA – International Energy Agency
IGCC – Integrated Gasification Combined Cycle
IGME – Instituto Geominero de España
ILCD – International Life-Cycle Data System
IMPACT – IMPact Assessment of Chemical Toxics
INDBIO – Industrial biomass
INDCOA – Industrial coal
INDELC – Industrial electricity
INDGAS – Industrial natural gas
INDHFO – Industrial heavy fuel oil
INDLFO – Industrial light fuel oil
INDMUN – Industrial MSW
INDSLU – Industrial sludges
INE – Instituto Nacional de Estadística

INVCOST – Investment cost
IPCC – Intergovernmental Panel on Climate Change
IRP – Ionising radiation
ISO – International Standards Organisation
JI – Joint Implementation
JRC – Joint Research Centre
LCA – Life Cycle Assessment
LCI – Life Cycle Inventory
LCIA – Life Cycle Inventory Analysis
LFO – Light Fuel Oil
LHV – Lower Heating Value
LIME – Life Cycle Impact Assessment Method based on Endpoint modelling
LNG – Liquified Natural Gas
LP – Linear Programming
LUP – Land use change
MAGRAMA – Ministerio de Agricultura, Alimentación y Medio Ambiente
MARKAL – MARket ALlocation model
MCFC – Molten Carbonate Fuel Cell
MCMBFS – Blast Furnace Slag used in Cement production
MCMCLK – Clinker
MEA – Monoethanolamine
MEEup – Method for the Evaluation of Energy using Products
MEP – Marine eutrophication
MFOM – Ministerio de Fomento
MINETUR – Ministerio de Industria, Energía y Turismo
MIP – Mixed Integer Programming
MMA – Ministerio de Medio Ambiente
MSW – Municipal Solid Waste
MTD – Mejores Técnicas Disponibles
MVIV – Ministerio de Vivienda
NAP – National Allocation Plan
NEC – National Emissions Ceilings
NEEDS – New Energy Externalities Development for Sustainability
NERP – National Emissions Reduction Programme
NGCC – Natural Gas Combined Cycle
NIM – National Implementation Measures
NMVOC – Non-Methane Volatile Organic Compounds
NoDir – No Directives
NREAP – National Renewable Energy Action Plan
O&M – Operation and Maintenance
OCC – Oxyfuel Combustion CO_2 capture
ODP – Ozone depletion
OECD – Organisation for Economic Co-operation and Development
OFICEMEN – Agrupación de Fabricantes de Cemento de España
OPEC – Organisation of the Petroleum Exporting Countries
PAH – Polyaromatic Hydrocarbons
PAN – Peroxyacetylnitrate
PANER – Plan de Acción Nacional de Energías Renovables
PCA – Portland Cement Association
PCC – Post-combustion CO_2 capture

PCDD - Polychlorinated dibenzo-p-dioxins
PCDF - Polychlorinated Dibenzofurans
PER – Plan de Energías Renovables
PET – PanEuropean TIMES model
PFC – Perfluorocarbons
PM – Particulate Matter
PMP – Particulate matter
PNRE – Programa Nacional de Reducción de Emisiones
POP – Photochemical ozone formation
PRTR – Pollutant Release and Transfer Register
PV – Photovoltaic
PWR – Pressurized Water Reactors
RD – Real Decreto (Royal Decree)
RE – Régimen Especial (Special Regime)
REAF – Registro de Economistas de Asesores Fiscales
REE – Red Eléctrica de España
RES – References Energy System (in TIMES) or Renewable Energy Sources (in general)
RO – Régimen Ordinario (Ordinary Regime)
SCP – Sustainable Consumption and Production
SCR – Selective Catalytic Reduction
SEE – Secretaría de Estado de Energía
SEI – Swedish Environmental Institute
SETAC – Society of Environmental Toxicology and Chemistry
SETIS – Strategic Energy Technologies Information System
SOFC – Solid Oxide Fuel Cell
SPOLD – Society for Promotion of Life-cycle Assessment Development
TEP – Terrestrial eutrophication
TFC – Total Final Consumption
TIMES – The Integrated MARKAL-EFOM System
TOC – Total Organic Compounds
TPES – Total Primary Energy Supply
TRACI - Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts
TSAP – Thematic Strategy on Air Pollution
TSP – Total Suspended Particulates
UK – United Kingdom
UNECE – United Nations Economic Commission for Europe
UNEP – United Nations Environmental Programme
UNIDO – United Nations for Industrial Development Organisation
US – United States
UV – Ultraviolet
VAROM – Variable operation and maintenance cost
VOC – Volatile Organic Compounds
WBCSD – World Business Council for Sustainable Development

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Abstract

During last decades the environmental protection awareness has been growing considerably in the European Union. Specially, climate change concern has become one of the foremost problems to fight with. In 2003, the European Commission approved Directive 2003/87/EC establishing a scheme for greenhouse gas (GHG) emission allowance trading. The main objective of this Directive was to promote the reduction of GHG emissions in a cost-effective and economically efficient manner to meet the Kyoto Protocol targets. After that, the European Commission approved Directive 2009/29/EC extending the scope of the previous one and establishing a reduction of 20% in the GHG emissions in 2020 respect to the 1990 level. Analogously, Directive 2001/81/EC set national ceilings for acidification, eutrophication and tropospheric ozone gases.

Cement production and electricity generation sectors are two of the main sources of pollutants in the European Union. This work has focused on the environmental consequences and the compliance of the emissions-related Directives in these sectors in Spain.

The current work applies the Life Cycle Assessment (LCA) method, an environmental management tool that evaluates the potential environmental impacts of a product or process throughout its entire life cycle, to the cement manufacture in Spain. As a result, main hotspots such as the combustion of fossil and alternative fuels at the kiln have been identified and assessed in detail. Moreover, various technology improvements such as Best Available Techniques (BAT), and material and fossil fuels substitution scenarios have been implemented. Results have revealed that changing the fossil fuels by alternative fuels derived from waste entails significant reductions in most of the impact categories except for eutrophication. In the same manner, to reduce the clinker content in cement diminishes most of the impacts. This measure shows more problems than fuel substitution because it requires substituting the clinker by secondary materials such as blast furnace slag, fly ashes and pozzolanas, at the same time that mechanical and chemical properties of the cement must be preserved. Going further, an exploratory analysis has been made including the CO_2 capture technology in the Spanish cement-making. Results have shown the effects of the post-combustion CO_2 capture. It has been observed that this technology is very expensive and most of the impact categories such as human toxicity, eutrophication, freshwater ecotoxicity, acidification, photochemical ozone formation and land use change grow by several times. The main problem is the extremely high amount of heat required - the energy penalty - so natural gas and biomass cogeneration (CHP) plants have been proposed as alternatives to substitute the coal-fired CHP plant. Consequently, more research is needed to reduce costs and emissions.

Along with the environmental assessment of the cement manufacture, a modelling analysis has been carried out in order to assess these Directives. TIMES-Spain energy optimisation model has been used. Previously, several calibrations, technology updates and other policies implementations have been made. In addition, measures analysed in the LCA study have been implemented in TIMES-Spain. Considering several scenarios related to CO_2 emissions, cement demands and investment costs, the effect of the Directives has been analysed from 2010 to the end of horizon, 2050. It has been concluded that Directive 2009/29/EC involves great reductions in CO_2 emissions respect to a case without Directive, reaching almost 50% in 2050.

The application of Directive 2001/81/EC is not significant from the point of view of the cement-making because NO_x and SO_2 emissions are already low respect to the total amounts. The high share of the cement sector CO_2 emissions respect to the total has shown the difficulties of the cement industry respect to other industries in terms of emissions reduction efforts. Also, it has been observed that CO_2 capture technology does not appear except when high cement demands and stringent sectorial CO_2 limits are imposed. It has been recommended to reduce the CO_2 emissions limits to the cement manufacturing sector in Spain assuming that 2013-2020 allowances allocation does not force the cement producers to make new investments since the expected cement demands are too low.

Besides, the application of the emissions-related Directives in the electricity production sector has been assessed. Several calibrations and developments have been implemented in TIMES-Spain. Emissions and fossil fuel prices scenarios have been included. Externalities of the electricity production have been internalised as well as taxes on CO_2, NO_x and SO_2 have been evaluated to assess the Directives effects. As a result, a high contribution of natural gas in the electricity mix takes place when Directives are applied. The evolution of the electricity production system is mainly characterized by the coal phase-out in 2015, followed by the growth of natural gas combined cycle plants and the entrance of natural gas cogeneration plants in industry from 2030. Beyond 2030 renewable technologies are significantly implemented, in particular wind and solar. The contribution of solar photovoltaic plants is remarkable in the long-term. In addition, it has been observed the disappearance of the CO_2 emissions in 2035. Taxes on CO_2 have effect from 30€/t CO_2 in 2030 and 50€/t CO_2 in 2050. It has also been relevant the taxation on NO_x, especially from 2030 with a considerable growth of natural gas cogeneration plants.

Finally, it has been recommended to update Directive 2001/81/EC for establishing a new ceiling for Spain. In particular, the SO_2 ceiling should be reduced below 450-500 kt SO_2 per year. On the other hand, it has been suggested to extend the target imposed by Directive 2009/29/EC, to a 50% reduction (in absolute CO_2) in 2050 respect to the 2005 level. Moreover, 80% reduction target by 2050 has been proved to be achievable. In that case, an energy carrier shift takes place from electricity to heat in industry, residential and commercial sectors.

The application of the previous methodologies shows the importance of considering integrated approaches which deal with more than one aspect. In the current work, environmental and prospective strategies have been merged. As a result, interesting conclusions and recommendations have been obtained not only relevant for the Spanish policymakers and industries but also for the Spanish society.

Resumen

El presente trabajo de investigación está basado en una evaluación de las directivas europeas relacionadas con contaminantes emitidos a la atmósfera. La Directiva 2009/29/EC mejora y extiende el esquema de mercado de derechos de emisión de gases de efecto invernadero mientras que la Directiva 2001/81/EC establece techos nacionales de emisión para las emisiones de SO_2, NO_X, COV y NH_3. En concreto, el análisis se ha enfocado en España.

Para evaluar la aplicación de las directivas así como sus consecuencias en los sectores del cemento y la producción eléctrica en España se han llevado a cabo varios análisis.

Primero, se ha analizado en detalle la industria del cemento en España a través de un Análisis de Ciclo de Vida (ACV) del sector y realizando posteriormente una prospectiva tecnológica por medio del modelo energético de optimización TIMES-Spain. La elección de esta industria no es arbitraria. Durante la última década, la industria española de producción de cemento se ha convertido en una de las principales fuentes emisoras de CO_2 alcanzando hasta un 7% del total nacional de emisiones. Además, la reducción de las emisiones de dicho sector presenta grandes dificultades ya que la mayoría no están relacionadas con la combustión de combustibles sino con la calcinación de la caliza, materia prima que constituye el cemento. Asimismo, producir cemento requiere enormes cantidades de calor lo cual supone un problema adicional para el futuro de la industria cementera.

Seguidamente, tras llevar a cabo el estudio de ACV del cemento en España, se han implementado varias soluciones tecnológicas relacionadas con el consumo de energía y la reducción de emisiones mediante el modelo energético de optimización TIMES-Spain. Así, ha sido posible desarrollar escenarios con el fin de explorar la evolución de la industria de producción de cemento en España hasta el 2050. Además, se han tenido en cuenta diversos límites de emisiones de CO_2, proyecciones de demanda de cemento y distintos costes de inversión de las tecnologías de captura aplicadas al sector, todo ello bajo el marco de las directivas referidas previamente.

Por otro lado, se ha estudiado el sector de la producción de electricidad en España usando el modelo TIMES-Spain. En dicho análisis se ha estudiado el efecto de las directivas considerando además varios escenarios en los que se han introducido tasas a las emisiones de CO_2, NO_x y SO_2. Asimismo se ha evaluado el efecto de la internalización de los costes externos medioambientales derivados de la producción de electricidad tanto en el sector eléctrico como de la producción eléctrica proveniente de plantas de cogeneración en industria. También se ha realizado un análisis de sensibilidad del sistema de producción eléctrica ante variaciones en el precio de los combustibles fósiles así como considerando diferentes límites de emisiones de CO_2.

Cumplimiento de los objetivos

Los tres principales objetivos del trabajo han sido totalmente satisfechos.

a. La evaluación de los impactos medioambientales derivados de la producción de cemento en España con el fin de identificar puntos conflictivos y aplicar soluciones sostenibles por medio del método de ACV.

El estudio de ACV de la producción de cemento en España ha hecho posible identificar puntos conflictivos así como evaluar las mejoras tecnológicas propuestas por la industria del cemento (Capítulo 4 Sección 1). En la siguiente Sección 3.1 se incluye una recopilación de las principales conclusiones obtenidas.

b. La evaluación de la aplicación de la Directiva 2009/29/EC y la Directiva 2001/81/EC en el marco de la producción de cemento en España de 2010 a 2050.

Gracias al estudio medioambiental realizado y al modelo de optimización TIMES-Spain, se ha evaluado el efecto de aplicar las directivas europeas sobre el sector del cemento en España a largo plazo (Capítulo 4 Sección 2). Las principales conclusiones y recomendaciones a este respecto se muestran en las siguientes Sección 3.2 y Sección 4.

c. La evaluación de la aplicación de la Directiva 2009/29/EC y la Directiva 2001/81/EC en el marco de la producción de electricidad en España de 2010 a 2050.

De forma análoga a la modelización de la industria del cemento, el presente trabajo da respuesta a cuestiones relacionadas con la aplicación de las directivas de emisiones sobre el sector de la generación de electricidad en España. Esta evaluación ha sido detalladamente discutida en el Capítulo 5. Las principales conclusiones y recomendaciones se presentan en las siguientes Sección 3.3 y Sección 4.

Conclusiones

ACV de la producción de cemento en España

En este trabajo se han desarrollado mejoras en la industria española de producción de cemento desde el punto de vista de los impactos sobre el medio ambiente y la salud humana. Para ello se han implementado Mejores Técnicas Disponibles (MTD) y otras soluciones de tipo prospectivo propuestas por la Comisión Europea.

- El principal punto conflictivo de la fabricación de cemento es la combustión de combustibles fósiles en el horno.

- Tanto la sustitución material como la sustitución de combustibles fósiles son las mejores soluciones para reducir la mayoría de los impactos medioambientales. La sustitución de combustibles fósiles por alternativos consigue las mayores reducciones en la mayoría de categorías pero la eutrofización empeora debido a las emisiones de fosfatos procedentes de los combustibles alternativos.

- La sustitución material es una buena solución para la industria en términos de impactos pero requiere un cambio en la demanda de tipos de cemento así como investigar en profundidad las propiedades físico-químicas de los mismos con el fin de asegurar su usabilidad.

- La necesidad de vapor, preferentemente desde una planta de cogeneración (CHP), cuando se implementa la captura de CO_2 vía post-combustión es extremadamente alta. Este es el origen del llamado *energy penalty*. La contribución relativa, en términos de impactos, de la planta CHP es del mismo orden que la de la planta de producción de cemento. Los resultados del presente trabajo, en consonancia con la literatura, revelan que el uso de una planta CHP de gas natural conllevaría reducciones importantes en la mayoría de impactos respecto de un caso en el que se usase una CHP de carbón. Además, la consideración de esta solución se ve reforzada por la retirada paulatina del carbón dentro del sistema de producción eléctrica nacional.

- Las tecnologías de captura de CO_2 aplicadas a la industria de cemento contribuyen a reducir el cambio climático mientras que los demás impactos se incrementan enormemente. Para lograr que dicha tecnología sea más competitiva se necesita más investigación. Por ello se recomienda llevar a cabo más estudios en los que se sustituya la CHP de carbón por opciones basadas en gas natural y/o biomasa, así como implementar otras opciones de captura diferentes tales como la oxi-combustión u otras técnicas de post-combustión.

Modelización de la industria española del cemento con TIMES-Spain

Tras llevar a cabo el estudio de ACV se implementaron varias soluciones y escenarios en TIMES-Spain para analizar la industria de la producción del cemento en España bajo el marco de la Directiva 2009/29/EC y la Directiva 2001/81/EC.

- La Directiva 2009/29/EC conduce a una reducción considerable de las emisiones de CO_2 provenientes de la producción de cemento respecto del caso de no aplicarse. Así, cuando la directiva es aplicada las emisiones del sector oscilan en el rango de 16 a 18 Mt CO_2 anuales a partir de 2020 mientras que sin directiva las emisiones alcanzarían los 30 Mt CO_2 en 2050.

- Como resultado de la reducción de las emisiones de CO_2 en otros sectores tiene lugar un incremento del peso relativo del CO_2 sectorial que va desde el 6% en 2010 hasta el 9% en 2050. Este es un problema que los productores de cemento españoles habrán de afrontar de cara al futuro del sector.

- Además, tras implementar soluciones MTD y escenarios de sustitución se ha concluido que la reducción del contenido de clínker en el cemento es la mejor opción para reducir las emisiones de CO_2 del cemento logrando reducciones de 2 a 2.4 Mt CO_2 al año desde 2030.

- Cuando se consideran todas las MTD y escenarios prospectivos de sustitución, el consumo de energía en la producción de cemento en España se reduciría hasta un 21% en 2050 respecto del consumo de 2010.

- El techo nacional de SO_2 de la Directiva 2001/81/EC es demasiado alto comparado con los valores históricos de emisiones. Por consiguiente se debería actualizar la Directiva 2001/81/EC para establecer un techo de SO_2 más estricto. En particular, las emisiones de SO_2 derivadas de la producción de cemento tienden a desaparecer en la medida en que el coque de petróleo es sustituido por combustibles alternativos.

- La tecnología de captura de CO_2 sólo aparece cuando las demandas de cemento son altas, los límites sectoriales de CO_2 estrictos y el resto de las tecnologías de producción de cemento no logran cumplir con los objetivos de CO_2 impuestos. En tal caso, la producción de clinker por ruta seca con captura de CO_2 mediante post-combustión aparecería tímidamente en 2050.

Modelización de la industria española de generación de electricidad con TIMES-Spain

Varios escenarios han sido implementados en TIMES-Spain para analizar el sector de la generación de electricidad bajo el marco de la Directiva 2009/29/EC y la Directiva 2001/81/EC.

- La aplicación de las directivas 2009/29/EC y 2001/81/EC conlleva una alta contribución del gas natural en la producción de electricidad a través de centrales de ciclo combinado. De 2030 en adelante dichas instalaciones son sustituidas por nuevas centrales de cogeneración de gas natural. Desde entonces y hasta 2050 se observa un incremento significativo en la contribución de las energías renovables.

- Cuando las directivas son aplicadas, la contribución en el horizonte lejano de las energías renovables es relevante y se basa en eólica, en menor medida tecnologías undimotrices y termosolar de cilindro parabólico. En 2050 las plantas de tecnología solar fotovoltaica contribuyen de forma notable al sistema de generación.

- Las plantas de fisión nuclear se extinguen en 2028 y las centrales hidroeléctricas mantienen estable su capacidad, produciendo siempre al máximo sin que nuevos embalses sean construidos.

- La aplicación de la Directiva 2009/29/EC sobre los gases de efecto invernadero (GEI) tiene un efecto significativo en lo que se refiere a reducción de emisiones de CO_2. Las emisiones de dicho gas provenientes del sector eléctrico desaparecen en 2035 debido a la retirada de las centrales térmicas de carbón y a que, desde 2030, la mayor parte de las emisiones de CO_2 de la producción de electricidad vienen imputadas al sector industrial a través de plantas de cogeneración de gas natural.

- Los resultados de fijar un objetivo de reducción de emisiones de CO_2 de un 50% en 2050 respecto del nivel de 2005 son muy similares a los obtenidos de aplicar la Directiva 2009/29/EC. Usando un objetivo de reducción más ambicioso de un 80% en 2050, se aprecia un cambio de uso de electricidad a calor que afecta principalmente al sector industrial (calor industrial para procesos) y al residencial-comercial (calor de distrito).

- Los resultados han mostrado que considerando una reducción de emisiones de un 80% en 2050, el aumento en el consumo de calor conllevaría la introducción masiva de plantas de gasificación de biomasa y el aumento del uso de biocombustibles en el transporte.

- El efecto de las Directivas 2009/29/EC y 2001/81/EC sobre la Directiva 2009/28/EC de energías renovables es notable. La referida directiva establece un objetivo del 20% de contribución de fuentes renovables en el consumo de energía final en 2020 para España. Teniendo en cuenta las directivas de emisiones evaluadas, el objetivo de la Directiva de renovables se satisface completamente.

- Aplicar el techo nacional de emisiones de NO_x de la Directiva 2001/81/EC conlleva la extinción de las emisiones de dicho gas procedentes del sector eléctrico a partir de 2030. Además de eso, tiene lugar un aumento en el uso de tecnologías renovables, principalmente eólica y solar, así como de nuevas plantas CHP de gas natural.

- Asimismo aplicar la Directiva 2001/81/EC conduce a la desaparición de las emisiones de SO_2 asociadas a la producción de electricidad desde 2015. Ello es debido al abandono de las tecnologías de carbón.

- La internalización de los costes externos derivados de la producción de electricidad favorece el uso del gas natural. En este caso, se instalan nuevas plantas de CHP de gas mientras que las tecnologías renovables mantienen la capacidad existente. Una consecuencia de las restricciones medioambientales impuestas es el alto grado de electrificación del sistema energético.

- Imponer una tasa al CO_2 de 30€/t en 2030 detendría el crecimiento de las emisiones derivado del progresivo aumento en el uso del gas natural y una tasa de 50€/t en 2050 conseguiría el objetivo de la Directiva. En particular, las tasas de CO_2 surten efecto sobre las emisiones derivadas del sector eléctrico a partir de 20€/t CO_2 en 2020 y logran estar en línea con la Directiva para 25€/t CO_2 en 2025.

- La imposición de tasas al NO_x y al SO_2 fuerza al sistema a continuar usando plantas de ciclo combinado de gas natural al tiempo que nuevas plantas CHP de gas son instaladas a partir de 2030. La aplicación de tasas al NO_x favorece el cumplimiento de la Directiva 2001/81/EC hasta 2030. De ahí en adelante, la instalación de nuevas CHPs de gas conlleva que el techo de emisión de NO_x sea sobrepasado. Por otro lado, la aplicación de tasas al SO_2 permite ir más allá de los objetivos de reducción de emisiones establecidos en la Directiva 2001/81/EC para dicho gas.

Recomendaciones

En cada capítulo se han propuesto diversas recomendaciones con el fin de comprender en profundidad tanto las tecnologías como las restricciones y medidas evaluadas, así como favorecer la toma de decisiones en lo que se refiere a desarrollo normativo. Las principales recomendaciones del trabajo se expresan a continuación.

Recomendaciones políticas

Las recomendaciones políticas están principalmente relacionadas con la Directiva 2009/29/EC y la Directiva 2001/81/EC.

- Se recomienda reducir los límites de emisiones de CO_2 a las emisiones de la producción de cemento en España. La asignación de derechos 2013-2020 no fuerza a los productores a realizar nuevas inversiones ya que las demandas de cemento esperadas son muy bajas. De lo anterior, se recomienda ir más allá de la Decisión 2013/448/EC después de 2020.

- Es necesario actualizar la Directiva 2001/81/EC para establecer nuevos techos de emisión. En particular, el techo establecido a las emisiones de SO_2 en 2010 para España fue satisfecho sin problemas. Por ello se recomienda establecer un nuevo límite en torno a 450-500 kt SO_2 por año.

- Se recomienda además, desde un enfoque conservador, extender el objetivo del 20% de reducción de GEI en 2020 respecto del nivel de 1990 (Directiva 2009/29/EC) a un 50% de reducción de CO_2 en 2050 respecto del nivel de 2005. Igualmente, desde un punto de vista más ambicioso, se propone una reducción del 80% de CO_2 en 2050 dado que dicho objetivo se ha mostrado alcanzable tanto desde un punto de vista técnico como económico.

Recomendaciones técnicas

- En la producción de cemento es necesario llevar a cabo más estudios sobre la preservación de las propiedades físico-químicas del cemento cuando el contenido de clinker se reduce mediante la sustitución de materiales secundarios.

- Deberían evaluarse otras soluciones tecnológicas para resolver el llamado *energy penalty* asociado a la purificación de los gases que conlleva la captura de CO_2 de post-combustión. De los resultados obtenidos tanto en el estudio de ACV como en el trabajo de modelización prospectiva con TIMES-Spain, se recomienda llevar a cabo un estudio detallado que sustituya la planta de CHP de carbón ligada a la post-combustión por plantas de CHP de gas natural y/o biomasa.

- Desarrollar sinergias y planes integrados entre la industria del cemento y las centrales de ciclo combinado de gas natural con el fin de aprovechar debidamente el calor residual y mitigar el *energy penalty* de la captura de CO_2 que conlleva la post-combustión.

Recomendaciones específicas

Finalmente, varios asuntos específicos tanto de la producción de cemento como de la electricidad en España han dado como resultado otras tantas recomendaciones:

- Además de los impactos derivados de las emisiones de CO_2, deberían considerarse otras categorías de impacto en el estudio de ACV tales como toxicidad humana, eutrofización, ecotoxicidad y acidificación puesto que tienen contribuciones relevantes.

- En especial, es interesante el análisis detallado de las consecuencias medioambientales de usar aminas en la captura de CO_2 de post-combustión realizando una extensión aguas arriba de los límites del sistema.

1 INTRODUCTION

1. Background

The risks of climate change are being addressed globally by the United Nations Framework Convention on Climate Change (UNFCCC) (http://unfccc.int/). The long-term objective is to stabilise atmospheric GHG concentrations at a level that would prevent dangerous anthropogenic interference with the climate system.

According to the Intergovernmental Panel on Climate Change (IPCC), to keep global warming below 2°C, GHG emissions must be halved by 2050 (compared with 1990 levels) (IPCC, 2007). Developed countries will need to reduce more, between 80% and 95% by 2050, whereas advanced developing countries with large emissions (e.g. China, India and Brazil) will have to limit their emission growth.

Numerous European countries have adopted national programmes aimed at reducing emissions. EU-level policies and measures include increased use of renewable energy and combined heat and power installations; improved energy efficiency in buildings, industry, and household appliances; reduction of CO_2 emissions from transport; abatement measures in the manufacturing industry; and measures to reduce emissions from landfills.

The EU climate and energy package (EC, 2008) was adopted in 2009 to implement the 20-20-20 targets endorsed by EU leaders in the Council of the EU 8/9 March 2007, Presidency Conclusions 7224/1/07REV1 - by 2020 there should be a 20% reduction of GHG emissions compared with 1990, a 20% share of renewables in EU energy consumption, and energy efficiency improvement by 20%.

Attending to the GHG emissions reductions, Directive 2009/29/EC (EC, 2009) improves and extends the GHG emission allowance trading scheme of the EC established by Directive 2003/87/EC (EC, 2003).

From a regional point of view, air pollution harms the environment and the human health. In Europe, emissions of many air pollutants have decreased substantially over the past decades, resulting in improved air quality across the region (EEA, 2012). However, air pollutant concentrations are still too high, and air quality problems persist. A significant proportion of Europe's population live in areas, especially cities, where exceedances of air quality standards occur: ozone, nitrogen dioxide and particulate matter pollution pose serious health risks. Several countries have exceeded one or more of their 2010 emission limits for four important air pollutants (EEA, 2012). In 2010, Spain exceeded the NO_x, VOC and NH_3 ceilings established (EEA, 2012). Reducing air pollution therefore remains important.

Air pollutants released in one country may be transported in the atmosphere, contributing to or resulting in poor air quality elsewhere. Main impacts derived from the referred air pollution are: acidification, eutrophication and crop damage caused by exposure to high ozone concentrations.

Attending to the air quality, Directive 2001/81/EC (EC, 2001) establishes national emission ceilings to NO_x, SO_2, VOC and NH_3.

The EU's long-term objective is to achieve air quality levels that do not result in severe impacts on human health and the environment. The EU acts at many levels to reduce exposure to air pollution: through legislation; research; and cooperation with sectors responsible for air pollution, as well as international, national and regional authorities and non-governmental organisations. EU policies aim to reduce exposure to air pollution by reducing emissions and setting limits and target values for air quality.

2. Justification

Due to the increasing importance of the climate change and air quality concerns, the European Union approved the EU climate and energy package in 2009 (EC, 2008b), which implements the 20-20-20 targets: by 2020 there should be a 20% reduction of GHG emissions compared with 1990, a 20% share of renewables in EU energy consumption, and energy efficiency improvement by 20%.

Regarding the GHG emissions reductions, Directive 2009/29/EC (EC, 2009) improves and extends the GHG emission allowance trading scheme of the Community established by Directive 2003/87/EC (EC, 2003b). Furthermore, to improve air quality levels Directive 2001/81/EC (EC, 2001) establishes national ceilings for NO_x, SO_2, VOC and NH_3 emissions in order to abate acidification, eutrophication and crop damages derived from ground-level ozone.

Looking at GHG emissions in 2010, Spain was the sixth-largest emitter in EU27 contributing with 7.5% of the total EU27. On the other hand, Spain released 10% of the NO_x, SO_2, VOC and NH_3 emissions of the European Union in 2010. Even though the Spanish emissions of most of the referred pollutants from 1990 to the present have been reduced, only SO_2 levels are below the Directive's limit. In particular, Spanish GHG emissions have been growing continuously until the beginning of the economic recession. In 2007, Spanish GHG emissions reached up to 149% respect to the 1990 level. From 2010 to 2012, this level has been stabilized in 120%, very far from the target of Directive 2009/29/EC for Spain in 2020, 80%.

In this context, Spanish electricity generation sector and cement production industry are two of the main emitters of CO_2, NO_x and SO_2 and, consequently, there is a common concern in both to accomplish with these Directives. In 2010, cement-making industry released 7% of the total Spanish CO_2 emissions and the electricity generation sector emitted 35%. The emissions of NO_x and SO_2 are also relevant because they are associated to the combustion of fossil fuels.

In recent years cement and electricity producers, supported by their Spanish and European associations, have developed roadmaps, studies and position papers to reduce emissions together with accomplishing the rules and restrictions derived from the Directives. These policies, by means of diverse mechanisms such as the Energy Trading System or the national ceilings, force the industries to upgrade their technologies by implementing BATs or high-efficient measures.

Therefore, it is opportune to carry out an integrated assessment of the emissions-related Directives focused on the cement production and the electricity generation in Spain. Accordingly, in order to evaluate the Directives, the combined approach of the LCA method and the energy optimisation modelling is well-suited since it gathers the environmental and prospective viewpoints.

To that end the TIMES–Spain energy optimization model will need to be updated and the cement sector to be completely reviewed so that it can properly represent the technologies implemented and the alternatives available to the industry.

To sum up, in the context of the emissions Directives and considering the importance of the cement and electricity production industries in Spain, results of this work will provide a well-established set of conclusions and recommendations in the interest of the policymakers, industry and society.

3. Objectives

In this work, the effects of applying Directive 2009/29/EC on GHG emissions and Directive 2001/81/EC on acidification, eutrophication and tropospheric ozone emissions are going to be evaluated focusing on the cement production and the electricity generation in Spain.

In order to develop an integrated assessment which includes environmental and prospective analyses, the LCA method and TIMES energy optimisation modelling will be used.

The three main objectives of this work are:

a. The assessment of the environmental impacts of the cement manufacturing technologies in Spain in order to identify hotspots and to apply environmental-friendly solutions using LCA method.

b. The evaluation of the application of Directive 2009/29/EC and Directive 2001/81/EC in the framework of the Spanish cement production from 2010 to 2050.

c. The evaluation of the application of Directive 2009/29/EC and Directive 2001/81/EC in the framework of the Spanish electricity production from 2010 to 2050.

4. Outline

This work has been divided in six chapters. A brief summary of each one is presented next.

Chapter 2 – Description of the sectors shows an extensive and detailed description of both the Spanish cement industry and electricity production sector. First the main socioeconomic drivers such as gross domestic product (GDP), population and households are depicted. Second, the most relevant Directives and national policies concerning emissions related to these industries are presented. Third, cement production is explained both from a technical approach and from the sectorial perspective using national statistics. Moreover, the CO_2 capture applied on cement has been described as well as other BAT and substitution scenarios. Finally, the Spanish energy system has been described focusing on the electricity production.

Chapter 3 – Methodologies describes the methodologies used in this work: the LCA method and the energy optimisation modelling. The LCA carried out is focused on the Spanish cement production. Furthermore, using the TIMES-Spain energy optimisation model it has been possible to explore the future of the cement sector as well as the electricity generation in Spain up to 2050. In this chapter how a TIMES energy optimisation model works has been explained in detail along with the TIMES-Spain model description.

Chapter 4 – Spanish cement sector includes the application of the LCA and the energy optimisation modelling to the Spanish cement production. In this chapter it is shown how results from LCA serve as basis of the solutions implemented in TIMES-Spain. By means of this integrated approach, it has been possible to identify the problems of the cement production industry and explore solutions in the long-term. In every case, the application of the Directives 2009/29/EC and 2001/81/EC has been assessed.

Chapter 5 – Spanish power generation sector presents the modelling results of the Spanish electricity production. The application of the Directives 2009/29/EC and 2001/81/EC has been evaluated in comparison to the imposition of taxes to certain pollutants. In the same manner, the internalisation of the environmental externalities associated to the electricity production has been carried out.

Chapter 6 – Summary and conclusions includes the summary and main conclusions of the work. Moreover, some recommendations and future research lines are presented.

2 DESCRIPTION OF THE SECTORS

1. Socioeconomic framework

1.1. Population

Spanish population reached 47.27 M inhabitants at the end of 2012 from which 5.75 M inhabitants were foreign-born population (INE, 2012a). As the extension of Spain is 504,645 km^2, the average population density was 93.7 pop/km^2 in 2012. Most of the population is located in the coast and in Madrid metropolitan area. In the inner area of Spain, population density is very low. Table 1 shows the evolution of the population (INE, 2012b).

Table 1. Historical evolution of the Spanish population

	2005	2006	2007	2008	2009	2010	2011	2012
Population (millions)	44.11	44.71	45.20	46.16	46.75	47.02	47.19	47.27

According to the Instituto Nacional de Estadística (INE), population will fall down severely in the next decades. At the end of horizon, 2052, Spanish population will be around 41.5 M inhabitants (Figure 1).

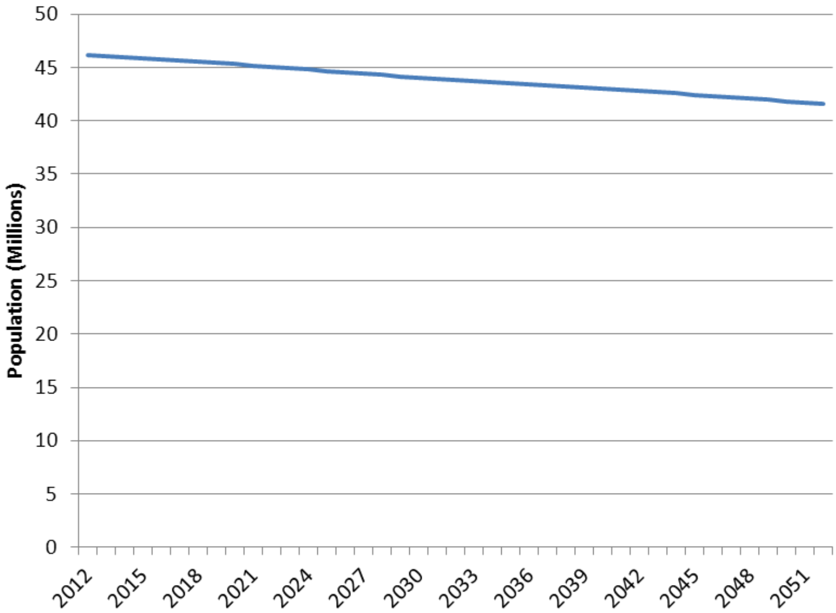


Figure 1. Projection of the Spanish population

Eurostat projections are considerably more optimistic (52.6 M inhabitants in 2055). Differences are due to different assumption in the immigration rate and the effect of the economic crisis. Since the trend is decreasing now, INE projections seem to be more realistic.

1.2. Economy

Spain joined the European Union (EU) in 1986 and since then and until 2007, it witnessed a rapid economic growth. Nevertheless, last figures show a negative growth rate due to the economic crisis. GDP evolution in constant €$_{2008}$ can be seen in Table 2 below (BdE, 2013).

Table 2. Evolution of the Spanish GDP at market prices, GDP_{mp}

	2005	2006	2007	2008	2009	2010	2011	2012
GDP_{mp} (M€)	909,298	985,547	1,053,161	1,087,788	1,048,060	1,048,883	1,063,355	1,049,525
GDP_{mp} interannual var. (%)	8.1	8.4	6.9	3.3	-3.7	0.1	1.4	-1.3

In the last years, Spain has suffered a recession with a decrease in the GDP by almost 4% in 2009 respect to 2008. In 2010 and 2011 the growth was positive although small, and in 2012 and 2013 a new recession occurred. The economic recovery is expected to start in 2014.

Comparing with the trend of the historical GDP data (in blue) in Figure 2, Bank of Spain predicts a smooth long-term GDP fall, going from the structural 2-2.5% inter annual growth from the 2000s decade to 1.5-2% (in red) from 2020 and beyond (BdE, 2013).

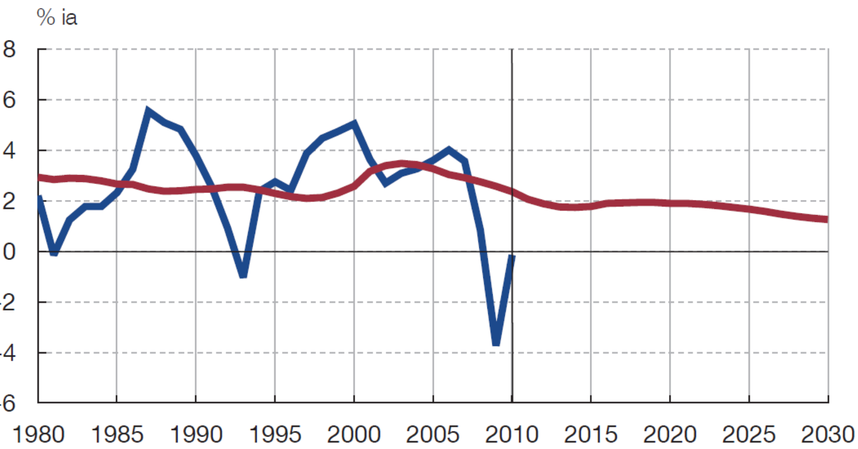


Figure 2. Comparison between GDP data and GDP projections for Spain

1.3. Other socioeconomic drivers

Residential sector in Spain grew steadily during the period 2000 to 2008. The economic growth boosted the construction of new dwellings and, due to the important multiplier effect of this activity on the economy; it became a key element in the Spanish economic development. When economic crisis began, this situation changed.

Table 3. Historical evolution of the Spanish stock of dwellings

	2005	2006	2007	2008	2009	2010	2011
Households (millions)	23.21	23.86	24.50	25.13	25.56	25.84	26.02
Main house (millions)	16.00	16.51	16.94	17.40	17.63	17.76	17.91

Table 3 shows the stock of households (MFOM, 2013). Demolition rate is around 0.21% of the total stock of dwellings. The evolution of the number of dwellings shows a slowing down fruit of the crisis, going from 3% inter annual variations in the period 2005-2006 to 0.7% in 2010-2011.

According to national figures, the average surface area of the Spanish dwellings is 119.4 m^2 (MVIV, 2006). Regarding occupation of the dwellings, the evolution of this parameter in the last years has been estimated using the ratio between population and the number of dwellings considered as main residential use. The number of people living in the same dwelling has been decreasing in the studied period. In 2005 this ratio was 2.75 inhabitants per dwelling and, by 2011, this value fell down to 2.63 (MVIV, 2006).

2. Policy framework

2.1. Directive 2009/29/EC

Directive 2003/87/EC of the European Parliament and of the Council of 13 October 2003 established a scheme for GHG emission allowance trading within the Community and amending Council Directive 96/61/EC, in order to promote reductions of GHG emissions in a cost-effective and economically efficient manner. Directive 2009/29/EC amends the previous one so as to improve and extend the GHG emission allowance trading scheme of the Community.

Directive 2003/87/EC established a scheme for achieving GHG emissions reductions: national allocation plans (NAPs), periods of application (2005-2007, 2008-2012, 2013-2020), as well as flexibility mechanisms (Clean Development Mechanisms and Joint Implementation) and the creation of a European market in GHG emission allowances. Originally, this Directive was signed following the *Sixth Community Environment Action Programme* established by Decision No 1600/2002/EC which identified the climate change as a major priority for the European Union. Apart from that, Decision 2002/358/EC included the Kyoto Protocol as an obligation for the Member States in such a way that countries were obliged to reduce their aggregate anthropogenic emissions of GHG coming from several activities (Annex A to the Kyoto Protocol) by 8% compared to 1990 levels in the period 2008 to 2012.

GHGs are declared in Annex II of Directive 2003/87/EC: carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs) and sulphur hexafluoride (SF_6).

To avoid dangerous anthropogenic interferences with the climate system, the overall global annual mean surface temperature should not increase more than 2°C above pre-industrial levels. The latest IPCC Assessment Report (IPCC, 2007) shows that global emissions of GHGs could peak by 2020. This implies the increasing of efforts by the Community, the quick involvement of developed countries and encouraging the participation of developing countries in the emission reduction process.

Directive 2009/29/EC amends the majority of the articles of Directive 2003/27/EC changing the goals, the scope of application and detailing different issues concerning specific sectors. *The European Council of March 2007 made a firm commitment to reduce the overall GHG emissions of the Community by at least 20% below 1990 levels by 2020, and by 30 % provided that other developed countries commit themselves to comparable emission reductions and economically more advanced developing countries contribute adequately according to their responsibilities and respective capabilities. By 2050, global GHG emissions should be reduced by at least 50% below their 1990 levels. All sectors of the economy should contribute to achieving these emission reductions, including international maritime shipping and aviation.*

The text remarks that *in order to contribute to achieving those long-term objectives, it is appropriate to set out a predictable path according to which the emissions of installations covered by the Community scheme should be reduced. To achieve cost-effectively the commitment of the Community to at least a 20 % reduction in GHG emissions below 1990* *levels, emission allowances allocated in respect of those installations should be 21 % below their 2005 emission levels by 2020.*

Directive 2009/29/EC changes the previous framework of national plans by a Community allocation scheme in which emission allowances are put in the market (via auction) by the countries according to the expected growth of the economy (Art. 9-10).

Annex I shows the categories of activities to which this Directive applies: production of coke, refining of mineral oil, combustion of fuels in installations (>20MW) (except incineration of hazardous or municipal waste), production of mineral products (metal ore, pig iron, steel, ferrous metals, aluminium, secondary aluminium, non-ferrous metals), production of lime, manufacture of glass, ceramic products, mineral wool, calcination of gypsum, pulp, paper and paperboard production, chemicals (carbon black, nitric acid, adipic acid, glyoxal, glyoxylic acid, ammonia, hydrogen, syngas, bulk organics chemicals, soda ash and sodium bicarbonate), and capture of GHGs coming from capture, transport and storage installations.

Cement industry is included in Annex I as "*Production of cement clinker in rotary kilns with a production capacity exceeding 500 tonnes per day or in other furnaces with a production capacity exceeding 50 tonnes per day*" focusing only on the main pollutant, CO_2.

2.1.1. Decision No 406/2009/EC

This Decision is an application of Directive 2009/29/EC.

This Decision lays down the minimum contribution of Member States to meeting the GHG emission reduction commitment of the Community for the period from 2013 to 2020 for GHG emissions covered by this Decision, and rules on making these contributions and for the evaluation thereof.

According to Article 3, *each Member State shall, by 2020, limit its GHG emissions at least by the percentage set for that Member State in Annex II to this Decision in relation to its emissions in 2005*. The Spanish GHG emission limit is -10%.

2.1.2. Decision 2013/162/EU and Decision 377/2013/EU

Decision 2013/162/EU is focused on determining Member States' annual emission allocations for the period from 2013 to 2020 pursuant to Decision 406/2009/EC of the European Parliament and of the Council. It was signed on March 26th, 2013. Besides, the document indicates how to calculate each national allocation caps depending on the year in which each Member State began to participate in the Emissions Trading Scheme (ETS) (2005, 2007 or 2013).

Annex I presents the national caps applying global warming potential values from the second IPCC assessment report. Annex II details the caps using both the second and the most recent fourth IPCC assessment report on global warming potentials (IPCC, 2007). Spanish GHG emissions allocations for the period 2013-2020 are as follows (see Table 4).

Table 4. Spanish emissions allocation for the period 2013-2020

	2013	2014	2015	2016	2017	2018	2019	2020
GHG (Mt) (2nd IPCC)	228.88	226.98	225.07	223.17	221.26	219.35	217.45	215.54
GHG (Mt) (4th IPCC)	235.55	233.49	231.43	229.37	227.30	225.24	223.18	221.12

Projections of the ETS and non-ETS emissions for Spain are presented in the national report concerning Decision 280, Art 3.2.b (MAGRAMA, 2013). In that report, the weight of CO_2 respect to the total of non-ETS GHG emissions is 66.6% (in CO_2 equivalent) being around 80% in the case of ETS. Consequently, non-ETS CO_2 emissions can be restricted using a cap of 147.26 Mt in 2020.

Decision 377/2013/EU amends the Art 16 of Directive 2003/87/EC by including aviation in the ETS market. This amendment affects consequently to Directive 2009/29/EC.

2.1.3. Decision 2013/448/EU

Decision 2013/448/EC concerning national implementation measures (NIM) for the transitional free allocation of GHG emission allowances approved and published the list of releasing installations proposed by the Spanish government in late 2012 for regulating the transitory period of the Phase III ETS market from 2013 to 2020.

This document lists all the installations registered in the European Union and only rejects the emission allowances to several facilities in Germany and Czech Republic. As a result, the proposed allowances for the Spanish installations in the document called "*Sistema Europeo de Comercio de Derechos de Emisión: Período 2013-2020. Medidas Nacionales de Aplicación de España* (EU Emissions Trading System: 2013-2020 Period. Spanish National Implementation Measures)" (MAGRAMA, 2012d) signed on June 26th 2012, have been approved entirely.

2.2. Directive 2001/81/EC

Signed on 23 October 2001, this Directive is the result of applying the Gothenburg Protocol conclusions, signed by the EU Member States on 1 December 1999 during the United Nations Economic Commission for Europe (UNECE) Convention on long-range transboundary air pollution to abate acidification, eutrophication and ground-level ozone. It is usually referred as National Emissions Ceilings (NEC) Directive.

The text remarks on significant areas of the EU exposed to depositions of acidifying and eutrophying substances at levels which have adverse effects on the environment and also human health.

Article 1 aims *to limit emissions of acidifying and eutrophying pollutants and ozone precursors in order to improve the protection in the Community of the environment and human health against risks of adverse effects from acidification, soil eutrophication and ground-level ozone and to move towards the long-term objectives of not exceeding critical levels and loads and of effective protection of all people against recognised health risks from air pollution by establishing national emission ceilings, taking the years 2010 and 2020 as benchmarks, and by means of successive reviews*.

The Directive also states that by 2010 at the latest, Member States shall limit their annual national emissions of SO_2, NO_X, VOC and NH_3 to not exceed the emission ceilings laid down in Annex I, taking into account any modification made by Community measures adopted following the reports referred to in Article 9. Member States shall ensure that the emission ceilings set in Annex I are not exceeded after 2010.

Besides, it is assumed that the long-term reduction objectives are too ambitious for the present time. Assuming that it is difficult to meet them, the Directive establishes interim environmental objectives for acidification and ground-level ozone pollution in Art. 5.

Arts. 6-8 detail the national implementation through national programmes to achieve the 2010 emission ceilings and, from then on, the Directive is focused on accomplishing the long-term objectives for 2020, not yet established.

Table 5 shows the emission ceilings for Spain for the year 2010 established in the so called "*Plan de Acción de Techos Nacionales de Emisión para la Aplicación del II Programa Nacional de Reducción de Emisiones* (II PNRE)" (Action Plan for the Implementation of the II National Emissions Reduction Programme in accordance with the National Emissions Ceiling Directive).

Table 5. Emissions ceilings for Spain by 2010

SO_2 (kt)	NO_x (kt)	VOC (kt)	NH_3 (kt)
746	847	662	353

2.2.1. II National Emissions Reduction Programme (NERP)

First Spanish NERP plan was approved and signed in late 2003 to develop measures for accomplishing Directive 2001/81/EC. On December 7th of 2007, Ministers Council agreed to transpose the European Directive 2001/81/EC on national emission ceilings for certain pollutants (NEC Directive).

II NERP (BOE 25, 2008) lists 45 measures for applying on different productive sectors. Some of them are already included in the Spanish Saving and Efficiency Strategy 2008-2012 (IDAE, 2007) and the most recent National Renewable Energy Action Plan (NREAP) 2011-2020 (IDAE, 2011).

The majority of the measures included in II NERP are aimed to the transport sector such as the establishment of a minimum percentage of biofuels in the mix, sustainable mobility plans, and supporting measures to railway transportation. In residential and commercial sectors, focus on promoting energy efficiency measures such as using high-efficiency electrical appliances. In the power sector, the measures are related to wind turbines repowering, offshore wind farms deployment, and smart electricity meters utilisation.

II NERP also includes an adjustment (see Table 6) of the established national emission ceilings for 2010 resulting from the update of the socioeconomic drivers to 2006 (BOE 25, 2008).

Table 6. Corrected 2010 emission ceilings for Spain

SO_2 (kt)	NO_X (kt)	VOC (kt)	NH_3 (kt)
837	950	742	396

The NEC Directive is the cornerstone of EU legislation on air pollution control. In the Commission 2005 Thematic Strategy on Air Pollution (TSAP), the revision of the NEC Directive was described as one of the key instruments to achieve the TSAP's interim objectives for 2020. The revision would set new emission ceilings for 2020, and expand the number of air pollutants covered from four to five by adding ceilings for fine particles ($PM_{2.5}$).

The NEC Directive has proven to be an effective tool to reduce air pollution after being implemented by Member States. According to the latest reporting by national governments for the year 2011, 92 of the 108 ceilings have been met. In the case of Spain, 2010 values were higher than ceiling values except for SO_2. Table 7 shows the 2010 Spanish emissions of the referred pollutants included in Directive 2001/81/EC (EEA, 2012).

Table 7. Spanish emissions of acidifying, eutrophication, ground-level ozone gases in 2010

SO_2 (kt)	NO_X (kt)	VOC (kt)	NH_3 (kt)
444 (59%)	900 (106%)	672 (102%)	368 (104%)

2.3. Directive 2009/28/EC

Directive 2009/28/EC on the promotion of the use of energy from renewable sources (RES) amends and repeals Directives 2001/77/EC and 2003/30/EC.

Article 1 *establishes a common framework for the promotion of energy from renewable sources. It sets mandatory national targets for the overall share of energy from renewable sources in gross final consumption of energy and for the share of energy from renewable sources in transport. It lays down rules relating to statistical transfers between Member States, joint projects between Member States and with third countries, guarantees of origin, administrative procedures, information and training, and access to the electricity grid for energy from renewable sources. It establishes sustainability criteria for biofuels and bioliquids*.

It is also relevant to point out that *each Member State shall ensure that the share of energy from renewable sources, in gross final consumption of energy in 2020 is at least its national overall target for the share of energy from renewable sources in that year (Art. 3.1)*. Such mandatory national overall targets are consistent with a target of at least 20 % share of energy from renewable sources in the Community gross final consumption of energy in 2020. In order to achieve these targets more easily, each Member State shall promote and encourage energy efficiency and energy saving.

National overall targets are published in Annex I (Part A) for each country, included Spain. Table 8 has been extracted from the Directive's annex.

Table 8. Spanish GHG overall targets

	Spain
Share of energy from renewable sources in gross final consumption of energy, 2005 (S_{2005})	8.7%
2011-2012	10.96%
2013-2014	12.09%
2015-2016	13.79%
2017-2018	16.05%
Target: share energy from renewable sources in gross final consumption energy, 2020 (S_{2020})	20.00%

Intermediate shares, between S_{2005} and S_{2020}, are calculated using the formulae of Annex I Part B as a sort of interpolation method.

There is also a biofuels target forcing each Member State *to ensure that the share of energy from renewable sources in all forms of transport in 2020 is at least 10 % of the final consumption of energy in transport in that Member State* (Art. 3.4).

In order to achieve this goal, and considering the current percentages of biofuels participation in the transportation mix, the promotion of the biofuels is needed.

2.4. Directive 2010/75/EU

Directive 2010/75/EU was signed and approved by the European Commission on 24 November 2010, grouping and repealing several preceding directives on industrial emissions. This Directive *lays down rules designed to prevent or, where that is not practicable, to reduce emissions into air, water and land and to prevent the generation of waste, in order to achieve a high level of protection of the environment taken as a whole*.

The cement industry is described (for its inclusion) in Annex I of the Directive, paragraph 3/3.1. *Production of cement, lime and magnesium oxide: (a) production of cement clinker in rotary kilns with a production capacity exceeding 500 tonnes per day or in other kilns with a production capacity exceeding 50 tonnes per day*; and the limits for the different pollutants are listed in Annex VI/Part 4/Epigraph 2 as *Special provisions for cement kilns co-incinerating waste*. The established restrictions are described as follows:

The emission limit values set out in points 2.2 and 2.3 apply as daily average values for total dust, HCl, HF, NO_x, SO_2 and TOC (for continuous measurements), as average values over the sampling period of a minimum of 30 minutes and a maximum of 8 hours for heavy metals and as average values over the sampling period of a minimum of 6 hours and a maximum of 8 hours for dioxins and furans (see Table 9).

All values are standardised at 10 % oxygen. Half-hourly average values shall only be needed in view of calculating the daily average values.

Table 9. Limit values of the different pollutants of Directive 2010/75/EU

Polluting substance	Limit value (mg/Nm^3)
Total dust	30
HCl	10
HF	1
NO_x	500
Cd + Tl	0.05
Hg	0.05
Sb + As + Pb + Cr + Co + Cu + Mn + Ni + V	0.5
SO_2	50
TOC	10
Dioxins and Furans (ng/Nm^3)	0.1

Article 30.2 and Annex V/Part 1 of the Directive refers to existing combustion generation plants (until 7 January 2013) larger than 50 MW (Art. 30.2).

After setting in the standard conditions to homogenize the emission limit values, the Directive lists the limit values for each pollutant. It is disaggregated by fuel type and, in all the cases, gas turbines and gas engines technologies are specified as exceptions, having different emission limits.

2.5. National Allocation Plans (NAP)

2.5.1. Emission Trading System (ETS)

Concerning GHG emissions, the ETS regulation established in Directive 2003/87/EC has passed through different phases: Phase I (2005-2007), Phase II (2008-2012), and recent Phase III (2013-2020).

In Phase I, the EU ETS included more than 10,000 installations, representing approximately 40% of EU CO_2 emissions, covering energy activities (combustion installations with a rated thermal input exceeding 20 MW, mineral oil refineries, coke ovens), production and processing of ferrous metals, mineral industry (clinker, glass and ceramic bricks), and pulp and paper. Nations had issued more permits to pollute than required in the first phase, which run until the end of 2007. This resulted in carbon prices falling as low as 8 € per tonne.

Phase II extended the regional scope of the scheme significantly including Liechtenstein, Norway and Iceland. Although Clean Development Mechanisms (CDM) and Joint Implementation (JI) mechanisms (via credits) were introduced as a theoretical possibility in Phase I, the over-allocation of permits combined with the inability to bank them for use in the second phase meant they were not taken up.

2.5.2. Phase III (2013-2020)

Finally, Phase III has been set in Decision 377/2013/EU derogating temporarily Directive 2003/87/EC and establishing a scheme for GHG emission allowances trading within the Community up to 2020. It is not permitted free allocation of allowances for the power generation industries except for the electricity coming from the waste incineration. This Decision includes two annexes with the annual emissions allocation for each Member State estimated using global warming potentials from the second and fourth IPCC reports respectively.

The last national allocation plan in Spain was the "Plan Nacional de Asignación de Derechos de Emisión 2008-2012" (NAP 2008-2012). This Plan was published in RD 1370/2006 and modified later on in February 26, 2007 Commission Decision, RD 1030/2007, RD 1402/2007, and order PRE/2827/2009. The last modification considered a total allocation of 152.25 Mt CO_2-eq disaggregated by sectors.

Nowadays, as Phase III is at an early stage, a new national allocation plan is still under study. Article 11 of Directive 2003/87/EC, according to the amendments included in Directive 2009/29/EC, sets the obligation of publishing applied national measures. These measures consist of basically listing the existing installations which will be included in the ETS after January 1, 2013 and their corresponding preliminary allocation. The Spanish Ministry of

Environment published this information in June 2012 (MAGRAMA, 2012d) Once it was examined, in 2013 the EC approved the text in Decision 2013/448/EU.

According to the Ministry of the Environment, 34 cement plants will be included, which amount to a total value of 24.73 $MtCO_2$-eq/year from 2013 to 2020 (MAGRAMA, 2012d; Decision 2013/448/EU). Table 10 shows the list of emissions allocations per cement plant.

Table 10. CO_2 emissions allocation to cement facilities for the period 2013-2020

Cement plant	2013-2020 (t/yr)
Alcalá de Guadaira	905,677
Gádor	511,383
Jerez	507,169
Carboneras	786,422
Córdoba	539,659
Niebla	366,803
Málaga	658,998
Morata de Jalón	715,710
Aboño	937,130
Mataporquera	519,710
Toral de los Vados	642,559
Venta de Baños	481,951
La Robla	734,628
Castillejo	1,003,986
Yeles	417,638
Villaluenga de la Sagra	1,240,962
Sant Vicenç del Horts	1,007,245
Alcanar	1,299,006
Sant Feliu de Llobregat	657,123
Montcada	482,098
Monjos	1,138,396
Sitges	813,328
Buñol	1,015,829
San Vicente del Raspeig	861,822
Sagunto	897,498
Alconera	707,407
Oural	327,082
Lloseta	409,393
Morata de Tajuña	1,805,980
Lorca	452,330
Olazagutía	643,505
Lemona	523,442
Añorga	391,705
Arrigorriaga	326,485
TOTAL	24,730,059

All the sources considered in Table 10 are cement facilities in which clinker is produced at site, not imported. These plants are included in the Spanish Registry of pollutants (PRTR-ES) using the code "*3.c.i. clinker or cement production in rotary kilns*" whereas the tag "*3.c. installations for producing cement and/or clinker in rotary kilns with production capacities more than 500 t/day, or lime […], or using other kilns with production capacities more than 50 tonnes per day*" are those with kiln (main source of emissions). Other cement facilities, without kiln, are excluded from this list.

An adjustment of NAP 2008-2012 was made in October 2009 for changing the allocation caps included in Royal Decree 1370/2006. This document indicates that the average CO_2 emission in the period 2000-2005 was 91.30 Mt CO_2/year. The effective allocation in 2005 was 86.25 Mt CO_2 and the average annual allocation in the period 2005-2007 was 85.40 Mt CO_2. Finally, the stated annual allocation for the period 2008-2012 was 54.566 Mt CO_2.

Phase III does not give free allowances to the power generation facilities except for the ones using waste as main fuel. Power producers which also produce heat as co-product will have certain amounts of free allowances using an established formula and it will be reduced 1.74% yearly from 2013 to 2020. Phase III free allocation mainly gives allowances to the industry in the so-called transitory period up to 2020. CCS (including transport) systems will not receive any free allowance during Phase III.

2.5.3. Future Phase IV (2021-2028)

Phase IV is expected to cover 2021 to 2028. Preliminary improvements include increasing the rate at which the overall emissions cap is reduced from 1.74% each year to a higher value; extending coverage to other sectors, such as household fuel consumption; limiting access to international credits; and introducing a price floor for allowance auctions (COM 2012 (652) final).

2.6. Renewable plan and regulation

2.6.1. Feed-in-tariffs

Electricity generation in Spain has two different regimes, the ordinary regime (RO), to which all the conventional generation belongs to, and the special regime (RE) to which the renewable energy generation and the CHP plants belong to. If the Spanish special regime generator sells electricity in the market, it will receive the market price plus a premium, subject to a cap and floor on final prices for each type of facility, depending on the technology used.

Besides fiscal support of investments and tax exemptions, premium prices for electricity production as regulated by the Royal Decrees 2818/1998, 436/2004, 661/2007 and 1578/2008 have promoted the penetration of RES in the electricity market and their technological development.

Since 2007, an intense public debate has emerged around the current FIT scheme and, in general, regarding renewable energy support measures. Such discontent has been originated by the unexpected deployment of some technologies which has surpassed the most positive expectations leading to undesirable costs for the public funds (Cabal *et al*., 2012).

RD 1578/2008 set some quotas on the maximum amount of solar PV plants eligible to participate in the FIT scheme.

RD 1565/2010 limited to 25 years the time horizon during which the PV plants were eligible to receive FIT and reduced the PV FIT set by RD 1578/2008 by 5% for small PV roof installations; by 20% for large PV roof installations and by 45% for ground PV installations.

In January 2012, the Government published the Royal Decree-Law 1/2012 cancelling the feed-in tariffs for the new facilities with the objective of eliminating the deficit of the electricity rate. Consequently, feed-in-tariffs policy system for new installations ended in 2012.

2.6.2. PANER 2011-2020

PANER is the National Action Plan on Renewable Energies 2011-2020 developed to fulfill Directive 2009/28/EC (RES) objectives. Some of the most relevant goals of the plan include reaching 22.7% of the final energy consumption from renewables and achieving 13.6% of biofuels contribution to the total transport fuel consumption by 2020. The Directive sets 20% of the final energy consumption from renewables, so there is 2.7% excess which would be allocated through the cooperation mechanisms listed in the EC Directive. To fully exploit this surplus, it will be essential to further develop Spain electricity interconnections with the European electricity system. The greatest potential for the development of renewable energy sources in Spain lies in the electricity generation.

3. Cement sector

3.1. General overview

Cement is a basic material for building and civil engineering construction. In Europe the use of cement and concrete (a mixture of cement, aggregates, sand and water) in large civic works can be traced back to antiquity. Portland cement, the most widely used cement in concrete construction, was patented in 1824. Output from the cement industry is directly related to the state of the construction business in general and therefore tracks the overall economic situation closely (EIPPCB-JRC, 2010).

Cement production is an energy intensive industry with energy costs normally accounting for about 40% of operational costs. Traditionally, the primary solid fossil fuel used has been coal. A wide range of other solid, liquid or gaseous fossil fuels are used now, such as petroleum coke, lignite, natural gas and oil (heavy, medium or light fuel oil). In addition to these fossil fuels, the cement industry has been using large quantities of waste fuels or biomass fuels, for more than 15 years (EIPPCB-JRC, 2010). Those waste and/or biomass replace conventional raw materials and fuels.

Cement industry releases large amounts of CO_2 and CO coming from both combustion and limestone calcination. Frequently, other emissions from cement plants cause greatest concern and reduction and prevention techniques are required. These harmful emissions are dust, nitrogen oxides (NO_x) and sulphur dioxide (SO_2). They are the main cause of eutrophication, acidification and human health problems. Besides, other secondary emissions are volatile organic compounds (VOCs), polychlorinated dibenzo-p-dioxins (PCDDs) and dibenzofurans (PCDFs) as well as hydrogen chloride (HCl). Also emissions of hydrogen fluoride (HF), ammonia (NH_3), benzene, toluene, ethylbenzene and xylene (BTEX), polyaromatic hydrocarbons (PAH), metals and their compounds, noise and odours may be considered under special circumstances.

According to the European Cement Association (CEMBUREAU), in 2010 there were 377 kilns in the EU-27. In recent years, typical kiln size has come to be around 3,000 tonnes clinker per day.

About 90% of Europe's cement production comes from dry process kilns, and 7.5% from semi-dry and semi-wet process kilns, with the remainder of European production – about 2.5% – now coming from wet process kilns. The choice of manufacturing process is primarily motivated by the nature of the available raw materials (EIPPCB-JRC, 2010).

The cement industry is also a capital-intensive industry. The cost of a new cement plant is equivalent to around three years' turnover, which ranks the cement industry among the most capital intensive industries. The profitability of the cement industry is around 10% as a proportion of turnover (on the basis of pre-tax profits before interest repayments) (EIPPCB-JRC, 2010).

3.2. Cement production

Cement is generally produced as a mixture of limestone, clay and sand, which provides the four key ingredients required: lime, silica, alumina and iron. By mixing these ingredients and exposing them to intense heat, the resulting chemical reactions convert the partially molten raw materials into pellets called clinker. After adding gypsum and other minerals, the mixture is ground to form cement, a fine grey powder (IEA, 2009a).

The process of producing cement consists of three main stages (IEA GHG, 2008):

Raw material preparation. Raw material is first crushed then ground and dried in mills until the 'raw mix' is prepared (homogenising with compressed air). Approximately 1.5-1.6 tonnes of raw mix are required to produce 1 tonne of clinker. Losses are due to the calcination of the limestone component of the raw mix.

Clinker burning (pyro-processing). Firstly, in the pre-heating stage raw mix is heated up through several heat exchangers made of cyclones. Secondly, there is an optional precalcination, to ensure complete calcinations of the mix prior to entering the kiln. Thirdly, clinker sintering or clinkerisation occurs when the raw mix enters the kiln at 1250-1450°C. Finally, an ultimate cooling takes place after the kiln, where a partial crystallisation of the calcium aluminate and calcium ferrite takes place.

Cement preparation. After cooling, clinker is mixed in a milling process with gypsum and other additives such as limestone, pozzolana, blast furnace slag (BFS) and fly ashes (FA) to produce cement with specific properties.

Next Figure 3 shows the complete cycle of cement production from raw material extraction in the quarry to final product (IEA GHG, 2008).

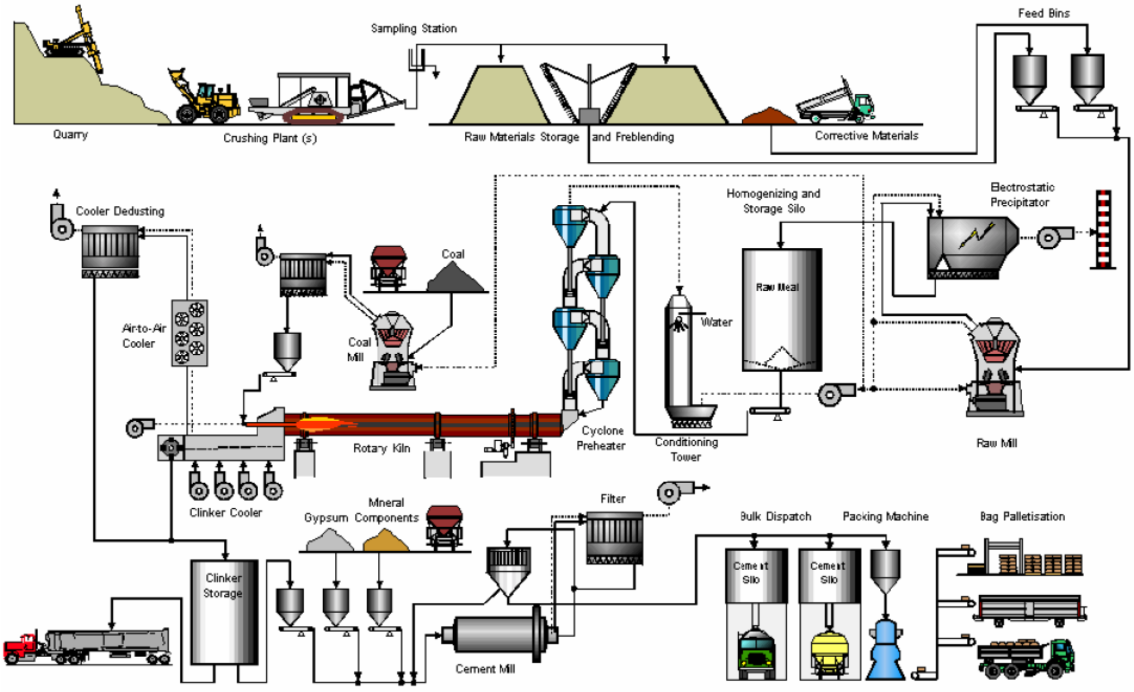


Figure 3. Scheme of the cement production with dry route process

Depending on the moisture content of the material, cement production routes may be classified into four types: dry, semi-dry, semi-wet, and wet. Nowadays, BATs in cement production are based on dry processes which require less energy than the wet ones (IEA GHG, 2008).

3.3. State-of-the-art technologies: BATs and prospective

In May 2010, European Commission published the *Reference Document on Best Available Techniques in the Cement, Lime and Magnesium Oxide Manufacturing Industries* (EIPPCB-JRC, 2010). This document details the state-of-the-art technologies and techniques for making cement in the most cost-benefit and environmental-friendly way. In addition, European Cement Research Association (ECRA) published a report concerning the state-of-the-art technologies of the cement making (ECRA, 2009a).

ECRA (2009a) summarizes the expected development of the cement industry depicting five different solutions:

- thermal energy efficiency improvements
- electric energy efficiency improvements
- use of alternative fuels and biomass
- reduction of the clinker content in cement, and
- CO_2 capture.

Most of the following information comes from both EIPPCB-JRC (2010) and specially, ECRA (2009a).

3.3.1. Thermal energy efficiency

In 2006, average global energy consumption was 3,690 MJ/ t clinker. The most efficient kilns (10% percentile) consumed around 3,100 MJ/t clinker and the least (90% percentile) 4,400 MJ/t clinker. In Europe, Pardo *et al*. (2011) showed a Cumulative Frequency Distribution (CFD) curve with an average thermal consumption around 3,500 MJ/t clinker. Spanish association of cement producers, OFICEMEN, gave a value of 3,536 MJ/t clinker in Spain in 2010 (OFICEMEN, 2010a).

The highest energy demand takes place in the wet production processes (up to more than 6,000 MJ/t clinker), while lowest values (down to 3,000 MJ/t clinker) are needed by state-of-the-art precalciner kiln technologies linked to large kiln capacity, low moisture content and good burnability of the raw materials. It has to be stressed that these data represent yearly averages whereas performance values are usually expressed as short-term (typically 24h- or 36h-average) values. Depending on kiln operation and reliability (e.g. number of kiln stops) and market situation, there can be a difference of 150 to 300 MJ/t clinker between these levels.

As cement manufacturing is highly capital-intensive, the lifetime of cement kilns is usually 30 to 50 years. On the other hand, the technical equipment of cement kilns is modernised continuously, meaning that often after 20 or 30 years most of the original equipment has been replaced (e.g. preheater cyclones, clinker cooler, burner, etc.) and adapted to modern technology. This can be seen in Europe, where kilns are relatively old, but nevertheless efficient. Only huge retrofits like changing from wet to dry process allow a significant step in increasing energy efficiency. For this kind of retrofits similar investment as for new kilns is required.

Therefore, they will only be carried out if the market situation is very promising or the equipment is already very old. By this kind of extensive retrofits it is often possible to largely close the efficiency gap to state-of-the-art technology. On the other hand retrofits often have to take compromises into account, e.g. due to limited downtime of the kiln.

Thermal energy demand for clinker production is ruled by endothermic reactions of the raw materials with required temperatures of up to 1,450°C for the formation of stable clinker phases. Therefore, a theoretical energy demand of 1,650 - 1,800 MJ/t clinker is needed for this process. Depending on the moisture content of raw materials, a further energy demand of about 200 - 1,000 MJ/t clinker, corresponding to a moisture content of 3 to 15%, is required for raw material drying. As a consequence, a theoretical minimum energy demand of 1,850 - 2,800 MJ/t clinker is set by chemical and mineralogical reactions and drying. Furthermore, waste heat (kiln exhaust gas, bypass gas and/ or cooler exhaust air) is often used for the drying of other materials like coal and petcoke or cement constituents like granulated blast furnace slag. Therefore, energy efficiency of cement kilns is very high compared to many other industrial processes, especially compared to power plants. As a consequence, kilns with significantly different specific thermal energy consumption can be similarly efficient if waste heat utilisation for raw materials drying, electric power consumption, etc. is taken into account.

Based on these assumptions the specific fuel energy demand of clinker burning may decrease from 3,690 MJ/t clinker to a level of 3,300 MJ/t clinker in 2030. However, without impairing efficiency these specific energy data can be higher if e.g. residual heat could be used to produce electricity. Similar considerations apply if Carbon Capture and Storage (CCS) would be implemented. It is supposed that no wet, semi-wet, semi-dry or long dry kilns will be in operation anymore, except at those sites with wet raw materials (ECRA, 2009a).

Thermal energy use can be reduced by considering and implementing different measures, such as thermal energy optimisation techniques in the kiln system. Several factors affect the energy consumption of modern cement kilns, such as raw material properties, e.g. moisture content, burnability, the use of fuels with different properties and varying parameters as well as the use of a gas bypass system (EIPPCB-JRC, 2010).

Nowadays, the dry process with precalcining is a state-of-the-art technology. Kiln systems with multistage (four to six stages) cyclone preheaters with an integral calciner and tertiary air duct are considered standard technique for new plants and major upgrades. In some cases of raw material with high moisture content, three stage cyclone plants are used. Under optimised circumstances such a configuration will use 2,900 – 3,300 MJ/t clinker.

3.3.2. Electrical energy efficiency

In 2008, according to ECRA (2009a), the average global electricity consumption for cement manufacturing was 110-120 kWh/t cement, the same as in Europe (WBCSD, 2010; Madlool *et al.*, 2011).

A significant decrease in specific power consumption is only achieved through huge retrofits like changing from cement grinding with ball mills to high efficient vertical roller mills or high pressure grinding rolls. For this kind of retrofits high investment is required. Therefore, they will only be carried out if the market situation is very promising or the equipment already very old.

Concerning the dry process the total power consumption can be allocated to about 5% for raw material extraction and blending, 24% for raw material grinding, 6% for raw material homogenisation, 22% for clinker production (incl. solid fuels grinding), 38% for cement grinding and 5% for conveying, packing and loading (ECRA, 2009a; Pardo *et al.*, 2011).

Concerning the clinker burning process, measures which increase thermal efficiency often need more electric power. For example, the installation of modern grate cooler techniques causes a reduction of thermal energy use, but increases the consumption of electrical energy.

On the other hand, changing from long wet kiln technology to modern dry process kiln precalciner saves theoretically up to 5 kWh/t clinker (ECRA, 2009a). Specific power consumption has increased in many countries in the past, because environmental requirements have increased. Lower dust emission limit values require more power for dust separation regardless of which technology is applied. The abatement of other pollutants (like NO_x or SO_2) might require additional units which require electricity.

Currently, the state-of-the-art grinding technologies are the high pressure grinding rolls and vertical roller mills. It can be expected that environmental requirements will increase and that the cement manufacturing process therefore will have to be enlarged by more and more units, ending up in a significant increase in power consumption. The most electricity intensive technologies which are being discussed for future potential implementation also in the cement industry are carbon capture technologies.

Based on these assumptions without CCS, the specific electricity demand of cement production (as a global weighted yearly average) could decrease from 110 kWh/t cement in 2006 to a level of about 105 kWh/t cement in 2030 (ECRA, 2009a; Moya *et al*., 2010).

3.3.3. Reduction of the clinker content in cement

In Europe, the average clinker-to-cement ratio is 0.75. From a technical point of view, lower values are possible. Materials like blast furnace slag, fly ash, natural pozzolanas (a sort of silica sand) or limestone meal are available globally; however, regional availability is very different and limits the use of such materials (ECRA, 2009a).

In addition, recycling or re-use of collected dust from the production processes reduces the total consumption of raw materials. This recycling can take place directly in the kiln or kiln feed (the alkali metal content being the limiting factor) or by blending with finished cement products. The use of suitable wastes as raw materials can reduce the input of natural resources, but should always be done with a satisfactory control of the substances introduced to the kiln process (EIPPCB-JRC, 2010).

Cements that contain other constituents besides clinker present a lower clinker-to-cement-ratio than Portland cement and consequently show less energy demand for the clinker burning as well as less process CO_2 emissions due to the decarbonisation of the limestone. The other cement constituents show hydraulic and/or pozzolanic activity or filler properties and contribute positively to the cement performance (ECRA, 2009a). The use of other constituents in cement besides clinker depends on six criteria: availability, properties and prices of the materials, intended application of the cement, national standards and market acceptance. The regional availability of clinker-replacing materials varies considerably. The properties of the constituent besides clinker are very important and always have to be assessed with respect to the intended application of the cement.

Blast furnace slag (BFS) is molten iron slag, a by-product of the pig-iron production process, which can be quenched in water or steam. Cements containing BFS usually show a lower early strength if ground to the same fineness and a lower heat of hydration. These cements often show higher long term strength and particularly improved chemical resistance.

Fly ashes (FA) are obtained by electrostatic or mechanical precipitation of dust-like particles from the flue gases from furnaces fired with pulverised coal. Cements containing FA typically show a lower early strength compared to ordinary Portland cement at similar fineness. They present a lower water demand, an improved workability, a higher long-term strength and a better durability such as an increased resistance against sulfate attack.

Natural pozzolanas are usually materials of volcanic origin or sedimentary rocks with suitable chemical and mineralogical composition. Cements containing pozzolanas are similar to FA cements and compared to Portland cement, the early strength of pozzolana-containing cements decreases with increasing proportion of pozzolana; they show a better workability, a higher long-term strength and, in particular, an improved chemical resistance.

The use of limestone as a minor or main constituent in cement is an efficient method to reduce the clinker-to-cement ratio of cement. If limestone-containing cements are adjusted to give the same strength as ordinary Portland cement they have to be ground to a higher fineness. The quantity of limestone in cement is decisive for the resistance of the hardened paste to acids and sulphates and its freeze-thaw-resistance. Typically limestone leads to a better workability of the concrete.

Regarding cement standard, blast furnace cements can contain up to 80 or even 95% of BFS. However, due to its low strength development, these cements are only suitable for very special applications. In any case, all cement constituents must comply with certain qualities like those given in the standards; otherwise the quality and performance of corresponding mortars or concretes might be significantly impaired.

In summary, the use of cements containing more constituents than clinker is determined by their future applications. In this context an increased use of such cements in mortar or concrete must always be safeguarded through good durability and workability, appropriate strength development and sufficient resistance against aggressive media if required. This would also imply that national standards and rules have to be revised accordingly. The market introduction will strongly depend on the performance of cements with lower clinker-to-cement-ratio and requires cement producers and cement users to introduce these cements into the market in a joint effort.

ECRA (2009a) assumes that the availability of slag, fly ash and pozzolana will increase at the same rate as cement consumption. Limestone is practically unlimitedly available. Under these conditions it is estimated that in 2030 the clinker-to-cement-ratio might be 0.7 (Moya *et al.*, 2010).

3.3.4. Use of alternative fuels and biomass

CEMBUREAU reports an energy substitution rate in the European Union of 34% in 2011 but higher rates are possible. In some European countries, the average substitution rate reaches more than 50% and up to 80% for single cement plants. Heidelberg Cement Group ENCI cement plant, in Maastricht (The Netherlands), is able to operate using up to 98% of alternative fuels.

As the fuel-related CO_2 emissions are about one third of the total emissions, the CO_2 reduction potential can be significant if pure biomass use is assumed. In addition to those direct effects, the use of waste as alternative fuel in cement kilns may contribute to lower overall CO_2 emissions, replacing fossil fuels and their relevant CO_2 emissions, which would otherwise have to be incinerated or land filled with their corresponding GHG emissions. Emissions from landfill consist of about 60% methane, a gas with a high global warming potential. The extent of this effect strongly depends on the waste properties and the local conditions of waste treatment (ECRA, 2009a; EIPPCB-JRC, 2010).

CO_2 reduction potential of alternative fuels containing biomass is principally based on two direct effects. First, many alternative fuels present a certain biomass content of which the CO_2 emission factor is zero. Second, most fossil alternative fuels have lower CO_2 emission factors related to its calorific value than coal or petcoke. Besides, there can be an indirect effect of emissions reduction outside the cement plant if wastes are used there instead of land filling or incineration in separate installations.

Typical alternative fuels classified as waste are used tyres, waste oil and solvents, pretreated industrial and domestic waste, plastic, textile and paper wastes etc. Pure biomass fuels used in the cement industry are mainly meat-and-bone meals, wood, sawdust and sewage sludge.

Cement kilns can burn up to 100% of alternative fuels. Nevertheless, there are certain technical limitations like the calorific value, and the content of side products like trace elements or chlorine. The low heating value of most organic material is comparatively low, 10 – 18 GJ/t while for the main firing of the cement kiln 20-22 GJ/t are required. In the precalciner of modern cement kilns, in which up to 60 % of the fuel is consumed, the lower process temperature allows also the use of low calorific fuels. Therefore, precalciner kilns are able to burn at least 60% of low calorific fuels. A lower calorific value as well as high-chlorine content (requiring a chlorine by-pass system) will increase the specific fuel energy consumption per tonne of clinker. Therefore, it is possible to reduce the CO_2 emissions despite the use of those fuels leads to lower energy efficiency (ECRA, 2009a).

When plants are suitable and especially designed for the use of certain types of waste fuels, thermal energy consumption can still be as low as 3,120 – 3,400 MJ/t clinker (EIPPCB-JRC, 2010).

Higher substitution rates of fossil fuels by alternative fuels will only take place if the waste legislation in the given region restricts land filling and allows a controlled waste collection and treatment, and alternative fuel production. According to Directive 2008/98/EC on waste, European Union allows to burn waste as fuel in cement kilns.

As a principle, the higher calorific value and the lower content of other elements, such as chlorine, the higher fuel price. In the future it can be expected that prices for alternative fuels and especially for biomass will increase significantly. It is assumed that alternative fuel prices will rise up to about 30% of conventional fuel costs in 2030. Before, it is expected that there will still be an economic benefit for cement plant operators to utilise alternative fuels, especially fuels containing biomass. This development will be significantly influenced by CO_2 prices (ECRA, 2009a).

It is very difficult to predict optimal values for future substitution of conventional fuels by waste or biomass fuels. Nevertheless, a conservative substitution rate of 50-60% in developed regions should be possible. Moya *et al*. (2010) project an energy substitution rate of 36% in 2020 and 50% in 2030.

3.4. CO_2 capture and storage

CCS is a new technology, not yet proven at the industrial scale in cement production, but potentially promising. CO_2 is captured as it is emitted, compressed to liquid, and then transported in pipelines to be permanently stored deep underground (IEA, 2009b).

Emissions of CO_2 from the cement industry account for 6% of the total emissions worldwide from stationary sources (IPCC, 2005). Cement production requires large quantities of fuel to drive the high temperature, energy-intensive reactions associated with the calcination of the limestone.

As been seen, there are several ways to reduce the CO_2 emissions from the cement plants: replacing the fossil fuels with alternatives, increasing the efficiency of the processes, shifting from 'wet' to 'dry' technologies, using low clinker/cement ratios and/or extracting the CO_2 from the exhaust gas.

Currently, CO_2 is not captured from cement plants. The concentration of CO_2 in the flue gases is between 15-30% by volume, which is higher than in flue gases from power and heat production (3-15% by volume). Describing the capture technologies, the pre-combustion is not taken into account for the cement plants because the main CO_2 emissions are released in the process production itself (calcinations and combustion). The capture techniques applied to the cement plants are (Kuramochi, 2011):

- Post-combustion capture (chemical)
- Oxyfuel combustion with CO_2 capture (physical)
- Other advanced CO_2 capture technologies (e.g. chemical looping using CaO)

Figure 4 shows a scheme of the three main CO_2 capture techniques (IPCC, 2005).

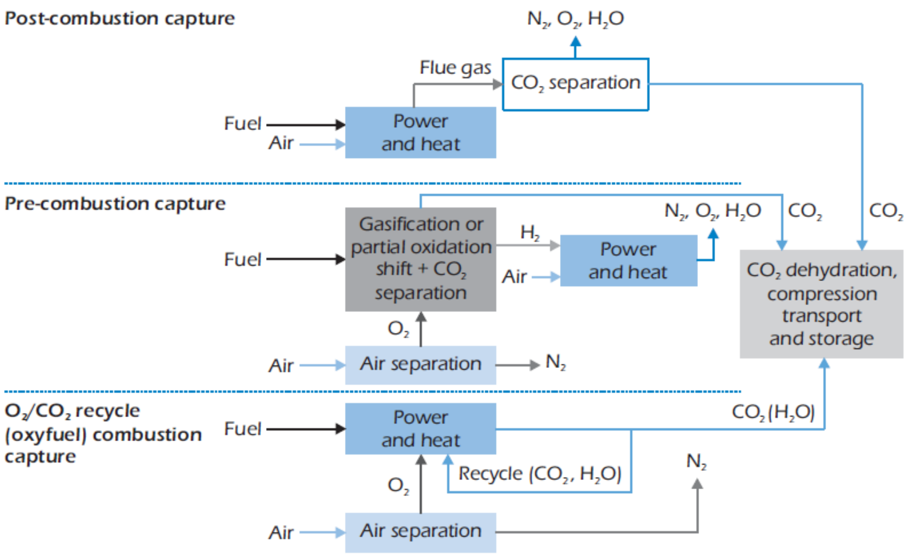


Figure 4. Scheme of the main CO_2 capture processes

Considering these three technologies, the post-combustion CO_2 capture is the only that may be implemented with a low technical risk and that enables retrofitting in the short-term (IEA GHG, 2008).

3.4.1. Post-combustion CO_2 capture (PCC)

In principle post-combustion technologies can be applied to large power plants, cement kilns, industrial boilers and furnaces or other CO_2 producing processes. According to ECRA (2007), there are different capture technologies depending on the type of the physical-chemical technique:

- Absorption, where CO_2 is selectively absorbed into liquid solvents.
- Membranes, where CO_2 is separated by semi-permeable plastic (polymer) or ceramic membranes.
- Adsorption, where CO_2 is separated using specially designed solid particles.
- Low temperature processes, where separation is achieved by chilling and/or freezing the gas stream.

Post-combustion technique adds a CO_2 removal stage onto the process of flue gas clean-up (IEA GHG, 2008). The flue gas is passed through equipments that separate out CO_2 while the remaining flue gas is discharged to the atmosphere. Figure 5 shows the scheme of the PCC process (IEA GHG, 2008).

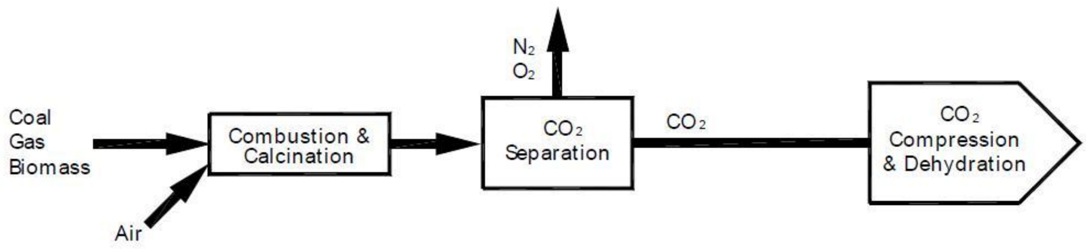


Figure 5. Scheme of PCC process in a cement plant

The leading commercial techniques utilise a chemical process that offers high capture efficiency, selectivity and the lowest energy use when compared with other existing and emerging capture processes (IEA GHG, 2008). These are 'end-of-pipe' options that would not require fundamental changes in the clinker-burning process so could be available for new kilns and in particular for retrofits to existing plants. The most promising technology options include (UNIDO, 2010):

- Chemical absorption using amines, ammonia and other chemicals. Nowadays, chemical absorption with alkanolamines is a proven technology and has an extensive history in the chemical and gas industries although at a much smaller scale than would be necessary in the cement industry (IEA, 2009). Most of chemical solvents are amine-based and the most widely used is monoethanolamine (MEA). Since CO_2 is an acid gas, alkaline solvents like MEA will form chemical bonds with it. This property can be used to absorb CO_2 from a flue gas stream. Once the CO_2 has been absorbed from the flue gas, heat can be applied to the absorbent to release the CO_2 for storage while simultaneously regenerating the solvent for reuse in the process (IEA GHG, 2008).

- Membrane technologies. Although this technology is not expected to be ready for commercial application by 2020 (LEK, 2009).
- Carbonate looping, an adsorption process in which calcium oxide is put into contact with the combustion gas containing CO_2 to produce calcium carbonate. This is a technology currently being assessed by the cement industry as a potential retrofit option for existing kilns and in the development of new oxy-firing kilns (IEA/WBSCD, 2009).

Depending on the type of technology different CO_2 capture efficiencies are achieved. It is assumed that both membrane and chemical absorption techniques may reach up to 95%. A conservative capture efficiency of 85% is commonly accepted.

Other post-combustion technologies such as physical absorption or mineral adsorption are at a much earlier stage of development but may become commercial within the timeframe of the roadmap.

3.4.2. Oxyfuel combustion with CO_2 capture (OCC)

The oxyfuel technology relies on oxygen instead of ambient air for combustion, i.e. the nitrogen is removed in a separation plant from the air prior to being applied to the kiln (ECRA, 2007). Figure 6 shows the scheme of the OCC process (IEA GHG, 2008).

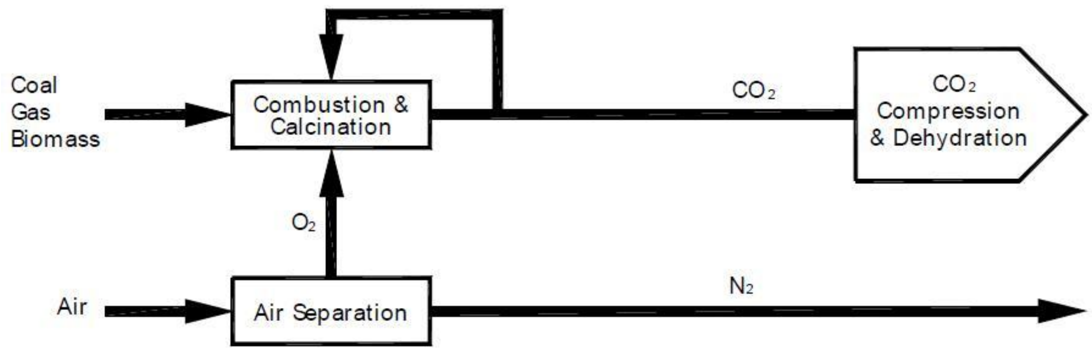


Figure 6. Scheme of an OCC process in a cement plant

Consequently, the concentration of carbon dioxide in flue gas is increased significantly and for CO_2 capture only a comparatively simple carbon dioxide purification is required, if any. To introduce oxy-fuel technology with flue gas recirculation into an existing cement plant is extremely challenging due to the difficulties that air intrusion causes. An air separation plant has to be established on the cement plant premises and the facilities of flue gas recirculation have to be included into the existing plant units. The different flue gas enthalpies and flows require a different design of all plant units. Hence implementation of oxy-fuel technology with flue gas recirculation seems to be predominantly an option for new plants (ECRA, 2007).

3.4.3. Other advanced CO_2 capture technologies

Besides the previous technologies applied in cement manufacture, there is a technique based on the separation of the combustion chamber of the precalciner which uses CaO as heat carrier (Kuramochi, 2011). Rodriguez *et al*. (2008) reports that the process allows splitting fuel combustion and calcination into two chambers within the precalciner unit. Some CaO generated in the calcinations chamber flows through the fuel combustion chamber and gets heated up to around 1000˚C. Then the heated CaO mixes with $CaCO_3$ in the calcinations chamber, heats up the $CaCO_3$, and drives the calcinations reaction. The CO_2 capture rate is lower than that for post-combustion capture because CO_2 is captured only from the calcinations chamber. This technology is nowadays under study and there are no techno-economic potentials related yet.

3.4.4. Performance of CO_2 capture technologies

Both OCC and PCC technologies will require high power consumption for oxygen production by air separation, regeneration of absorbent agents as well as for separation, purification and compression of CO_2. Therefore CO_2 capture would increase power consumption by 50% to 120% on plant level. Assuming a high implementation degree of max 20% of cement capacity in 2030 and up to 40% in 2050 a power demand of cement production (as global average) of 115-130 kWh/t cement is expected in 2030, and 115-145 kWh/t cement for 2050 (ECRA, 2009a).

If PCC is applied, UNIDO (2010) reports an extra consumption of 50-90 kWh/t clinker produced and a requirement of heat of 1,000-3,500 MJ/t clinker. In the OCC case, the extra amount of heat is 90-100 MJ/t clinker and the extra electricity required goes from 110-115 kWh/t clinker produced.

From an environmental point of view, the introduction of PCC leads to increases in most of the human and environmental impact categories respect to a case without CO_2 capture. This analysis has been developed extensively in Chapter 4. Basically, the extra energy requirements (mainly heat) for solvents regeneration are so huge that a large CHP plant is needed. Depending on the type of fuel burned, the emissions grow in a different manner. Anyhow, the so-called ‘energy penalty’ is the main problem of the post-combustion capture. On one hand, the problem is environmental but, on the other hand, due to the environmental problem, the amounts of fuel and the construction of new infrastructures, it is basically an economic problem.

On the contrary OCC presents an energy penalty lower than PCC. Main barriers for its implementation are the expected starting year (2030) and the major changes needed in the kiln for burning properly in a high-oxygen hearth. Consequently, this technology is feasible for new cement plants or when major modifications, as kilns substitution, happen.

UNIDO (2010) reports a global average gross CO_2 emission of 862 kg CO_2/t clinker (excluding CO_2 from electric power) and a global average net CO_2 emissions of 838 kg CO_2/t clinker hence OCC technology has the greatest potential for reducing emissions. ECRA (2009a) provided some estimates of the CO_2 reduction potentials for different capture technologies within the cement sector. These are summarised in Table 11 below and are in line with the CO_2 reductions reported by IEA GHG (2008).

Table 11. Potential CO_2 reduction for different CO_2 capture technologies in cement-making

Technology	Direct CO_2 reduction potential (kg CO_2/t clk)	Indirect CO_2 reduction potential (kg CO_2/t clk)
OCC	Decrease of 550-870	Increase of 60-80
PCC (Absorption)	Decrease up to 740	Increase of 6-25
PCC (Membranes)	Decrease of >700	n/a

3.4.5. Costs of CO_2 capture technologies

The assessment of the post-combustion CO_2 capture costs comes from IEA GHG (2008) for a cement plant using MEA. The European scenario is based on a 1 Mt/y plant sited in the UK. Investment costs for that European plant are 263 M€, 17 M€/year (net variable operation costs) and 19 M€/year (fixed operation costs). If PCC is applied, the investment cost will be 558 M€; the net variable operation costs, 31 M€; and the fixed operation costs, 35 M€. OECD/IEA (2008) reports a capture cost range of 75-100 $/t CO_2 based on new and retrofit PCC.

Table 12 shows the cost estimations for post-combustion capture using absorption technologies generated by ECRA (2009a). The costs are rough estimations based on IEA and McKinsey studies as well as own calculations. Investment costs have been indicated as additional costs to the cement plant investment cost. Costs for CO_2 transport and storage are excluded. A learning rate of 1% per year is considered for the period between 2030 and 2050.

Table 12. Cost estimation for PCC using absorption technologies

	New installation		Retrofit	
Year	**Investment (M€)**	**Operational (€/t clk)**	**Investment (M€)**	**Operational (€/t clk)**
2030	100 to 300	10 to 50	100 to 300	10 to 50
2050	80 to 250	10 to 40	80 to 250	10 to 40

In the case of PCC using membranes, UNIDO (2010) gives qualitative values since membrane technologies are not yet available for industrial application in the cement industry. As approach, it is expected that the cost of CO_2 captured using this technique will be lower than 25 €/t CO_2, from 2030 and beyond, both for new installation and retrofit.

IEA GHG (2008) also tests the introduction of the OCC in the previously referred European cement plant (see Table 13). The costs are lower than in PCC. The investment costs are 327 M€, the net variable operation costs, 23 M€, and the fixed operation costs are 23 M€.

Table 13. Cost estimation for OCC using absorption technologies

	New installation		Retrofit	
Year	**Investment (M€)**	**Operational (€/t clk)**	**Investment (M€)**	**Operational (€/t clk)**
2030	330 to 360	Plus 8-10	90 to 100	Plus 8-10
2050	270 to 295	Plus 8-10	75 to 82	Plus 8-10

3.5. Spanish cement industry

In 2010, the production of cement was 3,310 Mt worldwide and 191 Mt in the EU27 (CEMBUREAU, 2011), from which 23.5 Mt were produced in Spain (OFICEMEN, 2010a). Most of the cement was produced using dry-route techniques. In 2010, there were 58 clinker kilns in operation in Spain, from which 55 were dry-route kilns (OFICEMEN, 2010a).

According to the European standard EN 197-1:2000, there are 27 types of cement classified into 5 groups (CEN/TC-51, 2000). The most common is the “Portland cement” (type I), with a composition of 95-100% clinker and up to 5% gypsum. Portland cements entailed 91.5% of the total grey cement production in Spain in 2010 (OFICEMEN, 2010a). Cement produced in Spain in 2010 can be grouped in 16 types according to the standard (see Table 14). Several cement types, such as II/B-S, II/A-D, II/A-Q, II/B-Q, II/A-W, II/B-W, II/A-T, II/B-T, III/C and V/B, were not produced in Spain in 2010.

Table 14. Spanish cement production by type and cement sub-types composition in 2010

Cement type	Production (%)	Clinker (%)	BFS (%)	Pozzolana (%)	FA (%)	Limestone (%)
CEM I – Portland	25.4	97.5				
CEM II/A-M – Portland composite	10.8	84.0		0.3	5.4	9.2
CEM II/B-M – Portland composite	6.6	72.0		1.9	3.6	22.0
CEM II/A-L – Portland calcareous	13.4	87.0				13.0
CEM II/B-L – Portland calcareous	6.8	72.0				28.0
CEM II/A-V – Portland with fly ash	14.8	87.0			13.0	
CEM II/B-V – Portland with fly ash	3.0	72.0			28.0	
CEM II/A-S – Portland with BFS	4.4	91.0	9.0			
CEM II/A-P – Portland with pozzolana	5.2	87.0		13.0		
CEM II/B-P – Portland with pozzolana	1.1	72.0		28.0		
CEM III/A – Blastfurnace cement	3.3	64.0	36.0			
CEM III/B – Blastfurnace cement	0.5	34.0	66.0			
CEM IV/A – Pozzolanic cement	0.9	85.0		3.8	11.3	
CEM IV/B – Pozzolanic cement	2.4	66.0		8.5	25.5	
CEM V/A – Composite cement	0.9	52.0	27.8	10.0	10.0	
OTHER CEM (ESP VI, CAC, G)	0.4	40.0	20.0	20.0	20.0	

Grey cement production meant 97.3% of the total production in 2010, the rest being white cement. Grey clinker and grey cement productions were 21.2 Mt and 22.8 Mt in 2010, respectively (OFICEMEN, 2010a).

Regarding atmospheric emissions in Table 15, Spanish cement-making industry released 7% of the total CO_2 emissions in 2010 (PRTR-ES, 2010; MAGRAMA, 2012c). 63.1% came from process (calcination) and 36.9% from fuel combustion (OFICEMEN, 2010b).

Table 15. Main pollutants emitted by the Spanish cement industry in 2010

CO_2 (Mt)	CO (kt)	NO_x (kt)	SO_2 (kt)	VOC (kt)	$PM_{2.5}$ (t)	PM_{10} (t)
18.22	44.16	36.94	8.09	1.05	475	1068

Apart from CO_2 emissions, other pollutants also have significant contributions: NO_x, 3.8%; SO_2, 1.7%; CO, 2.5%; VOC, 0.15%. Particulate matter (PM) emissions are relevant in absolute terms because the emissions coming from cement-making can be captured unlike other sectors.

Regarding the production, Table 16 shows historical data of the Spanish cement production in tonnes since 1991 to 2011 (OFICEMEN, 2012).

Table 16. Historical figures of the Spanish cement production

	Clinker production	Cement production	Cement exported	Clinker exported	Cement imported	Clinker imported	Consumption per capita (kg/pop/yr)
1991	22118675	27581556	2146926	426366	3277918	127959	740
1992	19398564	24616107	1743245	438655	3245275	180782	668
1993	19007474	22838228	2645784	1090152	2555289		582
1994	21738540	25130751	3439480	1530439	2249822		614
1995	23464943	26421841	3482824	2068844	2796371	234140	650
1996	22898277	25406170	3879160	2384537	3167339	477095	630
1997	24104979	27933154	3812155	1759588	2558820	485191	682
1998	25942596	32449065	3471236	632385	1867680	1218872	778
1999	27280915	35781978	3062109	48110	1994311	2336027	861
2000	27840499	38115621	2120998	38783	2372476	2735028	949
2001	28382550	40510437	1436696	8488	3133942	3975629	1027
2002	29357596	42387660	1417564	33971	3173833	4649365	1068
2003	30316646	44746757	1241557	10916	2661026	5897219	1100
2004	30798002	46593482	1517609	6910	2570612	6266470	1124
2005	31742502	50347073	1447079		2887491	7804380	1164
2006	32078063	54048270	1126854		3164435	9587594	1268
2007	32146220	54720445	1091284		2853620	11015835	1248
2008	27304551	42083407	1349799	985396	1743867	5440339	936
2009	21594604	29504574	1481717	1355760	728716	2119666	630
2010	21207202	26161660	2528346	1364414	654311	1087184	531
2011	18242699	22178237	2322902	1645623	466310	576391	443

It is observed that the cement production reached up to 55 Mt in 2007 and, at the same time, the clinker production was 32 Mt. That difference is based on the imports of clinker to satisfy the pre-crisis cement demands.

According to Table 17, in 2010 and 2011, the fuel consumption in the Spanish cement industry fell down accordingly to the fall of the demand (OFICEMEN, 2010a; 2012). Note that natural gas is expressed in m3.

Table 17. Fuel consumption of the Spanish cement industry

FUEL (t)	2008	2009	2010	2011
Fossil				
Petcoke (imported)	1,714,175	1,381,011	1,320,337	892,843
Petcoke (national)	850,780	621,087	592,690	649,237
Fuel oil (kilns)	33,822	22,397	17,950	14,498
Natural gas	5,034,545	2,566,967	2,333,755	1,922,712
Gasoil (kilns)	562	472	316	385
Hard coal (import)	236,838	25,785	28,878	12,307
Hard coal (national)	85,996	7,139	6,186	4,491
Other solid fossil fuels	12,558	21,125	32,345	30,516
Propane	-	-	7	6
Alternative fossil				
Used oils	13,128	7,474	10,942	26,940
Solvents and varnishes	57,812	44,376	39,055	38,373
Industrial sludges	-	0	5,612	6,233
Other alt. liquids no bio	-	13,004	32,330	14,392
Other alt. solids no bio	5,904	8,460	6,613	9,156
Plastics	923	7,570	18,007	26,110
Waste liquid from hydrocarbons	16,786	0	4,263	684
Used vehicles waste	3,605	3,885	1,348	12,575
Waste solid from hydrocarbons	14,504	2,451	2,121	1,934
Alternative biomass				
Biomass	16,361	65,294	40,594	77,342
Meat and bone meal	82,973	58,606	55,655	59,814
Municipal sewage sludge	19,933	29,831	47,967	62,965
Wood	9,745	12,192	45,024	93,634
Other alt. solids bio	-	0	0	373
Other alt. liquids bio	-	216	34	0
Pulp and paper	750	575	990	13,223
Alternative partial bio				
Municipal solid waste	7,285	79,718	111,735	205,009
Used tyres	51,431	82,385	116,394	128,507
Sawdust	47,510	60,003	68,342	13,507
Textil	-	285	534	1,077

Finally, the electricity consumption of the Spanish cement industry is shown in Table 18 (OFICEMEN, 2012). Power consumption of the associated quarry is included.

Table 18. Electricity consumption of the Spanish cement industry

Consumption	2008	2009	2010	2011
Electricity (GWh)	3,891	3,108	2,984	2,495

4. Electricity sector

4.1. General overview

Fast changes have happened in the Spanish energy system during the last few years: massive introduction of renewable energy technologies, feed-in tariffs regulation, new natural gas combined cycle plants, etc.

The Spanish energy system is characterised by higher energy intensity than the rest of countries in Europe and its high dependence on energy imports. Currently, security and diversity of energy sources are the main arguments in favour of the growth of the Spanish renewable energy industry. A stable regulation framework based on feed-in tariffs rewarding the environmental benefits, promoted the development of renewable technologies (EREC, 2009) until those were eliminated in 2012. As a result, Spain became the world's third largest producer of wind energy, behind Germany and United States in 2008 (EREC, 2009). The photovoltaic energy, characterised by a similar industrial development, reached also remarkable contributions. From then, both wind and solar photovoltaic technologies growths have been decreasing.

Other emergent technologies like concentrated solar power (CSP) began to grow considerably from 2010, reaching 2 GW of capacity at the end of 2012 (REE, 2013). Most of the CSP installations are parabolic troughs but there are also three solar tower power plants in operation, contributing with up to 100 MW (Protermosolar, 2013). However, biomass has not developed as fast as expected (neither for electricity nor for heating purposes). Spain has very low district heat supply, and despite the fact that it has been the first European country to enforce the obligatory implementation of solar thermal energy in new and refurbished buildings, administrative barriers restrain the further development of RES for heating and cooling market (EREC, 2009).

Regarding biofuels, Spain was the third producer of bioethanol and biodiesel in Europe in 2011 (behind Germany and France). It is remarkable the biodiesel production growth from 2009. Spanish biofuel production reached 8.7% of the European production in 2010 but decreased to 6.8% in 2011 (EIA, 2013).

As regards fossil fuels, crude oil is transformed in refineries into oil products that are consumed mainly in the transport and industry sectors. Gas is consumed by the industry, power generation sector and residential. Coal is used mainly to produce electricity and only a small part is consumed in the industry sector (Cabal *et al*., 2012).

Finally, renewable technologies are used to produce electricity although part of the energy coming from solar and biomass is consumed in residential and industry sectors.

Primary energy is supplied mainly by crude oil and gas and, to a lower degree, by coal, nuclear fuel, imported oil products and biomass and waste. Most of the oil and gas supplied is imported whereas 73% of coal is imported and 27% produced domestically. Renewable energy contribution to primary energy supply reached 11.6% in 2011 (SEE, 2012).
Table 19 below shows the energy balance for Spain in year 2009. Data are expressed in ktoe on a net calorific value basis (IEA, 2013).

Table 19. Spanish energy balance in 2009

SUPPLY & CONSUMPTION	Coal & Peat	Crude Oil	Oil Products	Nat. Gas	Nuc.	Hydro	Geo, Solar, etc.	Biofuel & Waste	Elc.	Total
Production	3628	107	0	12	13750	2264	3936	6023	0	29720
Imports	9906	56976	25450	31765	0	0	0	450	581	125128
Exports	-935	0	-11071	-893	0	0	0	-265	-1278	-14441
Int. Marine Bunkers	0	0	-8644	0	0	0	0	0	0	-8644
Int. Aviation Bunkers	0	0	-3171	0	0	0	0	0	0	-3171
Stock Changes	-3125	817	-95	329	0	0	0	1	0	-2072
TPES	**9475**	**57900**	**2470**	**31213**	**13750**	**2264**	**3936**	**6209**	**-697**	**126520**
Transfers	0	827	-833	0	0	0	0	0	0	-6
Statistical Diffs.	909	0	-266	70	0	0	0	0	18	730
Electricity Plants	-8468	0	-3264	-13232	-13750	-2264	-3771	-955	22292	-23412
CHP Plants	-50	0	-668	-3196	0	0	0	-239	2736	-1418
Heat Plants	0	0	0	0	0	0	0	0	0	0
Gas Works	39	0	-55	0	0	0	0	0	0	-16
Oil Refineries	0	-58801	57756	0	0	0	0	0	0	-1046
Coal Transformation	-361	0	0	0	0	0	0	0	0	-361
Liquefaction Plants	0	0	0	0	0	0	0	0	0	0
Other Transformation	0	86	-89	0	0	0	0	0	0	-3
Energy Industry Own Use	-505	0	-4053	-1463	0	0	0	-174	-1527	-7722
Losses	-14	0	0	-108	0	0	0	0	-860	-982
TFC	**1026**	**12**	**50995**	**13284**	**0**	**0**	**165**	**4842**	**21962**	**92286**
Industry	701	12	4711	8255	0	0	2	1562	8109	23353
Transport	0	0	33046	57	0	0	0	1073	269	34444
Other	325	0	6466	4595	0	0	162	2207	13584	27340
Residential	257	0	3321	3132	0	0	125	2072	5978	14886
Commercial and Public Services	17	0	1424	681	0	0	28	91	6867	9108
Agriculture / Forestry	0	0	1722	281	0	0	8	36	493	2540
Fishing	0	0	0	0	0	0	0	0	0	0
Non-Specified	50	0	0	501	0	0	1	7	246	805
Non-Energy Use	0	0	6772	377	0	0	0	0	0	7149

4.1.1. Primary energy

During last decades oil contribution has meant around 50% of the primary energy (with no significant reductions) whereas other energy carriers have varied their contributions: natural gas and renewable sources are increasing in detriment of coal due to the fall in the demand and the coal power plants phase-out. Table 20 shows the evolution of the total primary energy supply in Spain (TPES) in PJ (SEE, 2001; 2006; 2012).

Table 20. Evolution of TPES in Spain

Carrier	1990	%	2000	%	2005	%	2010	%	2011	%
Coal (PJ)	784	20.0	907	17.3	888	14.5	355	6.4	522	9.6
Petroleum products (PJ)	2093	53.0	2709	51.7	3008	49.2	2620	47.3	2442	45.1
Gas (PJ)	208	5.0	638	12.2	1220	20.0	1299	23.5	1211	22.4
Nuclear (PJ)	574	15.0	679	13.0	628	10.3	677	17.5	629	11.6
Renewable (PJ)	262	7.0	293	5.6	372	6.1	615	11.1	634	11.7
Total (PJ)	3922		5225		6116		5566		5438	

As exception, 2010 coal consumption fell severely in an anomalous way compared to the years around due to political strategies. Nuclear energy remains almost constant in absolute values.

Renewable energy sources still provide a reduced amount of primary energy although wind and biomass has experienced a significant increase over last few years.

4.1.2. Final energy

Table 21 shows the total final consumption (TFC) in 2010 and 2011 (SEE, 2012).

Table 21. Final energy consumption in Spain

	2010	%	2011	%
Total energy uses (PJ):	3789		3610	
Coal	58.2	1.4	52.4	1.3
Coal derived gases	11.1	0.3	12.9	0.3
Petroleum products	1945	47.6	1841	47.2
Gas	599	14.7	535	13.7
Electricity	938	23.0	910	23.3
Renewables	237	5.8	258	6.6
Non-energy uses (PJ):				
Coal	1.51	0.04	2.34	0.06
Petroleum products	276	6.8	269	6.9
Natural gas	19.7	0.5	22.5	0.6
Total final consumption (PJ)	4085		3904	

35-40% of TFC goes to transport, 25% to industrial sectors and 30% is consumed in residential, commercial and agriculture. Within this group, residential sector means more than 50% of the energy consumed. Respect to the total, non-energy uses entail around 8%, coming from oil products used in refineries and petrochemical industries. Main consumer of coal is the iron and steel industry, followed by the cement industry, and residential sector.

4.1.3. Energy intensity

Recent final energy intensity evolution by subsector is differentiated in two phases, the first one from 1995 to 2004 and the second one from 2004 onwards. In the first period energy intensity grew following a trend contrary to the one in the EU15. After 2005 several circumstances have caused a reduction in the energy consumption and a decrease in energy intensity: in the electricity generation sector decreased its energy intensity thanks to the introduction of natural gas combined cycle plants and renewable energy technologies (Cabal *et al.*, 2012).

In the case of industry, there are two differentiated phases. Up to 2004 energy intensity grew 8% and after the opposite trend is observed. The same happened in the agriculture sector. One of the reasons of this evolution is the role played by the cement industry which highly contributes to the energy consumption but not so much to the gross added value of the sector. The cement industry is strongly linked to the construction sector which is very important in the productive structure of the Spanish economy. An expansion in the construction sector and the associated increase in the cement demand, which are very energy intensive, explain the growing pattern of this indicator (Cabal *et al.*, 2012).

Besides, great improvements in energy efficiency have been achieved in the transport sector leading its energy intensity to a strong diminution during the last years. Finally, both residential and services sectors have increased its energy intensity overall. The increment in energy consumption is probably due to the convergence to European standards processes in terms of electric equipments and to the number of vehicles per household as well as a low energy price (Cabal *et al.*, 2012).

4.2. Supply sector

4.2.1. Coal

According to national data (IGME, 2008a), proven reserves of coal and lignite were 23,800 PJ and 20,600 PJ in 2008, respectively.

As the Spanish coal is subsidised and supports are being reduced, national production is declining. From 2004 to 2008, the production has been falling down constantly. Moreover, brown lignite production stopped in 2007 due to the closure of the last two exploitations. Total coal imports (hard coal) in 2008 were 21 Mt, 14.3% less than the previous year, but the cost was 2,062.29 M€, 38.1% higher due to the strong rise in prices (Cabal *et al.*, 2012). Recent agreement Marco de Actuación de la Minería del Carbón 2013-2018 estimates a minimum contribution of the national coal in the electricity production mix of 7.5% from 2015 (MINETUR, 2013).

In 2005, 89% of the total coal was consumed in the thermal power plants. The trend of the coal use in the power sector in the last years has been to decrease until 2010 when the share of electricity generated with coal was 9%. In the last three years this trend has changed completely thanks to the subsidies received by the coal sector. Production with coal has increased resulting in a change also in the trend of the GHG emissions. Anyway, it is difficult to estimate how the future consumption of coal in the electricity sector will be because it is strongly dependent on the policies and subsidies (Cabal *et al.*, 2012).

4.2.2. Oil

According to the Oil and Gas Journal (EIA, 2008), Spanish proven reserves of oil have been quantified in 0.150 billion oil barrels (918 PJ). Domestic oil production is negligible attending to the 59.9 and 58.7 Mt crude oil imported in 2005 and 2012. The main oil import countries in Spain in 2005 were Mexico, Russia and Nigeria, and also the same in 2012. Other countries imports, such as Saudi Arabia or Iran, grew significantly some years (CORES, 2006; 2007; 2008; 2009; 2010; 2011; 2012; IGME, 2008b).

From 90s to present, main oil consumer has been the transport sector followed by the industry and commercial sectors. Oil consumption in power plants is supposed to disappear by the end of this decade (Cabal *et al.*, 2012).

The final refining capacity in 2010 was 70.8 Mt/y. Raw material processed in the refineries reached 58 Mt. Currently, there are no plans to build new refineries but the sector companies continue investing to improve the existing ones.

4.2.3. Gas

Domestic natural gas production is negligible compared to the imports. Extraction meant 2.4 PJ in 2010 and 2.1 PJ in 2011 (SEE, 2012). Spain imports more than 99% of its needs: imports in 2010 and 2011 resulted in 1,486 and 1,438 PJ, respectively (SEE, 2012). Most of the natural gas was liquefied natural gas (LNG) and the rest was natural gas in gaseous state (GNG) (SEE, 2012).

Main suppliers are Algeria and Nigeria as well as other relevant countries: Qatar, Trinidad and Tobago, Egypt, France, Norway and Peru (SEE, 2012).

In 2011, 29.8% of the total natural gas was consumed in the power thermal plants. The largest gas consumer was the industry sector, 36.7%. Cogeneration plants entailed 16% and other 16% was consumed in residential and commercial sectors (SEE, 2012). Considering cogeneration within power production, total natural gas share for producing electricity meant 45.8%.

4.2.4. Uranium

The last Uranium mine in Spain was closed in 2002. Spain's main import countries are Russia (45%), Australia (22%) and Niger (20%) (Foro Nuclear, 2010). The nuclear fuel supply in Spain is considered totally national by the Energy State Department (SEE). SEE explains that the security of supply of Uranium is guaranteed due to many factors such as the diversification and the stability of prices in the international market. In Spain there is a factory of nuclear fuel that in 2009 manufactured 325 tU, from which 245 tU were to reload pressurized water reactors (PWRs) and 82 tU were to reload boiling water reactors (BWRs). 71% of the production was exported to France, Germany, Finland, Belgium and Sweden (Cabal *et al.*, 2012).
Regarding radioactive waste disposal, there is a low and medium activity repository built in 1992. At the end of 2009, 61.6% of the total capacity was used. At present (2013) there is a project to install the first Centralized Interim Storage Facility (Almacén Temporal Centralizado) to store high-level radioactive waste in Villar de Cañas (Cuenca) (BOE 17, 2012).

4.2.5. Biofuels

Biofuel consumption in Spain in 2009 was around 1,052 ktoe (149 ktoe bioethanol and 903 ktoe biodiesel), what meant 3.45% of the total fuel consumption in transport (Cabal *et al.*, 2012). According to APPA (2008), biodiesel production in 2008 was 215 kt and bioethanol, 433 kt. On the other hand, installed capacities were: 3,290 kt for biodiesel and 456 kt for bioethanol. Low biodiesel production (in terms of installed capacity) is consequence of, first biodiesel imports from USA, and now, biodiesel imports from Argentina. In 2010, 75% of the biodiesel plants were almost stopped with an average working ratio of 10%.

Royal Decree 1088/2010 (BOE 215, 2010) established a 5.83% target for 2010 for the introduction of biofuels in gasolines as part of the implementation of Directive 2009/30/EC. Royal Decree 459/2011 (BOE 79, 2011) modified the annual targets establishing 6.2% in 2011, and 6.5% both 2012 and 2013. In this regulatory framework it was possible to blend biodiesel in diesel up to a 7% and bioethanol in gasoline up to a 10%. Recent Royal Decree-Law 4/2013 (BOE 47, 2013) reduces the target from 6.5% to 4.1% for biofuel introduction, starting in 2013 and keeping the percentage the following years. By biofuel type, bioethanol blending is up to 3.9% and biodiesel is up to 4.1%.

4.3. Power generation

4.3.1. Capacity

Installed power capacity in Spain is largely based on fossil fuels, hydroelectric power plants and renewable energy technologies. However, in the last years a great increment of investments in wind electricity has taken place, with almost 10 GW installed in year 2005 (18% of total), and 20 GW in 2010. Over the last few years, there has also been a remarkable investment in natural gas combined cycle power plants, having reached an installed capacity of 25 GW in 2010 (see Table 22). Total installed capacity in 2010 was 104.48 GW (SEE, 2011).

Table 22. Breakdown of installed power capacities in 2010

Electricity generation capacity (GW)	MW
Ordinary regime	69,975
Hydro	17,562
Nuclear	7,777
Coal	11,890
Fuel/Gasoil	5,699
Natural Gas	27,047
Special regime	34,504
Hydro	1,991
Wind	20,203
Solar PV	3,642
Solar thermoelectric	682
Coal	149
Natural Gas	5,718
Fuel/Gasoil	1,141
Biomass and Waste	979
TOTAL	104,479

Besides, in 2012 there were 39 solar thermal plants in Spain with a total capacity installed of 1,954 MW with an estimated generation of 5,138 GWh (Protermosolar, 2013). In June 2013, capacity was 2,054 MW corresponding to 45 plants in operation.

4.3.2. Generation

In 2010, the largest share (34.5%) came from fossil fuels, with an increasing participation of natural gas and a decreasing contribution of coal and fuel. Nuclear electricity remains constant over time in absolute values but its contribution becomes less important in relative terms. Renewables experienced a great increase in the last decade mainly due to the wind power that at the end of 2010 represented 14.6% of the total electricity generated in the country. Hydroelectricity varies a lot depending on the hydrological year. Table 23 shows the evolution of the Spanish electricity production in the last decade (SEE, 2001; 2006; 2011).

Table 23. Evolution of the Spanish electricity production

Source (GWh)	1990	2000	2005	2010
Nuclear	54270	62206	57539	61661
Coal	59734	80524	80922	25551
Coal	n/a	n/a	57865	17276
Lignite	n/a	n/a	23057	8275
Fuel/Gas	8602	21869	16243	11624
Natural Gas	-	21808	53831	66429
Combined Cycle	-	-	48840	64604
Hydro	26180	31806	19169	38653
Special regime	4275	6943	66538	96527
Hydro			3856	6793
Wind	14	-	21269	43784
Solar PV	-	-	78	6311
Solar thermal	-	-	-	875
Coal CHP	-	-	535	766
Nat. Gas CHP	-	-	25449	29555
Fuel/Gasoil CHP	-	-	6967	4333
Biomass & Waste	-	-	8384	4111
Gross production	153061	225156	294244	300775
Consumption in operation	-8040	-14844	-18308	-9989
Net electricity generation	144601	214754	274592	290786
International exchanges	-420	-4441	-1344	-8332
Pump consumption	-	4907	6360	4458
Final power demand	144181	215220	279608	277996

In 2010, Spanish electricity net consumption reached 278 TWh, which represented 1.5% increase over 2009 consumption. While in the period 2000-2005 the demand grew by 30%.

4.3.3. Regimes and Trade

Electricity generation in Spain has two different regimes, the Ordinary Regimen (RO) to which all the conventional generation belong to and the Special Regimen (RE) to which the renewable energy generation and the CHP plants belong to. In this last regime a feed-in tariff promotion mechanism was implemented in 2007, latterly modified and finally removed in 2012.

International power exchanges are four: France, Portugal, Andorra and Morocco. In 2010, net balance was positive. Although France has been traditionally an exporting country to Spain, the trend changed that year.

The interconnection capacity is 2,400 MW from Spain to Portugal. The connection with France has been recently increased to 2,800 MW (REE, 2013 web).

4.3.4. Cogeneration

In 2011, there were 693 cogeneration plants with a total capacity installed of 6,180 MW which generated 25,003 GWh (excluding the ones associated with the waste treatment) (SEE, 2012).

Most of the cogeneration plants belonged to the industry sector: food, 18%; paper, 15%; and chemical industries, 15% (SEE, 2012). The main fuel used in cogeneration was the natural gas with a share of 80%, followed by fuel oil and biomass. Regarding the technologies, internal combustion engine was the dominant one (49.5% of the installed capacity) followed by the combined cycle (19.4%).

4.4. Renewable energy potentials

In 2010, renewable energies primary consumption was 14,678 ktoe (615 PJ) which meant 11.1% of the total primary energy. Main technologies were biomass (3.8%), wind power (2.8%) and hydro (2.6%). From the 14,678 ktoe consumed, 63% was for power production, 27% for heat and 10% for biofuels.

Renewable energies final consumption was 5.4% of the total final energy, mainly from biomass and biofuels, and not considering the share of electricity generated with renewables (in such a case the share would be 14% approx.).

Total gross electricity production was 96,527 GWh. Electricity generated in RE meant 32.1% of the total. Main technologies contributing were wind power (14.6%), small hydro (2.3%), and solar (2.4%). There is also an important contribution of cogeneration (11.5%).

The total technical potential of the renewable resources in Spain is between 500 and 3,400 TWh/y (see Table 24). The highest potential technology is solar followed by wind power (Cabal *et al*., 2010; Cabal *et al.*, 2012).

Table 24. Estimated potential of the renewable energy sources in Spain

Potential (TWh)	Min	Max
Ocean	39	81
Solar PV	144	2157
Solar thermal	190	990
Hydro	7	9
Wind	140	260
Biomass	11	14
TOTAL	496	3438

4.5. Emissions

Spain ratified the Kyoto Protocol as member of the European Union compromising to reduce its GHG emissions. Established target was +15% of GHG emissions till 2012 compared to the 1990 emissions (see Figure 7). Despite the efforts of the last years, in 2005 Spain’s GHG emissions increased by approximately 53% compared to the 1990 level. However, this trend has changed in the last years. In 2007 emissions reached a maximum of 437 Mt CO_2-eq, 54% above the base year emissions. From 2008 this trend changed due to the economic crisis but also to the introduction of more efficient and cleaner technologies. Since 2010, GHG emissions are 20% above the 1990 level approximately (MAGRAMA, 2012a).

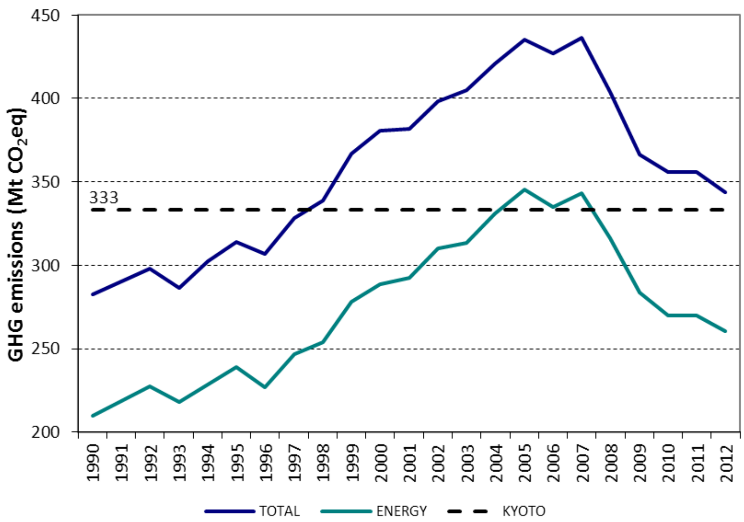


Figure 7. Evolution of the Spanish GHG emissions

CO_2 means 80% of the total GHG emissions (MAGRAMA, 2012a). Next Table 25 shows the evolution of the GHG emissions by sector (MAGRAMA, 2012a).

Table 25. Spanish total CO_2, CH_4, N_2O emissions by sector

Sector	1990			2005			2010		
	CO_2 Mt	CH_4 kt	N_2O kt	CO_2 Mt	CH_4 kt	N_2O kt	CO_2 Mt	CH_4 kt	N_2O kt
Energy production	77.26	70.91	259	124.91	94.05	747.90	71.71	125.61	585.75
Upstream	n.a.	2606	-	2.24	1850	-	2.23	1078	-
Industry	63.13	180.53	3025	97.94	244.35	2184	79.90	665.48	1072
Rsd, Com, Agr	18.24	888.97	230.29	39.13	667.77	342.70	38.14	1131	446.58
Agr. (non-combustion)		17844	n.a.	-	22667	22085	-	18408	21461
Transport	67.32	351.39	613.61	102.44	175.92	2711	90.42	96.93	903.98
Other	n.a.	8689	7494	1.48	11570	1498	1.05	13506	3157
TOTAL	228.22	30630	26158	368.14	37269	29571	283.45	35012	27626

In addition, Table 26 shows the evolution of other gases emissions. Data have been obtained from Ministry of Environment (MAGRAMA, 2012b). Energy processing includes industries in the energy sector (power stations and refineries), transport and combustion emissions from the industry, residential and commercial sectors (MAGRAMA, 2012b; Cabal *et al.*, 2012).

Table 26. Spanish emissions of acidifying, eutrophying and ozone precursors by sector

Sector	1990				2005				2010			
	NO_X kt	SO_2 kt	NMVOC kt	CO kt	NO_X kt	SO_2 kt	NMVOC kt	CO kt	NO_X kt	SO_2 kt	NMVOC kt	CO kt
Energy processing	1244	2161	516	2952	1376	1310	237	1432	954	469	160	1072
Industry	13.0	14.4	56.9	298	8.1	12.4	61.5	412	7.5	10.7	55.2	363
Use of solvents	-	-	376	-	-	-	477	-	-	-	406	-
Agriculture	28.6	4.4	57.9	413	19.3	3.0	39.3	280	22.1	4.2	55.7	397
Waste management and disposal	1.4	1.2	13.8	17.2	0.2	0.2	2.5	2.1	0.2	0.2	1.3	1.5
TOTAL	1287	2181	1021	3680	1404	1326	818	2126	984	484	679	1834

From 1990 to 2010, NO_X emissions mainly came from the energy generation and transport sectors and have decreased by 24%. In that period SO_2 emissions have been reduced by 78%. These emissions are mainly associated to the coal combustion both in power generation sector and industry. The sector with the greatest reduction is the energy sector. Attending to the CO emissions, they decreased 50% due to the severe reduction in the transport sector, in the waste management and treatment and in the non-combustion activities in agriculture. Finally, NMVOC emissions have been reduced in Spain 34% from 1990 to 2010, mainly due to the reduction of emissions in the transport sector.

3 METHODOLOGIES

To meet the objectives of this work, environmental analysis and energy prospective methodologies have been used. The LCA method has been chosen to identify and evaluate the environmental impacts of the cement sector in Spain. To analyse the effect of the environmental Directives in the cement and electricity generation sectors in the medium and long term, several scenarios have been built under different assumptions of efficiency improvements, introduction of policy and tax measures, new technologies implementation, etc. In this case, the energy optimization model TIMES-Spain has been used.

Both methodologies are widespread and backed up and acknowledged by the international scientific community. This chapter presents a general overview of the LCA method and the TIMES-Spain model.

1. Life Cycle Assessment method

Several methodologies are suitable to carry out environmental analyses. The LCA method makes possible to quantify the environmental consequences of processes, products and/or services throughout their life cycle.

The International Organization for Standardisation (ISO) prepared two rules focused on environmental management for setting in the bases and guidelines of the LCA methodology:

- ISO 14040: 2006. Environmental management – Life cycle assessment – Principles and framework.
- ISO 14044: 2006. Environmental management – Life cycle assessment – Requirements and guidelines.

The first studies date from the late 60s and early 70s, and focused on issues such as energy efficiency, the consumption of raw materials and waste disposal. In 1969, the Coca Cola Company funded a study to compare resource consumption and environmental releases associated with different beverage containers (EEA, 1997). During 90s, two organisations, SPOLD (Society for Promotion of Life-cycle Assessment Development) and SETAC (Society of Environmental Toxicology and Chemistry), became the most important associations for LCA issues.

1.1. Life Cycle Assessment

An LCA is "*a process to evaluate the environmental burdens associated with a product, process, or activity by identifying and quantifying energy and materials used and wastes released to the environment; to assess the impact of those energy and materials used and releases to the environment; and to identify and evaluate opportunities to affect environmental improvements. The assessment includes the entire life cycle of the product, process or activity, encompassing, extracting and processing raw materials; manufacturing, transportation and distribution; use, re-use, maintenance; recycling, and final disposal*" (SETAC, 1993).

The objectives of an LCA are (ISO 14040, 2006):

- To identify opportunities to improve the environmental performance of products at various points in their life cycle.
- To inform decision-makers in industry, government or non-government organizations (e.g. for the purpose of strategic planning, priority setting, product or process design or redesign).
- The selection of relevant indicators of environmental performance, including measurement techniques.
- Marketing (e.g. implementing an ecolabelling scheme, making an environmental claim, or producing an environmental product declaration).

There are four phases in an LCA study (ISO 14040, 2006):

- The goal and scope. The scope, including the system boundary and level of detail, of an LCA depends on the subject and the intended use of the study. The depth and breadth can differ considerably depending on the goal of a particular LCA.
- The life cycle inventory (LCI). It is an inventory of input/output data with regard to the system being studied.
- The life cycle impact assessment (LCIA). The purpose of LCIA is to provide additional information to help to assess a product system's LCI results to better understand their environmental significance.
- The life cycle interpretation. In this phase, the results of an LCI or an LCIA, or both, are summarized and discussed as a basis for conclusions, recommendations and decision-making in accordance with the goal and scope definition.

An LCA evaluates the environmental aspects and impacts of product systems, from raw material acquisition to final disposal, in accordance with the stated goal and scope. Its relativeness comes from the functional unit feature of the methodology and the depth of detail and time frame, which may vary to a large extent, depending on the goal and scope definition.

An LCA does not predict absolute or precise environmental impacts due to the relative expression of potential environmental impacts to a reference unit, the integration of environmental data over space and time, the inherent uncertainty in modelling, and the fact that some possible environmental impacts are clearly future impacts (ISO 14040, 2006).

1.2. Goal and scope

The goal of LCA defines its application, the reasons for carrying out the study, and the intended audience. On the other hand, the scope includes the product system description, its functions, the functional unit selected, the system boundaries, the allocation procedures, the impact categories selected and the methodology of impact assessment, the data requirements, assumptions, limitations, and the quality data requirements (ISO 14040, 2006).

The functional unit defines the quantification of the identified functions (performance characteristics) of the product. The primary purpose of a functional unit is to provide a reference to which the inputs and outputs are related. This reference is necessary to ensure comparability of LCA results.

LCA is conducted by defining product systems as models that describe the key elements of physical systems. The system boundary defines the unit processes to be included in the system. When setting the system boundary, several life cycle stages, unit processes and flows are taken into account in order to include the acquisition of raw materials, the inputs/outputs of the main processing sequence, transportation, production and use of fuels, electricity and heat, use of products, disposal of waste, recovery of used elements, use and construction of ancillary materials, etc. It is common that the initially defined system boundary had to be re-defined after taking into consideration all the processes and stages.

1.3. Life Cycle Inventory

Life Cycle Inventory (LCI) involves data collection and calculation procedures to quantify relevant inputs and outputs of a product system. Data collection of each unit process takes into consideration the inputs (energy, raw material, ancillary), emissions (to air, water and soil) and the products, co-products and waste. Calculation procedures consist in validating data collected, relating them to unit process as well as to the reference flow of the functional unit. This is remarkable since the modelled system, as a whole, must be referred to the same unit in order to standardize the assessment. Finally, it is important to detail the selected allocation procedure since most industrial processes yield more than one product and recycle intermediate or discarded products as raw materials. Allocation may be based on mass, energy or environmental relevance criteria.

1.4. Life Cycle Impact Assessment

Life Cycle Impact Assessment (LCIA) is focused on evaluating the significance of potential environmental impacts using LCI results. This process involves associating inventory data with specific environmental impact categories and category indicators, thereby attempting to understand these impacts (see Figure 8).

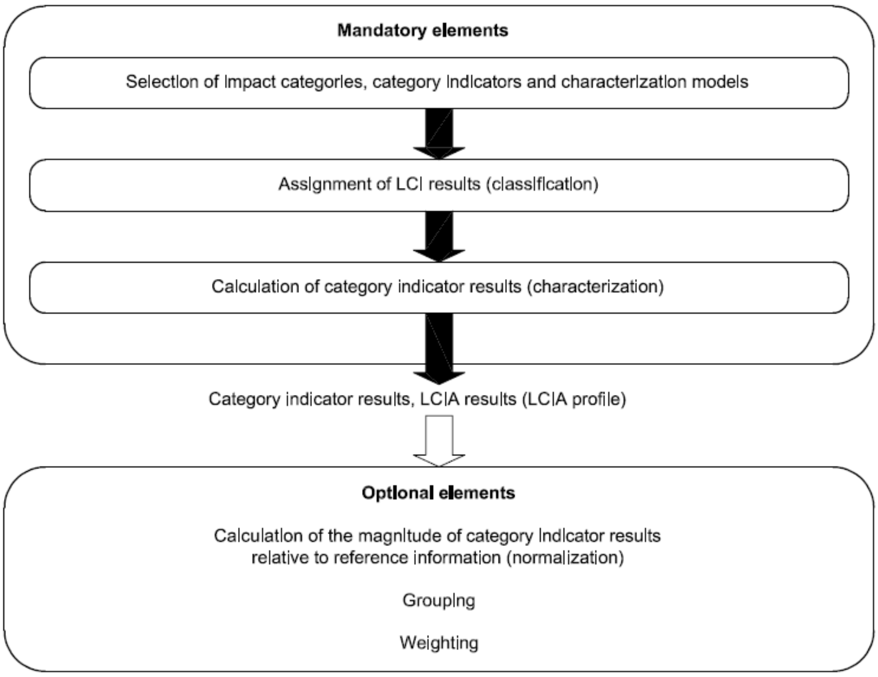


Figure 8. Elements of the LCIA phase (ISO 14040, 2006)

According to LCIA results, the interpretation phase may lead to modify the first goal and scope of the LCA so that LCIA is considered an iterative process. In order to avoid subjectivity it is necessary to keep the transparency.

1.5. Interpretation

Finally, the interpretation phase of an LCA includes the findings from the inventory analysis and the impact assessment both individually and separately. Results should be consistent with the goal and scope, allow reaching conclusions, explaining limitations and provide recommendations.

1.6. Characterisation methods

An impact category is a class representing environmental issues of concern to which life cycle inventory analysis results may be allocated (ISO 14044, 2006), whereas an impact category indicator (also referred as 'category indicator') is its quantifiable representation.

The mandatory elements of an LCIA are the classification which includes the selection of impact categories, category indicators and characterisation models as well as the assignment of LCI results to the selected impact categories; and the characterisation where the category indicator results are calculated.

Most common impact categories are climate change, stratospheric ozone depletion, acidification, nutriphication, human toxicity, ecotoxicity, depletion of fossil energy resources and depletion of mineral resources (ISO 14047, 2003).

According to SETAC (1993), environmental effects to consider within the impact categories should include resource exhaustion, global warming, ozone layer depletion, human toxicity, ecotoxicity, acidification, eutrophication, photochemical ozone formation, land use, noise, odour, and waste. There are different characterisation methods depending on the impact categories.

Regarding the evaluation process, analysis may be at mid- or endpoint level depending on the grouping level.

1.7. International Life Cycle Data System (ILCD) method

In the Communication on Integrated Product Policy, European Commission committed to produce a handbook on best practice in LCA (EC, 2003a). The Sustainable Consumption and Production (SCP) Action Plan (EC, 2008a) recommended that "(…) *consistent and reliable data and methods are required to assess the overall environmental performance of products* (…)". The International Reference Life Cycle Data System (ILCD) Handbook, based on the existing international standards on LCA, ISO 14040:44, provides governments and businesses with a basis to guarantee the quality and consistency of life cycle data, methods, assessments and recommendations. The recommendations are based on existing models assessed in the overall framework of the Areas of Protection: Human Health, Natural Environment, and Natural Resources.

Several methodologies have been developed for LCIA and many efforts have been made towards harmonisation. Starting from the first pre-selection of existing methods and the definition of criteria, ILCD Handbook (EC-JRC, 2011) describes the recommended methods for each impact category at both midpoint and endpoint.

Recommendations are given for the impact categories of climate change, ozone depletion, human toxicity, particulate matter/respiratory inorganics, photochemical ozone formation, ionising radiation impacts, acidification, eutrophication, ecotoxicity, land use and resource depletion. Research needs are identified for each impact category and differentiated according to their priority (EC-JRC, 2011).

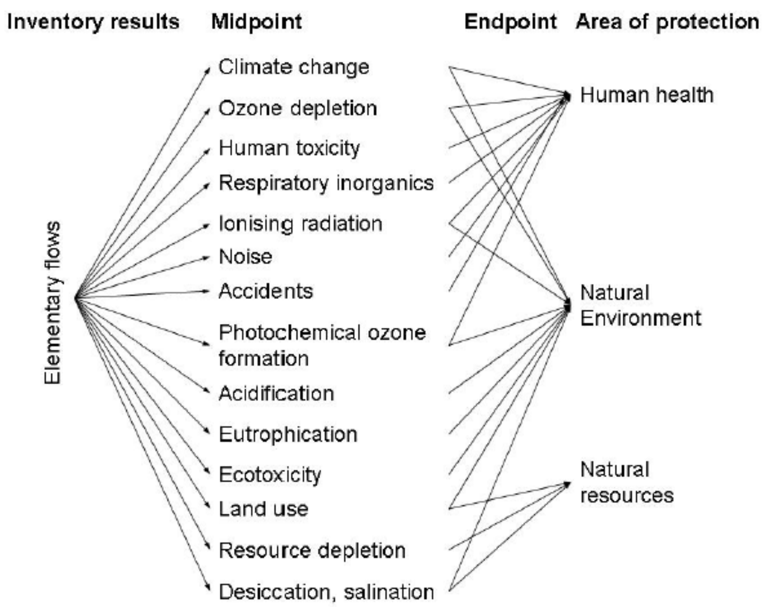


Figure 9. Framework of impact categories at midpoint and endpoint level

The extension from midpoint to endpoint requires grouping impact categories in order to evaluate the impacts over human health, natural resources and environment (see Figure 9).

ILCD Handbook (EC-JRC, 2010a) assesses several well-established LCIA methodologies in order to evaluate the impact categories from each of them and set in recommendations about what method to use depending on which impact category has to be analysed. Some of them are CML 2002, Eco-Indicator 99, EDIP 97 and EDIP 2003, EPS 2000, IMPACT 2002+, LIME, ReCiPe, Ecological Scarcity Method (Ecopoints 2006), TRACI, MEEup, and others more focused on specific impact categories.

1.7.1. Climate change

Climate change involves a number of environmental mechanisms that affect both the human health and natural environment. Climate change models are, in general, developed to assess the future impact on climate resulting from different policy scenarios. The environmental mechanisms used for this impact category have a somewhat different structure, compared to the fate, effect and damage steps applied to many of the other impact categories. Climate change is caused by the emission of anthropogenic GHGs (and by other activities influencing their atmospheric concentration). GHGs are substances with the ability to absorb infrared radiation from the earth (radiative forcing).

All LCIA methodologies have an impact category Climate Change, and they all use the Global Warming Potentials (GWPs) developed by the IPPC.

1.7.2. Stratospheric ozone depletion

Stratospheric ozone depletion refers to the thinning of the stratospheric ozone layer as a result of anthropogenic emissions. This causes a greater fraction of solar UV-B radiation to reach the earth’s surface, with potentially harmful impacts on human health, animal health, terrestrial and aquatic ecosystems, biochemical cycles and materials (UNEP, 1998).

1.7.3. Human toxicity

This impact category covers the impacts on human health of toxic substances present in the environment.

This impact category is disaggregated into two: human toxicity with cancer and non-cancer effects. This is due to the degree of knowledge in the effects of the substances as well as the characterization process (EC-JRC, 2011).

1.7.4. Particulate matter / Respiratory inorganics

Ambient concentrations of particulate matter (PM) are elevated by emissions of primary and secondary particulates. The mechanism for the creation of secondary emissions involves emissions of SO_2 and NO_x that create sulphate and nitrate aerosols (EC-JRC, 2010b). Particulate matter is classified in a variety of ways: total suspended particulates (TSP), particulate matter less than 10 microns in diameter (PM_{10}), particulate matter less than 2.5 microns in diameter ($PM_{2.5}$) or particulate matter less than 0.1 microns in diameter ($PM_{0.1}$).

EC-JRC (2010b) points out that for respiratory inorganics, all available methods are *de facto* endpoint methods. It is advised to report both the number of cases of different diseases as well as the related Years of Life Lost, Years of Life Disabled and DALYs.

1.7.5. Ionising radiation

Ionising radiation modelling starts with releases at the point of emission, expressed in Becquerel (Bq), and calculates the radiative fate and exposure, based on detailed nuclear physics knowledge.

For human toxicity, the exposure analysis calculates the dose that a human actually absorbs, given the radiation levels that are calculated in the fate analysis. The measure for the effective dose is the Sievert (Sv), based on human body equivalence factors for the different ionising radiation types (α-, β-, γ-radiation, neutrons: 1 Sv = 1 J/kg body weight).

1.7.6. Photochemical ozone formation

Photochemical ozone formation, also referred as photo-oxidant formation or summer smog, refers to the formation of reactive chemical compounds such as ozone by the action of sunlight on certain primary air pollutants. These substances may cause damages to human health, ecosystems, and crops. Photo-oxidants may be formed in the troposphere under the influence of ultraviolet light, through photochemical oxidation of Volatile Organic Compounds (VOCs) and carbon monoxide (CO) in the presence of nitrogen oxides (NO_x). Ozone is considered the most important of these oxidising compounds, along with peroxyacetylnitrate (PAN) (Guinée, 2001).

1.7.7. Acidification

Acidification entails a wide range of impacts on soil, ground- and surface water, organisms, ecosystems and buildings. The major acidifying pollutants are SO_2, NO_x and NH_x.

1.7.8. Eutrophication

This impact category can adopt different names like eutrophication, nutriphication or nutrient enrichment. It addresses the impacts from the macro-nutrients nitrogen and phosphorus in bio-available forms on aquatic and terrestrial ecosystems (EC-JRC, 2010b).

Terrestrial eutrophication is caused by deposition of airborne emissions of nitrogen compounds like nitrogen oxides from combustion processes and ammonia from agriculture. Airborne spreading of phosphorus is not prevalent, and terrestrial eutrophication is therefore mainly associated with nitrogen compounds.

In aquatic systems, the addition of nutrients has a similar primary impact by fertilising the plants (algae or macrophytes) with consequences for the ecosystem.

Freshwater and marine aquatic systems are exposed to water-borne emissions (nitrate, other nitrogen compounds expressed as total N, phosphate and other phosphorus-containing compounds expressed as total P). Marine aquatic systems and very large lakes are also substantially exposed by airborne emissions (NO_x).

As Heijungs *et al*. (1992) disregards the media of emission as well as the sensitivity of the receiving environment and the limiting nutrient, several suggestions have been made for overcoming these limitations: by distinguishing ecosystem subcategories, and by including fate and site- or region-dependent effect modelling. EC-JRC (2010b) establishes the disaggregation by ecosystem as the preferred option, splitting into terrestrial and/or aquatic eutrophication.

1.7.9. Ecotoxicity

Ecotoxicity reflects the impacts of toxic substances on aquatic, terrestrial and sediment ecosystems. The characterisation factors are generally referred as the Ecotoxicity Potentials (ETPs).

The characterisation factors are different if the ecosystem is terrestrial or aquatic. In EC-JRC (2011) it is concluded that no available method is recommended to address marine and terrestrial ecotoxicity. Besides, it is noted that the use of indicators for freshwater ecosystems is not a proxy for marine and terrestrial ones and, in many cases, only accounts for part of the long-term fate and ecosystem exposure of emissions.

1.7.10. Land use

This impact category reflects the damage to ecosystems due to the effects of occupation and transformation of land (agricultural production, mineral extraction and human settlement). Occupation of land can be defined as the maintenance of an area in a particular state over a particular time period. Transformation is the conversion of land from one state to another state. Often transformation is followed by occupation, or occupation takes place in an area that has previously been transformed.

In order to quantify the quality of a certain state (land use type) an appropriate indicator must be chosen along a relevant environmental pathway. Milà i Canals *et al*., (2007) identifies the following impact pathways as relevant: biotic production potential, biodiversity and ecological soil quality. The impacts can be described, on midpoint or endpoint level, by different quality indicators, such as species loss, primary production, soil organic matter content and soil loss.

1.7.11. Abiotic depletion

Van Oers *et al*. (2002) describe the abiotic resource depletion as the decrease of availability of the total reserve of potential functions of resources, due to the use beyond their rate of replacement. This impact category considers the effect on both renewable and non-renewable resources. Depletion of minerals and fossil fuels falls within the category non-renewable resources, while extraction of water, wind (abiotic) and wood (biotic) falls within renewable resources (EC-JRC, 2010b).

2. Energy optimisation models: TIMES-Spain

2.1. Introduction

After the 1973 price oil crisis, it was found that different geopolitical equilibria were very weak. Only a few countries owned, and still own, the oil global reserves and have the absolute power to fix the prices. This group of nations is known as the OPEC (Organization of the Petroleum Exporting Countries) and most of them can be considered politically unstable.

When the international community observed the disastrous consequences of the oil crisis (disturbances, lack of food, etc.), the countries began to build strategies to analyse and develop their energy systems at long term pursuing the energy independency. The aims were both to prevent such situations and to research on new types of energy which would not depend on limited and external resources such as renewable energies.

In addition, the target of the energy access is fully achieved in the developed economies but not in all the developing countries nor in the Third World. Expanding energy access is central to tackle global poverty and should be present within the objectives of any climate agreement. The guarantee of power and fuel availability is the next step. Once the states have assured the energy access for all their citizens, it is necessary that the energy will be available according to the needs of the people. The first point implies big investments to build the grid while the second one implies to keep the control of the energy system in order to make analysis and prospectives of the people’s energy demand and how to satisfy this in the near and further future.

Another energy related concern is conventional energy resources exhaustion. Throughout the course of the 20th century it has turned to be a great problem, not only socio-political but also economic. For instance, oil production prospectives are unflattering regarding the future of this fuel. Oil scarcity entails prices will rise more and more and never will fall again. Currently (2013), oil from the existing reservoirs is over 108 $/barrel of crude Brent. This price increases as reservoirs run out and new proven reserves have to be exploited. Finally, once reservoirs and reserves are exhausted, great investments have to be done on finding and prospecting new ones leading to a final and not affordable price. All this is important to understand how the optimisation models deal with the fuel scarcity issue, as will be seen in the following sections.

Finally, there are also other important impacts on the environment such as the impacts on human health, ecosystems, crops, and buildings. Due to the processes associated to the transformation technologies, many different pollutants are emitted to the atmosphere. Along with climate change, other impacts are produced such as ozone layer depletion or acidification, which have serious consequences on the environment.

To face all these complex problems it is necessary to use powerful tools that allow the countries to take them into consideration in the energy planning at long term.

Energy optimisation models are useful mathematical tools for energy planning purposes since they are able to represent and analyse complex energy systems. From a representation of the current energy system, the model finds an optimal solution for future energy systems under different social, economic, and environmental scenarios. For each solution, present and future energy demand is driven by socioeconomic parameters such as GDP, population, and number of households. Demand is then satisfied by the most cost efficient technology mix chosen from a wide present and future energy technology portfolio.

In summary, the use of energy optimisation models is one possible way to build those future scenarios. In this work, the energy model TIMES-Spain has been used. TIMES is a model generator developed by the Energy Technology Systems Analysis Programme (ETSAP), an Implementing Agreement of the International Energy Agency (IEA), whose functions are the cooperation to establish, maintain, and expand a consistent multi-country energy/economy/environment/engineering (4E) analytical capability. TIMES is used worldwide by many research centres, universities and public administrations, backed up and acknowledged by the international scientific community. TIMES-Spain is a national energy model part of the Pan European Times model (PET) resulted from the NEEDS (NEEDS, 2005) and RES2020 (Labriet *et al*., 2010) projects co-funded by the EC.

2.2. Energy models

Models make possible to understand the links between thousands of processes and commodities and to obtain results involving them (Connolly *et al*., 2010).

The use of energy models began in the 70s decade as a way to make quantitative analysis of the energy systems and avoid the terrible consequences of a mistaken decision making process. The level of detail in the representation of an energy system depends on the time and geographical scope of the problem. An energy model is described by specifying the characteristics of the technologies involved as well as the concerning reference energy system.

2.3. TIMES model generator

TIMES, acronym of *The Integrated MARKAL-EFOM System,* is an energy model generator used worldwide to implement national, regional and global models. A generic TIMES model is tailored by input data to represent the evolution over a period of up to 100 years of a specific energy-environment system at world, national, regional, state, province, or community level. Each TIMES model is based on a Reference Energy System (RES) that is a network depicting all possible flows of energy from resource extraction, through energy transformation and end-use devices, to demand for useful energy services. The optimisation procedure finds the most optimal RES for each time period by selecting the set of technologies and fuels that minimize the total system cost over the entire planning horizon. Thus, the model determines the optimal mix of technologies and fuels at each period, the associated emissions, trading activity, and the equilibrium levels of demands (Cuomo *et al*., 2009)

TIMES provides a technology-rich basis for estimating energy dynamics over long-term and multi-period time horizon. That is the main goal of a TIMES model. The user provides estimates of the existing stock of energy related equipment in all sectors, and the characteristics of available future technologies, as well as present and future sources of primary energy supply and their potentials. Using these inputs, the TIMES model aims to supply energy services at minimum global cost (equivalently 'at minimum loss of surplus') by simultaneously making equipment investment and operating, primary energy supply, and energy trade decisions, by region (Loulou *et al*., 2005a).

The choice by the model of the generation equipment (type and fuel) is based on the analysis of the characteristics of alternative generation technologies, on the economics on the energy supply, and, optionally, on environmental criteria. TIMES is thus a vertically integrated model of the entire extended energy system.

In TIMES the quantities and prices of the various commodities are in equilibrium, that is their prices and quantities in each time period are such that the suppliers produce exactly the quantities demanded by the consumers. When equilibrium is reached, total surplus is maximized.

The TIMES models are suited to the exploration of possible long term energy futures based on contrasted scenarios. A scenario consists of a set of coherent assumptions about the future trajectories of the involved drivers, leading to a coherent organization of the system under study.

In TIMES, a complete scenario consists of four types of inputs: energy service demands, primary resource potentials, a policy setting and the descriptions of a set of technologies.

The TIMES demand scenarios consist of a set of assumptions on the socio-economic drivers (GDP, population, households) and on the elasticities of the demands to the drivers and to their own prices. In the case of the policy scenarios, those limit or control special features of the energy systems such as emissions, the use of nuclear power, etc. These may set taxes, subsidies, restrictions and pre-established limits. Other scenarios consist of supply curves for primary energy and material resources. Each step of a supply curve represents a certain potential of the resource available at a particular cost. The potential may be expressed as a cumulative potential over the model horizon (gas or oil reserves), over the resource base (proper areas for windmills, areas for biocrops, etc.) and as an annual potential (extraction rates or available wind, hydro, biomass potentials). Last scenarios are the technical and economical parameters assumed for the transformation of primary resources into energy services. These parameters appear in form of technologies (or processes) that transform some commodities into others (fuels, materials, energy services, emissions).

2.3.1. General characteristics

The TIMES model generator is the source code, which processes a set of data describing a model instance (the Model) and generates a matrix with all the coefficients that specify the economic equilibrium model of the energy system as a mathematical programming problem (mainly LP problem). The model generator also post-processes the optimisation results to prepare them for the analysis (Loulou *et al*., 2005a). The main characteristics of a TIMES model are:

Technology explicit. Each technology is described in TIMES by a number of technical, environmental and economic parameters. Thus each technology is explicitly identified (given a unique name) and distinguished from all others in the model. A TIMES model may include several thousand technologies in all sectors of the energy system (energy supply, transformation, processing, transmission, and end-uses) in each region.

Multi-regional. The number of regions in a model is limited only by the difficulty of solving LP's of very large size. The individual regional modules are linked by energy and material trading variables, and by emission permit trading variables, if desired. The trade variables transform the set of regional modules into a single multi-regional (possibly global) energy model, where actions taken in one region may affect all other regions.

Partial equilibrium model. This kind of models is used to analyse trade issues in a single market (energy sector in this case). They are adaptations of standard supply and demand analysis to the specific features of trade policies. Partial equilibrium models are used in cases where linkages to other sectors of the economy are negligible enough to be ignored. A supply-demand equilibrium model has as economic rationale the maximization of the total surplus (see Figure 10).

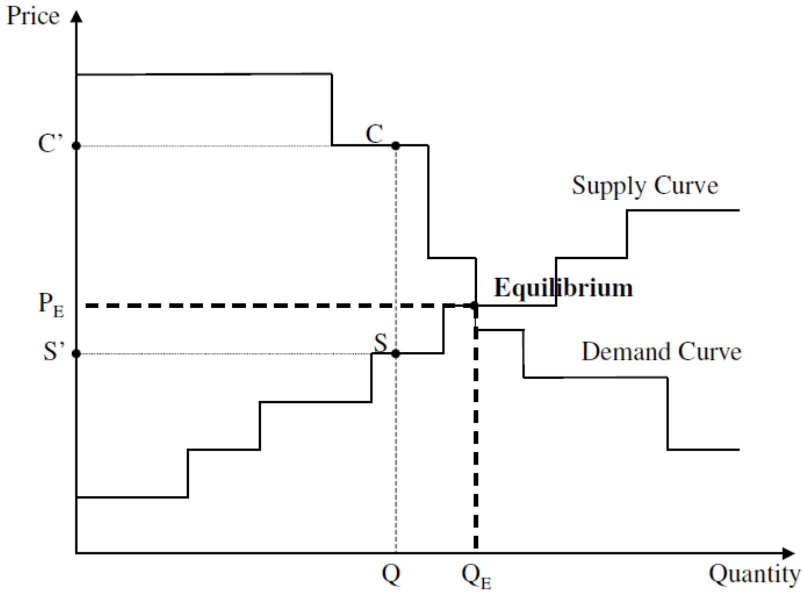


Figure 10. Market equilibrium in TIMES

Price elastic demands. Each energy service demand has a constant own price elasticity function as follows:

$$D/D_0 = (P/P_0)^E \quad (1)$$

where (D_0 ,P_0) is a reference pair of demand and price values for that energy service over the forecast horizon, and *E* is the (negative) own price elasticity of that energy service demand, as chosen by the user. The pair (D_0, P_0) is obtained by solving TIMES for a reference scenario. More precisely, D_0 is the demand projection estimated by the user in the reference case based upon explicitly defined relationships to economic and demographic drivers, and P_0 is the shadow price of that energy service demand obtained by running the reference case scenario of TIMES. It is important to point out that the shadow price is derived from the marginal value of a commodity. The qualifier 'shadow' is used to distinguish the competitive market price from the price observed in the real world, which may be different, as is the case of regulated industries or sectors where either consumers or producers exercise market power. When the equilibrium is computed using LP optimisation, the shadow price of each commodity is computed as the dual variable of that commodity's balance constraint (Loulou *et al*., 2005a).

The market is competitive with perfect foresight. The competitive markets are characterized by perfect info and atomic economic agents, which together preclude any of them from exercising market power. The perfect info assumption extends to the entire planning horizon, so that each agent has perfect foresight, i.e. complete knowledge of the present and future market's parameters.

The TIMES energy economy is made up of producers and consumers of commodities such as energy carriers, materials, energy services, and emissions. TIMES assumes competitive markets for all the commodities. The result is a supply-demand equilibrium that maximizes the net total surplus (i.e. the sum of producers' and consumers' surpluses). TIMES is distinguished from perfectly competitive market assumptions by the introduction of user-defined explicit constraints, such as limits to technological penetration, constraints on emissions, exogenous oil price, etc. Market imperfections can also be introduced in the form of taxes, subsidies and hurdle rates.

In summary, a TIMES model is a bottom-up, energy, partial equilibrium, optimisation and dynamic model. Energy model because it is mainly focused on the energy system and for the same it is a partial equilibrium model. Bottom-up because it arrives to general conclusions starting from regional or local data. Optimisation model because it has an objective function that must be maximized (or minimized) and it is dynamic because a TIMES model uses an objective function which covers the whole period simultaneously.

2.3.2. Specific characteristics

The structure of a model gives an idea, through its representation, of the type of the problem being analysed. All TIMES models make use of an identical mathematical structure. However, as TIMES is data driven, each model will vary according to the data inputs.

Data

The model database contains both qualitative and quantitative data. The qualitative data includes, for example, lists of energy carriers, the technologies applicable, to each region, over a specified time horizon, as well as the environmental emissions that are to be tracked. This information may be further classified into subgroups, for example energy carriers may be split by type: fossil, nuclear, renewable, etc. The quantitative data contains the technological and economic parameter assumptions specific to each technology, region, and time period. For example, when constructing multi-regional models it may happen that a technology may be available to be used in two different regions; however, cost and performance assumptions may be quite different.

In addition to time-periods which may be of variable length, there are time divisions within a year, also called time-slices, which may be defined at will by the user, e.g. the user may want to define seasons, day/night, and/or weekdays/weekends (Loulou *et al*., 2005a).

Time horizon

The time horizon can be split into a number of time-periods by the user. Each period may contain a different number of years. In TIMES, each year of a period is considered identical, except for the cost objective function which differentiates between payments in each year of a period.

Any model input or output variable attached to a period *t* applies to the years of that period (except for investment variables, which are usually made only once in a period). In TIMES, the initial period is considered a past period, over which the model has no freedom, and for which the parameters are all fixed by the user at their historical values. The main variables to be calibrated are the capacities and operating levels of all technologies, as well as the extracted, exported, imported, produced, and consumed commodities for all energy carriers, and the emissions.

Geographical coverage

Depending on which issues the modeller needs to address, the energy system can be modelled at global level describing the world economy situation, at regional or international level considering regions such as Europe, OECD-countries, Africa, etc., at national level and at local level (subnational, referring to regions within a country). A TIMES multiregional model consists of multiple regions, each having its own Reference Energy System. These regions can trade commodities via inter-regional exchange processes. These so called internal regions form together the area of study or the "model region". Furthermore, external regions for importing to and exporting from the model region may be defined. The external regions possess no inner structure, they are considered to be black boxes.

Decoupling

TIMES takes into account the investments made in past years and, for that, it is important to be able of modifying the choice of the initial and subsequent periods without major revisions of the database. The specification of process and demand input data is made by specifying the years when the data apply, and the model interpolates and extrapolates the data to represent the particular periods chosen by the modeller for a particular model run. This represents a great simplification of the modeller's work. In particular, it enables the user to define time periods that have varying lengths, without changing the input data.

Reference Energy System

The Reference Energy System (RES) is the main scheme which allows representing globally the three types of entities involved on an energy system modelled in TIMES:

- *Technologies (or processes)* are representations of devices that transform commodities into other commodities. Processes may be primary sources of commodities (mining, import processes), or transformation activities (conversion plants: electricity), energy-processing plants (refineries), end-use demand devices (cars, heating systems, etc.).

- *Commodities* consist of energy carriers, energy services, materials, monetary flows, and emissions. A commodity is generally produced by one or more processes and/or consumed by other processes.
- *Commodity flows* are the links between processes and commodities. A flow is of the same nature as a commodity but is attached to a particular process, and represents one input or output of that process.

The RES is presented as a diagram that links the previous entities. Processes are represented as boxes and commodities as vertical lines. Commodity flows are symbolized as links between process boxes and commodity lines. It must be read from left to right. Figure 11 shows an example of RES for a specific end-use service (Loulou *et al*., 2005a).

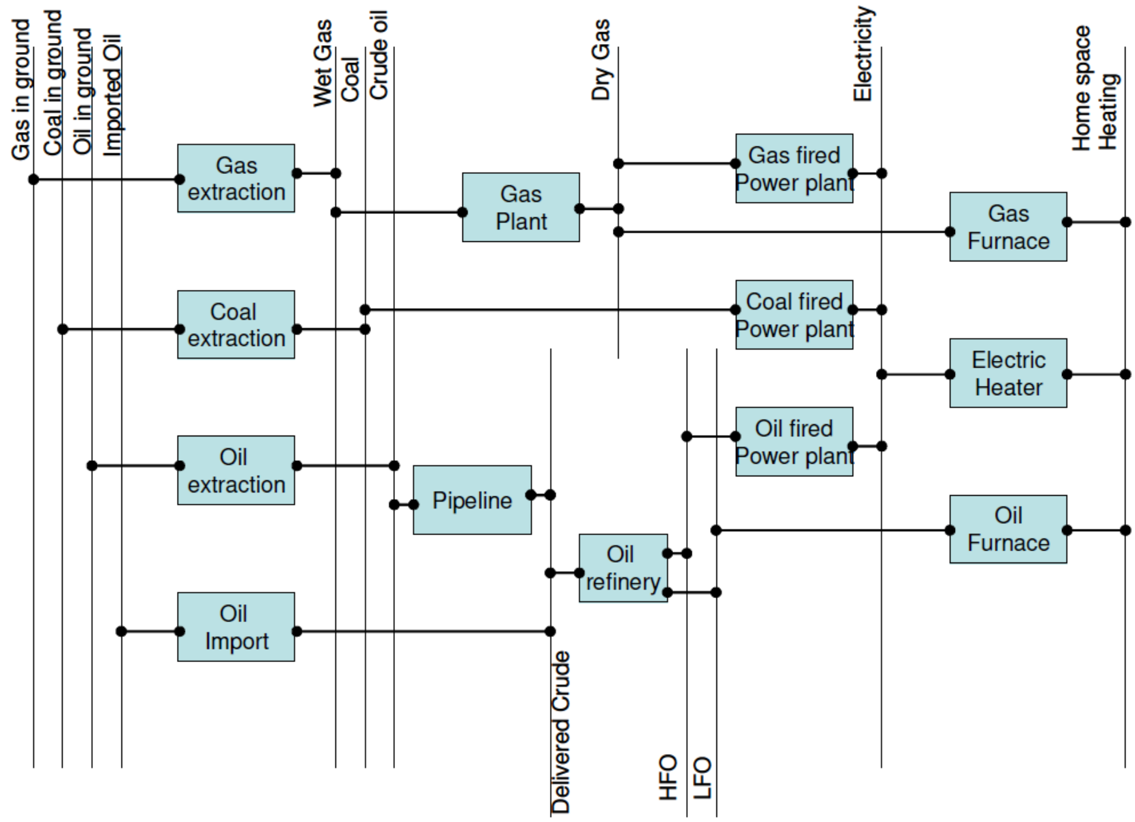


Figure 11. Example of RES for a residential space heating energy service demand

In Figure 11 there are three end-use space heating technologies using the gas, electricity, and heating oil energy carriers (commodities), respectively. These energy carriers in turn are produced by other technologies, represented in the diagram by one gas plant, three electricity-generating plants (gas fired, coal fired, oil fired), and one oil refinery. To complete the production chain on the primary energy side, the diagram also represents an extraction source for natural gas, an extraction source for coal, and two sources of crude oil (one extracted domestically and then transported by pipeline, and the other one imported).

2.3.3. Elements

Parameters

Process parameters

Each process is described in terms of its capacity and activity, availability, capacity factor, investment cost, fix and variable operation and maintenance costs, etc. The parameters related to the processes can be divided into three categories:

- T*echnical parameters* that include efficiency, availability factors, commodity consumptions per unit of activity, shares of fuels per unit activity, technical life of the process, construction lead time, dismantling lead-time and duration, amounts of the commodities consumed (respectively released) by the construction (respectively dismantling) of one unit of the process, and contribution to the peak equations.
- *Economic and policy parameters* that include a variety of costs attached to the investment, dismantling, and maintenance and operation of a process. Other economic parameters are the *economic life* of a process (the time during which the investment cost of a process is amortised, which may differ from the operational lifetime) and the process specific discount rate, both of which serve to calculate the annualized payments on the process investment cost. An example of a policy parameter may be a carbon tax.
- *Bounds* (upper, lower, equality) on the investment, capacity, and activity of a process.

Commodity parameters

The parameters attached to the commodities are divided into three types:

- *Technical parameters* associated with commodities include overall efficiency, and the time-slices over which that commodity is to be tracked.
- *Economic parameters* include additional costs, taxes, and subsidies on the overall or net production of a commodity. These cost elements are added to all other costs of that commodity. For demand services, additional parameters define the demand curve.
- *Policy based parameters* include bounds (at each period or cumulative) on the overall or net production of a commodity, or on the imports or exports of a commodity by a region.

Commodity flow parameters

In TIMES each flow has a variable attached to it, as well as several attributes (parameters or sets).

- *Technical parameters* allow controlling the share of a given inflow or outflow into the same commodity group. For instance, a particular process may accept oil or biomass as input, and the modeller may use a parameter to limit the share of oil in the total fuel input.

- *Economic parameters* include delivery and other variable costs, taxes and subsidies attached to an individual process flow.

Parameters concerning the RES

These parameters include currency conversion factors (in a multi-regional model), region-specific time-slice definitions, a region-specific general discount rate, and reference year for calculating the discounted total cost (objective function).

Commodities

Commodities can be grouped together in user-defined commodity groups (e.g. primary commodity group, pcg). This feature is important in connection with process description. The flows are measured using commodity units. Furthermore, a commodity type has to be specified.

Processes

All processes available in a Reference Energy System have to be a member of a certain set. In addition, all the individual commodities and commodity groups that are connected to the considered process have to be identified by the corresponding set.

The actual topology of the commodity flows through the considered process (i.e. which commodities are inputs and/or outputs) is described by other set. The entries of that set specify the region, the process, the commodity and whether that commodity is an input to the considered process or an output.

The most basic case is a process taking one input and one output. For example consider a power plant technology consuming natural gas as fuel and producing electricity.

2.4. Linear Programming optimisation in TIMES

An optimisation problem formulation consists of three types of entities:

- *Decision variables*
- *Objective function*
- *Constraints*

From now on, the model data structures (sets and parameters), variables and equations will use the following general indexes:

r: region

t or v: time period; t corresponds to the current period, and v is used to indicate the vintage year of an investment. When a process is not vintaged then $v = t$.

p**:** process (technology);

s**:** time-slice; this index is relevant only for user-designated commodities and processes that are tracked at finer than annual level (e.g. electricity, low temperature heat, and run-of-river hydro or solar power, etc.). Time-slice by default is “ANNUAL”, indicating that a commodity is tracked only annually.

c: commodity.

2.4.1. Indexes and sets

The sets are entities used in TIMES to group elements or combinations of elements with the purpose of specifying qualitative characteristics of the energy system. There are several types of sets depending on the characteristic that we are looking at. For example, there are one-/multi-dimensional sets depending on the number of elements within.

The former sets contain single elements, e.g. the set *prc* contains all processes of the model, while the elements of multi-dimensional sets are a combination of one-dimensional sets. An example of a multi-dimensional set is the set *top*, which specifies for a process the commodities entering and leaving that process.

There are other types of sets: user input sets and internal sets. User input sets are created by the user to describe qualitative information and characteristics of the depicted energy system. These sets could be used to define the elements or the structure blocks of the system (regions, processes, commodities), to establish the time horizon and/or to define other characteristics of the elements. On the other hand, TIMES generates its own internal sets which serve to both ensure proper exception handling (e.g., from what date is a technology available, or in which time-slices is a technology permitted to operate), as well as sometimes just to improve the performance or smooth the complexity of the actual model code.

Finally, it must be remarked a special type of one-dimensional set, also called index, which is needed to build multidimensional sets or parameters.

For example, the set *prc* contains all processes, the set *c* containing all commodities or the set *all_reg* containing all regions of the model. Some of the one-dimensional sets are subsets of another one-dimensional set, e.g., the set *r* comprising the so-called internal model regions is a subset of the set *all_reg* which in addition also contains the so-called external model regions. To express that the set *r* depends on the set *all_reg*, the master set *all_reg* is put in brackets after the set name *r: r(all_r).* The set *cg* comprises all commodity groups. Each commodity **c** is considered as a commodity group with only one element, the commodity itself. Thus the commodity set *c* is a subset of the commodity group set *cg*. Apart from indexes that are under user control, some indexes have fixed elements to serve as indicators within sets and parameters and should not be modified by the user.

2.4.2. Decision variables

The decision variables are the unknowns, or endogenous variables, to be determined by the optimisation. The decision variables represent the choices to be made by the model. Some of these decision variables in a TIMES model are:

- *NCAP(r,v,p)*: new capacity addition (investment) for process.
- *CAP(r,v,t,p)*: total installed capacity of a process.

- *CAPT(r,t,p)*: total installed capacity of a process (all vintages together).
- *ACT(r,v,t,p,s)*: activity level of a process.
- *FLOW(r,v,t,p,c,s)*: the quantity of commodity consumed or produced by a process
- *SIN(r,v,t,p,c,s)/SOUT(r,v,t,p,c,s)*: the quantity of commodity stored or discharged by a storage process.
- *TRADE(r,t,p,c,s,imp)* and *TRADE(r,t,p,c,s,exp)*: quantity of commodity sold (*exp*) or purchased (*imp*) through export and import.
- *D(r,t,d)*: demand for end-use energy service.
- *Other variables*: Commodity related variables convenient for reporting purposes and/or for applying certain bounds such as the total amount produced of a commodity (COMPRD), or the total amount consumed of a commodity (COMCON).

2.4.3. The objective function

The objective function expresses the criterion to be minimized or maximized. The TIMES objective is to minimize the total cost of the system (for more information see Loulou *et al*. (2005a)). All cost elements are appropriately discounted to a selected year. While the TIMES constraints and variables are linked to a period, the components of the system cost are expressed for each year of the horizon (and even for some years outside the horizon). Total cost for each year includes:

- Capital Costs incurred for investing into and/or dismantling processes.
- Fixed and variable Operation & Maintenance Costs. Fixed O&M costs consists primarily of plant operating labour whereas the variable O&M costs include fuels, periodic inspection, replacement, and repair of system components, as well as consumables.
- Costs incurred for imports and domestic resource production.
- Revenues from exports.
- Delivery Costs for required commodities consumed by processes.
- Taxes and subsidies associated with commodity flows and process activities or investments.
- Revenues from recuperation of embedded commodities, accumulated when a process' dismantling releases some valuable commodities.
- Salvage value of processes and commodities at the end of the planning horizon.
- Welfare loss resulting from reduced end-use demands.

The objective function is defined as follows. First, TIMES computes for each region a total net present value of the stream of annual costs, discounted to a user selected reference year:

$$NPV = \sum_{r=1}^{R} \sum_{y \in YEARS} (1 + d_{r,y})^{REFYR-y} \bullet ANNCOST(r, y) \quad (2)$$

where *NPV* is the net present value of the total cost for all regions; *ANNCOST(r,y)* is the total annual cost in region *r* and year *y*; $d_{r,y}$ is the general discount rate; *REFYR* is the reference year for discounting; *YEARS* is the set of years for which there are costs, including all years in the horizon, plus past years (before the initial period) if costs have been defined for past investments, plus a number of years after *EOH* (end of the horizon) where some investment and dismantling costs are still being incurred, as well as the salvage value; R is the set of regions in the area of study.

These regional discounted costs are then aggregated into a single total cost, which constitutes the objective function to be minimized by the model in its equilibrium computation. The regional objective $REG\_OBJ(z,r)$ is the sum of 9 components:

$$REG\_OBJ(z,r) = \sum_{y \in (-\infty,\infty)} DISC(y,z) \times \{INVCOST(y) + INVTAXSUB(y) + INVDECOM(y) + FIXCOST(y) + FIXTAXSUB(y) + VARCOST(y) + ELASTCOST(y) - LATEREVENUES(y)\} - SALVAGE(z)$$

(3)

where the regional index r is omitted for simplicity of notation, and $DISC(y,z)$ is the value, discounted to the beginning of year z, of a 1€ payment made at the beginning of year y, using the general discount factor. The description of the components of the objective function for year y, region r, is shown below.

- $INVCOST(r,y)$: investments.
- $INVTAXSUB(r,y)$: investment taxes and subsidies.
- $INVDECOM(r,y)$: capital costs linked to decommissioning of a process.
- $FIXCOST(r,y)$: fixed annual costs.
- $FIXTAXSUB(r,y)$: taxes and subsidies attached to fixed annual costs.
- $VARCOST(r,y)$: variable annual costs.
- $ELASTCOST(r,y)$: cost incurred when demands are reduced due to their price elasticity.
- $LATEREVENUES(r,y)$: certain late revenues from the recycling of materials from dismantled processes that occur after the *EOH*.
- $SALVAGE(r,y_0)$: salvage value of investments and other one-time costs. It is discounted to some base year y_0.

2.4.4. Constraints

Apart from the economic criteria (minimizing the total discounted cost), a TIMES model must satisfy a large number of constraints (*equations*). These entities express the relationships and restrictions that energy systems must satisfy in order to properly depict the system. Next some of the more representative constraints are described (see Loulou *et al*., 2005a; 2005c). Note that in the following equations several sub-indexes have been omitted in order to make easier the reading.

Capacity transfer constraint

Investing in a technology increases its installed capacity for the duration of the physical life of the technology. When this lifetime ends, the total capacity is decreased by the same amount.

The total available capacity for each technology p, in region r, in period t (all vintages), is equal to the sum of investments made by the model at past and current periods, and whose physical life has not yet ended, plus capacity in place prior to the modelling horizon that is still available.

Capacity transfer (see file *eqcpt.mod* in TIMES file structure):

$$CAPT\ r,t,p\ =\ \sum NCAP\ r,t',p\ \ +RESID(r,t,p) \quad (4)$$

where $NCAP(r,t',p)$ is $NCAP$ referred over all periods t' preceding or equal to t such that $t-t' < LIFE(r,t',p)$ and *RESID(r,t,p)* is the capacity of technology p due to investments that were made prior to the initial model period and still exist in region *r* at time t.

Process activities and flow variables

This constraint equates an activity variable, *ACT(r,v,t,p,s)*, with the appropriate set of flow variables, *FLOW(r,v,t,p,c,s)*, properly weighted. This is accomplished by identifying the group of commodities that defines the activity (and its capacity) of the process.

The simple processes are determined by one input commodity (consumption) and one output commodity (production). The activity is defined by one of these flows. Differently, complex processes enter a set of inflow or outflow entities with something in common (primary commodity group or *pcg*), which allow defining the activity by itself, e.g. a group of energy carriers, or the group of GHG emissions.

Activity-Flow definition (see file *eqactflo.mod* in TIMES file structure):

$$ACT\ r,v,t,p,s\ \ =\sum_{c\in pcg} FLOW(r,v,t,p,c,s)/ACTFLO(r,v,p,c) \quad (5)$$

where $ACTFLO(r,v,p,c)$ *i*s a conversion factor (often equal to 1) from the activity of the process to the flow of a particular commodity.

Use of capacity constraint

In each time period the model uses some or all of the installed capacity according to the availability factor (AF) of each technology. For each technology p, period *t*, vintage *v*, region *r*, and time-slice s, the activity of the technology may not exceed its available capacity, as specified by a user defined availability factor.

Use of capacity (see file *eqcapact.mod* in TIMES file structure):

$$ACT(r,v,t,p,s) \le AF(r,v,t,p,s)\cdot CAPUNIT\cdot FR\cdot CAP \quad (6)$$

where $CAPUNIT(r,p)$ is the conversion factor between units of capacity and activity (often equal to 1, except for power plants); the $FR(r,s)$ parameter is equal to the duration of time-slice s, and finally, the $CAP(r,v,t,p)$ variable, not explicitly defined in TIMES, which is replaced in Equation (6) by a fraction (less than or equal to 1) of the investment variable $NCAP(r,v,p)$.

Note that the number of 'use of capacity' constraints is at least equal to the number of time-slices at which the equipment operates. For technologies with only an annual characterization the number of constraints is reduced to one per period (where s=*"ANNUAL"*).

Commodity balance equation

The regional commodity production plus the imports is equal to the total consumption plus the exports. The balance constraint is very complex due to the many terms involving production or consumption of a commodity.

For each commodity c, time period t (vintage v), region r, and time-slice s, the commodity balance constraint is as follows (see file *eqcombal.mod* in TIMES file structure):

$$COM\_IE(r,t,c,s) \cdot \sum_{p,c \in TOP\ r,p,c} FLOW + SOUT \cdot STG\_EFF + \sum_{p,c \in RPC_{IRE\ r,p,c,imp}} TRADE + \sum_p Release \cdot NCAP \geq [\sum_{p,c \in TOP\ r,p,c,in} FLOW + SIN + \sum_{p,c \in RPC_{IRE\ r,p,c,\exp}} TRADE + \sum_p Sink \cdot NCAP\} + FR(c,s) \cdot DM(c,t)$$

(7)

In addition, $TOP(r,p,c,in/out)$ identifies that there is an input/output flow of commodity c into/from process p in region r; $RPC\_IRE(r,p,c,imp/exp)$ identifies that there is an import/export flow into/from region r of commodity c via process p; $STG\_EFF(r,v,p)$ is the efficiency of storage process p; $COM\_IE(r,t,c,s)$ is the infrastructure efficiency of commodity c; $Release(r,t,p,c)$ is the amount of commodity c recuperated per unit of capacity of process p dismantled (useful to represent some materials or fuels that are recuperated while dismantling a facility); $Sink(r,t,p,c)$ is the quantity of commodity c required per unit of new capacity of process p (useful to represent some materials or fuels consumed for the construction of a facility); $FR(c,s)$ is the fraction of the year covered by time-slice s (equal to 1 for non- time-sliced commodities).

The constraint is "$\geq$" for energy forms (energy carriers, emissions, demands) and "=" for materials and emissions.

Defining flow relationships in a process

If there are no relationships between input and output flow variables, it is necessary one or more constraints to set some kind of link. One of these constraints is that the ratio of the sum of some output flows to the sum of some input flows is equal to a constant. An important rule for this constraint is that each sum must be taken over commodities of the same type, and equally, the commodities of the output's sum.

Efficiency definition (see file *eqptrans.mod* in TIMES file structure):

$$\sum_{c \in cg2} FLOW = FLOFUNC(r,v,cg1,cg2,s) \cdot \sum_{c \in cg1} COEFF \cdot FLOW \quad (8)$$

where $COEFF(r,v,p,cg1,c,cg2,s)$ takes into account the harmonization of different time-slice resolution of the flow variables, which have been omitted here for simplicity, as well as commodity-dependent transformation efficiencies. Also, *cg1* identifies the input commodity group, *cg2* the output commodity group, and $FLOFUNC(p,cg1,cg2)$ is the efficiency ratio.

Limiting shares in flexible processes

The flow share constraint is intended to limit the flexibility by constraining the share of each flow within its own group. This is only possible when either of the commodity groups contains more than one element.

Limiting flow shares in flexible processes (see file *eqfloshr.mod* in TIMES file structure):

$$FLOW\ c \quad \geq\leq= FLOSHAR(c) \cdot \sum_{c' \in cg} FLOW(c') \tag{9}$$

where the commodity group cg may be on the input or output side of the process.

Peaking reserve constraint

The total capacity of all processes producing a commodity at each time period and in each region must exceed the average demand in the time-slice where peaking occurs by a certain percentage. This percentage is the Peak Reserve Factor, $RESERV(r,t,c)$, and is chosen to assure against several contingencies such as possible commodity shortfall due to uncertainty regarding its supply, unplanned equipment down time, and random peak demand that exceeds the average demand during the time-slice when the peak occurs.

For each time period t and for region r, there must be enough installed capacity to exceed the required capacity in the season with largest demand for commodity c by a safety factor E named peak reserve factor.

Commodity peak requirements (see file *eqpeak.mod* in TIMES file structure):

$$\sum CAPUNIT \cdot Peak \cdot FR \cdot CAP \cdot ACTFLO + \sum Peak \cdot FLOW \ + TRADE\ \ r,t,p,c,s,i \quad \geq \ 1 + RESERV \ \cdot [\sum FLOW + TRADE\ \ r,t,p,c,s,e\ ] \tag{10}$$

where the first summation is over all p producing c with $c = pcg$, the second one is over all p producing c with $c \neq pcg$ and the last one is over all p consuming c. Besides, $RESERV(r,t,c,s)$ is the region-specific reserve coefficient for commodity c in time-slice s, which allows for unexpected down time of equipment, for demand at peak, and for uncertain resource availability, and $Peak(r,v,p,c,s)$ (never larger than 1) specifies the fraction of technology p's capacity in a region r for a period t and commodity c (electricity or heat only) that is allowed to contribute to the peak load in slice s.

Many types of supply processes are predictably available during the peak and thus have a peak coefficient equal to 1, whereas others (such as wind turbines or solar plants in the case of electricity) are attributed a peak coefficient less than 1, since they are on average only fractionally available at peak (e.g., a wind turbine typically has a peak coefficient of 0.25 or 0.3, whereas a hydroelectric plant, a gas plant, or a nuclear plant typically has a peak coefficient equal to 1).

Constraints on commodities

This kind of constraints is defined to limit the share of process p in the total production of commodity c. It indicates that the flow of commodity c from/to process p is bounded by a given fraction of the total production of commodity c. This is very useful for cumulative bounding emissions or modelling reserves of fossil fuels.

User constraints

When the standard constraints are not enough, the user can introduce additional constraints to express special conditions, e.g. a constraint which limits a particular investment.

2.5. Working with TIMES

As has been seen, TIMES consists of generic variables and equations constructed from the specification of sets and parameter values depicting an energy system for each different region in a model. To run a TIMES model, a pre-processor first translates all data defined by the modeller into special internal data structures representing the coefficients of the TIMES matrix applied to each variable for each equation in which the variable may appear. This step is called matrix generation. Once the model is solved (optimised) a report writer assembles the results of the run. The matrix generation, report writer and control files are written in GAMS.

2.5.1. GAMS

GAMS is a high-level language for the compact representation of large and complex models. With GAMS, changes in the model specifications can be made in a simply and safely way (Rosenthal, 2010).

GAMS stands for General Algebraic Modelling System and it is suitable to model the energy systems by relying heavily on the concepts of sets, compound indexed parameters, dynamic looping and conditional controls, variables and equations. Thus there is a very strong synergy between the philosophy of GAMS and the overall concept of the RES specification embodied in TIMES making GAMS very well suited to the TIMES paradigm.

Furthermore, the GAMS code is very useful with the mathematical approach of the TIMES formulation. Thus, the approach to implement a TIMES model is to manipulate the input data by means of a pre-processor that handles the necessary exceptions to properly construct the matrix coefficients in a form ready to be applied to the appropriate variables in the respective equations. GAMS code is chosen to solve the actual TIMES linear programming (LP) or mixed integer programming (MIP) problems that represent the desired model.

2.5.2. CPLEX

The most used optimisers to solve the TIMES LP and MIP formulations are CPLEX, GUROBI, COIN-OR, XPRESS, etc. CPLEX solves LP problems using several alternative algorithms. The majority of LP problems are solved by using the dual simplex algorithm integrated in CPLEX. Certain types of problems make the best of using the primal simplex algorithm, the network optimizer, the barrier algorithm, or the sifting algorithm (IBM, 2009).

2.5.3. Source code

TIMES is written in a modular fashion using GAMS. The description of the problem is contained in the so-called <*case*>.run file, which is a GAMS command script that initiates and controls each model run. Each model run is tagged with the user provided *case name*. Each case is composed of a number of scenario data files (<*scenario*>.dd/dds).

Files structure

To run a TIMES model, the user has to provide two files: the <case>.run file, which is passed to GAMS to initiate a model run; and the data dictionary <scenario>.dd file(s), which contains the user input sets and parameters to fully describe the energy system to be analysed. As a result of a model run a listing file (<case>.lst) and a <case>.gdx file (GAMS dynamic data exchange file) are created. The <scenario>.lst file may contain an echo print of the GAMS source code and the input data, a listing of the specific model equations and variables, error messages, model statistics, model status and the solution. The amount of information displayed in the listing file can be adjusted by the user through GAMS options in the <case>.run file. The <case>.gdx file (GAMS Data Exchange) is an internal GAMS file that contains all the model input data and results and makes possible the understanding between Excel and GAMS. In addition to these two output files, TIMES may create a file called qa_check.log to report the user of possible errors or inconsistencies in the model formulation.

During a TIMES model run various tasks are performed: GAMS compile, initialisation, execution, pre-processing, coefficient calculation, generation of model equations, setting variable bounds, solving the model (CPLEX) and reporting. Figure 12 shows the tree of files in a TIMES model (Loulou *et al*. 2005b).

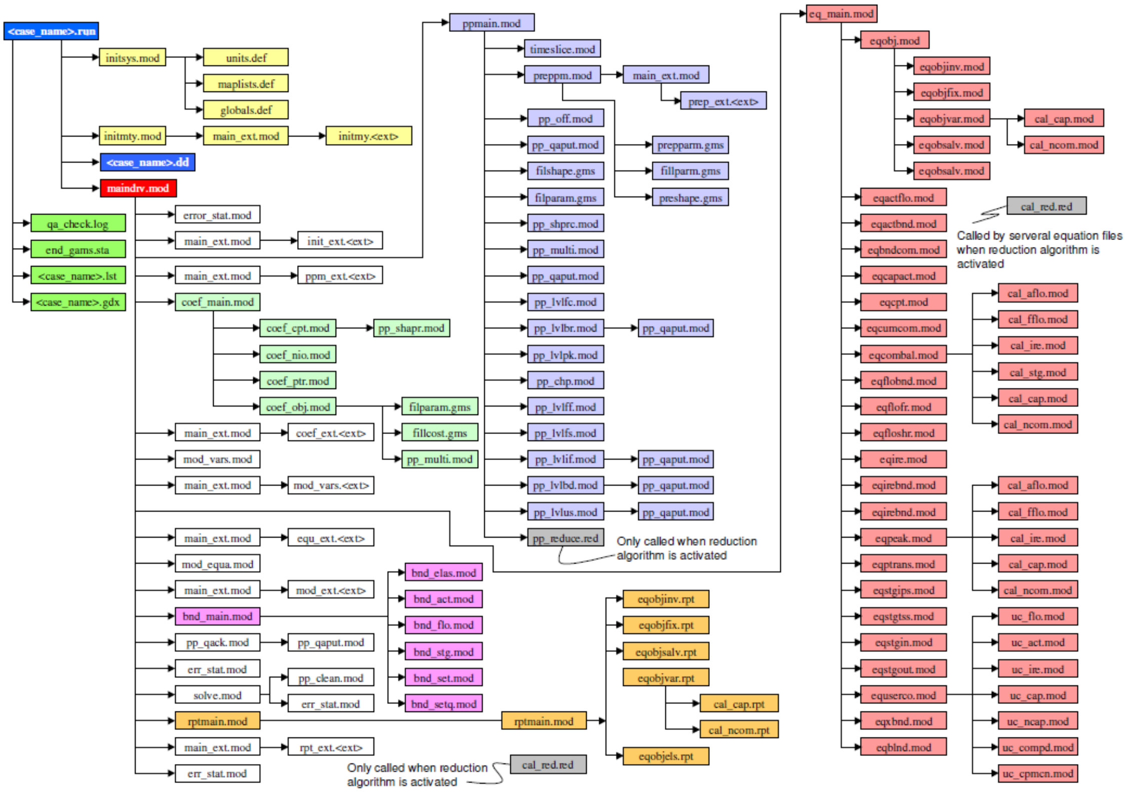


Figure 12. Files structure of a TIMES model

2.6. TIMES-Spain model

TIMES-Spain is an energy model or database used for the modelling of the Spanish energy system at medium and long term.

TIMES-Spain is a particular case of TIMES model constituted by a large database which is updated constantly with new and existing technologies concerning environmental or technical aspects, and economic data.

In TIMES-Spain the energy supply sector is divided in two parts: primary production and secondary transformation (including electricity and heat production).

The model contains data on primary production such as non-transformed fossil fuels, biomass and nuclear fuel, based on current and future energy resources potentials. Biomass refers to solid biomass, landfill biogas, liquid biofuels, energy crops and industrial and municipal wastes amongst others. Potentials of other renewable energies such as geothermal, hydro, solar photovoltaic, solar thermal and wind, are also included. Secondary transformations data-related on TIMES-Spain consist of the detailed information of the refineries, biofuel production plants and electricity and heat production technologies. The model also contains data on pulverized coal generation plants, integrated gasification combined cycle plants, natural gas combined cycle plants, diesel plants, fuel cells, biomass plants, nuclear, hydro, wind farms, solar PV fields, etc.

2.6.1. Electricity production technologies characterisation in TIMES-Spain

The TIMES-Spain model approximates the demand with twelve seasonal/day-night-peak slices. The model builds the electric supply load curves with the twelve time slices. Accordingly, power plants generate electricity by time slice and satisfy the demand. Centralised plants are separated from the decentralised ones, as well as main producers from self-producers and industrial plants. The model calculates the equilibrium prices by year and scenario for each commodity: electricity (in each time slice) and heat (in each season).

The power generation sector includes public power plants, auto-production of electricity and CHP plants. In the Reference Energy System (RES) the three electricity grids (high, medium and low voltage) have been modelled. Transmission efficiency values have been taken from Eurostat data. Figure 13 presents the RES of the electricity transmission sub-system in TIMES-Spain (Giannakidis, 2009).

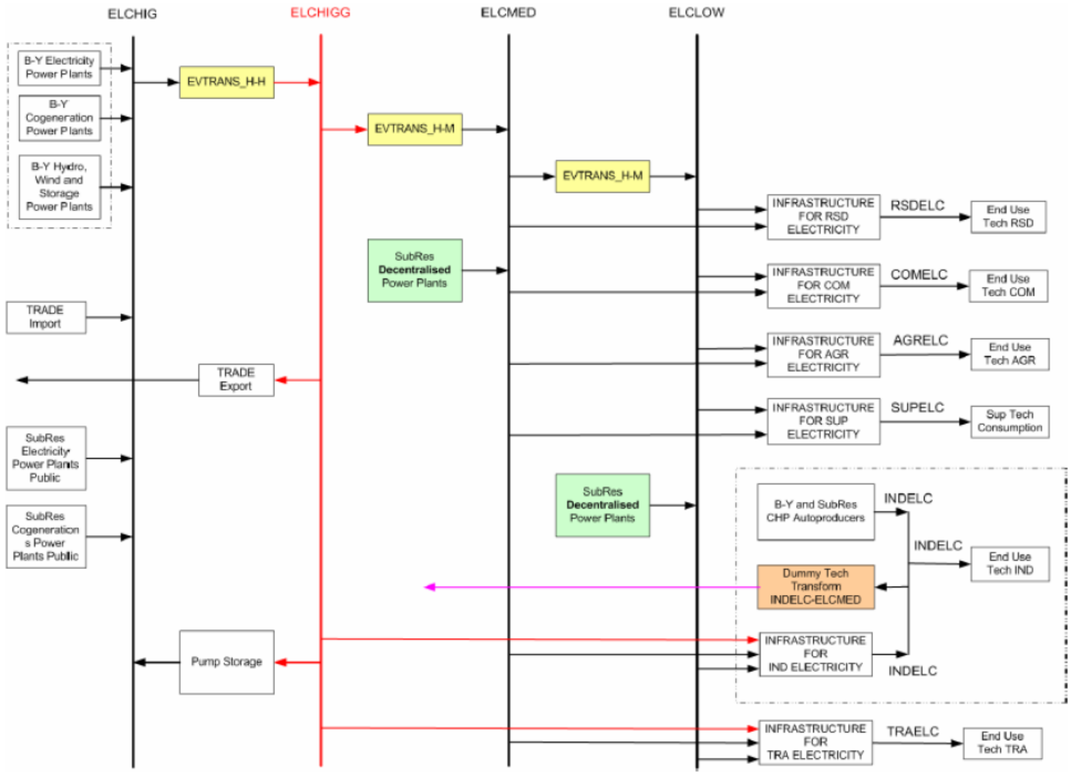


Figure 13. RES of electricity transmission and distribution sub-system in TIMES-Spain

Each demand sector receives a fixed share of different electricity voltages according to the nature of their specific consumption. In the residential sector almost 100% of the electricity consumed is low voltage, in the commercial and industrial sectors shares are different, involving two or three voltage levels. Furthermore, industrial sector electricity requirements can be satisfied both by grid (public production) and by auto-production without any loss of distribution (Cabal *et al*., 2011).

Distributed generation is the implementation of various power generating resources near the demand site, or for feeding power directly into the grid. Distributed generation may also be used to increase the transmission and distribution system reliability (Labriet *et al.*, 2011). Transmission and distribution grids are represented independently to distinguish from the commodities produced in the centralised power plants from those consumed and produced in decentralised technologies. The requested minimum data for these technologies (transmission processes) are the efficiencies (losses for each voltage level).

The TIMES-Spain model includes hundreds of plants which produce high voltage electricity. Each of them has specific data, including the retirement profile. According to NEEDS (2005), the calibration of the existing thermal electricity sector requires splitting along three dimensions of the net installed capacities (Public/Auto-production, Electricity/CHP, and by fuel) for the following six technologies: steam turbines, combined cycle power plants, gas turbines, internal combustion engine plants, hydro power stations and wind turbines. Steam turbines capacity has been also disaggregated into backpressure and condensing for CHP.

2.6.2. End-use services in TIMES-Spain

In addition the end-use energy satisfies the energy services demand for the agriculture, residential, commercial, industry and transport sectors. The end-use demands by sector are:

- **Residential**: Heating, air conditioning, water heating, others.
- **Commercial**: Heating, air conditioning, water heating, others.
- **Agricultural**: Final demand.
- **Industry**: Steel & iron, aluminium, copper, other non-ferrous metals, ammonia, chlorine, other chemical products, high quality paper, low quality paper, cement, glass flat, glass hollow, lime, other non-metallic minerals, other industries, non-energy uses (chemicals), non-energy uses (others).
- **Transport**: Car, truck, bus, motorbike, train, aviation, navigation.

Energy imports and exports are also described in the database.

TIMES-Spain contains CO_2, CH_4, N_2O, CO, NO_x, SO_2 and $PM_{2.5}$ and PM_{10} emission data derived from fuel combustion as well as some extra emission factors for processes without combustion. The model also includes the carbon capture potentials.

Besides, TIMES-Spain includes economic data such as investment costs and operation & maintenance costs, both fixed and variable, of the energy technologies, as well as the delivery costs referred to the energy resources or fuels.

2.6.3. TIMES-Spain structure

The database is stored in a set of Excel files easily readable by the model generator. There are five different files:

- **Templates**: there is a template file to describe each sector (supply, electricity, residential/commercial, transport, industry). Each one contains the basic model structure with end-use fuel consumption, energy production by fuel and the end-use demand, all of them referred to the base year; the existing technologies; the user constraints; the emission coefficients by fuel, and other parameters such as the demand elasticity and the discount rate.

- **Drivers**: include the socio-economic drivers for demand projections
- **Scenarios**: these templates are used to define data from new scenarios in the database (bounds to emissions, technological discount rates, investment costs, etc.)
- **Transformation**: these templates are used to fit the parameters to a specific region through correction factors.
- **Energy subsystem**: these are files related to a specific energy subsystem inside the total energy system. For instance, a subsystem may contain all the new technologies, but other subsystem may include only the technologies with carbon capture. This is useful to isolate and analyse a specific part of the system.

2.6.4. Applications

TIMES-Spain analyses the dynamics of the Spanish energy system considering the national and European concerns and commitments in environmental and energy security matters.

The TIMES-Spain model shows the complex relationships amongst the different energy uses and the existing technologies. It also shows the impacts of a specific measure over the entire energy system.

Other applications of the TIMES-Spain model are to assess technologies analysing the competitiveness under several economic hypothesis considering or not the existence of market barriers, the impact of technological developments, the supports to research, the cost curves and the LCA; to evaluate the impact of the energy policies and measures (efficiency programmes, levies, green and white certificates, social restrictions); to assess the environmental and emission-related policies and measures (emission taxes, subsidies, ETS, internalisation of the externalities and Clean Development Mechanisms (CDM)).

4 SPANISH CEMENT INDUSTRY

1. Life Cycle Assessment

1.1. Introduction

This chapter presents an analysis of the Spanish cement production from an environmental point of view, taking into account the lack of detailed research studies in Spain. Some relevant studies concerning cement production using LCA are Cardim de Carvalho (2001), Josa *et al*. (2007), Masanet *et al*. (2012), and especially Valderrama *et al*. (2012; 2013), which are based on a specific cement plant located in Spain.

This work is also remarkable due to the fact that the Spanish industry is obliged to reduce GHGs and industrial emissions in order to meet the targets set by the European Directives 2001/81/EC on national emission ceilings for certain atmospheric pollutants, 2009/29/EC which amends 2003/87/EC on GHG emission allowances trading scheme, and 2010/75/EC on industrial emissions.

The objective of this chapter is to carry out a LCA of the Spanish cement production sector looking at its hotspots and analysing the implementation of BAT as well as some improvement scenarios where technology prospectives are taken into consideration. Besides, CO_2 capture solutions have been assessed.

1.2. Goal and scope

The goal of this LCA is to analyse the Spanish cement production in 2010 and 2030 in terms of environmental impacts and to examine the effect of applying BATs according to the European Integrated Pollution Prevention and Control Bureau (EIPPCB, 2010) and Moya *et al*. (2010). The work also explores the introduction of the CO_2 capture in the Spanish cement industry.

First part of the work shows a cradle-to-gate analysis of the Spanish cement sector in 2010. It goes from the raw material extractive processes to the cement production as shown in Figure 14. The work is divided into two analyses:

- A technical approach by production phase using 1 t clinker as functional unit. This assessment excludes cement production phase to avoid confusions in the second analysis. As clinker is the same for each cement type although there is not one cement type that represents the entire production, it seemed reasonable to exclude the cement phase (mainly cement milling). Besides, cement milling only consumes an extra amount of electricity (around 1/3 of the electricity consumption in a cement plant).

- An assessment of the Spanish cement industry as a whole using 1 t of cement as functional unit. This analysis is done in absolute midpoint units.

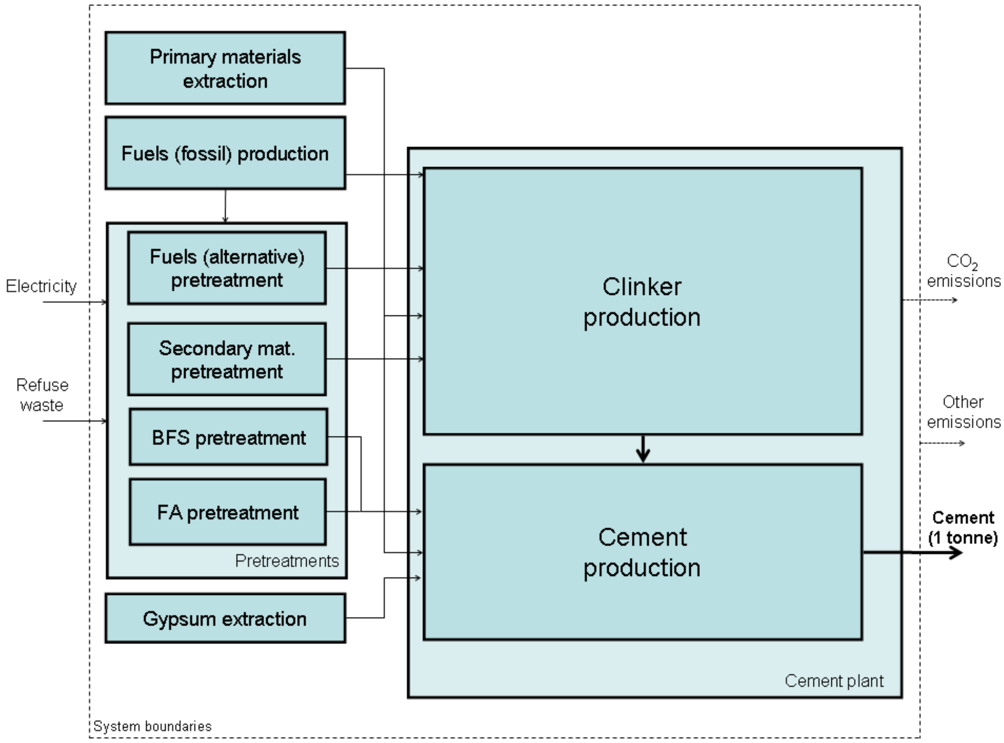


Figure 14. Scheme of the main processes in the Spanish cement production

Impact categories selected for the first analysis are: climate change (GWP), human toxicity with cancer effects (HTPce), photochemical ozone formation (POP), acidification (AP) and freshwater eutrophication (FEP).

Second part extends the previous analysis exploring the introduction of the post-combustion CO_2 capture within the cement industry. It is assumed that 100% of cement production includes this technology. Due to the environmental consequences, it seems interesting to select more impact categories than in the preceding analysis. Using the ILCD 2011 midpoint method, the impact categories evaluated in this assessment are: climate change (GWP), ozone depletion (ODP), human toxicity with cancer effects (HTPce), human toxicity with non-cancer effects (HTPnce), particulate matter (PMP), ionising radiation (IRP), photochemical ozone formation (POP), acidification (AP), terrestrial eutrophication (TEP), freshwater eutrophication (FEP), marine eutrophication (MEP), freshwater ecotoxicity (FETP), land use change (LUP) and abiotic depletion (ADP) (EC-JRC, 2012). In this case, the functional unit is 1 tonne of cement.

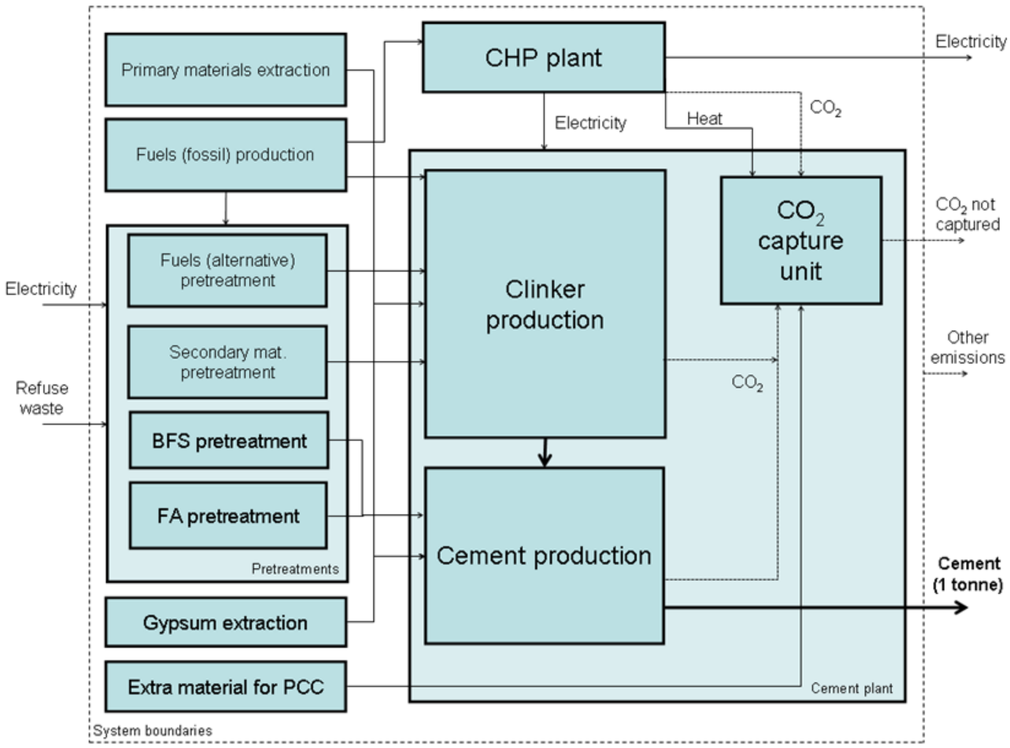


Figure 15. Scheme of the main processes in the Spanish cement production with PCC

Figure 15 shows how cement is produced considering the addition of CO_2 capture. To consider the cases without capture, Figure 14 scheme must be taken into account.

A CHP unit is included in the system to produce the heat required in the post-combustion CO_2 capture unit. By-produced electricity is used in the capture process and also satisfies the electricity demand of the cement plant (IEA GHG, 2008). The surplus is sent to the electricity grid. Multifunctionality is solved here by extending the system limits and including an avoided electricity production. It is assumed that the excess electricity will displace the electricity from the mix.

Both analyses are focused on several impact categories compiled by the recommendations for life cycle impact assessment from the International Reference Life Cycle Data System (ILCD) handbook (EC-JRC, 2011). The emissions and resources derived from LCI are classified to each of these impact categories. They are then converted into indicators by using characterisation factors calculated by impact assessment models. These factors reflect pressures per unit emission or resource consumed in the context of each impact category. Emissions and resources consumed, as well as different product options, can then be cross-compared in terms of the indicators (EC-JRC, 2011).

1.3. Life Cycle Inventory

Cement produced in Spain in 2010 can be grouped in 16 types according to the standard EN 197-1:2000 (CEN/TC-51, 2000) shown in Table 27. Several cement types, such as II/B-S, II/A-D, II/A-Q, II/B-Q, II/A-W, II/B-W, II/A-T, II/B-T, III/C and V/B, were not produced in Spain in 2010.

Table 27. European standard of cements composition EN 197-1:2000

Cement Type	Designation	Notation	Clinker K	G.G.B.S. S	Silica fume D	Pozzolana Natural P	Pozzolana Industrial Q	Fly ashes Silic. V	Fly ashes Calcar W	Burnt Shale T	Limestone L	Limestone LL	Minor Additional constit.
I	Portland Cement	I	95-100	-	-	-	-	-	-	-	-		0-5
II	Portland Slag Cement	II / A-S II / B-S	80-94 65-79	6-20 21-35	- -	- -	- -	-	-	-	-		0-5 0-5
	Portland Silica Fume Cement	II / A-D	90-94	-	6-10	-	-	-	-	-	-		0-5
	Portland Pozzolana Cement	II / A-P II / B-P II / A-Q II / B-Q	80-94 65-79 80-94 65-79	- - - -	- - - -	6-20 21-35 - -	- - 6-20 21-35	- - - -	- - - -	- - - -	- - - -		0-5 0-5 0-5 0-5
	Portland Fly Ash Cement	II / A-V II / B-V II / A-W II / B-W	80-94 65-79 80-94 65-79	- - - -	- - - -	- - - -	- - - -	6-20 21-35 - -	- - 6-20 21-35	- - - -	- - - -		0-5 0-5 0-5 0-5
	Portland Burnt Shale Cement	II / A-T II / B-T	80-94 65-79	- -	- -	- -	- -	- -	- -	6-20 21-35	- -		0-5 0-5
	Portland Limestone Cement	II / A-L II / B-L II / A-LL II / B-LL	80-94 65-79 80-94 65-79	- - - -	- - - -	- - - -	- - - -	- - - -	- - - -	- - - -	6-20 21-35	6-20 21-35	0-5 0-5
	Portland Composite Cement	II / A-M II / B-M	80-94 65-79	<-----6-20-----> <-----21-35----->									
III	Blastfurnace Cement	III / A III / B III / C	35-64 20-34 5-19	35-65 66-80 81-95	- - -	- - -	- - -	- - -	- - -	- - -	- - -		0-5 0-5 0-5
IV	Pozzolanic Cement	IV / A IV / B	65-89 45-64	- -	<-----11-35-----> <-----36-55----->				- -	- -	- -		0-5 0-5
V	Composite Cement	V / A V / B	40-64 20-39	18-30 31-50		←-----18-30-----→ ←-----31-50-----→			- -	- -	- -		0-5 0-5

Once the clinker is produced at the kiln, other extra constituents are added to make cement such as Blast Furnace Slag (BFS), Fly Ashes (FA), pozzolanas and non-calcined limestone (see Table 28). Pozzolana has been assimilated to silica sand from Ecoinvent database (ECOINVENT, 2010).

Table 28. Spanish grey cements production and composition in 2010

Cement type	Production (%)	Clinker (%)	BFS (%)	Pozzolana (%)	FA (%)	Limestone (%)
CEM I – Portland	25.4	97.5				
CEM II/A-M – Portland composite	10.8	84.0		0.3	5.4	9.2
CEM II/B-M – Portland composite	6.6	72.0		1.9	3.6	22.0
CEM II/A-L – Portland calcareous	13.4	87.0				13.0
CEM II/B-L – Portland calcareous	6.8	72.0				28.0
CEM II/A-V – Portland with fly ash	14.8	87.0			13.0	
CEM II/B-V – Portland with fly ash	3.0	72.0			28.0	
CEM II/A-S – Portland with BFS	4.4	91.0	9.0			
CEM II/A-P – Portland with pozzolana	5.2	87.0		13.0		
CEM II/B-P – Portland with pozzolana	1.1	72.0		28.0		
CEM III/A – Blastfurnace cement	3.3	64.0	36.0			
CEM III/B – Blastfurnace cement	0.5	34.0	66.0			
CEM IV/A – Pozzolanic cement	0.9	85.0		3.8	11.3	
CEM IV/B – Pozzolanic cement	2.4	66.0		8.5	25.5	
CEM V/A – Composite cement	0.9	52.0	27.8	10.0	10.0	
OTHER CEM (ESP VI, CAC, G)	0.4	40.0	20.0	20.0	20.0	

Grey cement production meant 97.3% of the total production in 2010, the rest being white cement, which has not been analysed. Grey clinker and grey cement productions were 21.2 Mt and 22.8 Mt in 2010, respectively (OFICEMEN, 2010a).

1.3.1. 2010-BASE scenario

In terms of energy, the average Spanish thermal consumption of the kiln was 3,536 MJ/t clinker and the electricity consumption was 92 kWh/t clinker in 2010. Thermal contribution of the alternative fuels was 15.8% of the total energy in 2010 (OFICEMEN, 2010a).

Table 29. LCI of the Spanish production of 1 t clinker in 2010

	Amount
Inputs	
Primary materials	
Limestone (t)	1.12
Calcareous marl (t)	2.77E-01
Clay (t)	7.97E-02
Sand (t)	2.73E-02
Iron ore, 46% Fe (t)	8.33E-03
Kaolin (t)	5.28E-03
Silica sand (t)	3.66E-03
Bauxite (t)	2.61E-03
Feldspar (t)	2.86E-04
Ammonia (t)	2.02E-04
Aluminium oxide (t)	1.27E-04
Secondary materials	
Aluminium oxide (t)	3.98E-04
Blast furnace slag (t)	3.16E-03
Carbonized sludges (t)	3.12E-03
Ceramic materials (t)	7.19E-04
Clay (recycling) (t)	7.01E-04
Sugar beet limes (t)	9.54E-05
Fly ashes (t)	2.98E-03
Foundry sand (t)	2.74E-04
Iron ore, waste (t)	4.76E-03
Iron recycled (t)	6.59E-04
Mining wastes (t)	1.61E-03
Oth. second materials (t)	1.80E-03
Other slag from meal (t)	4.45E-04
Pyrite ashes (t)	2.92E-03
Industrial solids (t)	1.00E-03
Water (m^3)	1.62E-03
Infrastructure	
Industrial machinery (t)	3.76E-05
Cement plant (p)	6.27E-12
Transport	
Conveyor belt (km)	2.00
Lorry 20-28t (tkm)	3.19
Lorry >28t (tkm)	1.89E+01
Fossil fuels	
Petroleum coke (GJ)	2.89
Heavy fuel oil (GJ)	3.41E-02
Natural gas (GJ)	4.36E-03
Diesel (GJ)	5.72E-04
Hard coal (GJ)	4.37E-02
Alternative fuels	
Oth. liquid fuels bio. (GJ)	3.23E-05
Used tyres (GJ)	1.72E-01
Meat bone and meal (GJ)	4.96E-02
Mun. sewage sludge (GJ)	3.01E-02
Refuse-derived fuel (GJ)	9.73E-02
Wood waste (GJ)	5.76E-02
Sawdust (GJ)	4.17E-02
Varnishes & solvents (GJ)	4.54E-02
Used oils (GJ)	6.57E-03
Plastics (GJ)	2.53E-02
Pulp, paper (GJ)	5.80E-04
Textile waste (GJ)	3.14E-04
Others no biomass (GJ)	3.13E-02
Hydrocarbon waste (GJ)	3.03E-03
Electricity	
Electricity (MWh)	9.20E-02
Outputs	
Emissions to air	
CO_2 (process) (t)	5.28E-01
Particulates (PM_{10}) (t)	1.04E-05
Products	
Clinker (t)	1.00

In addition, cement subtypes classification and productions (Table 28) as well as the LCI of the clinker (Table 29) have been described. The LCI of the cement production (Table 30) is completed grouping production shares and adding both the electricity consumed and PM_{10} emissions released by cement mills in the latter phase of the production (Cardim de Carvalho, 2001).

Table 30. LCI of the Spanish production of 1 t cement

	Amount
Inputs	
Materials/Fuels	
Cement sub-types from Table 28	
Electricity/Heat	
Electricity (MWh)	3.91E-02
Outputs	
Emissions to air	
PM_{10} (t)	4.57E-06

LCI of the alternative fuels used has been built using data from CORINAIR (2006), CEMA (2010), and OFICEMEN (2010a). The inventory of the alternative raw materials pre-treatment, BFS and FA, has been extracted from Habert (2013). Limestone has been taken from an Ecoinvent existing process and pozzolana assimilated as silica sand (ECOINVENT, 2010). As a summary of the 2010 BASE case, key data are listed in Table 31.

Table 31. Key figures of 2010 Spanish cement production

	Units	**Value**
Clinker production	Mt	21.2
Grey cement production	Mt	22.8
Raw meal consumption	t/t clinker	1.57
Thermal consumption	MJ/t clinker	3536
Electric consumption	kWh/t cement	130
Alternative fuels substitution	% (energy)	15.8

1.3.2. Thermal energy efficiency scenario (E1)

This scenario considers a reduction in the use of thermal energy in the clinker kiln. The World Business Council for Sustainable Development (WBCSD) gives some values depending on the kiln technology (WBCSD, 2009): the lowest figure (from 2006) is for dry kilns with preheater and precalciner, 3,382 MJ/t clinker. EIPPCB (2010) points out that consumption varies depending on the type and size of the kiln system. Plants using dry process, with multistage cyclone preheaters and precalcining kilns (the most common in Spain), start at about 3,000 MJ/t clinker and can reach more than 3,800 MJ/t clinker. Spanish statistics from OFICEMEN (2010a) give an average thermal consumption of 3,536 MJ/t clinker in 2010. Moya *et al*. (2010) show that thermal consumption in clinker production is expected to be 3,300 MJ/t clinker in 2030. E1 scenario includes this reduction. Some BAT options for meeting that target are to install modern clinker coolers; to optimise the length of the kiln, as well as its design considering the fuels selection; to optimise the process controls; to reduce the air-in leakage; to extent the precalcination to the raw material; to increase the number of cyclone stages, to reduce the moisture content of the raw meal, etc. (MMA, 2004; EIPPCB, 2010).

1.3.3. Electrical energy efficiency scenario (E2)

According to EIPPCB (2010), the electricity demand of a cement plant in Europe ranges from 90 to 150 kWh/t of cement. Although electricity consumption reported in Moya *et al*. (2010) in the EU27 is around 110 kWh/t cement, Spanish statistics (OFICEMEN, 2010a) show a value of 130 kWh/t of cement.

In the Spanish case, system boundaries include not only the electricity consumption regarding raw material grinding, fuel preparation and cement milling, but also the consumption of the associated quarry. In spite of that, electricity consumption at quarry is very low (Cardim de Carvalho (2001) reports 1%) so the value is accepted.

Projections of the electricity consumption reach 106 kWh/t cement in 2030 (Moya *et al*., 2010; Pardo *et al*., 2011). Subsequently, this scenario entails a reduction of 19% in the total electricity consumption compared to 2010 statistics. EIPPCB (2010) remarks one single BAT option in order to reduce consumption: exchanging old raw material mills for new alternatives.

1.3.4. Material substitution scenario (E3)

E3 scenario analyses the reduction of the clinker-to-cement ratio, from 0.8 in 2010 to 0.7 in 2030 (Moya *et al*., 2010).

In order to build E3, European Standard EN197-1 (CEN/TC-51, 2000) for cement compositions has been adjusted keeping the 2010 cements production breakdown (see Table 28).

Table 32. Spanish grey cements composition with E3 scenario adjustment

Cement type	Clinker (%)	BFS (%)	Pozzolana (%)	FA (%)	Limestone (%)
CEM I – Portland	**94.9**				
CEM II/A-M – Portland composite	**73.1**		0.4	8.2	14.1
CEM II/B-M – Portland composite	**59.8**		2.8	5.3	32.2
CEM II/A-L – Portland calcareous	**75.8**				19.9
CEM II/B-L – Portland calcareous	**59.4**				40.6
CEM II/A-V – Portland with fly ash	**75.7**			19.9	
CEM II/B-V – Portland with fly ash	**59.4**			40.6	
CEM II/A-S – Portland with BFS	**79.2**	13.8			
CEM II/A-P – Portland with pozzolana	**75.7**		19.9		
CEM II/B-P – Portland with pozzolana	**59.4**		40.6		
CEM III/A – Blastfurnace cement	50.3	49.7			
CEM III/B – Blastfurnace cement	22.7	77.3			
CEM IV/A – Pozzolanic cement	74.0		5.7	17.2	
CEM IV/B – Pozzolanic cement	52.5		11.9	35.6	
CEM V/A – Composite cement	38.2	36.0	12.9	12.9	
OTHER CEM (ESP VI, CAC, G)	27.5	24.2	24.2	24.2	

Table 32 shows the adjustment of the cement subtypes composition. Achieving this target requires to replace part of the clinker for other mineral compounds. Attending to OFICEMEN (2010a), alternative materials used to produce cement in Spain in 2010 were mainly ashes and slag from the recycling of cement and steel production, waste from iron ore, and recycled gypsum. This is in line with the considered assumption of blast furnace slag, fly ashes, pozzolana and limestone, as the main extra constituents of Spanish cement. Subsequently, BASE scenario entails a clinker-to-cement ratio by 0.8 and E3 scenario, as a consequence of Table 32 adjustment, introduces a clinker-to-cement ratio of 0.7.

To keep the cements production breakdown constant, it is necessary to modify the percentages of the cement constituents. As shown in Table 32, it is quite difficult to keep the ranges for the classification of cements according to EN 197-1:2000 standard while keeping the same production breakdown. For this reason, a breach beyond the limits for the Portland cements only, (types I and II, in bold) has been assumed. Besides, gypsum addition has been increased up to 6.9%. Furthermore, secondary material pre-treatment has been considered (see Table 33), using data from Habert (2013).

Table 33. LCI of the material pre-treatment of 1 kg FA and 1 kg BFS

		FA	BFS
Input			
Materials/Fuels			
Natural gas	MJ	2.90E-01	3.16E-01
Transport, lorry 20-28t	tkm	3.00E-03	5.30E-03
Transport, freight, rail	tkm	-	3.00E-03
Diesel	MJ	4.12E-05	4.56E-05
Water	kg	-	1.00E+01
Electricity/Heat			
Electricity	kWh	6.82E-03	7.20E-02
Output			
Emissions to air			
Sulfur oxides	kg	9.13E-08	2.07E-04
Hydrogen sulfide	kg	-	2.43E-04
Carbon monoxide	kg	9.05E-06	3.54E-05
Methane	kg	-	1.20E-06
Nitrogen oxides	kg	1.75E-05	2.17E-05
Emissions to water			
Waste water	m^3	8.48E-05	4.50E-03
Final waste flows			
Fly ash (waste flow)	kg	3.23E-05	1.29E-04
Product			
Material (usable)	kg	1.00	1.00

Alternative materials can be used to replace traditional raw materials extracted from quarries, such as clay, shale and limestone, which are introduced in the kiln, not only for cement production. The chemical suitability of alternative raw materials is important to ensure that they provide the necessary constituents in the formation of clinker (CEMBUREAU, 2009). Boesch and Hellweg (2010) describe a case with 4% weight of material substitution (1% more of slag, fly ash, waste limestone, and contaminated soil). In Spain, the material substitution before kiln entailed 1.3% (in mass) in 2010 (OFICEMEN, 2010a). Material substitution before kiln is not considered in this work.

1.3.5. Fossil fuel substitution scenario (E4)

E4 scenario considers the fossil fuel substitution by alternative fuels. The use of this type of fuels in the cement industry offers the opportunity to reduce production costs, disposal of waste and CO_2 emissions. Cement kilns are well-suited for waste combustion due to their high process temperature and also because clinker product and limestone feedstock act as gas-cleaning agents (IEA, 2007). OFICEMEN (2010a) reported that 15.8% of the thermal energy came from alternative fuels in 2010. EC made several projections for the fossil fuel substitution assuming fifty-fifty between fossil and alternative fuels in 2030 in EU27 (Moya *et al*., 2010). In order to meet this target, alternative fuels have been carefully described in Appendix I. For the implementation of this scenario, fuels input listed in Table 29 have been modified to accomplish the fifty-fifty and at the same time keep the 2010 fuel shares.

1.3.6. Ideal scenario (E5)

This scenario gathers all the measures previously described for the reduction of CO_2 emissions released by cement production (see Table 34). It is akin to an ideal scenario where all possible expected improvements take place. It describes the optimum expected situation in the Spanish cement industry by 2030.

Table 34. Measures implemented in the 2030 Spanish cement production

Measure description	Detail
Thermal efficiency	From 3,536 MJ/t clinker to 3,300 MJ/t clinker
Electrical efficiency	From 130 kWh/t cement to 106 kWh/t cement (69.43 kWh/t clinker)
Material substitution	Clinker-to-cement ratio: from 0.8 to 0.7
Fossil fuel substitution	Alternative fuels share: from 15.8% to 50% (in energy)

Both thermal and electrical energy efficiency measures are achieved by implementing BATs in the thermal-related processes (mainly the kiln) and in the grinding mills, respectively. The 2030 expected values have been obtained from Moya *et al*. (2010). Raw material and fossil fuel substitution scenarios are based in projections from ECRA (2009a), Moya *et al*. (2010) and EIPPCB (2010).

1.3.7. 2030-PCC scenario

The consideration of the CO_2 capture, based on the previous 2030-BASE scenario, involves modifying the LCI of the clinker, adding a coal fired CHP plant and a post-combustion CO_2 capture unit.

A new coal-fired CHP process has been implemented with a thermal efficiency of 59% and a net electrical efficiency of 30% (ETSAP, 2010). IEA (2005) refers that the electricity generating efficiency of condensing steam plants with heat extraction depends upon the amount of heat produced, pointing out that in a completely condensing mode (when no useful heat is produced), the electricity efficiency can reach 40%. In this scenario, values from ETSAP (2010) seem to be more reasonable. In addition, a natural gas-fired CHP plant with extraction condensing turbine has been modeled in order to evaluate in a sensitivity analysis the effect of introducing other type of CHP in the system. It is supposed that thermal efficiency is 47.5% and net electrical energy efficiency is 32.5% (ETSAP, 2010).

Consequently, it is assumed that CHP generates heat as main product and electricity as by-product. All the electricity produced is enough to supply the entire cement plant and the CO_2 capture unit. Besides, there is still surplus of electricity that is delivered to the grid. It is considered that flue gas streams from both CHP plant and cement production plant are directed to a common capture process.

Detailed CHP data from Table 35 have been extracted from CASES project (Mayer-Spohn and Blesl, 2007) for a hard coal plant with extraction condensing turbine and for a natural gas one with extraction condensing turbine. Flue gas purification has been introduced via existing Ecoinvent processes for NO_x & SO_x retentions (ECOINVENT, 2010).

Table 35. LCI of a coal-fired and a natural gas CHP plants per 1 MJ heat produced in Spain

	Hard coal-CHP	Natural gas-CHP
Inputs		
Resources		
Coal, brown, in ground (kg)	6,70E-03	2,28E-03
Coal, hard, in ground (kg)	5,84E-01	2,67E-03
Gas, natural, in ground (Nm3)	2,12E-03	5,84E-01
Oil, crude, in ground (kg)	7,72E-03	2,89E-03
Uranium, in ground (kg)	3,53E-07	1,18E-07
Water, lake (m3)	3,74E-05	3,59E-07
Water, river (m3)	2,49E-04	5,91E-05
Water, well, in ground (m3)	7,36E-04	4,75E-05
Materials/fuels		
Transport, lorry >16t (tkm)	6,60E-05	-
Transport, freight, rail (tkm)	1,78E-04	-
Pipeline, natural gas, high pressure distr. network (km)		9,85E-09
Transport, natural gas, pipeline, long distance (tkm)		9,04E-01
SO_x retained, in hard coal FGD (kg)	5,99E-05	1,18E-04
NO_x retained, in SCR (kg)	1,57E-05	3,09E-05
Ouputs		
Emissions to air		
Carbon dioxide, fossil (kg)	1,70E-01	1,85E-01
Sulfur dioxide (kg)	1,18E-03	4,59E-04
Nitrogen oxides (kg)	1,30E-03	1,29E-03
Arsenic (kg)	1,92E-08	3,56E-09
Benzene (kg)	2,44E-06	1,25E-07
Benzo(a)pyrene (kg)	6,24E-10	2,52E-10
Cadmium (kg)	2,38E-09	1,09E-09
Carbon monoxide, fossil (kg)	3,31E-04	3,35E-04
Chromium (kg)	8,02E-08	1,36E-07
Chromium VI (kg)	2,65E-09	3,30E-09
Dinitrogen monoxide (kg)	4,91E-05	3,11E-05
Dioxin, 2,3,7,8 Tetrachlor. (kg)	9,49E-14	5,35E-14
Formaldehyde (kg)	5,79E-07	6,51E-07
Lead (kg)	7,66E-08	3,03E-08
Mercury (kg)	4,00E-08	6,88E-09
Methane, fossil (kg)	3,23E-03	3,04E-03
Nickel (kg)	1,51E-07	1,55E-08
PAH (kg)	2,48E-08	1,55E-07
Particulates, < 2.5 um (kg)	1,99E-05	2,51E-05
Particulates, > 10 um (kg)	6,29E-05	2,07E-05
Particulates, > 2.5 um, and < 10um (kg)	1,10E-03	1,34E-05
Thorium-230 (kBq)	3,22E-07	1,26E-07
Uranium-238 (kBq)	5,13E-06	5,35E-07
Aerosols, radioactive (kBq)	1,49E-07	4,84E-08
Ammonia (kg)	2,44E-05	7,97E-07
Hydrogen-3, Tritium (kBq)	3,60E-03	1,18E-03
Iodine-129 (kBq)	6,35E-07	2,07E-07
Iodine-131 (kBq)	3,69E-05	1,33E-05
Iodine-133 (kBq)	7,87E-10	2,50E-10
Krypton-85 (kBq)	2,92E-04	1,05E-04
Krypton-85m (kBq)	1,41E-05	4,70E-06
NMVOC (kg)	7,31E-05	3,24E-04
Noble gases, radioactive (kBq)	6,09	1,99
Radon-222 (kBq)	2,95E-04	9,80E-05
Uranium-234 (kBq)	1,01E-06	3,54E-07
Uranium-235 (kBq)	4,90E-08	1,62E-08
Products		
Heat (MJ)	1,00	1,00
Avoided products		
Electricity mix (MJ)	3,94E-01	1,24E+00

PCC requires extra material, more electricity, and a thermal input coming from the CHP. Table 36 shows the extra material and energy inputs for post-combustion CO_2 capture (ECRA, 2009a; IEA GHG, 2008; UNIDO, 2010).

Table 36. Extra LCI for the production of 1 t clinker with PCC

	Amount
Inputs	
Material/Fuels	
Ammonia (kg)	2.04
MEA (kg)	2.64
Limestone (kg)	1.41E+01
Electricity/Heat	
Heat (GJ)	2.25
Electricity (MWh)	7.00E-02

All input processes in Table 36 have been extracted from Ecoinvent database (ECOINVENT, 2010) with the exception of heat and electricity, which come from the CHP plants (Table 35).

Ammonia is needed in the Selective Catalytic Reduction (SCR) process. SCR technique allows the transformation of the NO_x into N_2 and water by adding certain catalysts. The application of SCR systems to the cement industry is at pilot scale nowadays and there are several case studies on large cement plants, such as Solnhofen in Germany, and Monselice in Italy (IEA GHG, 2008). Besides, limestone is required by the Flue Gas Desulphurisation (FGD) system. According to IEA GHG (2008), this system achieves high levels of flue gas desulphurisation, as required for post-combustion capture, and it is also currently the most common way to mitigate SO_x emissions in power plants. A by-product of the wet limestone process is gypsum, which can be used later to mix with the clinker and finally form the cement.

1.3.8. Background LCI processes

The LCI database Ecoinvent v2.2 (ECOINVENT, 2010) is used to provide background process LCI data. The LCA results are calculated using the SimaPro software 7.3.3 (PréConsultants, 2012).

It is assumed that both 2010 cement production (22.8 Mt) and cement types breakdown (see Table 28) will be kept constant in such a way that the depicted 2030 scenarios are alike to the 2010-BASE scenario.

The Spanish electricity mix in 2010 (Table 37) has been built in order to describe the burdens of the electricity compiling data from REE (2011) and using existing electricity processes from Ecoinvent database (De La Rúa, 2009; ECOINVENT, 2010; Labriet *et al.*, 2010; REE, 2011). Knowing that electricity consumption is a relevant aspect in CO_2 capture, and taking 2030 as horizon for the introduction of post-combustion, a 2030-electricity production mix resulting from TIMES-Spain modelling has been used (see Lechón *et al.*, 2009; Cabal *et al.*, 2009; Labriet *et al.*, 2010; and Chapter 3).

Table 37. LCI of the production of 1 kWh in Spain in 2010 and 2030

Technology	2010 (kWh)	2030 (kWh)
Hard coal	0.0810	0.0059
Lignite	0.0040	0.0000
Natural gas, NGCC	0.2308	0.4042
Natural gas, GT	0.0065	0.0000
Hydropower, large	0.1381	0.1075
Hydropower, small	0.0244	0.0149
Nuclear	0.2215	0.0000
Solar, PV	0.0219	0.0221
Solar, CSP	0.0025	0.0917
Wind	0.1544	0.3369
Biomass	0.0088	0.0000
Biogas cogeneration	0.0025	0.0025
Natural gas cogeneration	0.0892	0.0100
Gas oil, fuel, propane cogeneration	0.0092	0.0000
MSW at incineration plant	0.0052	0.0000

1.4. Results and discussion

1.4.1. Clinker production assessment (by process stage)

Table 38 shows the absolute values (per tonne of clinker) for the selected impact categories using the ILCD 2011 midpoint method. As this analysis is referred to the generic Spanish cement (which encompasses the 16 subtypes produced in Spain in 2010), values from Table 38 cannot be disaggregated by production stages.

Table 38. LCIA results of Spanish clinker production in 2010 per 1 t clinker

Impact category	Amount
GWP (kg CO_2 eq)	9.29E+02
HTPce (CTUh)	1.20E-06
POP (kg NMVOC eq)	1.24
AP (molc H+ eq)	3.93
FEP (kg P eq)	1.21E-02

From the LCIA results (see Figure 16) each cement subtype contribution has been obtained for every impact category.

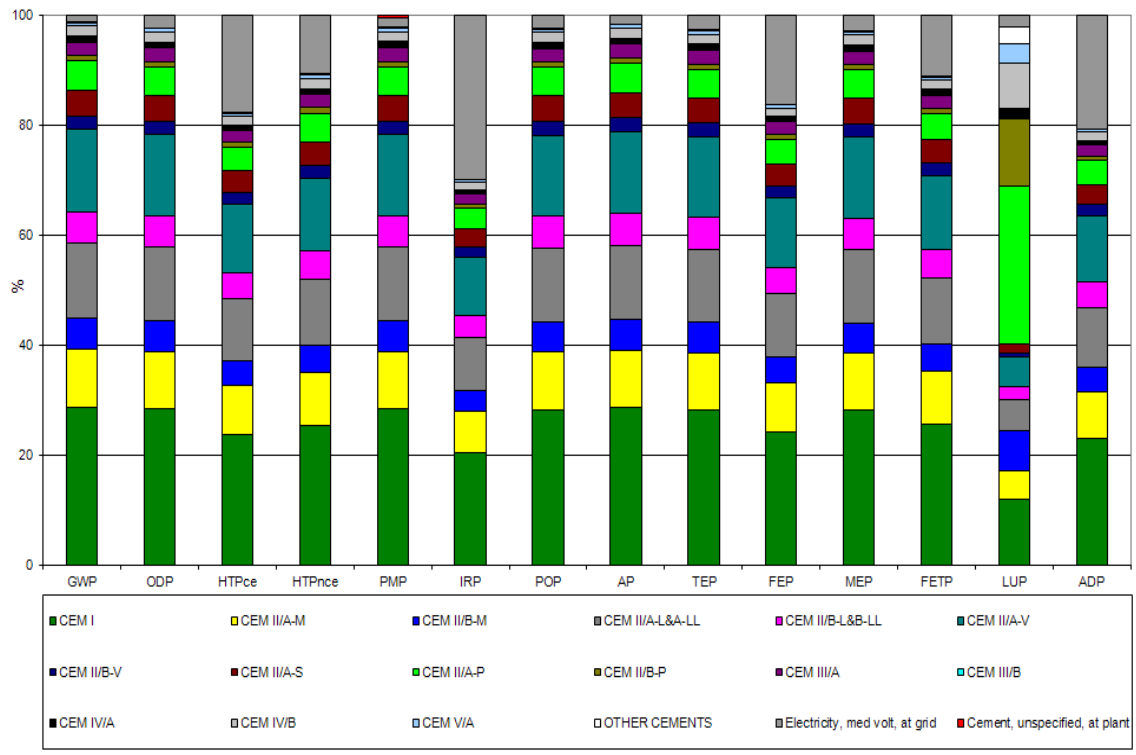


Figure 16. LCIA results of the production of 1 t cement in Spain in 2010

Portland cement type I contributes with up to 30% to each impact. Portland cement types II/A-V (fly-ashed), II/A-L (calcareous), II/A-M (composite) also have remarkable contributions in terms of impacts, accounting for 10-15% each category. Apart from this analysis by cement type, it is interesting to consider the impact of the different process stages in the production of clinker, since it is the most energy intensive phase in cement manufacture because it includes kiln.

Table 39. Weight of the clinker production in cement manufacture in 2010

GWP	HTPce	POP	AP	FEP
93.5%	77.4%	91.7%	92.9%	78.9%

Impacts derived from clinker respect to the ones from cement are higher enough for considering reasonable to focus only on the clinker production (Table 39). This avoids misunderstandings with the selection of Spanish cement which is considered generic (as in Table 38) and makes possible to carry out a technical approach by production stage.

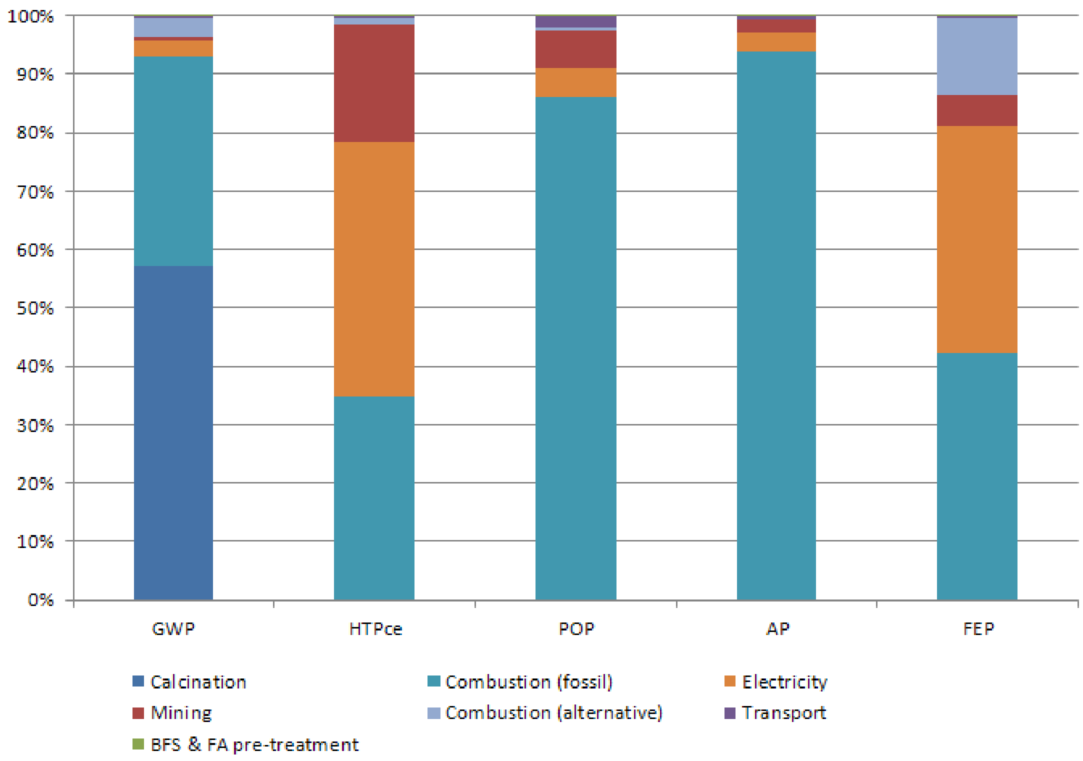


Figure 17. LCIA results of producing 1 t Spanish clinker in 2010 by production stage

Figure 17 shows the LCIA results for the production of 1 t of clinker in 2010 in Spain. The most relevant point is the large contribution of fossil fuel combustion in all the impacts, especially in POP and AP. The contribution of transport is up to 2% in POP but, in the same way as the material pre-treatment, it is almost negligible when compared to the rest of the categories.

Contribution of calcite's calcination entails 58% of GWP, whereas 36% comes from combustion: this is connected to the origin of the CO_2. OFICEMEN (2010b) reports that 63% of CO_2 comes from process (calcination) and 27% from combustion. From the total emissions coming from combustion, petcoke entails 98%, being 99% CO_2 and almost 1% methane. A slight 3.5%-contribution of alternative fuel combustion is linked to the non-bio part, mainly used tyres (52%).

Human toxicity with cancer effects has three main contributions: 36% fossil fuel combustion, 42% electricity coming from the network and 20% mining. Analysing the upstream processes, this impact derives from the introduction of aluminium oxides associated to mining processes. Material input introduces a chromium VI burden into the water, imputing up to 86% of the mining process contribution to the human toxicity. Fossil fuel combustion contribution is mainly linked to the petroleum coke combustion (98%), and electricity consumed drags the chromium VI burden from the grid. Contribution of the chromium VI (compared with the rest of HTPce-substances) is 85% in the case of electricity. This value falls to 51% when looking at petcoke combustion where other substances such as mercury and nickel also have significant contributions.

In the category of photochemical ozone formation, combustion of fossil fuels means 86% of the total. Within this contribution, 68% comes from nitrogen oxides, 19% from sulphur dioxides and 11% from NMVOC.

Something similar happens with acidification impact, where fossil fuel combustion contributes, through petcoke combustion, up to 94% of the total, from which 86% is originated by sulphur dioxides and 14% comes from the nitrogen oxides released.

Finally, the eutrophication impact is constituted by fossil fuel combustion, 41%, and by electricity consumed, 41%. Mining processes mean 5% and alternative fuels combustion reaches up to 12%. This impact category is characterised in ILCD 2011 method by a unique substance, phosphates. Attending to the fossil fuel combustion, petcoke is the cause of the 86% of the contribution. Phosphates from electricity are due to the coal existing in the electricity mix. In addition, most of the phosphates in the alternative fuel contribution come from the combustion of municipal sewage sludges, refuse-derived fuel MSW, used oils, and varnishes & solvents.

Comparing other impact categories with Cardim de Carvalho (2001), which thoroughly depicts the Spanish production, a higher contribution of the eutrophication has been observed, mainly due to the alternative fuels combustion (in 2001, cement plants did only burn fossil).

Aside from the national statistics (see Table 28), OFICEMEN (2010b) reported a value of 837 kg of CO_2/t clinker in 2010. For the total cement production, Portland Cement Association (PCA) gives an approximate value of 900 kg CO_2/t clinker for a dry kiln with preheater and precalciner (Masanet *et al*., 2012), while other authors (Van Oss and Padovani, 2003) report 940 kg CO_2/t clinker, of which 54.2% comes from calcination and 45.8% from combustion. This share is very dependent on the fuel mix and the energy required. In this work, absolute CO_2 emission in the production of clinker is 919 kg CO_2/t (929 kg CO_2-eq), being CO_2 from process (limestone's calcination) 57.9% and CO_2 from combustion equal to 42.1%. A ratio of CO_2 emissions from process and combustion of 60/40 is usually accepted.

Several hotspots have been found from the LCIA results obtained for the clinker production (see Figure 17). Due to the contribution of the fossil fuel combustion to each impact, it is crucial to focus on that point. The main solution for the 'combustion problem' is to apply energy consumption improvements (BAT measures). This idea encompasses scenarios E1, E2 and E4. Additionally, the electricity consumption and the burdens dragged from its coal-part origin (see Table 37), impel to build an electrical efficiency scenario, i.e. E3.

1.4.2. Cement production assessment (sectorial analysis)

Once the technical approach has been done and hotspots have been identified, the scope of the LCA has been broadened, focusing on the Spanish cement production sector in 2010. Attending to the European Standard of cements EN 197-1:2000 (CEN/TC-51, 2000) and introducing the modifications included in the different scenarios, LCIA results for the cement produced in Spain have been obtained.

Table 40. LCIA results of the production of 1 t cement in Spain under different scenarios

	BASE	E1	E2	E3	E4	E5
GWP (kg CO2 eq)	7.99E+02	7.78E+02	7.92E+02	6.98E+02	7.43E+02	6.28E+02
HTPce (CTUh)	1.25E-06	1.23E-06	1.11E-06	1.12E-06	1.13E-06	8.73E-07
POP (kg NMVOC eq)	1.09E+00	1.03E+00	1.07E+00	9.59E-01	7.30E-01	5.98E-01
AP (molc H+ eq)	3.40E+00	3.18E+00	3.36E+00	2.98E+00	2.13E+00	1.73E+00
FEP (kg P eq)	1.23E-02	1.19E-02	1.10E-02	1.10E-02	1.35E-02	1.05E-02

Total values for each impact category are shown in Table 40. GWP goes from 799 kg CO_2-eq in the BASE scenario to 628 kg CO_2-eq in the ideal scenario, E5. In addition, both AP and POP decrease almost to half. Besides, HTPce and FEP are reduced around 30% and 15% in E5, the most advantageous scenario. It is observed that FEP grows significantly (+10%) in E4, the fossil fuel substitution scenario. It is also remarkable that other impact categories such as HTPce and FEP do not achieve their main reductions in the substitution scenarios (E3 and E4).

In Figure 18, all the impact categories of ILCD (2011) are presented for evaluating the LCIA results of the production of cement in Spain in 2010.

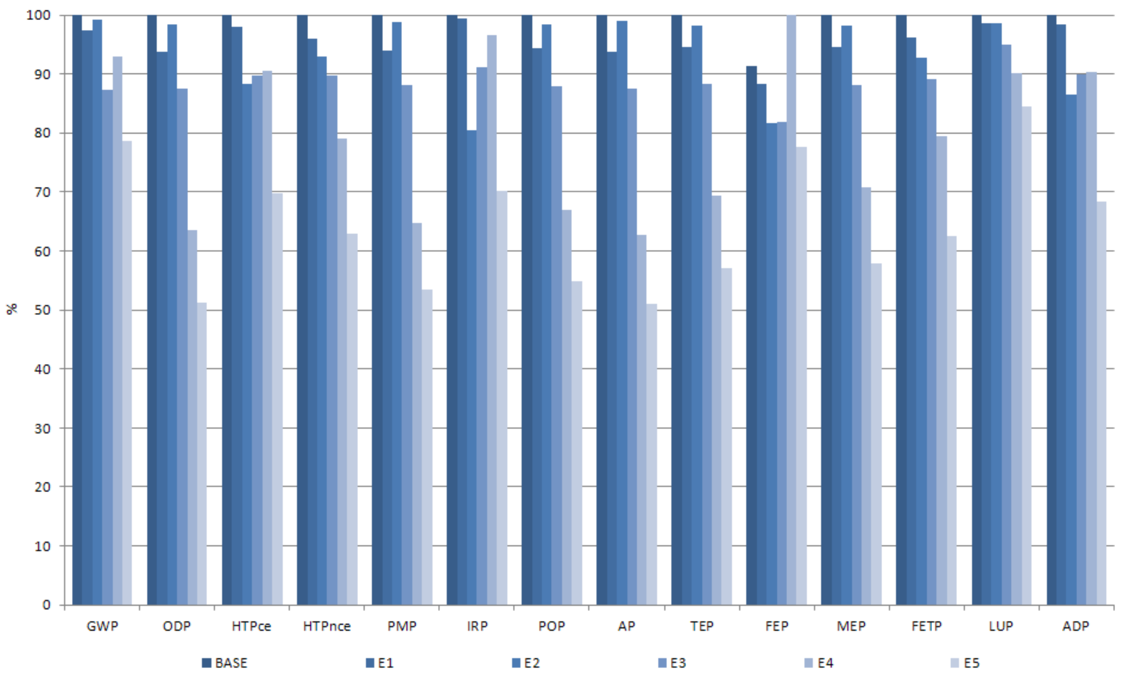


Figure 18. LCIA results of the production of 1 t cement in Spain under different scenarios

LCIA results from Table 40 and Figure 18 have been obtained using the 2010 Spanish electricity mix according to REE (2011). To consider properly the ideal scenario, E5, it is necessary to use an electricity mix projected to 2030. As shown in Table 37, 2030 modelling results from the TIMES-Spain model have been used. The adjusted E5 scenario is then the 2030-BASE scenario. Table 41 includes both the 2010-BASE and 2030-BASE LCIA results for all the ILCD 2011 impact categories.

Table 41. LCIA results of the production of 1 t cement in Spain in 2010 and 2030

Impact category	2010-BASE	2030-BASE	Reduction (%)
GWP (kg CO_2eq)	7.99E+02	6.26E+02	21.6
ODP (kg CFC-11 eq)	4.37E-05	2.28E-05	47.8
HTPce (CTUh)	1.25E-06	4.31E-07	65.5
HTPnce (CTUh)	2.68E-06	1.14E-06	57.4
PMP (kg $PM_{2.5}$ eq)	1.75E-01	8.82E-02	49.6
IRP (kg U_{235} eq)	3.60E+01	2.28E+00	93.7
POP (kg NMVOC eq)	1.09E+00	5.67E-01	48.0
AP (molc H+ eq)	3.40E+00	1.64E+00	51.9
TEP (molc N eq)	3.41E+00	1.84E+00	46.2
FEP (kg P eq)	1.23E-02	6.52E-03	47.1
MEP (kg N eq)	3.09E-01	1.68E-01	45.6
FETP (CTUe)	2.80E+01	1.13E+01	59.6
LUP (kg C déficit)	2.53E+00	8.57E-01	66.2
ADP (kg Sb eq)	1.98E-04	5.23E-05	73.6

The implementation of all BAT measures and substitution scenarios leads to reductions in all the impact categories considered. Climate changed is the category with the lowest reduction, 21.6%, while ionising radiation shows the largest decrease, 93.7%.

Scenario E1 achieves 6% reductions both in acidification and photochemical ozone formation and 2-3% in the other categories.

Scenario E2 diminishes freshwater eutrophication up to 11% and human toxicity with cancer effects 8%, being the rest negligible. Scenario E3, the material substitution scenario, achieves 10-13% reductions in each category impact. Finally, scenario E4 reaches great reductions in acidification and photochemical ozone formation, 37% and 33% respectively. Besides, a decrease of 7% takes place in climate change and 5% in human toxicity with cancer effects. By applying alternative fuels in the kiln, it is observed that freshwater eutrophication grows 10% respect to the 2010 base case. This is due to the introduction of phosphates coming from the sewage sludges, refuse-derived fuel, MSW, used oils and varnishes.

The ideal scenario, E5, proposed as an exploration for 2030 using the projections of the European Commission (Moya *et al.*, 2010), entails very different reductions: 21% in climate change, 49% in acidification, 45% in photochemical ozone formation, 30% in human toxicity (cancer effects) and 15% in freshwater eutrophication. These achievements are only attained as a result of all improvements described.

Focusing on achieving reductions in the climate change impact category the best way is to reduce the clinker-to-cement ratio followed by substituting fossil fuels with alternative ones. In terms of reducing the impacts in all environmental categories, fossil fuel substitution would be the first solution to be taken into consideration.

Material substitution scenario, E3, is the second best way to achieve reductions. This scenario is linked to the decarbonisation of the cement production process, i.e. reducing CO_2 emissions coming from limestone's calcination, and it could contribute positively to diminish the climate change. Nevertheless, its implementation is difficult since keeping both the European standard ranges for cements and production breakdown is quite complex. In this work, a breach of the European standard has been needed to reduce the clinker-to-cement ratio from 0.8 to 0.7. In order to achieve that target, it would be needed a change in both cement's demand, going from the current majority of Portland cements (type-II, 66.1% and type-I, 25.4%) to a major participation of non-Portland cements (types-III-IV-V), i.e. more declinkered cements; and more research on mechanical and chemical properties of cements (IEA, 2009b). To do so, an improvement in the process control systems is required to ensure that mineral composition of the product is kept. Currently, some material substitution projects are taking place in many countries, but they are still at an early stage (CEMBUREAU, 2012).

Valderrama *et al*. (2013) show results of a Spanish cement plant with two scenarios: a material one and a fossil fuel substitution scenario. Material substitution scenario introduces 1.35% (in mass) of dried sludge into the kiln, the rest being limestone. As E3 scenario introduces secondary materials after the kiln, comparison is unsuitable since Valderrama *et al.* (2013) introduces 5.8% of dried sludge matter (in mass). In the same manner, that study achieved reductions of 1% in GWP, 5.2% in AP, 4.6% in POP and 3% in FEP. In contrast, our BASE scenario (depicting a sectorial framework) enters 15.8% (in energy, what is slightly different) through 14 alternative fuels and E4 scenario extends the contribution up to 50%, reason for which our reductions are higher.

From the point of view of industry, fossil fuel substitution is the most advantageous measure. In 2002, the substitution rate was 2%, growing up to 15.8% in 2010 and to 22% in 2011 (OFICEMEN, 2010a; 2011). Spanish cement producers are in favour of fuel substitution, not only because it is the most cost-effective option (according to EIPPCB (2010), energy-related costs mean 40% of the total production costs), but also because the use of alternative fuels is carbon neutral and avoids burning waste at incineration plants.

Nowadays, the Spanish cement producers association, OFICEMEN, and the Labour Foundation's State cement field and the environment, CEMA (CEMA, 2009; 2010) are developing the current framework to apply all these measures in the Spanish cement industry, mainly substitution scenarios and use of waste. The European Cement Research Association, ECRA, is developing an ambitious plan to build a satisfactory cement industry roadmap where BAT, substitution scenarios and even CO_2 capture have been studied.

To sum up, results have shown that a swap to alternative fuels usage is the best option to achieve the highest reductions in most of the impact categories considered, followed by the use of alternative materials in the composition of cement. However, these solutions are not ideal, since burning waste also releases large amounts of pollutants. Emissions derived from alternative fuels or materials also have a negative impact in human health and the environment, so these effects should be considered and evaluated in depth. Despite the cement industry is very interested in reducing its emissions of mainly CO_2, NO_X, SO_2 and particulates, all options must be very carefully taken into account.

1.4.3. CO_2 capture in cement production

Comparison 2030-BASE vs. 2030-PCC

In the same manner, a comparison between the explorative scenarios for 2030 has been carried out: one without CO2 capture and one with CO2 PCC. In this case, the electricity mix used is the same, i.e. 2030 electricity mix from Table 37.

Table 42. LCIA results for the production of 1 t cement in Spain without and with PCC

Impact category	2030-BASE	2030-PCC	Change compared to 2030-BASE (%)
GWP (kg CO_2eq)	6.26E+02	5.34E+02	-15
ODP (kg CFC-11 eq)	2.28E-05	1.67E-05	-27
HTPce (CTUh)	4.31E-07	2.52E-06	+6-fold
HTPnce (CTUh)	1.14E-06	6.00E-05	+53-fold
PMP (kg $PM_{2.5}$ eq)	8.82E-02	2.10E-01	+2-fold
IRP (kg U_{235} eq)	2.28E+00	2.97E+00	+30%
POP (kg NMVOC eq)	5.67E-01	2.73E+00	+5-fold
AP (molc H+ eq)	1.64E+00	4.73E+00	+3-fold
TEP (molc N eq)	1.84E+00	1.05E+01	+6-fold
FEP (kg P eq)	6.52E-03	7.41E-03	+14
MEP (kg N eq)	1.68E-01	9.17E-01	+5-fold
FETP (CTUe)	1.13E+01	3.86E+01	+3-fold
LUP (kg C déficit)	8.57E-01	4.27E+00	+5-fold
ADP (kg Sb eq)	5.23E-05	4.64E-05	-11

Once cement production is optimised by applying the most promising solutions for making cement efficiently, the CO_2 post-combustion capture using monoethanolamine (MEA) as solvent has been introduced. This comparison takes place in 2030, so the electricity mix is a projection of the Spanish electricity mix resulting from a modelling exercise.

Results show (see Table 42) that applying post-combustion capture using MEA on a well-optimised cement sector allows reducing by 15% GWP, 27% ODP and 11% ADP, but worsens the rest of the impact categories. HTPnce is increased 53 times with respect to the case without capture.

As detailed in Table 35 and Table 36, PCC requires an extra amount of energy and material to capture CO_2. The extra energy required is the so-called 'energy penalty'. This penalty is quantified in 1,000-3,500 MJ/t clinker and 50-90 kWh/t clinker (UNIDO, 2010). Attending to the LCI of the Spanish clinker in 2030, the thermal input is 3,300 MJ and the electricity input is 69.4 kWh/t clinker. A quick comparison indicates that PCC energy requirements are at the same level than clinker production.

A detailed analysis has been carried out using data from Table 42. The introduction of PCC achieves reductions in GWP, ODP and ADP. The rest of the impact categories get significantly worse. The reason is founded on the energy penalty.

In the 2030-BASE scenario, clinker production is the main process in the GWP category (63%) and the petcoke burned is the second (19%) whereas in 2030-PCC, the CHP plant is the main contributor direct and/or indirectly. Similarly, petroleum coke burned is the main contributor in 2030-BASE in PMP, POP, AP, TEP and MEP. ODP is linked to the imported crude oil production. HTPce is driven by disposal processes (redmud from bauxite digestion, spoil from lignite and coal mining) in 2030-BASE scenario and by the disposal of spoil from coal mining in the 2030-PCC scenario. IRP grows because the uranium milling processes grow accordingly to the extra energy requirements. FEP shows a similar behaviour in both scenarios, approximately half of the impact is linked to disposal of spoil from lignite and coal mining processes and the other half comes from the combustion of alternative fuels. FETP grows significantly in 2030-PCC due to the highest coal-related disposal process contribution and the ammonia burdens. In 2030-PCC LUP is increased, since the extra energy of the system comes from hard coal, therefore land use requirements for the extra coal entail a huge growth in this category. Finally, ADP shows 11% reduction based on the avoidance of resources utilisation.

2030-PCC scenario analysis

Finally, a comparison between the three scenarios is presented in Figure 19.

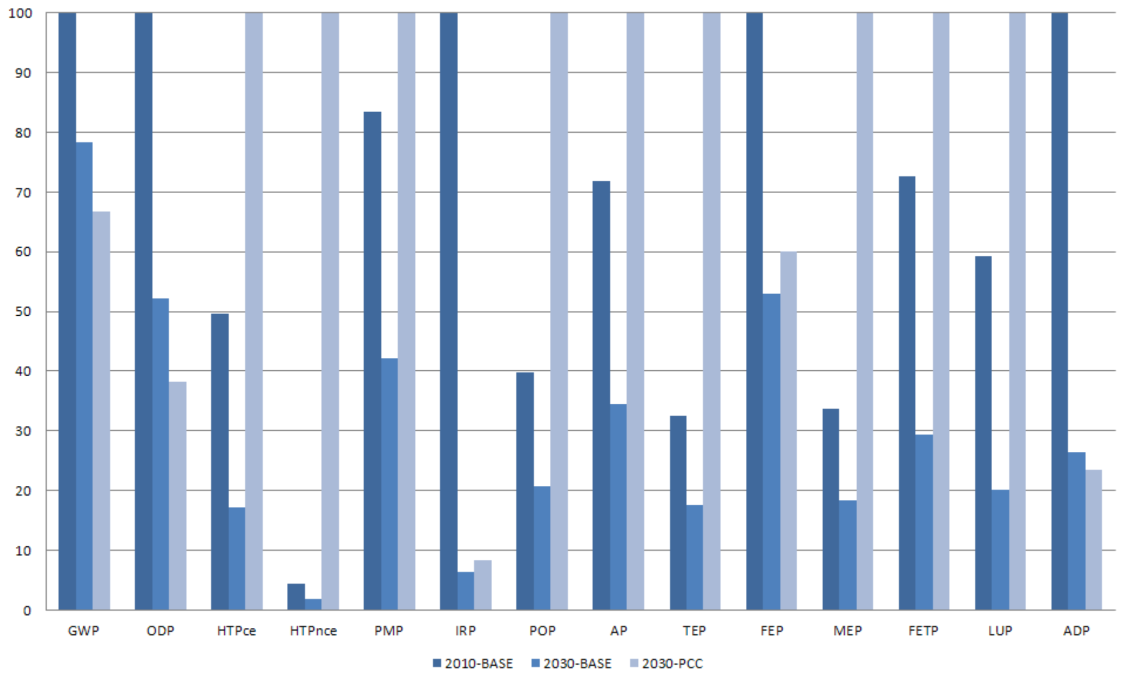


Figure 19. LCIA results comparison of the 2010-BASE, 2030-BASE and 2030-PCC scenarios

Figure 19 shows the effect of implementing all available BAT and other technological solutions (2030-BASE), what leads to reductions in every impact category compared to the 2010-BASE, and including the application of CO_2 capture (2030-PCC). In that case (compared to the 2030-BASE) it is observed that climate change, ozone depletion and abiotic depletion achieve reductions, while the rest of categories grow.

Table 43. LCIA results for 2030-PCC scenario with a coal-fired CHP plant per 1 t clinker

GWP	kg CO_2 eq
CHP	4,41E+02
Clinker, at plant	5,88E+01
Rest of processes	3,36E+01
ODP	kg CFC11 eq
Crude oil, at production onshore (Middle East)	8,91E-06
Crude oil, at production onshore (Russia)	6,18E-06
Crude oil, at production onshore (Africa)	3,75E-06
Crude oil, at production (Nigeria)	1,22E-06
Transport, natural gas, onshore pipeline, long dist.	-1,33E-06
Transport, natural gas, pipeline, long distance	-1,95E-06
Rest of processes	-7,05E-08
HTPce	CTUh
Disposal, spoil from coal mining, landfill	1,20E-06
CHP	8,44E-07
Disposal, spoil from lignite mining, landfill	1,66E-07
Disposal, redmud from bauxite digestion, landfill	2,27E-07
Rest of processes	1,55E-07
HTPnce	CTUh
CHP	5,88E-05
Rest of processes	1,17E-06
PMP	kg $PM_{2.5}$ eq
CHP	1,71E-01
Rest of processes	3,84E-02
IRP	kg U_{235} eq
Tailings, uranium milling	1,94E+00
Nuclear spent fuel, in reprocessing, at plant	9,15E-01
Rest of processes	1,16E-01
POP	kg NMVOC eq
CHP	2,51E+00
Rest of processes	2,27E-01
AP	molc H+ eq
CHP	4,29E+00
Rest of processes	4,40E-01
TEP	molc N eq
CHP	9,79E+00
Rest of processes	7,02E-01
FEP	kg P eq
Disposal, spoil from lignite mining, landfill	2,89E-03
Other fuels (no biomass) burned	1,09E-03
Varnishes and solvents burned	9,53E-04
Disposal, hard coal ash, 0% water, landfill	5,72E-04
Refuse-derived fuel MSW burned	4,28E-04
Rest of processes	1,47E-03

MEP	kg N eq
CHP	8,48E-01
Rest of processes	6,90E-02
FETP	CTUe
Disposal, hard coal ash, 0% water, landfill	1,50E+01
CHP	5,98E+00
Discharge, produced water, onshore	2,93E+00
Ammonia, steam reforming, liquid, at plant	2,81E+00
Ammonia, partial oxidation, liquid, at plant	2,15E+00
Disposal, spoil from lignite mining, landfill	2,13E+00
Rest of processes	7,55E+00
LUP	kg C deficit
Limestone, at mine	5,42E+01
Clay, at mine	1,09E+01
Gypsum, mineral, at mine	7,67E+00
Sand, at mine	7,62E+00
Bauxite, at mine	2,59E+00
Hard coal supply mix (Spain)	3,96E+00
Hard coal, at mine (West Europe)	3,04E+00
Bauxite, at mine	2,60E+00
Electricity, hydropower, at reservoir power plant	1,19E+00
Recultivation, bauxite mine	-1,57E+01
Recultivation, limestone mine	-6,57E+01
Rest of processes	6,84E-01
ADP	kg Sb eq
Zinc concentrate, at beneficiation	2,16E-05
Bauxite, at mine	1,53E-05
Uranium natural, at underground mine	6,29E-06
Iron ore, 46% Fe, at mine	4,71E-06
Crude oil, at production onshore (Middle East)	4,21E-06
Uranium natural, at open pit mine	4,19E-06
Crude oil, at production offshore (Norway)	3,57E-06
Crude oil, at production onshore (Russia)	2,98E-06
Crude oil, at production offshore (Great Britain)	2,96E-06
Natural gas, at production onshore (Algeria)	-2,47E-06
Lead	-3,01E-06
Resource correction, PbZn, indium, negative	-1,88-05
Rest of processes	4,94E-06

Table 43 shows the process contribution to each impact category with a cutoff of 5%. The introduction of the coal-fired CHP required for CO_2 capture entails the major contribution in most categories: GWP, HTPce, HTPnce, PMP, POP, AP, TEP and MEP. In addition, coal-related processes are the main contributors in the rest of the categories.

Ozone depletion is affected by oil crude production processes which are dragged from behind. Human toxicity with cancer effects, freshwater eutrophication and ecotoxicity are affected mainly by disposals of coal mining, i.e. CHP entails an indirect effect on those impact categories.

Land use and abiotic depletion are also affected by the extra resource extraction processes.

Most categories (GWP, HTPnce, PMP, POP, AP, TEP, MEP) are directly affected by the coal-fired CHP plant introduced for the PCC. In addition, other categories such as HTPce, FEP and FETP undergo its effect indirectly due to the increase of the coal-derived disposal processes or the extra demand of coal (LUP, for instance). The extra material introduced in the CO_2 capture unit (ammonia, limestone and MEA) leads to an increase in the FETP but it is not the main contribution to the category. MEA's effect is negligible (below the 5% cutoff of Table 43). This is in line with the results obtained by Singh *et al*. (2011) and Volkart *et al.* (2013).

The major points of discussion concerning the introduction of PCC in 2030 are two: the energy penalty and, subsequently, the election of the CHP plant.

As shown in the results, CHP contribution is crucial when capture is considered. Energy penalty is related to the huge amounts of heat (in form of steam) needed for the solvent regeneration, i.e. as cement is a very energy-intensive industry, large amounts of CO_2 emissions are released and consequently huge quantities of solvent are required for capture (which must be treated with steam). Assuming that, the question is: *how to produce the required enormous amount of heat?*

IEA GHG (2008) is the reference document on CO_2 capture in cement production. In this report, a cement plant with post-combustion CO_2 capture unit is presented. The selection of a coal-fired CHP plant in the current work is based on the same guidelines than in IEA GHG (2008). From the results, this point seems to be the most controversial because the introduction of the capture unit is applied on a well-optimised system and, furthermore, the expected Spanish electricity mix in 2030 is almost decarbonised. Consequently, the fact of avoiding electricity from the electricity mix (see Table 35 and Table 43) entails severe increases in most of the categories due to the introduction of a coal-fired CHP plant in a system where coal contribution is negligible in 2030, 0.5% (see Table 37). Table 42 shows the mentioned effect: except for the reductions in GWP, ODP and ADP, the rest of the categories grow 2-, 3-, 5-, 6- and even 53-times like HTPnce.

Consequently, a detailed analysis has been performed testing a natural gas CHP plant which displaces electricity from the mix.

CHP analysis

As the projected 2030 Spanish electricity mix has a negligible coal contribution (Table 37), it seems reasonable to test the introduction of a natural gas-fired CHP plant in place of a coal one. In Table 35 the detailed inventory of that CHP plant is included. Figure 20 shows the comparison of the LCIA results of the 2010-BASE, 2030-BASE and 2030-PCC scenarios. Each impact category is described using standardised units (see Table 42).

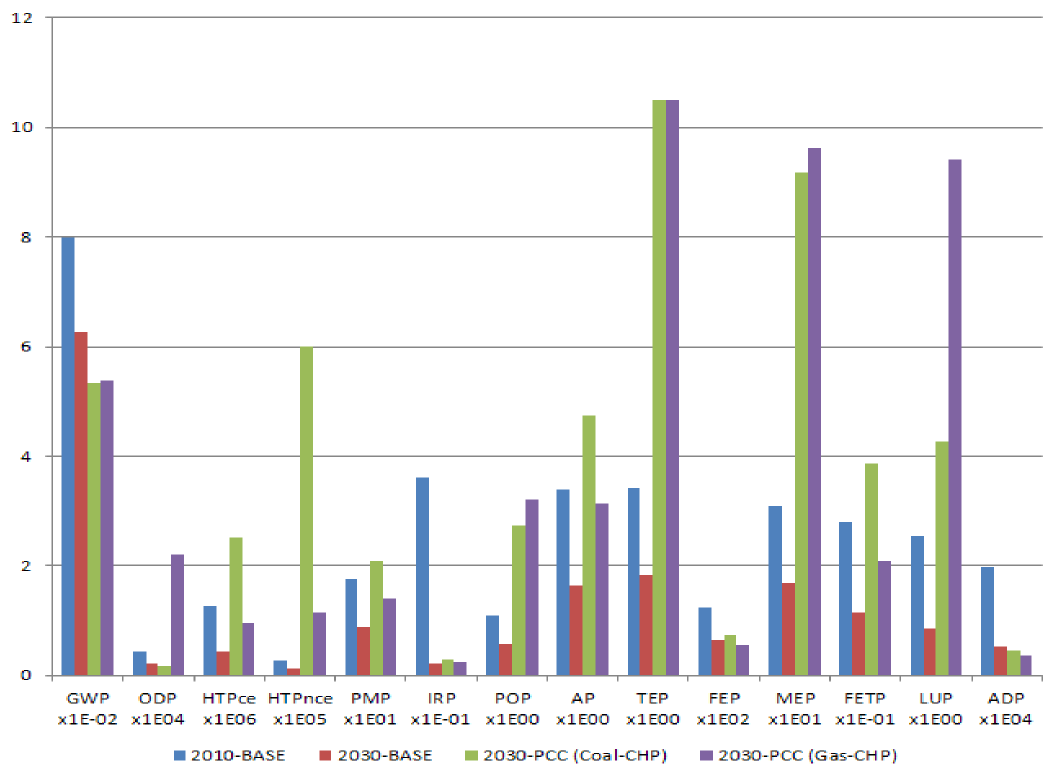


Figure 20. LCIA comparison of the 2010-BASE, 2030-BASE and 2030-PCC scenarios

The resulting effect of using a natural gas CHP plant is a generalised reduction in most categories, except in POP, MEP, ODP and LUP which worsen compared to the 2030-PCC (coal-CHP) scenario.

With respect to the 2030-BASE case, the introduction of a natural gas CHP plant does not change the overall behaviour; most categories are increased when PCC takes place. Only freshwater eutrophication, abiotic depletion, and climate change are significantly reduced.

Results (Figure 20) show a reduction in the categories' magnitude (compared to the case with a coal-fired CHP plant) but it can be concluded that introduction of PCC is still a bad option when looking at most of the impacts.

LCIA results are in line with Volkart *et al*. (2013) who obtain general results for a cement plant in Switzerland by applying post-combustion capture under several scenarios. The quoted article analyses the introduction of several CHP plant types (coal, natural gas, electricity from grid, waste) achieving the best results in the case of natural gas CHP plant.

1.5. Conclusions

1.5.1. BAT and substitution scenarios in the Spanish cement industry

This work has addressed both human and environmental impact improvements applied to the Spanish cement making industry, implementing BAT on efficiency measures and considering other prospective solutions suggested by the European Commission.

The first part of the study is focused on a technical analysis of the clinker production by process stage. Several hotspots have been found, depending on the impact category analysed: fossil fuel combustion, use of electricity and mining (quarry). Besides, climate change presents an extra contribution coming from the CO_2 from limestone's calcination, the so-called CO_2 from process. It is also remarkable that alternative fuels combustion is low with respect to the total in every impact category. Material pre-treatments and transportation are negligible.

Going beyond the hotspots' identification, this work has explored the Spanish cement sector in 2010, but looking at future. Consequently, a variety of scenarios have been developed in order to implement BAT and other technical solutions to reduce emissions, waste, as well as energy consumption.

Most significant improvements are related to the energy requirements, both at the clinker kiln and power consumption. To face these challenges, it is needed to improve (or re-design) the kiln or change the mills by new ones. Notwithstanding, reductions in the considered impact categories are low (as much as 11% in freshwater eutrophication in E2). On the other hand, both material and fossil fuel substitution scenarios are the best options to achieve impact reductions.

Thus, changing the primary materials entered in the cement mill with clinker by secondary materials, previously considered waste (fly ashes, blast furnace slag, sands and non-calcined limestone), leads to 10-13% reductions in each impact category. Furthermore, using alternative fuels instead of fossil has shown its advantages, decreasing 37% and 33% acidification and photochemical ozone formation, and freshwater eutrophication remains equal. Finally, in an ideal scenario where all technological options are implemented, reductions would reach from 21% in climate change to 49% in acidification.

On this sectorial approach to the Spanish cement industry, it is concluded that, in order to face the problems derived from fossil fuel combustion, a fuel shift is needed to reach less contaminant options. Material substitution is another good solution for the industry in terms of impacts, but it requires a change in the demand and further research to keep the properties of cement. Beyond that, statistics are showing that the best cost-benefit option for cement producers in Spain is fossil fuel substitution, since alternative fuels shares are continuously growing (15.8% in 2010, 22.4% in 2011). It is recommended taking into consideration the collateral increase of the freshwater eutrophication due to the phosphates rise coming from the alternative fuels combustion.

1.5.2. CO_2 capture in the Spanish cement industry

Albeit Spanish cement industry is well upgraded, there is a great interest among cement producers to continue reducing the impacts derived from the emissions to the environment. At the same time, the European Commission is very interested in deploying the CCS technology in the next decades, but problems associated to this technology look like impassable barriers at present time. Enormous costs of the technologies and slow implementation are not the only ones. Competition with other solutions such as BAT implementation, fossil fuel substitution or clinker-cement ratio reduction is possibly the main challenge for CCS on cement industry.

Carbon capture technologies, as part of CCS, are frequently assessed focusing on their GHG emissions reduction potential but forgetting other impacts on environment and human health. This work explores the addition of a post-combustion CO_2 capture unit using MEA within the cement production from an LCA perspective.

The application of all the BAT measures on efficiency as well as material and fuel substitution achieve reductions in all impact categories with respect to the values observed in 2010. Decreases go from 22% in climate change to 94% in ionising radiation.

It is assumed that first cement plants with CO_2 capture will emerge in 2030. The effect of applying post-combustion CO_2 capture in a well-optimised cement industry which uses BAT, burns alternative fuels at fifty-fifty and has 0.7 clinker-cement ratio, causes reductions in climate change, ozone depletion and abiotic depletion of 15%, 27% and 11%, respectively. Simultaneously, the rest of the categories increase significantly.

The need of steam from a CHP plant is extremely high. This is the basis of the 'energy penalty' handicap. The weight of the CHP plant, in terms of impacts, is at the same level than the cement production plant. Although main specialised references (IEA GHG, 2008; UNIDO, 2010) describe a coal-fired CHP plant to achieve the heat required, we strongly recommend looking for other solutions. Results of the present work, in line with Volkart *et al*. (2013), show that using a natural gas-fired CHP plant entails a significant reduction in most impact categories. Another point for the consideration of this solution is the expected decarbonisation of the Spanish electricity mix in 2030.

The extra material (ammonia, monoethanolamine, limestone) required for PCC has no relevant effects, only secondary increases on freshwater ecotoxicity.

In summary, CO_2 capture technologies applied to the cement industry contribute to reduce the climate change, while other impact categories grow. In order to make this technology more competitive to reduce CO_2 emissions derived from the cement production, additional technical research is needed. Consequently, it is recommended that further studies take into account both the substitution of the hard coal in the CHP plant by alternative choices such as natural gas, biomass, etc., as well as the consideration of different CO_2 capture technologies, e.g. OCC and/or other PCC technologies. Accordingly, it is suggested the creation of synergies between cement industry and NGCC power plants in order to use their residual heat to face the energy penalty.

Therefore, including environmental and human health impact categories different than climate change in the assessment of the CO_2 capture technologies applied to cement plants is strongly recommended.

2. Modelling with TIMES-Spain

Since the global economic crisis began in September 2008, the Spanish cement industry has been living a dramatic fall in the production due to the contraction of the cement demand. This reduction is based on the withdrawal of the public administration investments and the difficulties that citizens find to get credits.

The LCA of the Spanish cement industry identified relevant hot points in the production processes. The next step consists of analysing possible solutions and the compliance of the environmental Directives (2001/81/EC and 2009/29/EC).

The modelling exercise has been carried out using the TIMES-Spain energy optimisation model. Firstly, Directives 2001/81/EC and 2009/29/EC have been implemented. Secondly, cement production processes have been described, adding the BAT and potential solutions in the medium term. Finally and going further the Directive's targets, specific scenarios concerning CO_2 emissions, cement demands, costs of the CO_2 capture technologies and fossil fuel prices have been built.

2.1. Meeting the Directives targets

There are several environmental policies that concern the cement sector: European Directives, Spanish laws, national plans, etc. OFICEMEN refers to different types of targets depending on the scope: sustainable resources management, environment, climate change, security and health, and formation (OFICEMEN, 2012). Security, health and formation targets have not been taken into account in this study.

In terms of waste, EC JRC (EIPPCB, 2010) supports its use to substitute both primary materials and fossil fuels in the cement industry claiming that waste valorization does not entail risk for health and/or ecosystems. According to Directive 2008/98/EC on waste, 'waste recovery' is *any operation the principal result of which is waste serving a useful purpose by replacing other materials which would otherwise have been used to fulfill a particular function, or waste being prepared to fulfill that function, in the plant or in the wider economy*. The use of waste as alternative fuel is one of the main recovery functions.

Spanish Law 22/2011 is the national transposition of the Directive. This law promotes the economic valuation of the waste recovery and the energy efficiency measures setting as priorities the prevention, recovery preparation, recycling and other recovery methods, and removal.

In addition, the Renewable Energy Plan 2011-2020 (PER) indicates that the waste recovery, mainly for thermal uses, should achieve the same contribution rates than in the most advanced European countries in 2020. The Plan focuses on the promotion of several wastes: municipal solid waste, industrial waste such as pulp, paper and used tyres, and sewage sludges. The target of this plan, where cement kilns are included besides other industrial kilns, is to recover up to 2 Mtoe of fuel from waste in 2020.

In 2011, the thermal contribution of the alternative fuels coming from waste recovery entailed 22.4%. On the other hand, the petroleum coke contribution entailed 76% of the energy consumed (OFICEMEN, 2012).

Phase II of the CO_2 National Allocation Plan expected 20% of alternative fuels substitution in the Spanish cement industry by 2012. As OFICEMEN reported, this target has already been surpassed, with 22.4% in 2011. Furthermore, countries like Netherlands, Austria, Germany and Norway have alternative fuels contributions higher than 60% in average so the target for Spain is to continue increasing the waste recovery for energy uses.

The Spanish cement industry must achieve not only the sectorial agreements signed with the Spanish government and the autonomous regions but also the national targets. Even though the cement sector has been highly upgraded in Spain in the last decade, more investments are still required to continue reducing the CO_2, NO_X, SO_2 and particulate emissions.

In addition to those specific guidelines and targets, the Spanish cement industry has an important role in the fulfillment of Directive 2009/29/EC on GHG allowances, which sets an objective of 20% GHG reduction by 2020 respect to the 1990 level. Also, it is relevant its contribution to the accomplishment of Directive 2009/28/EC on the use of energy from renewable sources because biomass has a role in the waste recovery. Additionally, the most recent Directive 2010/75/EU on industrial emissions shows the site-specific emission limits of the cement industry (see Chapter 2). Finally, Directive 2009/31/EC establishes the legal framework for CO_2 geological storage establishing the possibility of applying CCS technologies to the cement manufacture.

2.1.1. Emission factors in the cement industry

Emissions from the combustion of fossil fuels have been introduced into the model (see Table 44) after a broad literature review on emission factors ((IPCC, 2006), (MAGRAMA, 2012a) and (SEI, 2012) among others).

Table 44. Emission factors of the main GHG from the combustion of fossil fuels

	CO_2 (kt/PJ)	**CH_4 (t/PJ)**	**N_2O (t/PJ)**
Hard coal	98.3	1	1.5
Lignite	101.2	1	1.5
Brown coal	101.2	1	1.5
Refinery gases	56.1	1	0.1
LPG	63.1	1	0.1
Gasoline	69.3	3	0.6
Kerosene	71.9	3	0.6
Naphtha	73.3	3	0.6
Diesel	74.1	3	0.6
Heavy fuel oil	77.4	3	0.6
Others	73.3	3	0.6
Natural gas	56.1	1	0.1
Cogeneration gases	108.2	1	0.1
Blast furnace gases	108.2	1	0.1
Gasworks gases	56.1	1	0.1
Wood	0.0	30	4
Biogas	0.0	1	0.1
MSW	85.9	30	4
Sewage sludge	85.9	30	4
Bio liquids	0.0	3	0.6

In order to complete the emission factors already existing in TIMES-Spain with other non GHG, a compilation of relative emissions per tonne of clinker (see Table 45) has been performed (MAGRAMA, 2012c).

Table 45. Emission factors of the production of 1 t clinker in Spain

Year	SO_2 (g/t)	NO_X (g/t)	VOC (g/t)	CO (g/t)
1990	755	3756	67	2652
1991	747	3631	67	2599
1992	740	3506	66	2546
1993	732	3380	65	2492
1994	725	3255	65	2439
1995	717	3130	64	2386
1996	710	3005	63	2333
1997	702	2880	63	2280
1998	695	2754	62	2227
1999	687	2629	61	2174
2000	679	2504	61	2121
2001	672	2379	60	2068
2002	664	2254	59	2015
2003	657	2128	59	1962
2004	649	2003	58	1909
2005	642	1878	57	1856
2006	642	1880	57	1858
2007	607	1843	54	2213
2008	607	1843	54	2213
2009	617	1871	55	2247
2010	381	1740	50	2080
2011	381	1740	50	2080

The only emissions coming from 'process' are CO_2 and particulates. While the CO_2 comes from the calcination of the limestone at the kiln, meaning about 60% of the global CO_2 released, particulates emission is linked to the fine granulate nature of the substances. According to Cardim de Carvalho (2001), it has been assumed that 64.87% of the PM_{10} emissions come from the clinker unit process and 30.62% from the cement mills. PM_{10} emissions from quarrying, transportation and fuel preparation are not considered.

2.1.2. Directives implementation

Directive 2009/29/EC

Concerning cement industry, Directive 2009/29/EC on GHG emissions reductions (extension of Directive 2003/87/EC) has been implemented in the TIMES-Spain model assuming CO_2 national bounds.

GHG emissions in Europe are recorded until 2010, so it is possible to estimate the fulfillment rate comparing 1990 (4,420 Mt GHGs) to 2010 (3,891 Mt GHGs) levels. Furthermore, the CO_2 expected value for 2020 is 3536 Mt for the EU27 (EEA, 2012).

In Spain, CO_2 emissions in 2010 reached up to 284.4 Mt. Using the 2010 European fulfillment rate to extrapolate the 2010 Spanish value to 2020, the expected CO_2 bound would be 258.4 Mt. As the Directive only fixes the target for 2020, this scenario keeps the bound until 2050 (see Table 46). It has been assumed that the CO_2 weight respect to the GHG is 80% (MAGRAMA, 2012c).

Table 46. Spanish CO_2 bounds derived from the Directive 2009/29/EC

Year	CO_2 (Mt)
2010	284.4
2020-2050	258.4

Separately, the non ETS CO_2 emissions have been limited using the historical weight of the non-ETS respect to the ETS emissions, 66.6% (Decision 280/2004/EC; MAGRAMA, 2012c) and Decision 2013/162/EU which fixes the Spanish CO_2 caps from 2013 to 2020. In this case, the bound would be 147.3 Mt in 2020.

Directive 2001/81/EC

As shown in Chapter 2, Directive 2001/81/EC on National Emission Ceilings (NEC Directive) for certain atmospheric pollutants establishes that by 2010 at the latest, Member States should have limited their annual national emissions of sulphur dioxide (SO_2), nitrogen oxides (NO_x), volatile organic compounds (VOC) and ammonia (NH_3) to amounts below the emission ceilings.

In the cement production, it is particularly interesting to analyse the behaviour of both SO_2 and NO_x because they have an important contribution to the Spanish total emissions. In order to assess those pollutants, the Spanish limits set by the Directive have been considered (see Table 47).

Table 47. Spanish emissions ceilings of Directive 2001/81/EC

SO_2 (kt)	NO_x (kt)	VOC (kt)	NH_3 (kt)
746	847	662	353

According to 2010 inventory (EEA, 2012), Spain only met SO_2 target and it was mainly due to the economic crisis (see Table 48). The downfall in cement demand led to a downfall of the petcoke combustion so the sectoral SO_2 emissions decreased.

Table 48. Spanish emissions in 2010 from inventory

SO_2 (kt)	NO_X (kt)	VOC (kt)	NH_3 (kt)
444 (59%)	900 (106%)	672 (102%)	368 (104%)

Note: comparison with Directive's ceilings in brackets.

In this modelling approach, SO_2 and NO_X emission ceilings are extended from 2010 to 2050.

2.2. Cement technologies characterisation in TIMES-Spain

As it has been described in the TIMES methodology section (see Chapter 2 Section 2), cement industry is depicted by means of its specific Reference Energy System (RES). In TIMES-Spain, the cement sector is described as follows (see Figure 21).

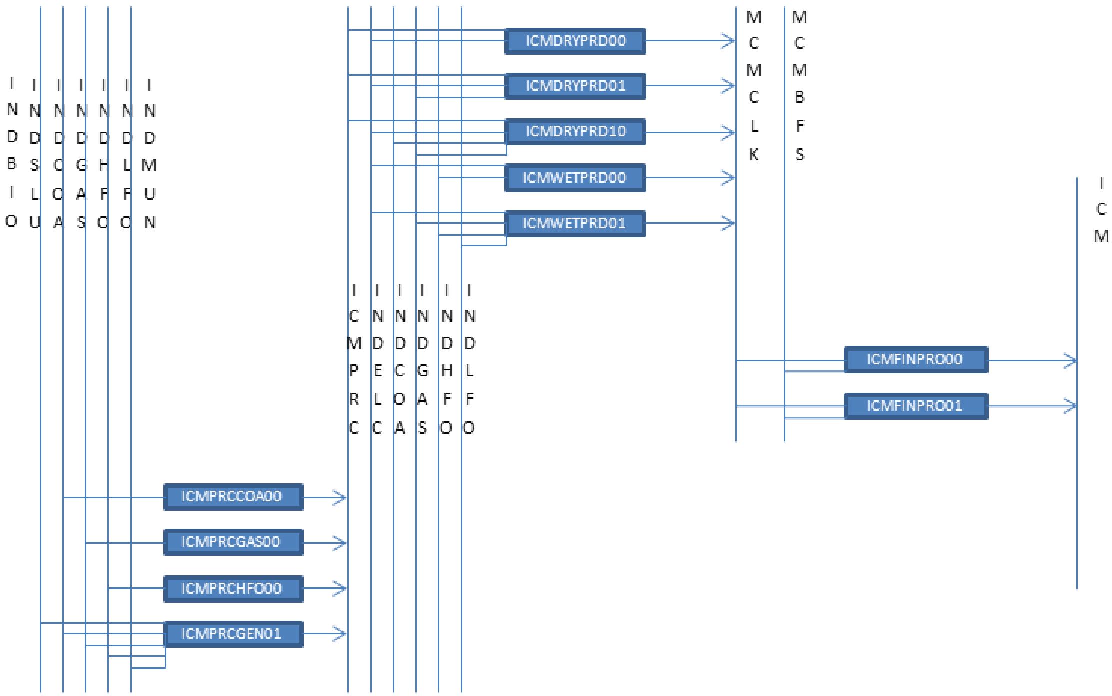


Figure 21. RES scheme of the cement production in TIMES-Spain

The cement demand (ICM) is met by a finishing process (ICMFINPRO*) which uses clinker (MCMCLK), blast furnace slag from Iron and Steel used in cement production (MCMBFS) and energy. At the same time, clinker is the resulting product of wet or dry processes (ICMDRYPRD* and ICMWETPRD*). In Europe, sectorial prospectives (EIPPCB, 2010) indicate that dry processes have been substituting wet or semi-wet processes during the last decades. In this work, it is assumed that clinker produced via wet-route will be extinguished by 2020. In fact, in 2010 there were 3 wet-route versus 55 dry-route kilns in Spain (OFICEMEN, 2010a).

Wet and dry processes of clinker production use different commodities such as cement process heat (ICMPRC), electricity (INDELC), heavy fuel oil (INDHFO), light fuel oil (INDLFO), natural gas (INDGAS), coal (INDCOA). Furthermore, the kilns also use waste sludge (INDSLU), biomass (INDBIO) and municipal solid waste (INDMUN). Besides, commodities also feed the kilns, not only the clinker production processes (INDGAS, INDCOA, INDHFO, INDSLU, INDLFO, INDBIO, INDMUN), where the heat is produced and sent to the clinker production process. In TIMES-Spain there are four clinker kilns: three using only one fuel, and one flexible with the possibility of using different fuels at the same time. In this work, only flexible kilns have been considered.

The TIMES processes tagged with -00 are those for depicting the existing technologies in the reference year (2005) whereas the ones with terminations -01 or -10 are those new processes included in the model to substitute the existing ones. Next Table 49 shows the techno-economic data for the new processes included in TIMES-Spain.

Table 49. Description of the cement-related technologies available within TIMES-Spain

TechName	TechDesc	Output	INVCOST	FIXOM	VAROM	AF
			M€	M€	M€	
ICMPRCGEN01	ICM.Generic fuel kiln COA, COK, HFO, LFO, GAS, SLU, BIO, MUN	heat, emissions	15.2	n.a.	0.01	1
ICMDRYPRD01	ICM.Dry Process Production.01	clinker, emissions	247.8	19	17	0.95
ICMWETPRD01	ICM.Wet Process Production.01	clinker, emissions	224.8	10	17	0.95
ICMFINPRO01	ICM.Finishing Processes.01	cement, emissions	10	3.0	3.0	0.95

For both, existing and new clinker and cement production technologies, the investment costs and fixed and variable operation & maintenance costs are expressed in M€/Mt and M€/Mt/yr, respectively. Energy efficiency of the kiln process is 0.9.

Energy production units are PJ/yr. Material production unit is Mt/yr. EFF is the efficiency of the process and AF is the availability factor.

2.3. Implementation of improvements in TIMES-Spain

According to the European Cement Research Association (ECRA) and the EC-JRC (EIPPCB, 2010) several measures have been taken into account in order to reduce emissions. ECRA guidelines (ECRA, 2009a) present the measures as follows: electrical energy efficiency measures, thermal energy efficiency measures, material substitution (reduction of the clinker content in cement), fossil fuel substitution by alternative fuels and finally, CCS.

Next subsections depict the different implementations introduced in the TIMES-Spain model concerning the BAT and prospective solutions applied to the cement production in Spain. They are implemented to be achieved from 2030 and beyond.

2.3.1. Thermal energy efficiency measures

The more relevant thermal energy efficiency improvement measures are the installation of modern clinker coolers; the optimisation of the length of the kiln, as well as its design regarding the fuels selection; the optimisation of the process controls; the reduction of the air-in leakage; the extension of the precalcination to the raw material; the increment of the number of cyclone stages; and the reduction of the moisture content of the raw meal. (MMA, 2004; EIPPCB, 2010).

The extra costs resulting of incorporating those measures in the new technology have been extracted from Worrell and Galitsky (2008).

- *Dry process conversion to multi-stage preheater kiln. Older dry kilns may only preheat in the chain segment of the long kiln, or may have single- or two-stage preheater vessels. Especially, long dry kilns may not have any preheater vessels installed at all. This leads to a low efficiency in heat transfer and higher energy consumption. Installing multi-stage suspension preheating (i.e. four- or five-stage) may reduce the heat losses and thus increase efficiency. Energy savings depend strongly on the specific energy consumption of the dry process kiln to be converted as well as the number of* *preheaters to be installed.* The specific costs of this measure are at 29€/t capacity for conversion to a multi-stage preheater kiln.

- *Installation or upgrading of a preheater to a preheater/precalciner kiln. An existing preheater kiln may be converted to a multi-stage preheater precalciner kiln by adding a precalciner and, when possible an extra preheater. The addition of a precalciner will generally increase the capacity of the plant, while lowering the specific fuel consumption and reducing thermal NO_x emissions (due to lower combustion temperatures in the pre-calciner). Fuel savings will depend strongly on the efficiency of the existing kiln and on the new process parameters (e.g. degree of precalcination, cooler efficiency).* Worrell and Galitsky (2008) assume a cost of 12 €/t of clinker.

- *Heat recovery for cogeneration. Waste gas discharged from the kiln exit gases, the clinker cooler system, and the kiln pre-heater system all contain useful energy that can be converted into power. Only in long-dry kilns is the temperature of the exhaust gas sufficiently high, to cost-effectively recover the heat through power generation.* It is assumed installation costs for such a system at 1.6-3.2 €/t clinker capacity with operating costs of 0.2 €/t of clinker.

- *Optimisation of heat recovery/upgrade clinker cooler. The clinker cooler drops the clinker temperature from 1200°C down to 100°C. The most common cooler designs are of the planetary (or satellite), traveling and reciprocating grate type. All coolers heat the secondary air for the kiln combustion process and sometimes also tertiary air for the precalciner. Reciprocating grate coolers are the modern variant and are suitable for large-scale kilns (up to 10,000 tpd, tonnes per day). Grate coolers use electric fans and excess air. The highest temperature portion of the remaining air can be used as tertiary air for the precalciner. Heat recovery can be improved through reduction of excess air volume, control of clinker bed depth and a new grate such as ring grates. Control of cooling air distribution over the grate may result in lower clinker temperatures and high air temperatures. Additional heat recovery results in reduced energy use in the kiln and precalciner, due to higher combustion air temperatures.* The costs of this measure are 0.16 €/t of clinker capacity.

- *Kiln combustion system improvements. Fuel combustion systems in kilns can be contributors to kiln inefficiencies with such problems as poorly adjusted firing, incomplete fuel burn-out with high CO formation, and combustion with excess air. Improved combustion systems aim to optimise the shape of the flame, the mixing of combustion air and fuel and reducing the use of excess air.* An average cost of 0.7 €/t of clinker capacity is assumed.

As a result, the extra cost of including all the previous measures would be 43-44 €/t clinker. For 0.8 Mt clinker needed to produce 1 Mt cement, the extra cost assumed is 35 M€. The total investment cost of this new technology will be then 248.1 M€/Mt clinker.

Moreover, the European Integrated Pollution Prevention and Control Bureau points out that thermal energy consumption varies depending on the type and size of the kiln system (EIPPCB, 2010). Plants using dry process, with multistage cyclone preheaters and precalcining kilns (the majority in Spain), start at about 3,000 MJ/t clinker and can reach more than 3,800 MJ/t clinker. Spanish statistics from OFICEMEN (OFICEMEN, 2010a) give an average thermal consumption of 3,536 MJ/t clinker in 2010. Moya *et al*. (2010) show that thermal consumption in clinker production is expected to be 3,300 MJ/t clinker in 2030 as European average. In this work it is assumed that a new high-efficient technology for clinker production with multi-cyclones, preheater and precalciner will consume 3,000 MJ/t clinker. Using IEA GHG (2008) as main source of data, a new and more thermal-efficient technology (ICMDRYPRD02) has been added. This new process has been implemented in the so-called '**E1 scenario**'.

Table 50. E1 scenario description in TIMES-Spain

Input	Output	Amount	AFA	Life	INVCOST	FIXOM	VAROM	CO_{2p}
				years	M€	M€	M€	kt
Heat		3.00 PJ						
Electricity		0.33 PJ						
	Clinker	1.00 Mt	0.95	30	248.1	19	17	510

In Table 50, electricity consumption is 91.98 kWh/t of clinker (0.33 PJ/Mt) according to the LCI of clinker.

The costs of this new technology are based on IEA GHG (2008) and UNIDO (2010) estimated for a new 1-Mt cement plant. In these reports, the investment costs are 263 M€/Mt of cement in the European scenario, fixed operation and maintenance costs are 19 M€/Mt of cement and net variable operation costs are 17 M€/Mt of cement. As the clinker process does not include either the kiln or the cement milling inside, 50 M€ have been subtracted from the investment costs of the clinker production process (Ybema *et al*., 1995, 1995; IEA GHG, 2008; ECRA, 2009a). It is assumed that 50 M€ is enough for considering the cement milling and cement dispatching stages in order to link the investment costs from the literature (for 1 Mt-cement plant) to the modelled process, i.e. clinker production process, without using any mass/energy allocation criteria.

Both fixed and variable operation and maintenance costs are kept constant because they mean less than 1% of the investment costs.

2.3.2. Electrical energy efficiency measures

Using IEA GHG (2008) as main reference, a new electrical high-efficient technology (ICMDRYPRD03) has been added. This new process has been implemented in the so-called '**E2 scenario**'.

Table 51. E2 scenario description in TIMES-Spain

Input	Output	Amount	AFA	Life	INVCOST	FIXOM	VAROM	$CO2_p$
				years	M€	M€	M€	kt
Heat		3.30 PJ						
Electricity		0.25 PJ						
	Clinker	1.00 Mt	0.95	30	219.3	19	17	510

Table 51 shows the electricity consumption for producing clinker, according to EIPPCB (2010) and Moya *et al.* (2010). According to the LCI of the clinker, the production of 1 t consumes 91.98 kWh in the 2010 case and it goes down to 69.44 kWh if the projections of Moya *et al*. (2010) are taken into account. Heat consumption has been assumed of 3.3 PJ, the same amount than in the existing dry-route clinker production process from TIMES-Spain. The CO_2 emissions coming from the limestone's calcination are 510 kt/Mt clinker (IPCC, 2006). The other emissions come from fuels combustion at the kiln.

As in the previous scenario, the costs of this new technology are based on IEA GHG (2008) and UNIDO (2010) estimates for a new 1-Mt cement plant. So, the investment costs are 263 M€/Mt cement in the European scenario, fixed operating and maintenance costs are 19 M€/Mt cement and net variable operating costs are 17 M€/Mt cement. In addition, 6.3 M€/Mt cement have been added to consider the evolution of the technology respect to the current dry-route referred in IEA GHG (2008). This value comes from the consideration of replacing traditional ball mills by high efficiency roller mills, ball mills combined with high-pressure roller presses, or horizontal roller mills according to Worrell and Galitsky (2008) estimates. As a result, the investment cost of this new technology would be then 219.3 M€/Mt clinker produced.

2.3.3. Material substitution

This measure is proposed by ECRA (2009a) to reduce both thermal and electrical energy consumption reducing at the same time than the direct and indirect CO_2 emissions linked to the process.

According to Worrell and Galitsky (2008), blended cements production requires extra necessities of storage as well as the pre-treatment of the secondary materials such as blast furnace slag, fly ashes, etc. It has been assumed an extra cost of 1 M€/Mt clinker produced.

Nevertheless, this measure is not BAT-typed since it entails a change in the average composition of the cement where the clinker content has to be reduced. According to the European standard EN 197-1:2000 (CEN/TC-51, 2000) there are different cement sub-types. It would be necessary a shift in the cement demand to shift the cement production from the most common Portland types to non-Portland types (III, IV and V). More research is needed to keep the mechanical and chemical cement properties.

Moya *et al.* (2010) gives a clinker-to-cement ratio of 0.7 in 2030 for the European Union. The Spanish ratio was 0.8 in 2010 so it seems reasonable the goal of 0.7 for the Spanish case.

In the model, the clinker-to-cement ratio is modified in the finishing process where cement is produced from the clinker and the extra material. In this case, this measure is implemented via scenario modifying the ICMFINPRO01 process. A new commodity (MCMBFS) including the minor constituents of the cement has been designed. To avoid the market competition with the steel industry (due to the need of BFS as waste), MCMBFS has been built separately assuming a market price of 75 €/t BFS (CEDEX, 2011).

This measure is the basis of the so-called '**E3 scenario**' where the assumed investment cost of the new clinker production process is 214 M€/Mt clinker produced (see Table 52).

Table 52. E3 scenario description in TIMES-Spain

Input	Output	Amount
		Mt
Clinker		0.7
BFS		0.3
	Cement	1.0

The result of the clinker content decrease is a reduction in the emissions coming from the clinker production processes.

2.3.4. Fossil fuel substitution

The use of alternative fuels in the cement industry gives the opportunity to reduce production costs, dispose of waste and reduce CO_2 emissions. Cement kilns are well-suited for waste combustion due to their high process temperature and because clinker product and limestone feedstock act as gas-cleaning agents (IEA, 2007). OFICEMEN (2010a) reported that 15.8% of the thermal energy came from alternative fuels in 2010. Lately, OFICEMEN (2012) has reported that the alternative fuels contribution was 22.4% in 2011 proving that the introduction of alternative fuels in substitution of the fossil fuels is a promising option for the sector.

The EC made several projections for the fossil fuel substitution assuming a ratio of 50/50 between fossil and alternative fuels in 2030 in EU27 (Moya *et al.*, 2010). Several countries like The Netherlands or Norway have achieved substitution rates higher than 60% and in some plants in The Netherlands have reached up to 100%.

This measure is not a BAT option. It entails to modify the inputs of the flexible kiln included in the TIMES-Spain model, i.e. ICMPRCGEN01. As in the previous cases, it is assumed that the investment cost of the flexible kiln is 50 M€/Mt clinker. As producing 1 Mt clinker requires 3.3 PJ of heat, the investment cost of the kiln would be 15.15 M€/PJ heat. Besides, extra processes needed in this new kiln process such as pre-treatment of secondary fuels, silos, and drying processes, entail an extra cost of 2 M€/PJ heat.

Consequently, this measure establishes the basis of the so-called '**E4 scenario**' where the investment cost of the new kiln process is 17.2 M€/PJ of cement process heat produced.

Table 53. E4 scenario description in TIMES-Spain

LimType	Attribute	Year	Input	Output	Amount	INVCOST
					PJ	M€
UP	SHARE	2030	Petcoke		0.50	
LO	SHARE	2030	Bio		0.30	
LO	SHARE	2030	Sewage sludge		0.10	
LO	SHARE	2030	MSW		0.10	
				Heat	1.00	17.2

Table 53 shows the fuel use constraints in 2030. Petcoke contribution is restricted using an upper bound of 50%. The lower bounds for the alternative fuels are based on the OFICEMEN (2010a) statistics. It is worth noting that TIMES-Spain does not include all the commodities required to represent the 14 waste materials introduced as alternative fuels (see Appendix I) so the alternative fuels considered are biomass, MSW and sludge.

2.3.5. CO_2 capture solutions

In Chapter 4 Section 1.3.7 CO_2 capture technology has been applied to the cement industry. In that assessment, the technology used was the post-combustion CO_2 capture using chemical absorption (MEA, monoethanolamine). The reference document was IEA GHG (2008).

In the modelling exercise, two new technologies have been implemented to analyse the role of CO_2 capture in the future cement production. First, the post-combustion CO_2 capture (PCC) using MEA, a well-proven technology in other industries such as food and chemicals. Second, the oxyfuel combustion CO_2 capture (OCC) being currently tested in some pilot power plants such as Compostilla, in Spain. Main design parameters of both have been taken from IEA GHG (2008) and UNIDO (2010).

It is expected that PCC will be suitable for its application at large scale in cement production beyond 2020 whereas OCC is expected to emerge in 2030. The main difference is that PCC is valid as retrofit in existing cement plants but OCC requires new kiln designs so its application is more appropriate to new cement plants.

Table 54. Clinker production with post-combustion CO_2 capture in TIMES-Spain

Input	Output	Amount	Start	AFA	Life	INVCOST	FIXOM	VAROM	CO_2 capture
					years	M€/Mt	M€/Mt	M€/Mt	%
ICMHTH		6.49 PJ							
ICMPRC		3.00 PJ							
Limestone		1.51 Mt							
	Clinker	1.00 Mt	2020	0.95	25	508	35	31	85
	Electricity	0.08 PJ							

The PCC technology modeled in TIMES-Spain (Table 54) introduces two different kind of heat: ICMPRC which is the process heat generated in the kiln required for the clinker production and ICMHTH is the heat produced by CHP plants used by the CO_2 capture unit to produce steam which is used for solvent regeneration and to avoid the membrane degradation. Furthermore, the CHP produces electricity, as co-product, enough to satisfy the power demand of both, the cement plant and the CO_2 capture unit. The electricity surplus is then released to the grid (IEA GHG, 2008). In this work, the consideration of the electricity surplus has been removed to avoid the competition between the cement production and the electricity production.

CO_2 capture efficiency is 85%. According to IEA GHG (2008) this capture could reach up to 95% but only under special conditions.

Table 55. Clinker production with oxyfuel combustion CO_2 capture in TIMES-Spain

Input	Output	Amount	Start	AFA	Life	INVCOST	FIXOM	VAROM	CO_2 capture
					years	M€/Mt	M€/Mt	M€/Mt	%
Electricity		0.53 PJ							
INDCOA		0.25 PJ							
ICMPRC		3.00 PJ							
Limestone		1.51 Mt							
	Clinker	1.00 Mt	2030	0.95	25	277	23	22	52

Table 55 above shows the main parameters of the clinker production with OCC technology. CO_2 capture efficiency is 52%, much lower than in PCC (IEA GHG, 2008; UNIDO, 2010). In contrast to PCC, OCC has not a CHP plant associated to produce heat and electricity. Electricity consumption is significant and it is linked to the compressors and pumps as well as the Venturi scrubber (IEA GHG, 2008) although the total is higher in the PCC mainly due to the flue gas treatments (SCR, FGD) and the compression. In the PCC case, the total electricity consumed for the CO_2 capture reaches 0.53 PJ/yr whereas the OCC consumes around 0.36 PJ/yr. According to IEA GHG (2008), an extra amount of coal is needed (0.25 PJ). Finally, process heat needed in the clinker production is the same in both cases, 3 PJ, considering that when CO_2 capture takes place, the thermal consumption of the kiln is optimised. The costs have been obtained from IEA GHG (2008) and UNIDO (2010).

2.4. Modelling the improvement scenarios

2.4.1. Directives scenario

In this section the reference modelling case is described in depth: **Directives scenario (Dir)**. This scenario includes the main adjustments and calibrations described in Chapter 2 (Table 56).

Table 56. Directives scenario description

Development	Description
Directive 2009/29/EC (ETS)	20% GHG emissions reduction by 2020 respect to the 1990 level as has been described in Chapter 4 Section 2.1.2.
Directive 2001/81/EC (NEC)	Ceilings for several pollutants (NO_x and SO_2) for Spain in 2010 as described in Chapter 4 Section 2.1.2.
Directive 2009/28/EC (RES)	20% share in the final energy consumption coming from renewable sources by 2020. It also includes the biofuels target for Spain: 10% of consumption from biofuel in 2020.
Nuclear	No new nuclear capacity
Feed-in tariffs	Feed-in tariffs in Spain from 2005 to 2012.

Furthermore, other several implementations have been carried out in TIMES-Spain. The projection of the end-use demand services such as cement, steel, aluminium, paper, transport, residential water heating, cooling, etc., has been updated. Emissions factors for different pollutants have been introduced by sector and by process. The costs of power production technologies such as wind turbines, solar photovoltaic systems, NGCC, etc., have been updated. In the same manner, fossil fuel prices have been updated using projections of the International Energy Agency and a sensibility analysis has been done. The delivery costs of the fuels by sector are also included in TIMES-Spain and renewable sources potentials have been updated.

Finally, specific adjustments (stocks, activity bounds, costs, etc.) in industrial and electricity generation processes have been implemented in the model.

Additionally, a case considering all the items of Table 56 but excluding the Directives 2009/29/EC and 2001/81/EC has been built. This scenario is the so-called **NoDir scenario**. It is important to remark that Directive 2009/28/EC concerning the renewable energy systems is included in every run.

2.4.2. CO_2 bounds in cement industry

Aside from the bounds derived from applying Directive 2009/29/EC on GHG reductions, the Spanish proposal of National Implementation Measures (NIMs) for the allocation of free allowances provides a list with the registered installations. According to MAGRAMA (2012d), where the NIMs are presented, the sum of the free allowances of the cement facilities is equal to 24.73 Mt CO_2/yr from 2013 to 2020. This is the limit set to the CO_2 emissions in the **ICM-CO_2-Cap scenario**. Besides, the limit has been kept beyond 2020 and up to 2050.

The Spanish NIMs document (MAGRAMA, 2012d) was published on June 26th, 2012. Recently, on September 5th 2013, European Commission published the Decision 2013/448/EU where the Spanish NIMs proposal was accepted.

Furthermore, an extra scenario has been built to assess the sensibility of the cement industry under stricter CO_2 limits (see Table 57). This case has been named as **ICM-CO2-Cap-High scenario**.

Table 57. ICM-CO_2-Cap-High scenario implementation in TIMES-Spain

Year	CO_2 (Mt)
2015-2020	24.73
2025	22.00
2030	20.00
2035	18.00
2040-2050	16.00

2.4.3. Cement demand projections

As has been seen in Chapter 3, end-use demands are exogenously introduced into the model. Spain produced 55 Mt of cement in 2005, 26.2 Mt in 2010 and 15.8 Mt in 2012 (OFICEMEN web). It is expected that the cement demand reaches the bottom in 2014. Therefore, three demand scenarios have been built using different criteria according to the sectorial projections (OFICEMEN, 2013a; 2013b), GDP, and population. Those demand projections are represented in the following Figure 22.

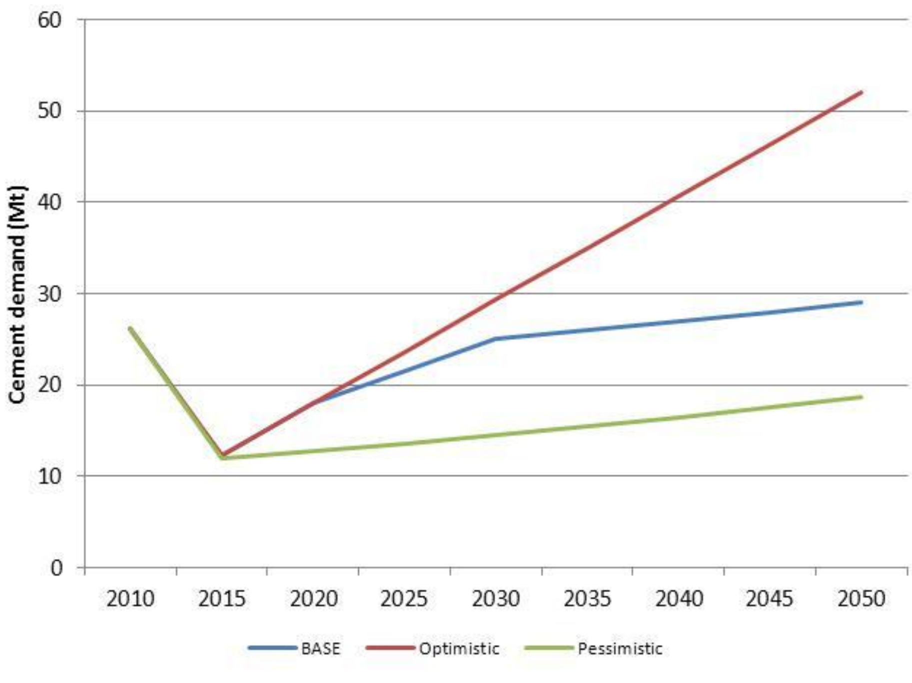


Figure 22. Cement demands projections

Next, in Table 58, it is expressed the detailed values of the cement demands projections.

Table 58. Cement demands scenario implementation in TIMES-Spain

Year	Base	Optimistic	Pessimistic
	ICM-DemProj-BASE	ICM-DemProj-A	ICM-DemProj-B
	Mt	Mt	Mt
2010	26.22	26.22	26.22
2015	12.33	12.33	12.02
2020	18.00	18.00	12.81
2025	21.50	23.67	13.65
2030	25.00	29.34	14.54
2035	26.00	35.00	15.49
2040	27.00	40.67	16.51
2045	28.00	46.34	17.59
2050	29.00	52.00	18.74

- **BASE**: this scenario has been built using the cement demand projection expected by OFICEMEN until 2030 (OFICEMEN, 2013b). In this projection it is assumed that 18 Mt will be achieved in 2020 and 25 Mt in 2030. The 2015 value is an extrapolation of 2013 and 2014 expected production (OFICEMEN, 2013b). Beyond 2030 and considering the optimisation of the cement consumption per capita as 550 kg/yr demand is supposed to reach 25 Mt/yr. From then on it is assumed a slight growth reaching 29 Mt in 2050.
- **Optimistic**: according to OFICEMEN (2013a), it is assumed 10.7 Mt in 2013, 11.2 Mt in 2014 and 18 Mt in 2020.The 2015 value is also an extrapolation of 2013 and 2014 expected production. The same growth in each 5-years period from 2020 and beyond has been considered. This is a very optimistic scenario.
- **Pessimistic**: The 2015 value is based on the GDP growth (FUNCAS, 2013) starting from 2013 expected production, 10.7 Mt (OFICEMEN, 2013a). From 2020 to 2050, a growth of 6.55% has been estimated from the productions from 1975 to 2010 (OFICEMEN, 2010). On the other hand, assuming the European Commission estimates for the cement consumption per capita in 2030, 450 kg/yr (EC-SETIS web), and the Spanish population projections (INE, 2012b), i.e. 41.8 M of inhabitants in 2050, the cement demand foreseen is 18.8 Mt. This result supports the initial growth hypothesis of this scenario.

2.4.4. Costs of the cement technologies with CO_2 capture

The investment costs for the new clinker production processes with CO_2 capture are 558 M€ for PCC (from 2020) and 327 M€ for OCC (from 2030) (IEA GHG, 2008; UNIDO, 2010). To estimate the cost of capture, 50 M€ have been subtracted from the cement production facility costs in both cases as it is the cost that corresponds to the kiln process and the cement mills.

A sensitivity analysis of the investment costs of clinker processes has been carried out increasing and decreasing the investment cost 20% and 10% in both technologies. Table 59 shows the scenario matrix for the sensitivity analysis.

Table 59. Sensitivity tableau of the investment costs of clinker production with CO_2 capture

	ICM-OCC-20	ICM-OCC-10	ICM-OCC-00	ICM-OCC+10	ICM-OCC+20
ICM-PCC-20	A1	B1	C1	D1	F1
ICM-PCC-10	A2	B2	C2	D2	F2
ICM-PCC-00	A3	B3	C3	D3	F3
ICM-PCC+10	A4	B4	C4	D4	F4
ICM-PCC+20	A5	B5	C5	D5	F5

Each scenario is further analysed in the following results section. The discount rate is 12%.

2.5. Results and discussion

Several runs have been performed with TIMES-Spain with each scenario built to analyse the different aspects of the cement industry in Spain (NO_X, SO_2, CO_2 bounds, cement demands, costs of production with CCS). Results from those runs are thoroughly discussed in this section. It is noted that years in the X axis are 'milestone years' which correspond to periods around this year.

2.5.1. CO_2 emissions

The application of Directive 2009/29/EC on GHG emissions has a strong effect in terms of CO_2 emissions as can be seen in the next figure where the results are compared with those from a hypothetical scenario where the Directive is not in force.

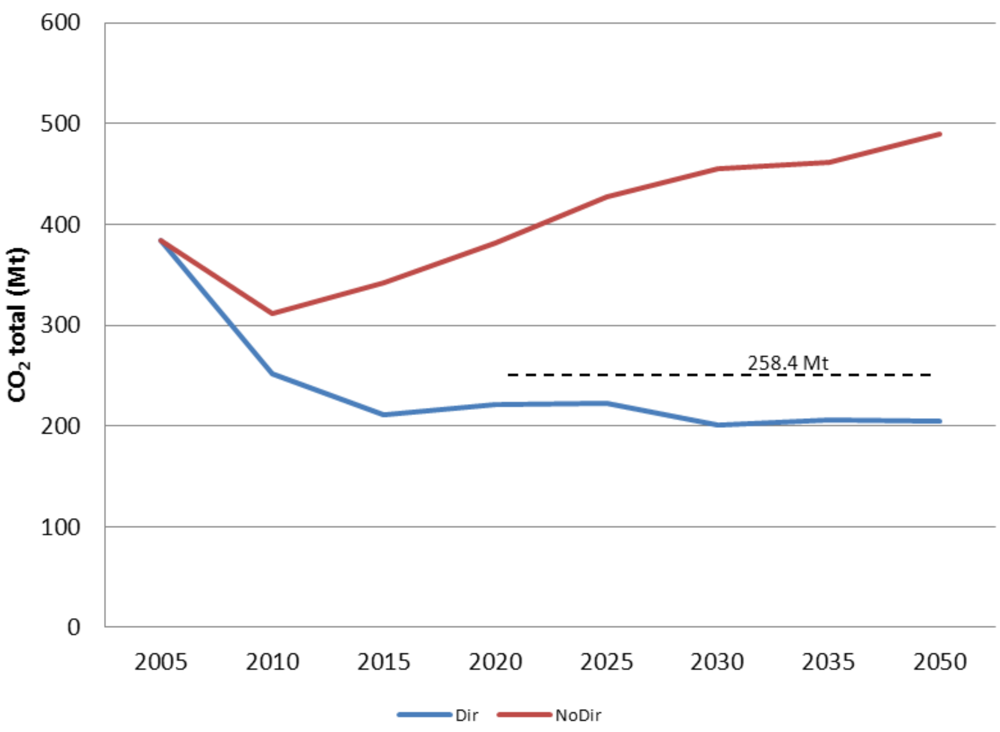


Figure 23. Total CO_2 emissions in Spain wo/w the Directive scenario

In Figure 23 results highlight the consequences of applying Directive 2009/29/EC. The decrease observed from 2005 to 2015 is due to the downfall of the end-use services demands during the recession years (2008-2013). From 2015 CO_2 targets established by the Directive (dotted line) are achieved. CO_2 emissions are 72% in 2020, 126% in 2030 and 139% in 2050, respect to the case with no Directive.

Figure 24 shows how restrictions affect to each energy demand sector when the Directive is applied.

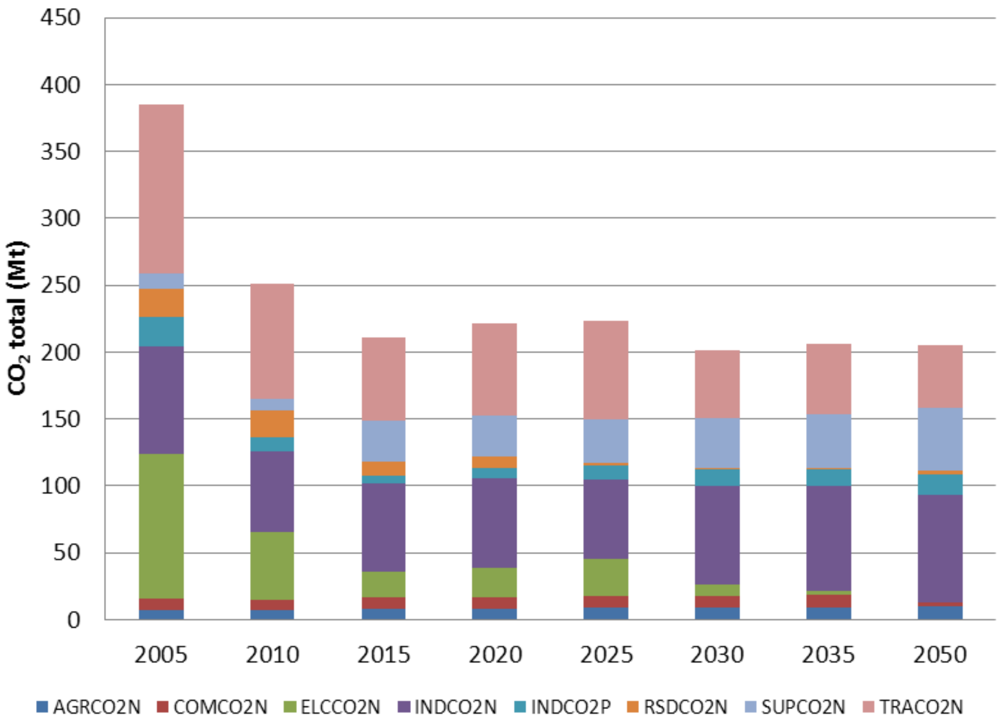


Figure 24. Sectorial CO_2 emissions considering Directive scenario

As discussed in Chapter 5, it is observed that CO_2 emissions coming from electricity production go down progresively until disappearing after 2035. Figure 25 show the shift in CO_2 emissions from electricity to industry in the NoDir (left) and Dir (right) scenarios .

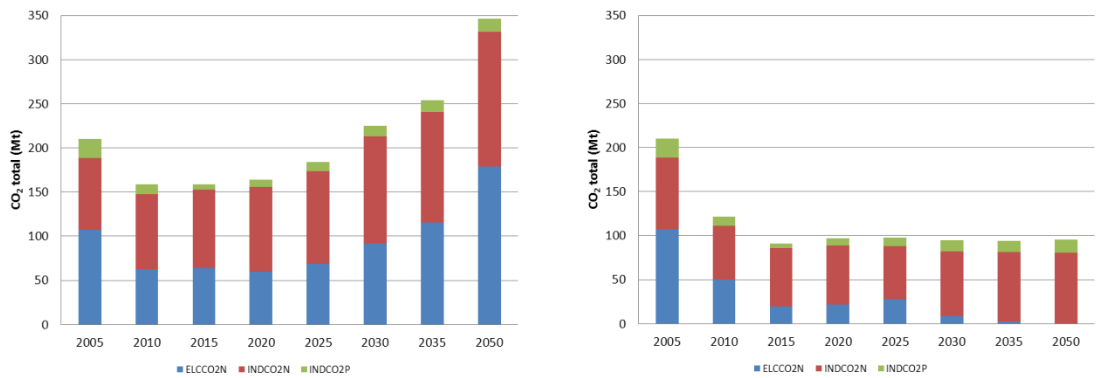


Figure 25. CO_2 emissions from electricity and industry wo/w the Directive scenario

In the NoDir scenario CO_2 emissions grow, especially those coming from the production of electricity. This is due to the use of coal power plants at the same time than NGCC plants continue producing electricity and natural gas CHP facilities emerge in the industry sector. On the contrary, in Dir scenario emissions decrease. Electricity is produced with natural gas CHP plants substituting NGCC plants. Consequently, CO_2 emissions from power disappear in 2035 and the CO_2 emissions coming from industrial combustion grow.

Likewise, CO_2 emissions of the cement industry have been assessed. The following Figure 26 shows the projections with and without applying the Directive 2009/29/EC.

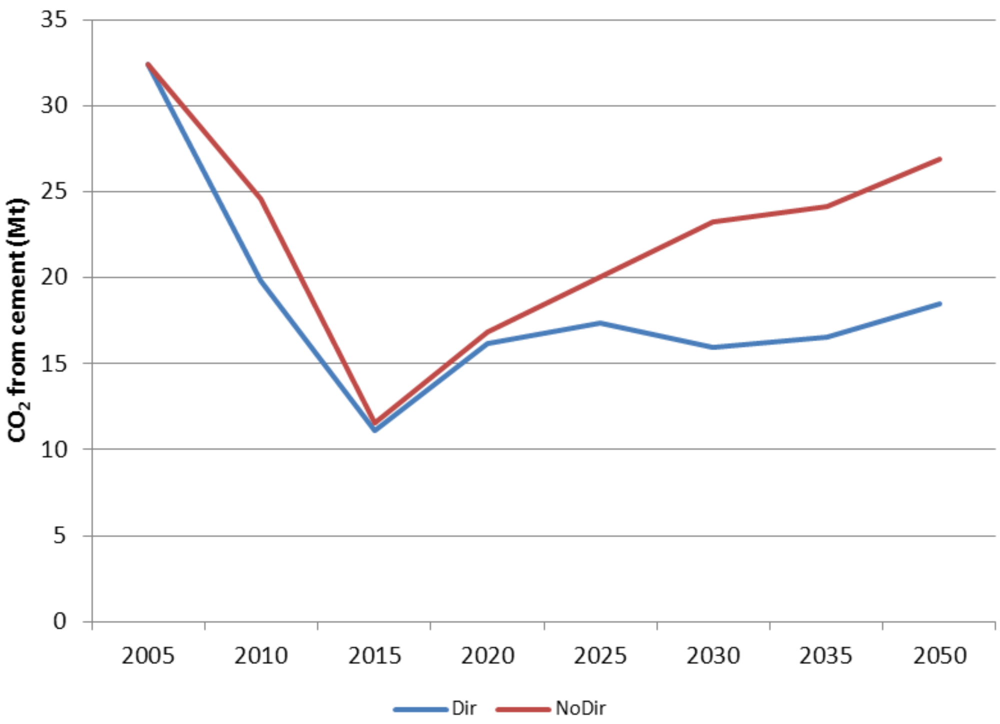


Figure 26. CO_2 emissions from cement production wo/w Directive scenario

Figure 26 shows that the Directive leads to reductions in the cement industry emissions of 7-8 Mt CO_2 respect to the case without Directive. The 2005-2015 fall is due to the cement demand decrease experimented by the Spanish cement industry from 2008 until 2013. According to the OFICEMEN estimates (OFICEMEN, 2013b), cement demand will start growing from 2015. The effect of Directive 2009/29/EC is remarkable from 2020. Deviation observed between NoDir and Dir is 15.5% in 2025 and 46% from 2030 and beyond. The effect of the Directive on the CO_2 emissions of the cement manufacture industry is also observed by means of a comparison with the total CO_2 emissions in Spain. This may be seen in next figure.

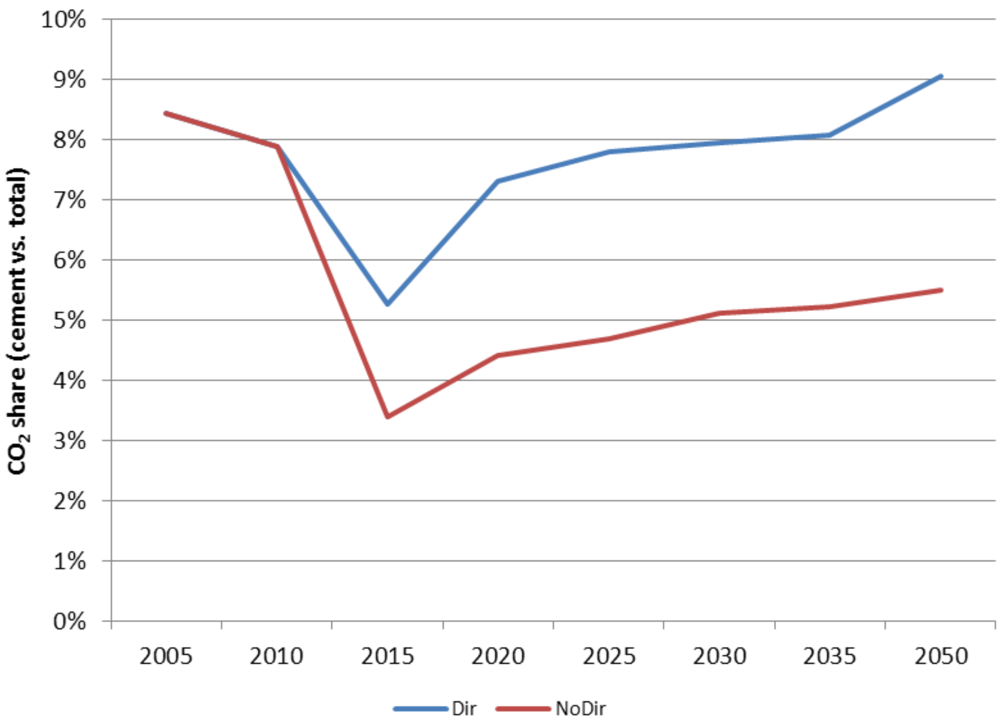


Figure 27. Share of CO_2 emissions from cement production respect to the Spanish total

Looking at Figure 27 it can be concluded that the share of the CO_2 emissions resulting from the cement production grows significantly from 2015. Results show a panorama where sectorial emissions reach 9% share in 2050 when Directive 2009/29/EC is considered whereas in NoDir scenario this value reaches 5.5%. This is due to the fact that other sectors make bigger efforts than cement industry to reduce emissions and meet the Directive.

From the point of view of the industry this is challenging. The majority of the CO_2 emissions in cement-making are not caused by energy use from fuel combustion, but come from the calcination of raw materials (CEMBUREAU, 2013). As said before, CO_2 from process entails 60% while CO_2 from combustion is 40% approximately. To solve that, different solutions have been considered by the cement industry in the last years (ECRA, 2012).

Table 60. Measures implemented in the 2030 Spanish cement production in TIMES-Spain

Code	Measure description	Detail
E1	Thermal energy efficiency	From 3,536 MJ/t clinker to 3,300 MJ/t clinker
E2	Electric energy efficiency	From 130 kWh/t cement to 106 kWh/t cement (69.43 kWh/t clinker)
E3	Material substitution	Clinker-to-cement ratio: from 0.8 to 0.7
E4	Fossil fuel substitution	Alternative fuels share: from 15.8% to 50% (in energy)
E5	Ideal case	All measures together

The effects of applying those measures (see Table 60) are shown in Figure 28.

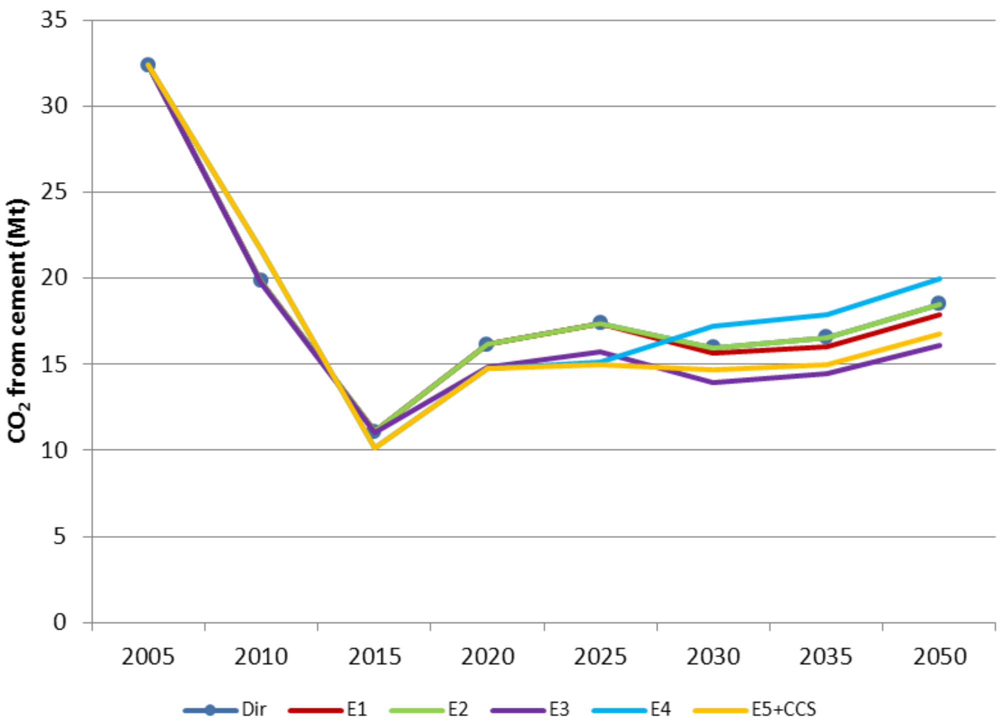


Figure 28. CO_2 emissions from cement production considering several measures

Measures implemented in TIMES-Spain, both BAT and substitution scenarios, allow to reduce the CO_2 emissions except for the fossil fuel substitution scenario, E4. This scenario leads to an increase of 1.3 Mt CO_2 emissions per year from 2030. This is due to the higher contribution of alternative fuels (10% sludges, 10% MSW and 30% biomass). The rest of the alternative fuels (see Appendix I) have been assimilated to MSW and sludges. Cement producers take into account the positive effect of removing waste from another place, mainly from landfill. In this work, only pure biomass has been considered CO_2 neutral.

E3 scenario involves the major reductions, 2-2.4 Mt CO_2 per year from 2030. In second place, E5 scenario achieves reductions of 1.3-1.7 Mt CO_2 respect to the Dir scenario from 2030 and beyond. Implementing all the measures together, E5, is not the best solution for reducing CO_2 emissions in the cement industry in the long-term.

Besides, the E1 scenario, introducing thermal energy efficiency measures, reduces 0.3-0.6 Mt from 2030. Finally, the electrical efficiency measures, E2, do not achieve any significant reduction respect to the Dir scenario in the long-term.

It has been assumed that cement demand is totally satisfied by the national cement production. Therefore, several scenarios have been built to analyse the effects of the different demands. The following Figure 29 shows the CO_2 projections obtained using those cement demands.

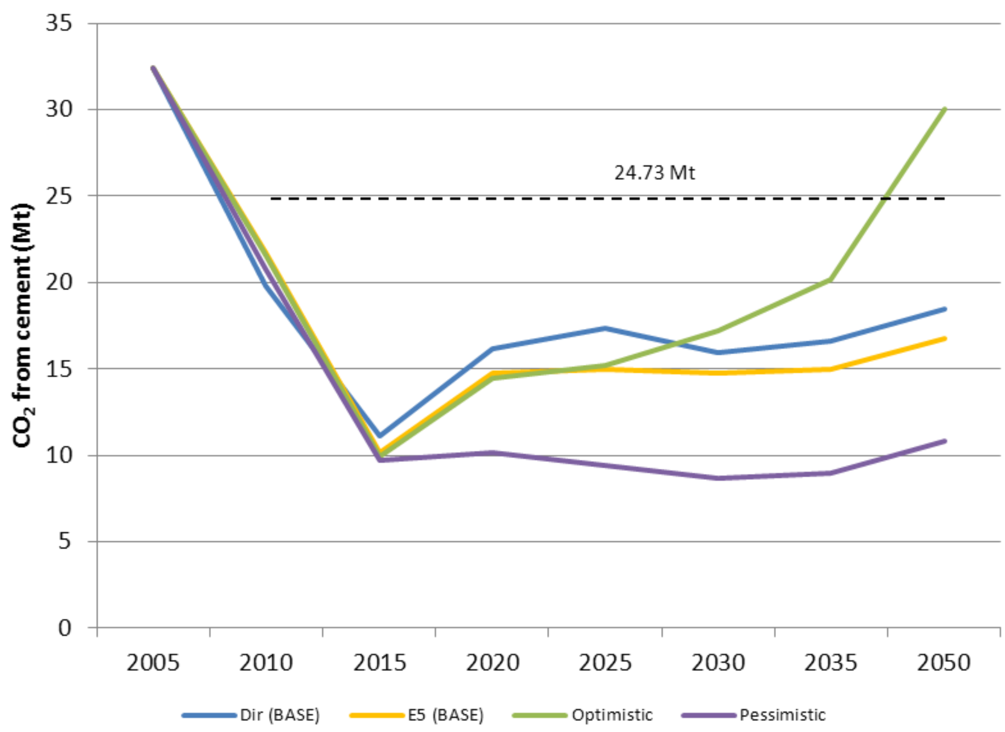


Figure 29. CO_2 emissions from cement production considering several cement demands

Results highlight that only Optimistic (DemProjA) scenario overtakes the limit imposed by the CO_2 sectorial cap (24.73 Mt) in 2050. In other words, CO_2 limits imposed by the NIM approved in Decision 2013/448/EU are higher than CO_2 emissions of the industry. In the conservative assumption of keeping the bound equal between 2020 and 2050, there would not be difficulties to meet the Directive since the expected cement demands are low.

It is likely that the European Commission updates the NIMs after 2020 using stricter allocation allowances for the CO_2. As a result, it seems reasonable to build a more stringent case: ICM-CO2-Cap-High scenario. This is discussed in Chapter 4 Section 2.5.5.

2.5.2. NO_x emissions

One of the main purposes of this work is to assess the application of Directive 2001/81/EC on the Spanish energy system. Furthermore, it is interesting to analyse the effect of the Directive at sectorial level looking at the NO_X emissions resulting from the cement production.

In the following Figure 30, total NO_x emissions with and without the Directive scenario are presented.

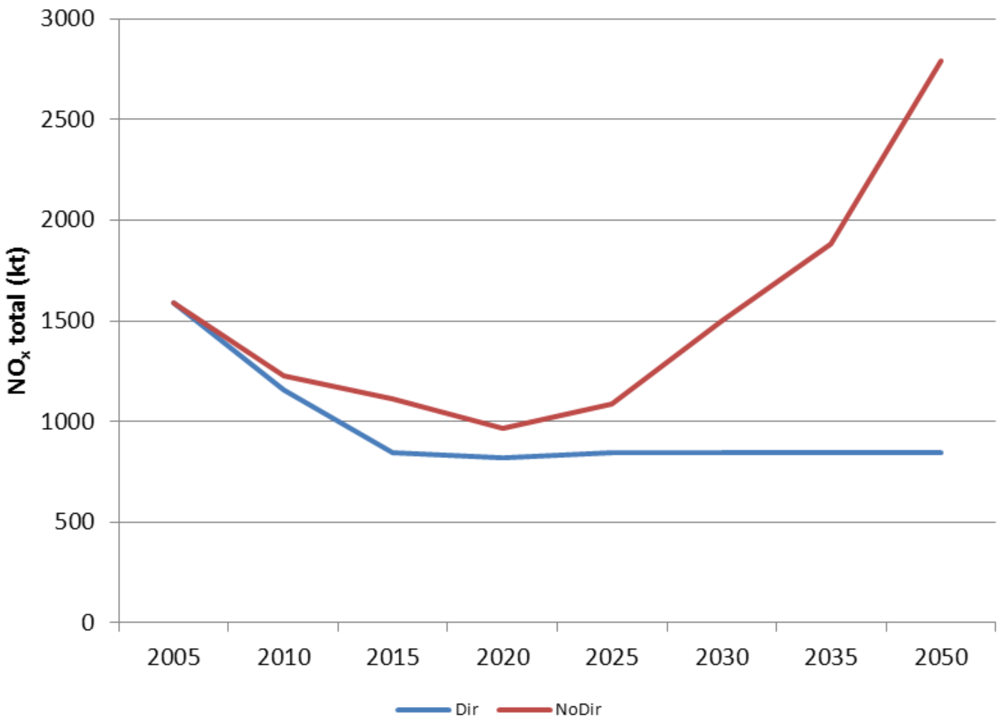


Figure 30. Total NO_X emissions in Spain wo/w Directives scenario

When Directive 2001/81/EC is applied, NO_x emissions remain constant from 2015 and stick to the limit set. Differences between NoDir and Dir scenarios are 18% in 2020, 77% in 2030 and 330% in 2050. These differences are due to the use of coal. In NoDir scenario, coal is used massively for producing electricity because it is the cheapest option. On the contrary, in Dir scenario coal consumption disappears in 2015. This may be observed in detail in the following Figure 31 where NO_x emissions are disaggregated by sector.

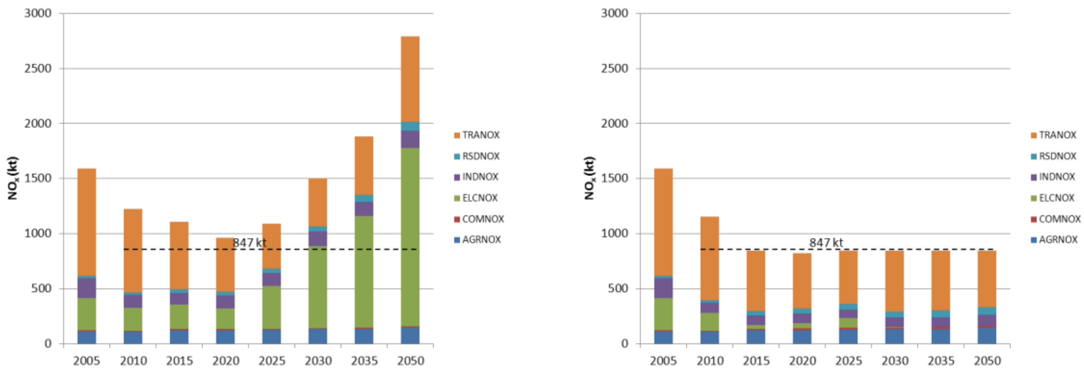


Figure 31. Sectorial NO_X emissions wo/w the Directive scenario

Figure 31 shows the total NO_x emissions without (left) and with (right) Directive 2001/81/EC. The emissions from electricity disappear in 2030 when the Directive is applied. In opposition, NO_X emissions from transport are significant until the end of horizon in both scenarios. This is due to the different sectorial reduction efforts. Specifically, Dir scenario reduces CO_2 emissions by means of reducing the use of coal in the electricity production (to accomplish with Directive 2009/29/EC). Consequently, NO_x emissions are extinguished in the electricity sector. This fact allows other sectors, such as transport, releasing more NO_x because the ceiling is not yet reached.

NO_X emissions from cement production are low compared to the total: 20-30 kt per year, 2.3-3.5%, with respect to the total. In Figure 32, NO_x emissions from cement production are shown considering several scenarios.

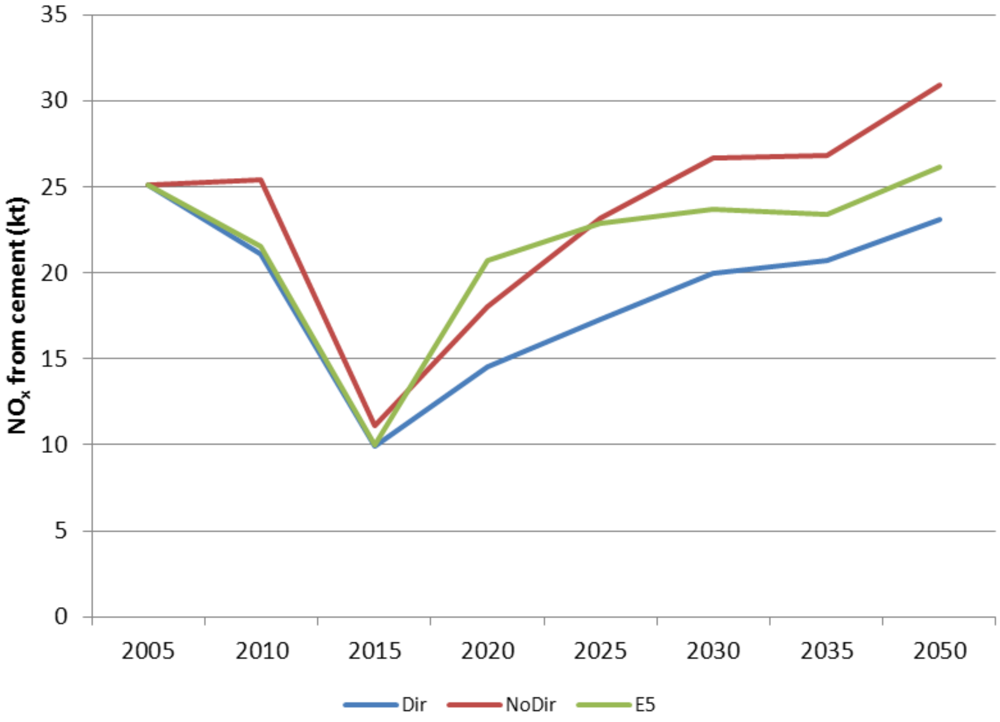


Figure 32. NO_X emissions from cement production considering several scenarios

NO_x emissions in the E5 scenario are higher than in the Dir one due to the use of alternative fuels. In particular, the major presence of sludge and its higher emission factor (compared to the petroleum coke) causes this increase.

Respect to the Dir scenario, the application of Directive 2001/81/EC involves a reduction of 6-8 kt NO_x in the emissions regarding the NoDir one, resulting from the cement production from 2030.

2.5.3. SO_2 emissions

SO_2 emissions are linked to the coal utilisation both in electricity production and industrial combustions. Next, total SO_2 emissions released in Spain with and without Directive 2001/81/EC are shown in Figure 33.

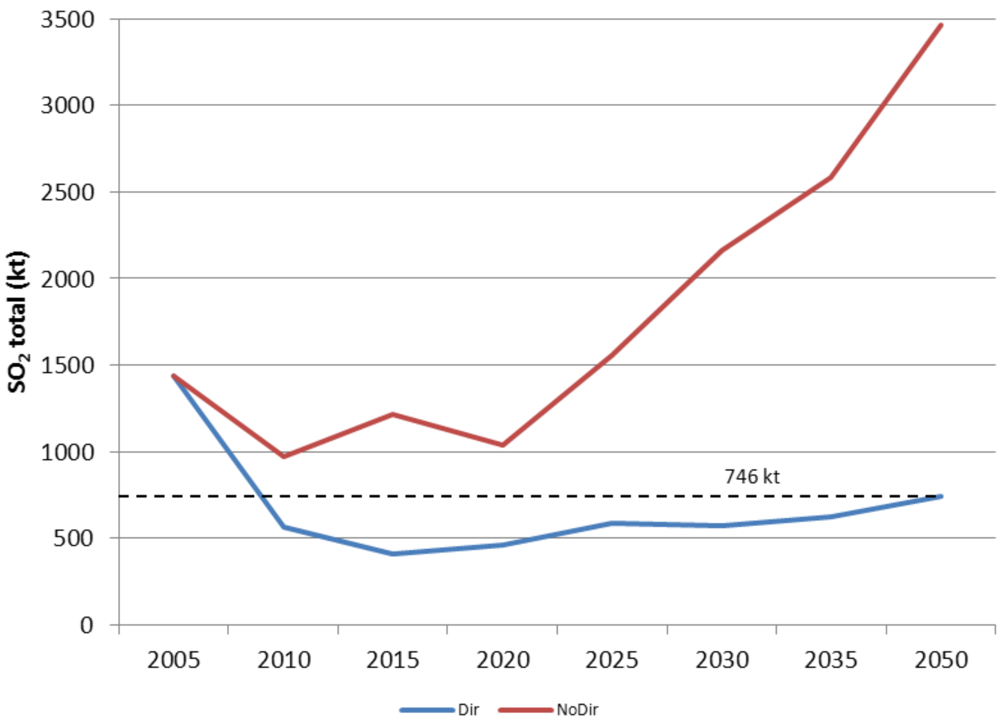


Figure 33. Total SO_2 emissions in Spain wo/w Directives scenario

In the Dir scenario emissions do not exceed the Directive's ceiling although it is reached in 2050. The main reason of the great decrease in the first periods is the economic crisis which led to a fall in the end-use demands. Besides, during 2010 period renewable energy technologies grew and the use of coal fell. This can be seen in detail in Figure 34.

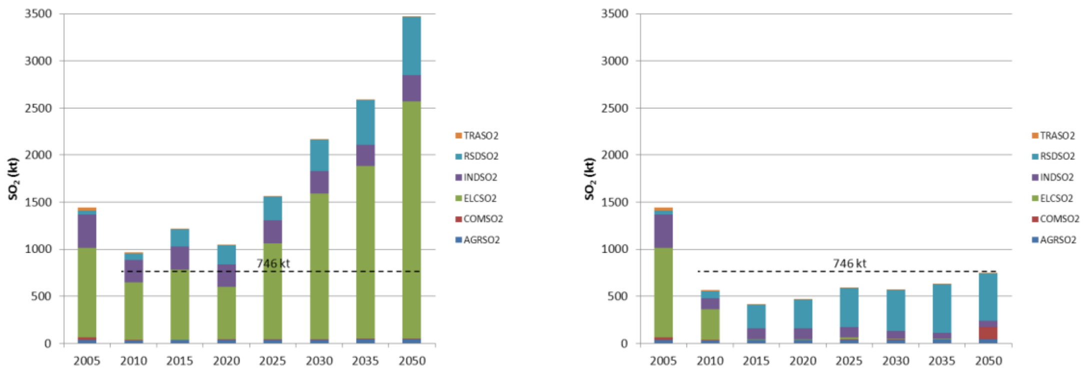


Figure 34. Sectorial SO_2 emissions wo/w Directives scenario

SO_2 emissions from the electricity production sector reduce in 2015 when Directive 2001/81/EC is applied. This is a consequence of the coal power plants phase out. It can be seen that the ceiling is too high compared to the projection of the emissions what points out the need to update the Directive establishing a new stricter limit. As has been discussed, when this ceiling was set in 1998, the 2008 recession and its consequences were not foreseen.

In summary, it is strongly recommended to review the SO_2 ceiling and consider setting a stricter one.

Next figure presents the projection of the SO_2 emissions derived from cement production considering several scenarios.

Figure 35. SO_2 emissions from cement production considering several scenarios

As has been said, cement demand went from 55 Mt in 2005 to 24 Mt in 2010. This reduction and the technology upgrade led to a decrease in the use of petroleum coke for the kilns from 3.21 Mt to 1.91 Mt (OFICEMEN 2005; 2010a). Petroleum coke has high sulphur content so its decrease and the progressive entrance of alternative fuels lead to the exhaustion of the SO_2 emissions in the cement production.

Figure 35 shows that Dir scenario leads to the disappearance of the SO_2 emissions coming from the cement production from 2010. The E5 scenario, on the contrary, results in an increase in the SO_2 emissions from 2015 due, once more, to the introduction of the alternative fuels. Finally, emissions from NoDir scenario grow in the same manner as cement demand does because the sector continues using petroleum coke at maximum level.

2.5.4. Clinker production technologies

Cement production is modelled in TIMES-Spain using a specific scheme where cement is produced in an auxiliary entity called “finishing process” just after the clinker is produced (see Figure 21). In the following figures clinker production technologies have been evaluated for the five technological scenarios described above which allow reducing the CO_2 emissions and increasing the efficiencies. Figure 36 shows the clinker production breakdown when any measure is implemented.

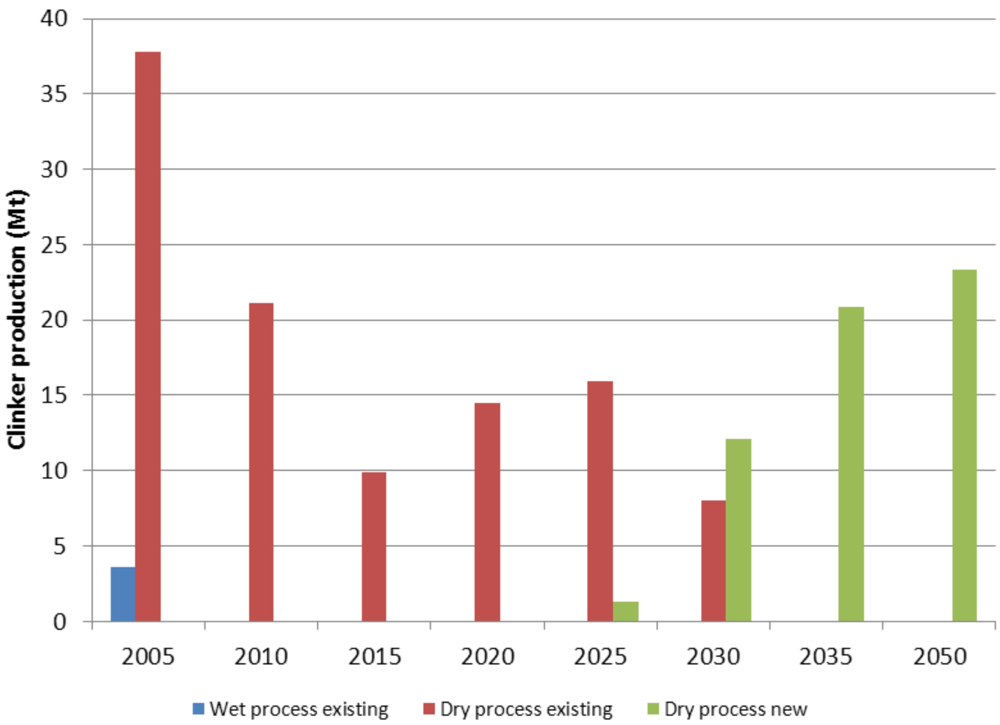


Figure 36. Clinker production technology breakdown without measures

What is interesting in Figure 36 above is the early retirement of the wet-route processes. There were 3 wet route-typed kilns in operation in 2010 in Spain. This deviation is assumed in modelling terms but there is a clear trend pointing out the retirement of this technological option, as literature foresees.

Besides, it is observed that the existing dry-route clinker processes also retire in 2030, being substituted by new dry-route processes.

There are some changes when the expected 2030 BAT measures and substitution scenarios are taken into consideration. Figure 37 shows the clinker technology projections when several technology improvements are considered. From top to bottom and left to right, figures represent E1, E2, E3 and E4 scenarios.

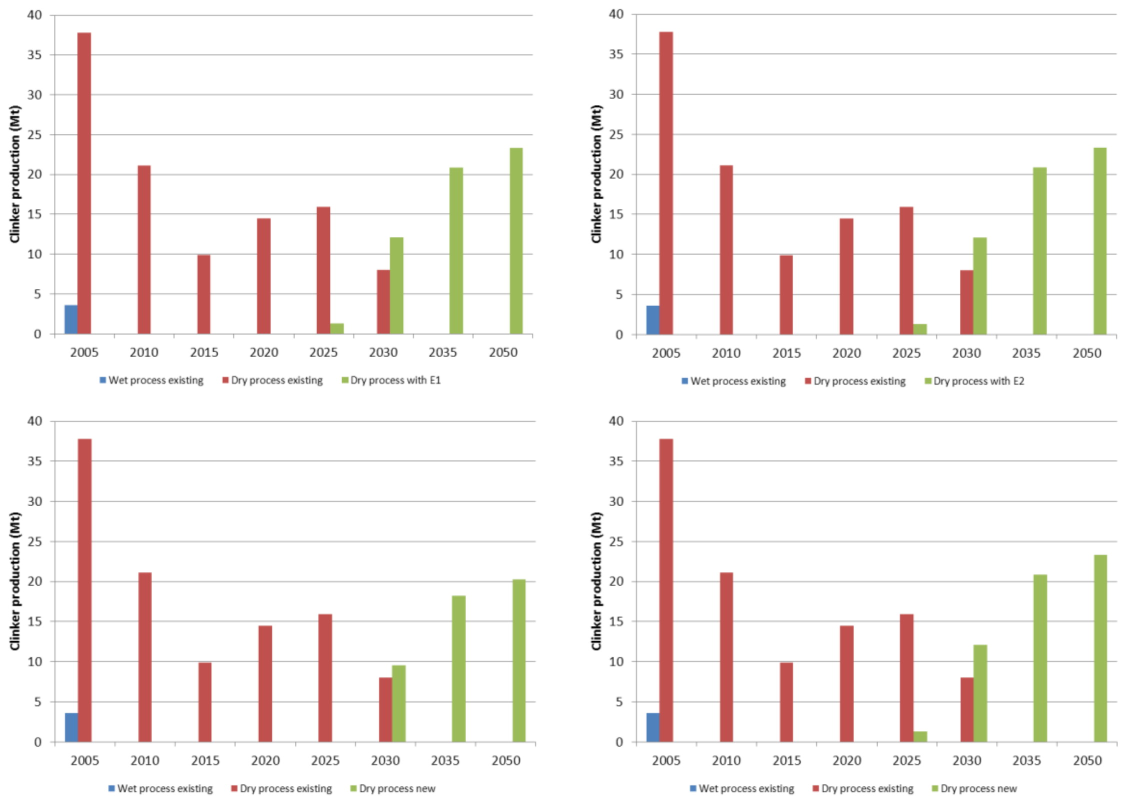


Figure 37. Clinker production technology breakdowns with measures

BAT solutions (E1 & E2) entry the system when existing dry production processes disappear (2025-2030) because in these technologies energy consumption is optimised and they do not involve significant changes in the investment costs. The E3 scenario includes the effect of modifying clinker content in cement. In such a case, only the existing processes would satisfy the cement demand up to 2025 and new dry-route clinker processes would begin to produce in 2030. Finally, the E4 scenario results are the same as those from the scenario without measures (see Figure 36) since the fossil fuel substitution does not involve changes in the technology selection for the clinker production.

In the ideal scenario of applying all the previous measures together, E5 scenario, the resulting breakdown of the clinker production processes would be as follows (see Figure 38).

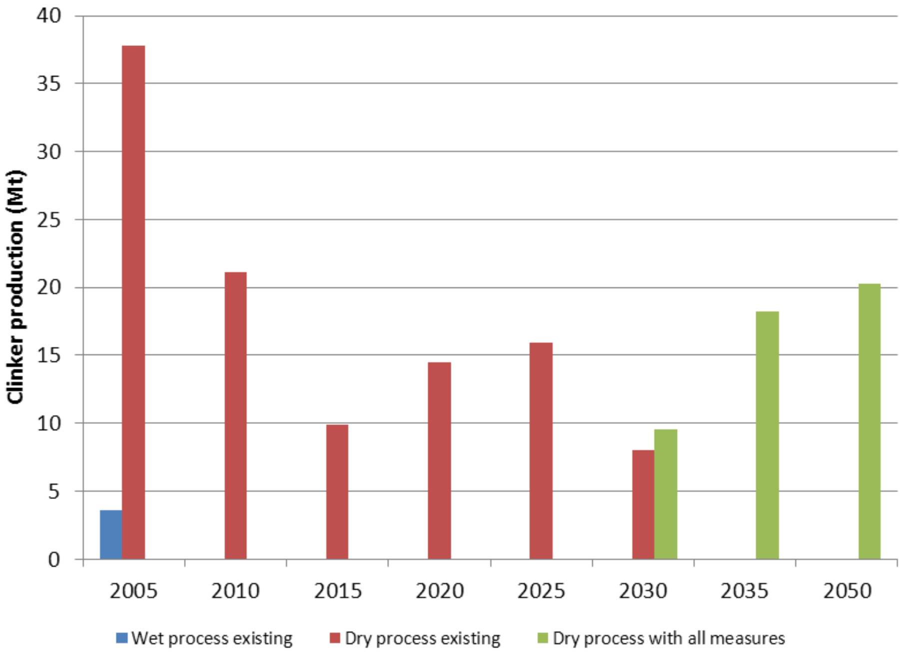


Figure 38. Clinker production technology breakdown with all measures implemented

These results are identical to the E3 scenario ones but differ in the energy consumption and emissions which are related to the higher efficiencies and nature of the fuels used in the E3 case.

Further analysis on energy consumed by the cement industry is shown in Figure 39 below. It represents the total energy consumed including different energy carriers as electricity and heat.

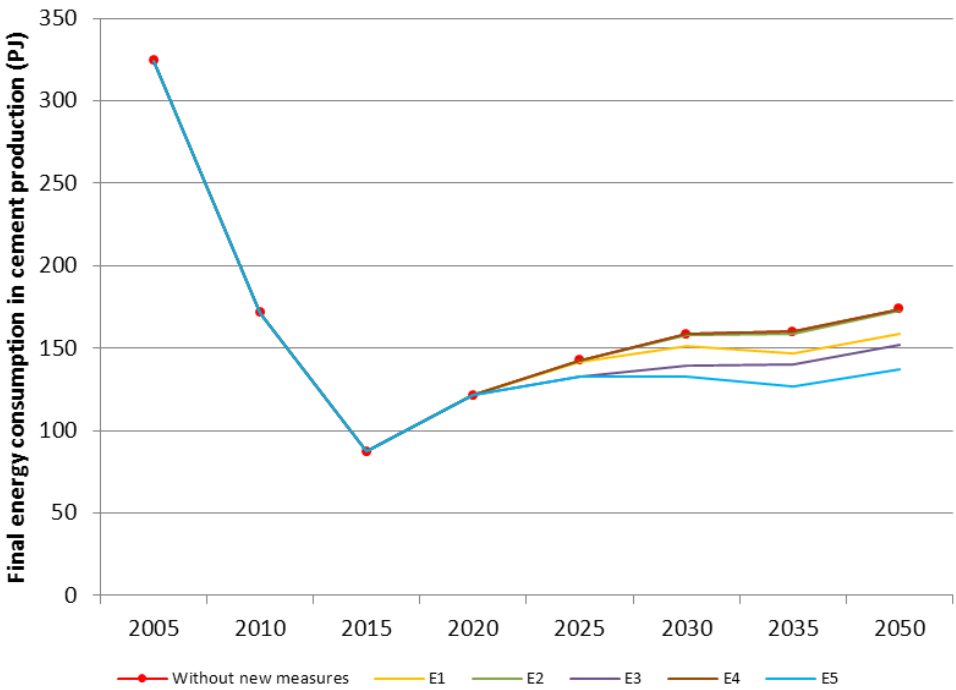


Figure 39. Final energy consumption of the Spanish cement industry

Results highlight that the best way to reduce energy consumption is the E5 scenario which achieves up to 21% reduction compared to a case without measures. After E5, the material substitution and the increase of the thermal efficiency achieve the major reductions.

2.5.5. CO_2 capture in the Spanish cement industry

From the results derived from applying Directive 2009/29/EC, it has been observed that carbon capture technologies do not emerge in any case.

As shown in Figure 29, only the scenario with high cement demands (Optimistic) involves an overtaking of the CO_2 sectorial cap, 24.73 Mt CO_2 in 2050. Subsequently, to observe the behaviour of the cement production in the most advantageous case for the CO_2 capture, two scenarios has been analysed: ICM-CO2-Cap and ICM-CO2-Cap-High scenarios. In both cases, a high cement demand has been assumed. Next figures show the clinker technology selected considering those scenarios.

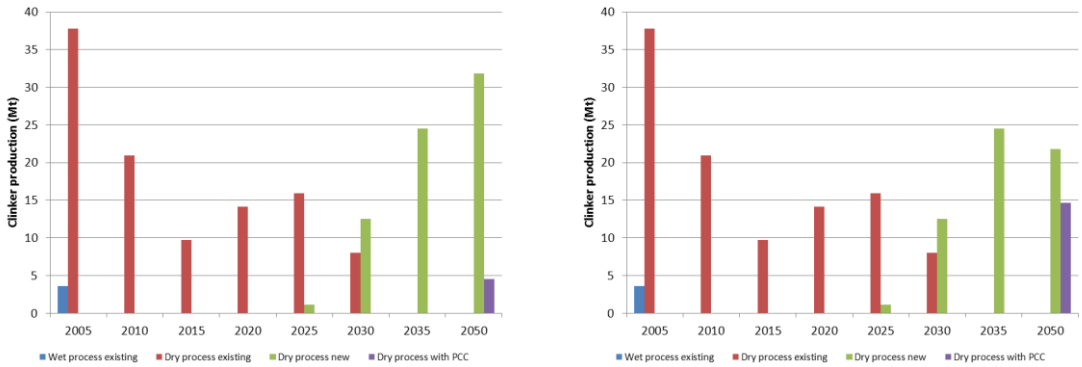


Figure 40. Clinker technology breakdown with high cement demand and CO_2 strict limits

Results from Figure 40 show the emergence of the CO_2 capture in 2050. It is observed that in ICM-CO2-Cap scenario (left), clinker plants with PCC produce 12.4% and 40.2% in ICM-CO2-Cap-High scenario (right).

The optimal CO_2 capture technology for clinker production is the post-combustion using MEA as membrane (PCC) due to the higher level of development of this technology comparing with oxyfuel (OCC) processes.

Additionally, a sensitivity analysis of the investment costs of the clinker production processes with PCC has been carried out. The following Figure 41 shows the amounts of CO_2 captured considering different CO_2 caps and investment costs of the technologies.

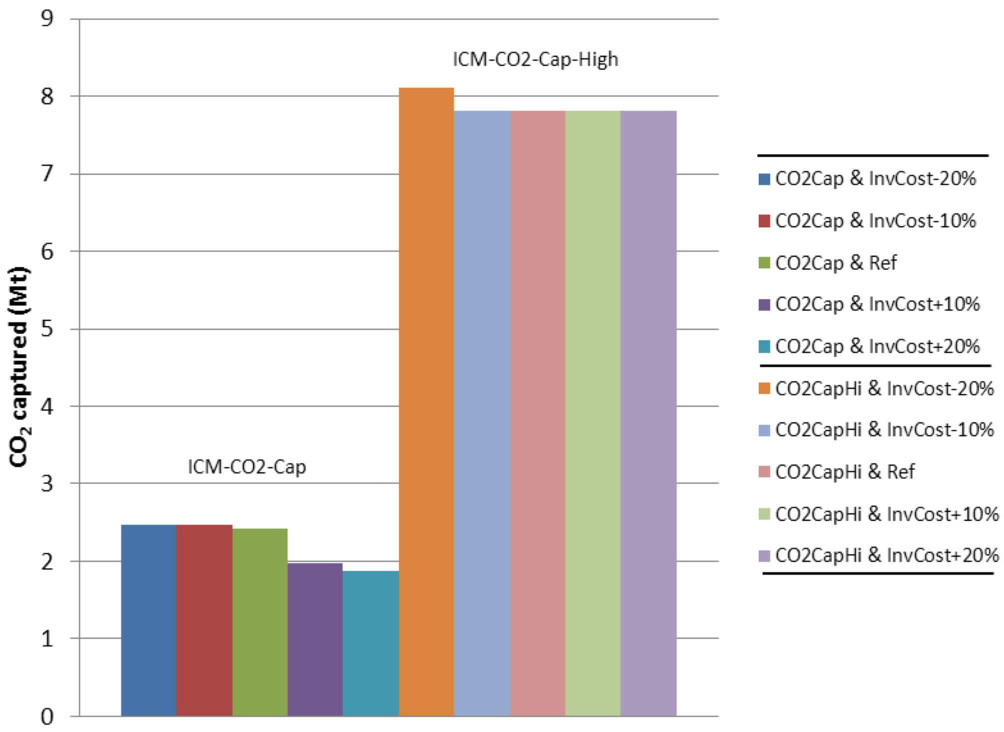


Figure 41. CO_2 emissions captured in cement production in 2050 with high cement demand

±10% and ±20% variations in the technology investment costs have been analysed (see Table 59). Results highlight that OCC does not appear in any case, even in the most advantageous one for this technology (A5: OCC-20% and PCC+20%).

Figure 41 shows the CO_2 emissions captured in 2050 in the different investment costs scenarios of the PCC. In the case of considering the ICM-CO2-Cap scenario, PCC would capture 2.41 Mt CO_2 in 2050 period. CO_2 emissions show sensitivity to the investment costs increase (it would be captured less) but does not to the diminution of the costs. Furthermore, in the ICM-CO2-Cap-High scenario there is only a slight sensitivity to 20% decrease of the investment costs. In such case, PCC grows and CO_2 emissions captured reach 8.11 Mt in 2050. In the rest of the cases, the CO_2 emissions captured mean 7.80 Mt.

In addition, considering the ICM-CO2-Cap-High scenario, PCC start would anticipate to 2030 period capturing up to 0.38 Mt CO_2.

In summary, CO_2 capture technologies are not an optimal solution for the cement production industry unless cement demands are high and CO_2 sectorial limits stricter.

2.6. Summary

In this chapter, Spanish cement production has been deeply analysed. The effect of Directives 2009/29/EC and 2001/81/EC in the cement sector in the medium and long term has been evaluated using an energy optimisation model. Moreover, a technology assessment has been carried out to observe the solutions discussed in the preceding LCA study concerning the Spanish cement manufacture.

Many scenarios have been built to analyse CO_2 emissions, cement demands and investment costs of the production technologies with CO_2 capture. Furthermore, the specific emissions of CO_2, NO_X and SO_2, the clinker production technology breakdowns, the final energy consumption and the CO_2 captured under different considerations have been evaluated.

CO_2 emissions

As expected, Directive 2009/29/EC on GHG emissions has a significant effect in terms of CO_2 reductions compared to a case without restrictions. Particularly, the CO_2 emissions of the electricity production sector are extinguished in 2035 due to the phase out of the coal power plants and the shift to natural gas from 2015.

Moreover, the Directive leads to reductions of 7-8 Mt CO_2 in the emissions resulting from the cement industry respect to the case without Directive, reaching a ceiling of 18 Mt CO_2 per year at the end of the horizon. Looking at the evolution of the share of cement sector emissions compared to the total, it grows from 6% in 2010 to 9% in 2050. An interesting challenge of the cement producers arises: *how to be competitive with other industries or sectors in terms of CO_2 reductions*.

In order to face this challenge, solutions identified in the LCA of the Spanish cement industry have been modelled with TIMES-Spain: thermal and electric energy efficiency measures, material substitution and fossil fuel substitution by alternative fuels derived from waste. Furthermore, several clinker production processes with CO_2 capture have been modelled, one with post-combustion and other with oxyfuel. Results have shown that the major CO_2 reductions come from the material substitution (up to 2-2.4 Mt of CO_2 reduction yearly from 2030). Besides, the implementation of all measures together allows reducing 1.3-1.7 Mt every year.

When the cement demand is high, CO_2 limits imposed by the NIMs approved in Decision 2013/448/EU are higher than CO_2 released by the industry in 2050. In the conservative assumption of keeping the bound equal beyond 2020, there would not be difficulties for reaching the CO_2 targets.

NO_x emissions

When Directive 2001/81/EC is applied, NO_x emissions coming from electricity disappear. NO_x emissions from the cement sector mean around 2.3-3.5% from the total. Nevertheless, when technological measures are considered, NO_x emissions grow slightly due to the alternative fuels combustion.

SO_2 emissions

In the cement production sector, SO_2 emissions disappear rapidly when the petroleum coke is substituted by alternative fuels.

The Directive's ceiling is too high compared with the reality. Consequently, Directive 2001/81/EC should be updated to establish a stricter SO_2 ceiling.

Clinker production technology breakdown

Clinker production has been analysed looking at the processes which satisfy the cement demands. Results have shown the early extinction of the wet-route processes as well as the retirement of the existing dry-route processes in favour of new solutions.

Attending to the energy consumption of the different technological options implemented, the ideal scenario with all measures together achieves up to 21% reductions in the long-term.

CO_2 capture in the Spanish cement industry

CO_2 capture solutions in the Spanish cement production only seem to be an optimal solution when cement demands are high and CO_2 sectorial limits are stricter. Only when with the rest of the technological options, CO_2 target is not achieved, dry-route clinker production with post-combustion CO_2 capture using MEA appears in 2050. In such case, depending on the CO_2 restrictions, it is possible to capture from 2 Mt CO_2 in the conservative CO_2 cap scenario to 8 Mt CO_2 under stringent CO_2 bounds.

5 SPANISH ELECTRICITY INDUSTRY

1. Modelling with TIMES-Spain

As for the cement production, a modelling exercise has been carried out using the TIMES-Spain energy optimisation model to explore the degree of accomplishment of the environmental Directives in the electricity generation sector.

Firstly, recalibration from 2000 to 2005 and other adjustments concerning the technology parameters have been done. Next, Directives 2001/81/EC and 2009/29/EC have been implemented similarly to the cement case. The composition of the electricity generation system has been analysed. Finally, specific scenarios concerning CO_2 emissions and fossil fuel prices have been built to assess the evolution of the Spanish energy system until 2050.

1.1. Meeting the Directives targets

1.1.1. Directive 2009/29/EC

Directive 2009/29/EC on GHG emissions reductions (extension of Directive 2003/87/EC) has been implemented in TIMES-Spain imposing CO_2 national bounds. Power generation plants are included in the list of activities subject to the Directive (see Chapter 2).

The CO_2 bounds imposed are 284.4 Mt CO_2 in 2010 and 258.4 Mt CO_2 from 2020 to 2050.

1.1.2. Directive 2001/81/EC

Directive 2001/81/EC establishes national emission ceilings for certain atmospheric pollutants (SO_2, NO_x, VOCs and NH_3) in the year 2010. To assess these substances, Spanish ceilings imposed have been introduced in the Directive scenario.

The bounds considered are 746 kt for the SO_2 and 847 kt for the NO_x from 2015 to 2050.

1.2. Modelling electricity-specific scenarios in TIMES-Spain

1.2.1. CO_2 scenarios

Apart from the Directive scenario (see Chapter 4) which is the reference case, several scenarios have been built to evaluate the response of the power system under different CO_2 caps.

- **CO2_50-2050 scenario**: 50% CO_2 emissions reduction in 2050 below 2005 levels: 183.3 Mt CO_2
- **CO2_80-2050 scenario**: 80% CO_2 emissions reduction in 2050 below 2005 levels: 73.3 Mt CO_2
- **CO2_Dec162 scenario**: based on Decision 2013/162/EU, establishes bounds to CO_2 emissions in Spain following the transitory allocation for the period 2013-2020: 185.1 Mt in 2015 and 176.9 Mt in 2020 and beyond.

It has been assumed that the share of the CO_2 emissions is 80% of the total GHG emissions.

1.2.2. Fuel prices scenarios

A literature review on fuel prices has been carried out. The US Energy Information Administration (EIA, 2013) gives projections up to 2040 (see Table 61).

Table 61. Fossil fuel prices projections

FUEL	2010	2015	2020	2025	2030	2035	2040
IEA crude oil imports ($/bbl)	78.8	-	102.3	113.7	126.4	140.9	157.6
OECD steam coal imports ($/tonne)	58.1	-	74.9	87.6	102.3	118.3	136.4
Natural gas imports (Europe) ($/MBtu)	7.0	-	6.9	7.5	8.0	9.0	10.6

The UK Department of Energy and Climate Change has also published a report concerning the fossil fuel price projections (DECC, 2013).

IEA World Energy Outlook 2010 report (IEA, 2011) gives forecasts up to 2035. The most conservative 'current policies scenario' has been selected. Historical 2000 and 2005 prices have been taken from the Statistical Review of World Energy (BP, 2013). In order to extend the forecast, the growth between 2030 and 2035 has been used to linearly extrapolate to 2050.

Consequently, several scenarios have been built to analyse the sensitivity to the fossil fuel prices using the 2010 World Energy Outlook projection (IEA, 2011):

- **Ref scenario**: using the projected prices of IEA (2011) (see Table 62 below).
- **Coal+10% scenario**: 10%-increase in the coal prices projected (IEA, 2011) from 2010.
- **Gas+10% scenario**: 10%-increase in the gas prices projected (IEA, 2011) from 2010.
- **Oil+10% scenario**: 10%-increase in the oil prices projected (IEA, 2011) from 2010.

Table 62. Fossil fuel prices scenarios

FUEL	Scenario	2005	2010	2015	2020	2025	2030	2035	2040	2045	2050
Crude oil	*Ref*	6.75	8.61	11.72	13.02	14.03	14.82	15.43	16.06	16.72	17.40
Crude oil	*Oil+10%*	6.75	9.47	12.88	14.32	15.43	16.30	16.97	17.67	18.39	19.14
Steam coal	*Ref*	1.64	2.37	2.50	2.61	2.70	2.77	2.83	2.89	2.96	3.02
Steam coal	*Coal+10%l*	1.64	2.61	2.75	2.87	2.97	3.05	3.11	3.18	3.26	3.32
Natural gas	*Ref*	4.50	4.78	6.25	7.02	7.59	8.04	8.29	8.56	8.83	9.11
Natural gas	*Gas+10%*	4.50	5.26	6.88	7.72	8.35	8.84	9.12	9.42	9.71	10.02

Prices in Table 62 above are expressed in €$_{2005}$ since this is the reference year in the TIMES-Spain model. Values have been deflated from 2010 to 2005 by means of the difference in the Retail Price Index (RPI), 12.3% (INE, 2013).

Finally, it has been assumed an exchange rate dollar/euro of 0.756 (2010). In addition, material prices used in TIMES-Spain such as limestone, iron ore, aluminium oxide, gypsum, have been updated.

1.3. Internalisation of external costs

1.3.1. Externalities

Welfare economics aims to maximise individual and social welfare through optimal resource allocation (Pigou, 1928). The concept of externalities has been well established in the theory of welfare economics for more than half a century. However, it is only since the 1960s that environmental externalities have received a lot of attention, both in terms of quantification and action to internalise them (Coase, 1960).

Externalities are defined as *the costs and benefits which arise when the social or economic activities of one group of people have an impact on another, and when the first group fails to fully account for their impacts* (EC, 1995).

The externalities are the difference between social and private costs. The social cost is built as follows: *Social Cost = Private Cost + External Cost* and consequently,

$$MSC = MPC + MEC \tag{11}$$

Where *MSC* is the marginal social cost, *MPC* is the marginal private cost, and *MEC*, the marginal external cost.

1.3.2. Externalities of the electricity production

Electricity production causes environmental damages whose associated costs are not assumed by the producers or consumers of that electricity (EC, 1995). Traditional energy prices reflect the use of a number of scare resources needed to produce energy and to make it available to the consumer. These energy prices cover the inputs of labour, capital and operating costs, fuel, taxes and insurance. The externalities reflect the damages to human health, the environment and also some non-environmental aspects and benefits, such as employment and energy security, which are not reflected in the energy prices. These costs and benefits are passed on to society as a whole and to future generations.

The ExternE methodology, developed within a project co-funded by the European Commission, is used to value environmental damages and benefits of electricity production technologies in monetary units. The external costs used in this work have been obtained from the CASES project which was based on ExternE methodology (CASES, 2008).

1.3.3. Internalisation of externalities in TIMES-Spain

There are different ways to introduce the external costs in TIMES-Spain. In the current work externalities coming from CO_2, NO_x and SO_2 pollutants have been introduced as extra variable costs.

CO_2 external costs

As described in Chapter 4 Section 2.1.2., the Directive 2009/29/EC has been transposed to the Spanish laws setting CO_2 bounds. Those bounds have been included into the model. In addition, to analyse the effect of the internalisation of the external costs of CO_2 emissions, a scenario has been built using CASES project data (Mayer-Spohn and Blesl, 2007) in Table 63.

Table 63. CO_2 external costs of power technologies in TIMES-Spain

Power technology	External cost (M€/PJ)		
	2005-2010	2020	2030
NGCC with CO_2 Sequestration (475 MW) New	-	0.500	0.705
NGCC hybrid hard coal Base-Year	4.546	3.789	5.391
NGCC Large (800 MW) New	2.352	2.181	3.081
NGCC Small (400 MW) New	2.352	2.181	3.081
NGCC (400 MW) Base-Year	2.352	2.181	3.081
Nuclear (PWR) Base-year	0.113	0.053	0.041
Nuclear (PWR 3rd generation) (1756 MW) New	0.113	0.053	0.041
Nuclear (PWR 4th generation) (600 MW) New	0.113	0.053	0.041
Fuel Cell (MCFC) Biogas (300 kW) New	1.832	1.829	2.304
Fuel Cell (MCFC) Natural Gas (300 kW) New	0.847	0.834	1.073
Fuel Cell (SOFC) Biogas New (250 kW) New	0.601	0.531	0.762
Fuel Cell (SOFC) Natural Gas (250 kW) New	0.601	0.531	0.762
Gas Turbine Biogas Base-Year	3.516	3.426	4.796
Gas Turbine Oil Base-Year	2.475	2.475	3.553
Geothermal Hot Dry Rock (5 MW) New	n.a	n.a	n.a
Geothermal Steam Turbine (120 MW) New	n.a	n.a	n.a
Hydro Lake (100 MW) New	0.041	0.041	0.060
Hydro Pumped Storage New	0.028	0.028	0.040
Hydro Run of River Large (50 MW) New	0.022	0.022	0.031
Hydro Run of River Medium (1-5 MW) New	0.024	0.024	0.035
Hydro Run of River Small (0.2 MW) New	0.034	0.034	0.049
Hydro Run of River Base-year	0.022	0.022	0.031
Hydro Dam Base-year	0.041	0.041	0.060
IGCC Hard Coal with CO_2 Sequestration (425 MW) New	-	0.589	0.837
IGCC Lignite with CO_2 Sequestration (425 MW) New	-	0.589	0.837
IGCC Hard Coal (450 MW) New	4.546	3.789	5.391
IGCC Lignite (450 MW) New	5.365	4.541	6.457
Internal Combustion Oil Base-Year	2.475	2.475	3.553
Ocean Power Tidal Stream Generator New	n.a	n.a	n.a
Ocean Power Wave Energy Converter New	n.a	n.a	n.a
Solar PV Plant (500 Kw) New	0.480	0.366	0.483
Solar PV Roof panel (2 Kw) New	0.483	0.364	0.482
Pumped Storage (500 MW) Base-year	0.028	0.028	0.040
Super Critical Steam Turbine Hard coal with CO_2 Sequestration Large New	-	0.589	0.837
Super Critical Steam Turbine Hard coal Large (800 MW) New	4.450	4.094	5.652
Super Critical Steam Turbine Hard coal Medium (600 MW) New	4.450	4.094	5.652
Super Critical Steam Turbine Lignite Large (965 MW) New	5.307	4.723	6.782
Super Critical Steam Turbine Lignite Medium (450 MW) New	5.307	4.723	6.782
Super Critical Steam Turbine Oil New	1.115	1.115	1.601
Solar Thermal New	0.054	0.042	0.048
Steam Turbine Hard coal Base-Year	4.450	4.094	5.652
Steam Turbine Hard coal & Lignite Base-Year	4.450	4.094	5.652
Steam Turbine Hard coal & Coke oven gas Base-Year	4.450	4.094	5.652
Steam Turbine Lignite Base-Year	5.307	4.723	6.782
Steam Turbine MSW Base-Year	n.a	n.a	n.a
Steam Turbine Oil Base-Year	1.115	1.115	1.601
Steam Turbine Sludge Base-Year	n.a	n.a	n.a
Steam Turbine Wood Base-Year	0.298	0.298	0.428
Steam Turbine Hard coal New	4.450	4.094	5.652
Gas Turbine Diesel New	2.475	2.475	3.553
Gas Turbine Natural gas New	3.516	3.426	4.796
Gas Turbine Oil New	2.475	2.475	3.553
Wind Offshore New	0.045	0.027	0.035
Wind Onshore New	0.056	0.035	0.044
Wind Onshore Base-year	0.056	0.035	0.044

NO_x external costs

As described in Chapter 4 Section 2.1.2., Directive 2001/81/EC target was to not exceed 847 kt NO_X in 2010 in Spain. NO_X emissions in 2010 amounted for 900 kt, 6% above the Directive's ceiling. External costs of NO_X have been included in TIMES-Spain through scenario using CASES project data (Mayer-Spohn and Blesl, 2007) in Table 64.

Table 64. NO_X external costs of power technologies in TIMES-Spain

Power technology	External cost (€/GJ)		
	2005-2010	2020	2030
NGCC with CO_2 Sequestration (475 MW) New	-	1.300	1.502
NGCC hybrid hard coal Base-Year	1.183	1.377	1.603
NGCC Large (800 MW) New	0.885	1.175	1.359
NGCC Small (400 MW) New	0.885	1.175	1.359
NGCC (400 MW) Base-Year	0.885	1.175	1.359
Nuclear (PWR) Base-year	0.134	0.103	0.086
Nuclear (PWR 3rd generation) (1756 MW) New	0.134	0.103	0.086
Nuclear (PWR 4th generation) (600 MW) New	0.134	0.103	0.086
Fuel Cell (MCFC) Biogas (300 kW) New	1.999	2.681	2.821
Fuel Cell (MCFC) Natural Gas (300 kW) New	1.532	2.063	2.171
Fuel Cell (SOFC) Biogas New (250 kW) New	0.784	0.935	1.099
Fuel Cell (SOFC) Natural Gas (250 kW) New	0.784	0.935	1.099
Gas Turbine Biogas Base-Year	1.334	1.859	2.131
Gas Turbine Oil Base-Year	1.476	2.065	2.427
Geothermal Hot Dry Rock (5 MW) New	0.220	0.220	0.220
Geothermal Steam Turbine (120 MW) New	0.007	0.007	0.007
Hydro Lake (100 MW) New	0.039	0.053	0.063
Hydro Pumped Storage New	0.032	0.044	0.052
Hydro Run of River Large (50 MW) New	0.018	0.025	0.029
Hydro Run of River Medium (1-5 MW) New	0.020	0.027	0.032
Hydro Run of River Small (0.2 MW) New	0.028	0.038	0.045
Hydro Run of River Base-year	0.018	0.025	0.029
Hydro Dam Base-year	0.039	0.053	0.063
IGCC Hard Coal with CO_2 Sequestration (425 MW) New	-	1.548	1.801
IGCC Lignite with CO_2 Sequestration (425 MW) New	-	1.548	1.801
IGCC Hard Coal (450 MW) New	1.183	1.377	1.603
IGCC Lignite (450 MW) New	0.452	0.562	0.655
Internal Combustion Oil Base-Year	1.476	2.065	2.427
Ocean Power Tidal Stream Generator New	0.570	0.362	0.423
Ocean Power Wave Energy Converter New	0.570	0.362	0.423
Solar PV Plant (500 Kw) New	0.504	0.520	0.562
Solar PV Roof panel (2 Kw) New	0.483	0.497	0.538
Pumped Storage (500 MW) Base-year	0.032	0.044	0.052
Super Critical Steam Turbine Hard coal with CO_2 Sequestration Large New	-	1.548	1.801
Super Critical Steam Turbine Hard coal Large (800 MW) New	1.859	2.442	2.761
Super Critical Steam Turbine Hard coal Medium (600 MW) New	1.859	2.442	2.761
Super Critical Steam Turbine Lignite Large (965 MW) New	1.281	1.684	1.981
Super Critical Steam Turbine Lignite Medium (450 MW) New	1.281	1.684	1.981
Super Critical Steam Turbine Oil New	1.679	2.388	2.807
Solar Thermal New	0.091	0.099	0.094
Steam Turbine Hard coal Base-Year	1.859	2.442	2.761
Steam Turbine Hard coal & Lignite Base-Year	1.859	2.442	2.761
Steam Turbine Hard coal & Coke oven gas Base-Year	1.859	2.442	2.761
Steam Turbine Lignite Base-Year	1.281	1.684	1.981
Steam Turbine MSW Base-Year	n.a.	n.a.	n.a.
Steam Turbine Oil Base-Year	1.679	2.388	2.807
Steam Turbine Sludge Base-Year	0.629	0.722	0.844
Steam Turbine Wood Base-Year	0.908	1.234	1.450
Steam Turbine Hard coal New	1.859	2.442	2.761
Gas Turbine Diesel New	1.476	2.065	2.427
Gas Turbine Natural gas New	1.334	1.859	2.131
Gas Turbine Oil New	1.476	2.065	2.427
Wind Offshore New	0.047	0.042	0.044
Wind Onshore New	0.059	0.049	0.050
Wind Onshore Base-year	0.059	0.049	0.050

SO_2 external costs

As described in Chapter 4 Section 2.1.2., Directive 2001/81/EC target was to not exceed 746 kt SO_2 in 2010 in Spain. In 2010, SO_2 amount was 444 kt, 41% under the Directive's ceiling.

Consequently, a scenario has been built including the external costs of SO_2 in place of applying the ceilings enforced by Directive 2001/81/EC. Similarly, SO_2 external costs have been introduced as an extra variable cost using data from CASES project (Mayer-Spohn and Blesl, 2007) in Table 65.

Table 65. SO_2 external costs of power technologies in TIMES-Spain

Power technology	External cost (M€/PJ)		
	2005-2010	2020	2030
NGCC with CO_2 Sequestration (475 MW) New	-	0.459	0.532
NGCC hybrid hard coal Base-Year	1.041	1.112	1.300
NGCC Large (800 MW) New	0.348	0.415	0.482
NGCC Small (400 MW) New	0.348	0.415	0.482
NGCC (400 MW) Base-Year	0.348	0.415	0.482
Nuclear (PWR) Base-year	0.193	0.118	0.078
Nuclear (PWR 3rd generation) (1756 MW) New	0.193	0.118	0.078
Nuclear (PWR 4th generation) (600 MW) New	0.193	0.118	0.078
Fuel Cell (MCFC) Biogas (300 kW) New	3.898	4.967	5.238
Fuel Cell (MCFC) Natural Gas (300 kW) New	2.172	2.793	2.951
Fuel Cell (SOFC) Biogas New (250 kW) New	0.757	0.871	1.027
Fuel Cell (SOFC) Natural Gas (250 kW) New	0.757	0.871	1.027
Gas Turbine Biogas Base-Year	0.588	0.735	0.843
Gas Turbine Oil Base-Year	2.314	2.985	3.521
Geothermal Hot Dry Rock (5 MW) New	0.101	0.101	0.101
Geothermal Steam Turbine (120 MW) New	0.003	0.003	0.003
Hydro Lake (100 MW) New	0.032	0.041	0.048
Hydro Pumped Storage New	0.018	0.023	0.027
Hydro Run of River Large (50 MW) New	0.019	0.025	0.030
Hydro Run of River Medium (1-5 MW) New	0.022	0.028	0.033
Hydro Run of River Small (0.2 MW) New	0.030	0.039	0.047
Hydro Run of River Base-year	0.019	0.025	0.030
Hydro Dam Base-year	0.032	0.041	0.048
IGCC Hard Coal with CO_2 Sequestration (425 MW) New	-	1.250	1.459
IGCC Lignite with CO_2 Sequestration (425 MW) New	-	1.250	1.459
IGCC Hard Coal (450 MW) New	1.041	1.112	1.300
IGCC Lignite (450 MW) New	0.585	0.630	0.737
Internal Combustion Oil Base-Year	2.314	2.985	3.521
Ocean Power Tidal Stream Generator New	1.053	0.461	0.546
Ocean Power Wave Energy Converter New	1.053	0.461	0.546
Solar PV Plant (500 Kw) New	0.633	0.633	0.691
Solar PV Roof panel (2 Kw) New	0.757	0.735	0.800
Pumped Storage (500 MW) Base-year	0.018	0.023	0.027
Super Critical Steam Turbine Hard coal with CO_2 Sequestration Large New	-	1.250	1.459
Super Critical Steam Turbine Hard coal Large (800 MW) New	1.705	2.000	2.270
Super Critical Steam Turbine Hard coal Medium (600 MW) New	1.705	2.000	2.270
Super Critical Steam Turbine Lignite Large (965 MW) New	1.408	1.590	1.876
Super Critical Steam Turbine Lignite Medium (450 MW) New	1.408	1.590	1.876
Super Critical Steam Turbine Oil New	3.254	4.167	4.916
Solar Thermal New	0.072	0.072	0.067
Steam Turbine Hard coal Base-Year	1.705	2.000	2.270
Steam Turbine Hard coal & Lignite Base-Year	1.705	2.000	2.270
Steam Turbine Hard coal & Coke oven gas Base-Year	1.705	2.000	2.270
Steam Turbine Lignite Base-Year	1.408	1.590	1.876
Steam Turbine MSW Base-Year	0.932	1.191	1.409
Steam Turbine Oil Base-Year	3.254	4.167	4.916
Steam Turbine Sludge Base-Year	0.312	0.399	0.472
Steam Turbine Wood Base-Year	0.334	0.432	0.509
Steam Turbine Hard coal New	1.705	2.000	2.270
Gas Turbine Diesel New	2.314	2.985	3.521
Gas Turbine Natural gas New	0.588	0.735	0.843
Gas Turbine Oil New	2.314	2.985	3.521
Wind Offshore New	0.066	0.050	0.051
Wind Onshore New	0.076	0.054	0.055
Wind Onshore Base-year	0.076	0.054	0.055

External costs implementation

The sum of CO_2, NO_x and SO_2 external costs has been included in TIMES-Spain via variable costs for each electricity generation technology and period (see Table 66). A new scenario on external costs implementation has been built with these data: **ExtCosts scenario**.

Table 66. Internalisation of external costs related to power technologies in TIMES-Spain

Power technology	Cost (M€/PJ)			
	2005-2010	2020	2030	2050
NGCC with CO_2 Sequestration (475 MW) New	-	2.728	3.209	3.209
NGCC hybrid hard coal Base-Year	7.197	6.705	8.721	8.721
NGCC Large (800 MW) New	4.012	4.198	5.350	5.350
NGCC Small (400 MW) New	4.012	4.198	5.350	5.350
NGCC (400 MW) Base-Year	4.012	4.198	5.350	5.350
Nuclear (PWR) Base-year	0.452	0.286	0.216	0.216
Nuclear (PWR 3rd generation) (1756 MW) New	-	0.548	0.348	0.348
Nuclear (PWR 4th generation) (600 MW) New	-	-	1.011	1.011
Fuel Cell (MCFC) Biogas (300 kW) New	14.39	16.14	17.03	17.03
Fuel Cell (MCFC) Natural Gas (300 kW) New	8.441	9.580	10.08	10.08
Fuel Cell (SOFC) Biogas New (250 kW) New	8.810	9.004	9.556	9.556
Fuel Cell (SOFC) Natural Gas (250 kW) New	6.032	6.227	6.778	6.778
Gas Turbine Biogas Base-Year	6.007	6.590	8.339	8.339
Gas Turbine Oil Base-Year	6.835	8.094	10.07	10.07
Geothermal Hot Dry Rock (5 MW) New	0.655	0.655	0.655	0.655
Geothermal Steam Turbine (120 MW) New	0.311	0.311	0.311	0.311
Hydro Lake (100 MW) New	0.113	0.136	0.171	0.171
Hydro Pumped Storage New	0.079	0.096	0.120	0.120
Hydro Run of River Large (50 MW) New	0.060	0.072	0.091	0.091
Hydro Run of River Medium (1-5 MW) New	0.067	0.080	0.101	0.101
Hydro Run of River Small (0.2 MW) New	0.093	0.113	0.142	0.142
Hydro Run of River Base-year	0.070	0.082	0.101	0.101
Hydro Dam Base-year	0.123	0.146	0.181	0.181
IGCC Hard Coal with CO_2 Sequestration (425 MW) New	-	4.382	5.093	5.093
IGCC Lignite with CO_2 Sequestration (425 MW) New	-	4.382	5.093	5.093
IGCC Hard Coal (450 MW) New	7.623	7.131	9.147	9.147
IGCC Lignite (450 MW) New	7.255	6.587	8.702	8.702
Internal Combustion Oil Base-Year	6.835	8.094	10.07	10.07
Ocean Power Tidal Stream Generator New	1.623	0.824	0.969	0.969
Ocean Power Wave Energy Converter New	1.623	0.824	0.969	0.969
Solar PV Plant (500 Kw) New	1.618	1.520	1.737	1.737
Solar PV Roof panel (2 Kw) New	1.725	1.597	1.821	1.821
Pumped Storage (500 MW) Base-year	0.089	0.106	0.130	0.130
Super Critical Steam Turbine Hard coal with CO_2 Sequestration Large New	-	4.216	4.927	4.927
Super Critical Steam Turbine Hard coal Large (800 MW) New	8.725	9.247	11.39	11.39
Super Critical Steam Turbine Hard coal Medium (600 MW) New	8.725	9.247	11.39	11.39
Super Critical Steam Turbine Lignite Large (965 MW) New	8.266	8.269	10.90	10.90
Super Critical Steam Turbine Lignite Medium (450 MW) New	8.266	8.269	10.90	10.90
Super Critical Steam Turbine Oil New	6.476	8.098	9.752	9.752
Solar thermal New	0.218	0.213	0.210	0.210
Steam Turbine Hard coal Base-Year	8.725	9.247	11.39	11.39
Steam Turbine Hard coal & Lignite Base-Year	8.725	9.247	11.39	11.39
Steam Turbine Hard coal & Coke oven gas Base-Year	8.725	9.247	11.39	11.39
Steam Turbine Lignite Base-Year	8.266	8.269	10.90	10.90
Steam Turbine MSW Base-Year	1.358	1.617	1.835	1.835
Steam Turbine Oil Base-Year	6.476	8.098	9.752	9.752
Steam Turbine Sludge Base-Year	1.367	1.548	1.742	1.742
Steam Turbine Wood Base-Year	1.967	2.390	2.814	2.814
Steam Turbine Hard coal New	8.725	9.247	11.39	11.39
Gas Turbine Diesel New	6.693	7.952	9.929	9.929
Gas Turbine Natural gas New	6.007	6.590	8.339	8.339
Gas Turbine Oil New	6.835	8.094	10.07	10.07
Wind Offshore New	0.159	0.120	0.131	0.131
Wind Onshore New	0.191	0.139	0.150	0.150
Wind Onshore Base-year	0.201	0.149	0.160	0.160

Likewise, external costs of the CHP technologies have been included using data from the CASES project (Meyer-Spohn and Blesl, 2007) (see Table 67).

Table 67. Internalisation of external costs related to CHP plants in TIMES-Spain

CHP technology	Cost (M€/PJ)			
	2005-2010	2020	2030	2050
CHP: Comb Cycle condensing Natural Gas	3.707	3.935	5.025	5.025
CHP: Comb Cycle condensing Natural Gas CCS	-	2.551	3.007	3.007
CHP: Steam Turb condensing Hard Coal	7.766	8.375	10.55	10.55
CHP: Steam Turb condensing Lignite	7.766	8.375	10.55	10.55
CHP: Steam Turb condensing Sludge	7.766	8.375	10.55	10.55
CHP: Steam Turb condensing MSW	7.766	8.375	10.55	10.55
CHP: IGCC Lignite CCS	-	4.378	5.089	5.089
CHP: Comb Cycle Backpressure Natural Gas	4.006	4.487	5.777	5.777
CHP: Steam Turb Backpressure Hard Coal	8.337	9.143	11.53	11.53
CHP: Steam Turb condensing Wood	1.971	2.394	2.818	2.818
CHP: Steam Turb condensing Straw	2.237	2.901	3.483	3.483
CHP: IGCC Wood	2.947	3.611	4.193	4.193
CHP: Fuel Cell MCFC Natural Gas	8.442	9.581	10.08	10.08
CHP: Fuel Cell SOFC Natural Gas	6.034	6.228	6.779	6.779
CHP: Fuel Cell MCFC Biogas	14.40	16.14	17.03	17.03
CHP: Fuel Cell SOFC Biogas	8.814	9.008	9.559	9.559
CHP: Fuel Cell SOFC Hydrogen	3.890	3.890	3.890	3.890
CHP: Int Combust Natural Gas Small	10.15	11.41	13.39	13.39
CHP: Int Combust Natural Gas Medium	9.047	10.30	12.28	12.28
CHP: Int Combust Natural Gas Large	8.347	9.606	11.58	11.58
CHP: Int Combust Biogas Small	9.737	10.99	12.97	12.97
CHP: Int Combust Biogas Large	8.347	9.606	11.58	11.58
CHP: Int Combust Oil Small	10.15	11.41	13.39	13.39
CHP: Int Combust Oil Medium	9.047	10.30	12.28	12.28
CHP: Int Combust Oil Large	8.347	9.606	11.58	11.58
CHP: Int Combust DME Small	3.890	3.890	3.890	3.890
CHP: Int Combust DME Large	2.080	2.080	2.080	2.080
CHP: Recovery Boiler Black Liquor from Pulp&Paper Large	7.766	8.375	10.55	10.55
CHP: IGCC Black Liquor from Pulp&Paper Large	7.766	8.375	10.55	10.55
CHP: Comb Cycle condensing Oil Industrial	7.766	8.375	10.55	10.55

1.4. Emission taxes

Traditional forms of regulation (technology and performance standards) represent an alternative to emissions trading or CO_2 taxes, but can be much more costly because they do not allow the flexibility to shift efforts toward the cheapest mitigation opportunities. As a complement to emissions trading or CO_2 taxes, however, flexible standards can address possible additional market failures and potentially lower costs.

Meeting the Directive objectives entails considering measures such as taxation, agreements with industry and regulation.

1.4.1. CO_2 taxes

Both, CO_2 taxes and tradable allowances or emission permits are regulation tools that impose a tax or a price to the emissions leading to reductions. Both can be charged on upstream fossil-fuel producers (based on the carbon content of fuels) or on downstream emitters. And both can incorporate incentives for carbon sequestration and other carbon offset activities (Parry and Pizer, 2013).

Taxes fix the price of emissions and leave the annual level of emissions uncertain; in contrast, tradable emission permits managed by Directive 2009/29/EC generally fix the level of emissions, and leave the price uncertain. Because climate change is caused by the long-term accumulation of global emissions, a predictable price tends to have advantages - for both the environment and the economy - over fixing the level of European emissions for a short time horizon of several years (Parry and Pizer, 2013). Over longer horizons, as nations converge on a common target for stabilising atmospheric GHGs concentrations and as international participation in global emission-reduction efforts grows, fixed emissions targets become increasingly advantageous.

Taxes raise government revenue, while tradable permits do not. New government revenue, if used to cut other taxes or provide valuable public goods, generates additional economic benefits that are not achieved under a system of tradable permits in which the majority of permits or allowances is allocated for free to regulated entities (Parry and Pizer, 2013).

There are different ways to consider the impacts of climate change. On one side, some experts recommend to estimate GHG-related damage by means of integrated models which take into account climate characteristics as well as their socioeconomic aspects. On the other hand, some authors defend a conservative approach via emission reduction costs. In this work, CASES project data have been used (Meyer-Spohn and Blesl, 2007). CASES project has followed the first approach estimating the damage costs caused by GHG. In addition, CASES uses results coming from FUND model (Climate Framework for Uncertainty, Negotiation and Distribution) (see http://www.fund-model.org/).

To analyse the effect of introducing CO_2 taxes in the electricity generation sector, a new scenario has been built: **CO2_Tax scenario**. In this scenario taxes are estimated based on the marginal damage costs of CO_2 used in CASES project (Meyer-Spohn and Blesl, 2007) (see Table 68).

Table 68. CO_2 taxes in TIMES-Spain

	2006	**2010-2015**	**2020-2025**	**2030-2035**	**2040-2045**	**2050**
CO_2 tax (€/tonne)	8.07	12.21	15.85	17.63	20.16	31.37

Besides, an extra scenario has been included (Table 69) to analyse the sensitivity of the energy system to higher CO_2 taxes. This scenario has been called **CO2_Tax_High scenario**.

Table 69. High CO_2 taxes in TIMES-Spain

	2006	**2010**	**2015**	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
CO_2 tax (€/tonne)	8.07	12.21	15.00	20.00	25.00	30.00	35.00	40.00	45.00	50.00

1.4.2. NO_x and SO_2 taxes

In the same manner as discussed for CO_2 taxes, both NO_X and SO_2 taxes have been introduced in TIMES-Spain using data from CASES project (Meyer-Spohn and Blesl, 2007). A new scenario has been built with data from the following Table 70: **NOX_SO2_TAX scenario**.

Table 70. NO_X and SO_2 taxes in TIMES-Spain

	2006	2010	2015	2020	2025	2030	2035	2040	2045	2050
NO_X tax (€/tonne)	4,103	4,364	4,430	4,784	5,169	5,589	5,814	6,048	6,291	6,546
SO_2 tax (€/tonne)	5,792	6,195	6,920	7,527	8,189	8,909	9,294	9,695	10,115	10,552

NO_x and SO_2 emissions are already regulated by several Directives (2001/80/EC and 2001/81/EC), national taxes and international agreements. In addition to EU environmental legislation, NO_X and SO_2-intensive industries have to comply with national environmental measures such as taxes and fees, and often take part in voluntary agreements (CEMBUREAU, 2007).

In Spain, the different regional governments regulate the environmental taxes. For instance, the autonomous region of Aragón fixes common taxes for NO_X and SO_2 of 50€/t and for CO_2 of 200€/kt (REAF, 2013). Besides, other regions such as Andalucía and Murcia establish other taxation types, i.e. Andalucía utilises fixed taxes depending on the range of the emissions (BOJA 251, 2003; BORM 301, 2005; BOA 117, 2007).

1.5. Results and discussion

Once all the scenarios have been built for analysing the different aspects of the power generation sector in Spain, it is important to remark several things concerning the results obtained.

As it was explained in Chapter 4, a base case has been established as the reference scenario. This is the so-called Directive's scenario (Dir). The list of assumptions included is detailed in the quoted section. All the results are related to gross electricity production.

1.5.1. Electricity production

The following Figure 42 shows the results by energy source for the scenarios without (left) and with (right) Directives 29/2009/EC and 81/2001/EC. The electricity production figures show the gross electricity generation including not only the power production sector but also the electricity coming from industry via CHP.

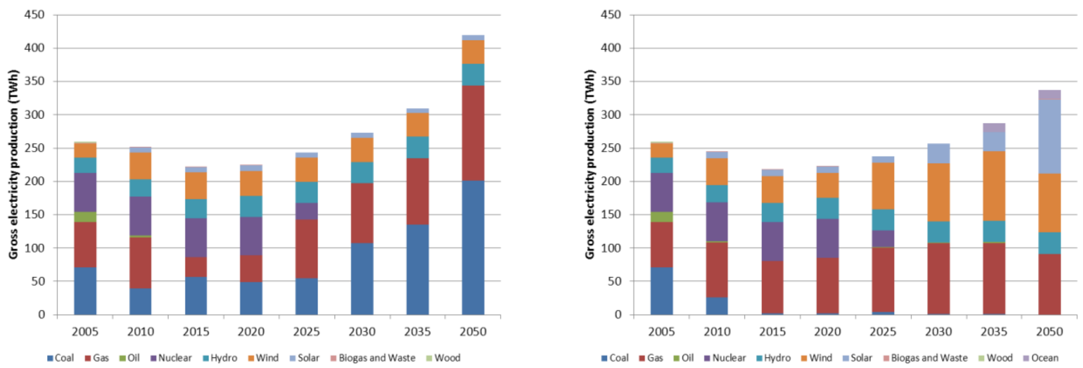


Figure 42. Gross electricity production in Spain by source wo/w the Directive scenario

According to the national figures, electricity generation in Spain was 260.7 TWh in 2005 (REE, 2006) and 275.8 TWh in 2010 (REE, 2011).

Results show that NoDir and Dir scenarios have similar electricity productions until 2025. From then, the production of NoDir scenario grows up to 420 TWh in 2050 whereas in Dir scenario reaches 335 TWh. This difference is due to a shift from natural gas and coal to biomass to produce industrial heat so the energy carrier varies. Consequently, the electricity produced in Dir scenario is less than in NoDir. In the case without directives there are a considerable contribution of coal and gas and, analysing the technologies, an important part comes from CHP plants. On the opposite, the Dir scenario leads to the progressive introduction of renewable technologies, such as wind and solar, which contribute with lower efficiencies to satisfy the electricity demands of the end-use sectors.

In the Dir scenario the solar technologies grow especially in 2050 when large photovoltaic systems are massively installed. Solar thermal contribution is noteworthy from 2030, entailing 21% of the electricity produced with solar technologies in 2050. In the same way, natural gas processes keep their contribution due to the installation of natural gas CHP plants in 2030 substituting existing NGCC plants. Furthermore, the implementation of ocean technologies (wave generation processes) from 2035 is observed.

In both scenarios, with and without Directives, nuclear energy phases out in 2028 when the activity license of the last nuclear power plant expires. Moreover, the electricity produced from hydropower plants remains constant until the end of horizon.

Nevertheless, it is interesting going beyond the Directive’s targets. Therefore various CO_2 scenarios have been created to evaluate the behaviour of the system when different bounds are imposed.

Firstly, the **CO2_50-2050 scenario** enforces a reduction of 50% in total CO_2 emissions in 2050 respect to the 2005 levels. This scenario is guided by Directive 2009/29/EC until 2020.

Results show (see Figure 43) that the technology breakdown of the power generation is quite similar to the Dir scenario. It can be concluded that applying the Directive has the same effect on the system than imposing 50% CO_2 reduction by 2050.

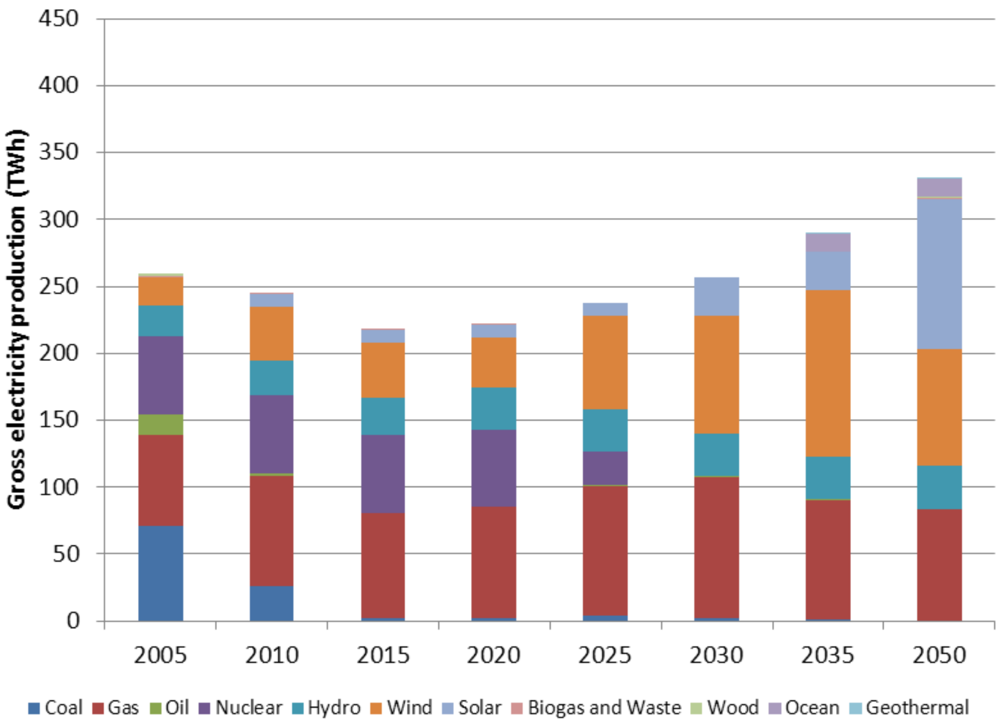


Figure 43. Gross electricity production in Spain considering 50% CO_2 reduction in 2050

Secondly, the **CO2_80-2050 scenario** enforces a reduction of 80% in total CO_2 emissions respect to the 2005 levels (see Figure 44).

In this case, up to 2030, both the electricity generated and the technology breakdown remain similar than in the Dir and the previous CO2_50-2050 scenarios. However, in 2050 the electricity production decreases and the composition of the system changes.

So a first question may emerge on *why the electricity production reduces when the system is forced to increase CO_2 emission reduction.*

When the CO_2 limits are stricter, some end-use services change the energy consumption from electricity to heat. This heat is produced by biomass-based integrated gasification combined cycle plants which produce heat to be used by different industrial processes. One of the main consumers of that heat is the cement industry because this sector begins to have problems with its CO_2 emissions therefor new dry clinker production processes with post-combustion capture are installed. The heat required by cement industry when CO_2 capture takes place is what has been called 'energy penalty'. The introduction of this technology and its competition with other technology solutions, have been already evaluated in Chapter 4. In summary, under stricter CO_2 limits, electricity production falls down because there is a shift from electricity to heat mainly to satisfy the growing industry demands.

Besides, there is also an important contribution to electricity generation from CHP process (steam turbine condensing from wood combustion) to produce high temperature heat used in district heating plants. Then, another question may arise on *how to explain the new technology generation breakdown.*

The electricity generation system becomes more carbon free installing new options (mainly photovoltaic power plants), keeping the existing wind capacities up to 2050 and introducing new renewable processes such as fuel cells (SOFC) and wave technologies. As a result of the 80% CO_2-reduction scenario, the natural gas contribution disappears and 100% of the electricity production is renewable by 2050.

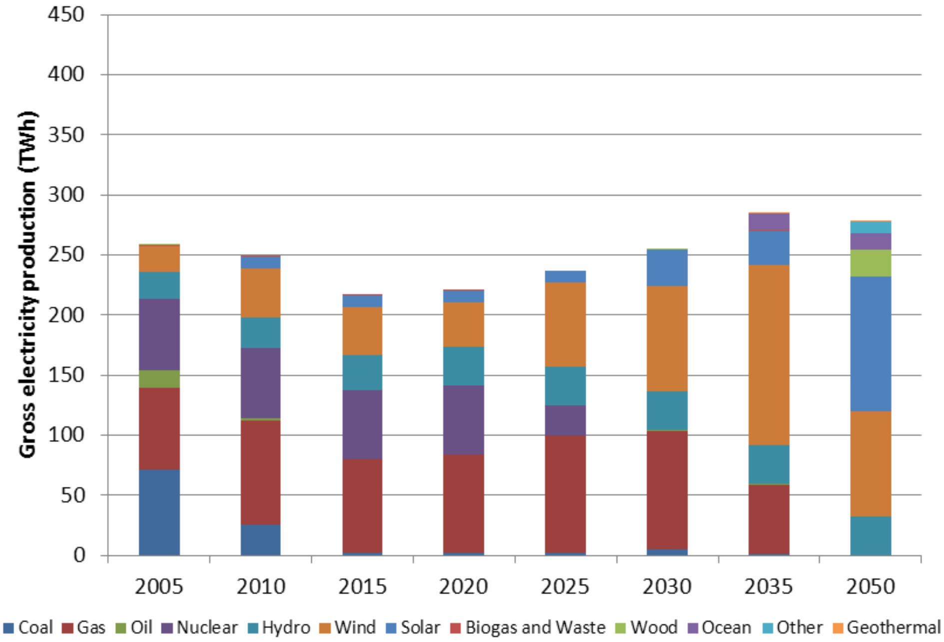


Figure 44. Gross electricity production in Spain considering 80% CO_2 reduction in 2050

Finally, **CO2_Dec162 scenario** is an alternative approach to implement Directive 2009/29/EC. This scenario extends the transitory period of Dec 162/2013/EU from 2020 to 2050.

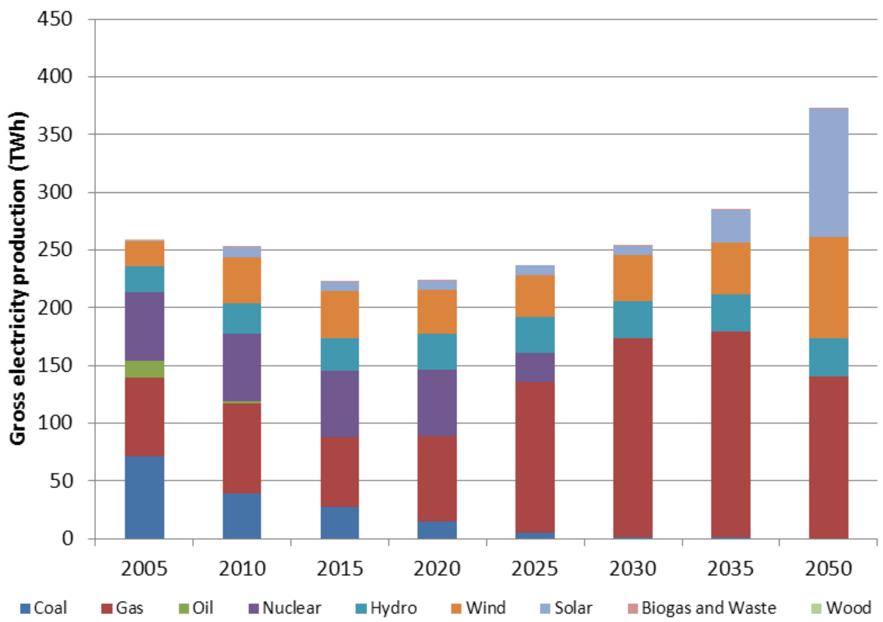


Figure 45. Gross electricity production in Spain considering Decision 2013/162/EU

The CO2_Dec162 scenario (Figure 45) produces more electricity than the Dir one. The composition of the system is quite similar except for the natural gas contribution which is 50 TWh higher in 2050 and the fact that ocean technologies do not appear in this case. The higher contribution of natural gas is due to a major installation of gas CHP plants.

A sensitivity analysis of the fossil fuel prices has been carried out. As in the description of the scenarios, three cases have been built increasing each fossil fuel price 10% in order to analyse its effect on the system. In the following Figure 46, results from Coal+10% (top left), Gas+10% (top right) and Oil+10% (down left) scenarios are presented.

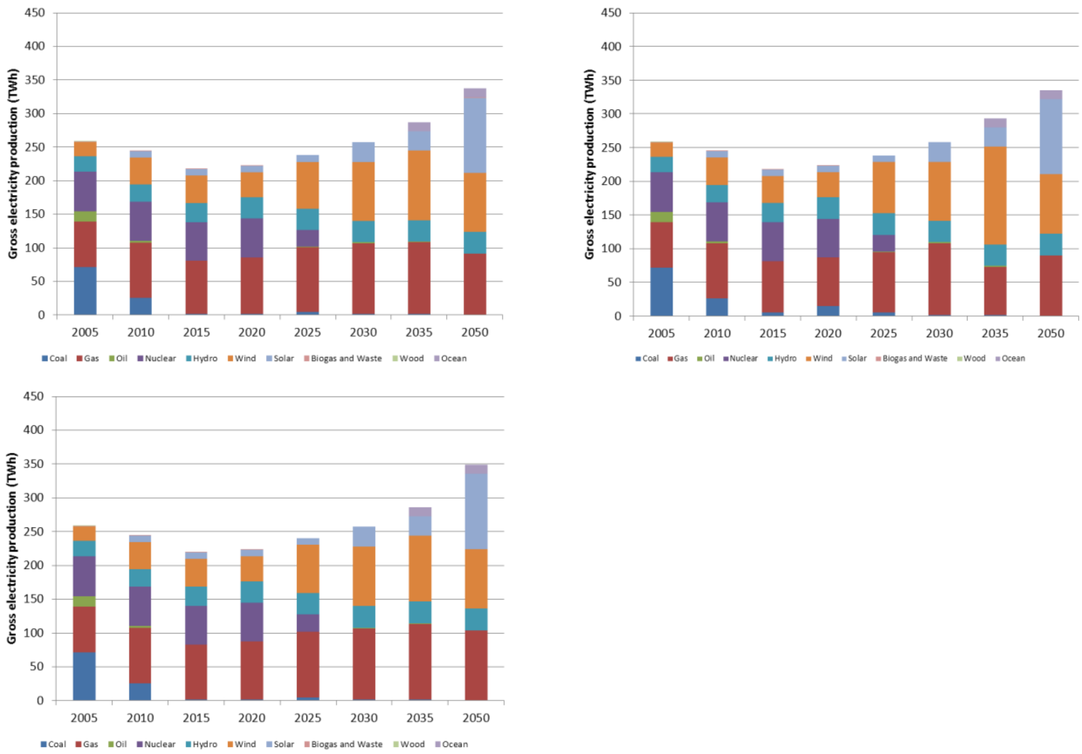


Figure 46. Gross electricity production in Spain considering several fuel prices scenarios.

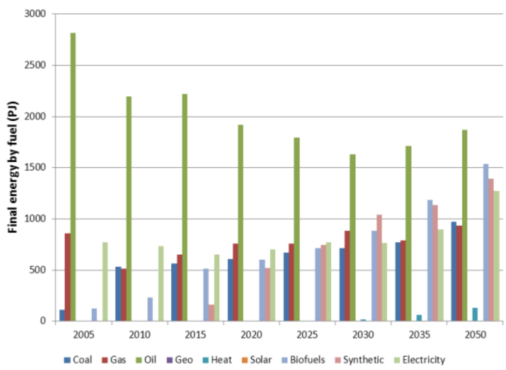
When coal prices increase 10%, there is any difference respect to the Dir scenario, neither in coal or gas electricity production processes. After a slight growth in the electricity produced from coal in 2025, the coal contribution goes down in 2030 and disappears in 2035.

On the contrary, electricity generation is noteworthy sensitive to changes in gas prices. This is due to the major contribution of the natural gas to the mix. In the Dir scenario, natural gas share goes from 38% in 2020 to 27% in 2050. When the gas prices are increased, the share of the gas goes from 32% in 2020 to 26% in 2050. The major difference takes place in 2035 when the share of the gas is 37% in Dir and 24% in Gas+10% scenarios. Regarding coal technologies, it is observed a slight growth in 2015-2020 due to the gas price increase. Less natural gas consumption when compared to the Dir scenario leads to a fuel shift to coal in 2015 and 2020 periods. From 2030, it is more similar to Dir scenario due to the installation of natural gas CHP plants in 2030 to reach other targets. In 2035, in the Dir scenario it is consumed more gas while in the Gas+10% one it is electricity from wind technologies. The electricity produced from oil is negligible and it is not influenced by the natural gas price increase.

Finally, it is important to point out that electricity production from oil is irrelevant to an increase of 10% of the oil prices due to the fact that the oil demand is related to the transport sector where the more fuel needed the more production of biofuels to satisfy the consumption. The electricity production from oil is not affected by oil prices changes because oil is being extinguished from this sector in favour of gas and renewable technologies. Nevertheless, looking at the final energy consumption by fuel it can be observed the shift from oil to biofuels when the oil price grows.

1.5.2. Final energy consumption

In the NoDir scenario (Figure 47 left) there is a major consumption of oil derived from its use in transport. In the Dir scenario (Figure 47 right) however it is observed a flattening in the oil consumption around 1,500 PJ at the same time than biofuels increase reaching this value and almost 3,000 PJ in 2050.



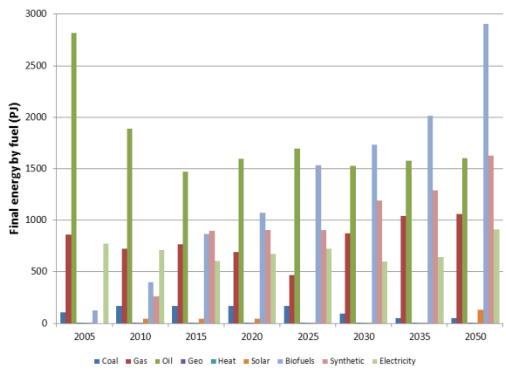


Figure 47. Final energy consumption by fuel in Spain wo/w the Directive scenario

It is noteworthy the implementation of the synthetic energy carriers up to 1,400 PJ in the NoDir scenario and more than 1,500 PJ in the Dir scenario in 2050. Those synthetic carriers include dimethyl ether (DME) as well as Fischer-Tropsch diesel and methanol derivatives. Major consumption of these synthetic fuels is linked to heavy truck vehicles which have hybrid combustion engines.

An assessment on the compliance degree of Directive 2009/28/EC on the promotion of the use of energy from renewable sources with and without considering the other two Directives, 2009/29/EC and 2001/81/EC has been carried out.

Directive 2009/28/EC established a European target of at least 20 % share of energy from renewable sources in the gross final consumption in 2020. The Spanish target is also 20%. Consequently, it has been analysed how the compliance of the RES Directive is influenced by NoDir and Dir scenarios.

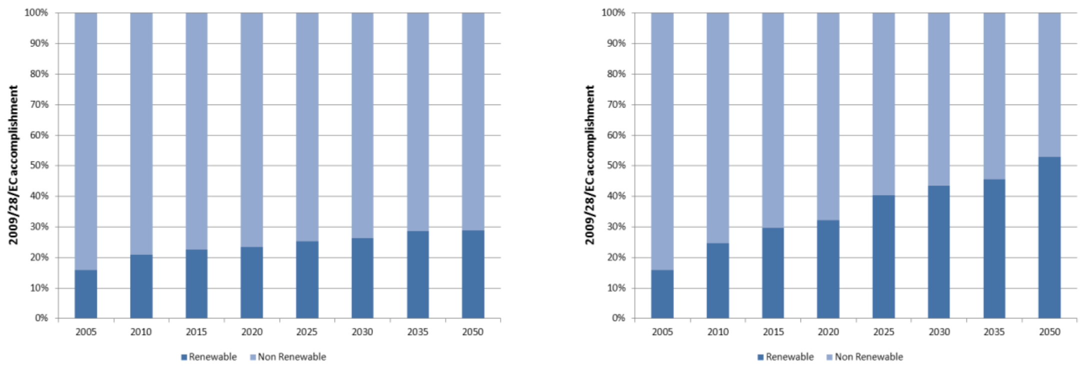


Figure 48. RES Directive compliance wo/w the Directive scenario

In the NoDir scenario (Figure 48 left), the renewable contribution to the gross final energy consumption is 23.44% in 2020, 26.45% in 2030 and 28.96% in 2050 while in the Dir scenario (Figure 48 right) a higher fulfillment degree is achieved: 32.12% in 2020, 43.53% in 2030 and 52.91% in 2050.

1.5.3. CO_2 emissions

The imposition of CO_2 caps affects the system in different ways. Fixing emissions bounds forces the system to not exceed the CO_2 limits. CO2_50-2050 and CO_80-2050 scenarios allow for flexibility in order to meet the targets.

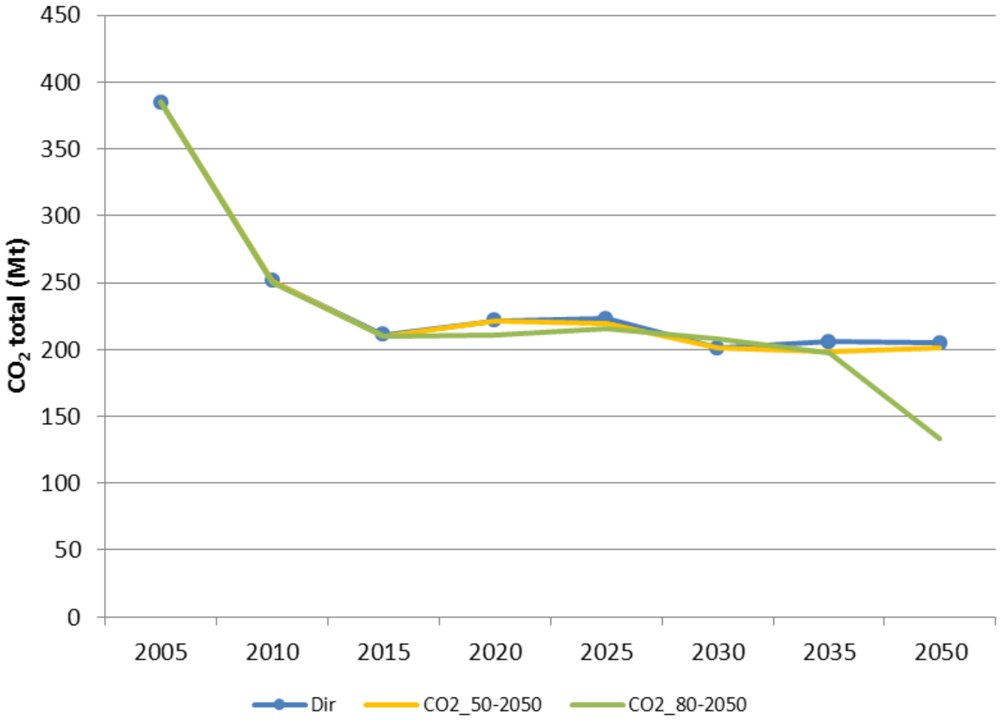


Figure 49. Total CO_2 emissions under several CO_2 caps

Figure 49 shows the CO_2 emissions under different long-term targets. CO2_50-2050 scenario presents almost the same behaviour than Dir scenario. In addition, the stricter limit of the CO2_80-2050 scenario leads to CO_2 emissions of 133 Mt CO_2 in 2050 in contrast with 205 Mt

CO_2 in the Dir scenario. Main differences come from industrial combustion and transport. Specifically, in the Dir scenario 17% of the total CO_2 emissions comes from natural gas CHP plant processes in 2050 whereas the CO2_80-2050 scenario uses biomass-based IGCC instead. Besides, in the Dir scenario emissions from transport come from the gasoline cars whereas in the CO2_80-2050 those vehicles are substituted by bio-based solutions, mainly ethanol, in hybrid cars.

Once the total Spanish CO_2 emissions have been assessed under different long-term goals, the CO_2 emissions coming from electricity production have been analysed (see Figure 50).

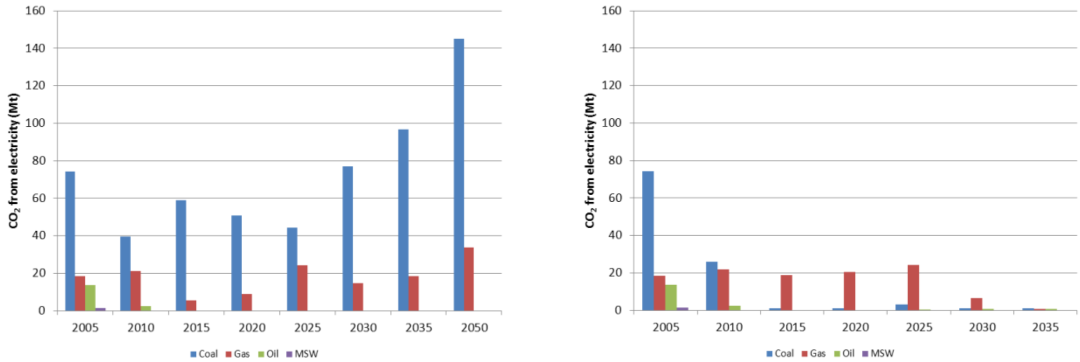


Figure 50. CO_2 emissions of the Spanish electricity production by fuel wo/w the Directive scenario

In the NoDir scenario (left) coal is the main electricity source and entails huge CO_2 emissions. In the Dir scenario (right), CO_2 emissions coming from electricity production go down progresively up to their extinction in 2035. Coal processes are removed from the electricity mix from 2015. After that, natural gas produces great amounts of electricity in NGCC plants but in 2030 there is a switch to natural gas CHP plants. The extinction of the CO_2 emissions resulting from electricity is due to the fact that emissions associated to CHP plants are now recorded in the industry sector.

In 2010, CO_2 emissions from transport meant 34.5% of the total, from industry 28.3%, from electricity production 20.1% and from upstream processes 3.5%. The residential, commercial and agricultural sectors meant 13.7%. In 2050, the CO_2 emissions come in 46.7% from industry, 22.7% from transport, and 23.2% from upstream processes. The upstream sector emissions growth is due to a process for synthetise natural gas to produce diesel via Fischer-Tropsch techniques. In 2050 most of the emissions coming from residential and commercial sectors are derived from biomass combustion so they are considered neutral.

Finally, CO_2 emissions of the electricity generation system have been represented for different scenarios.

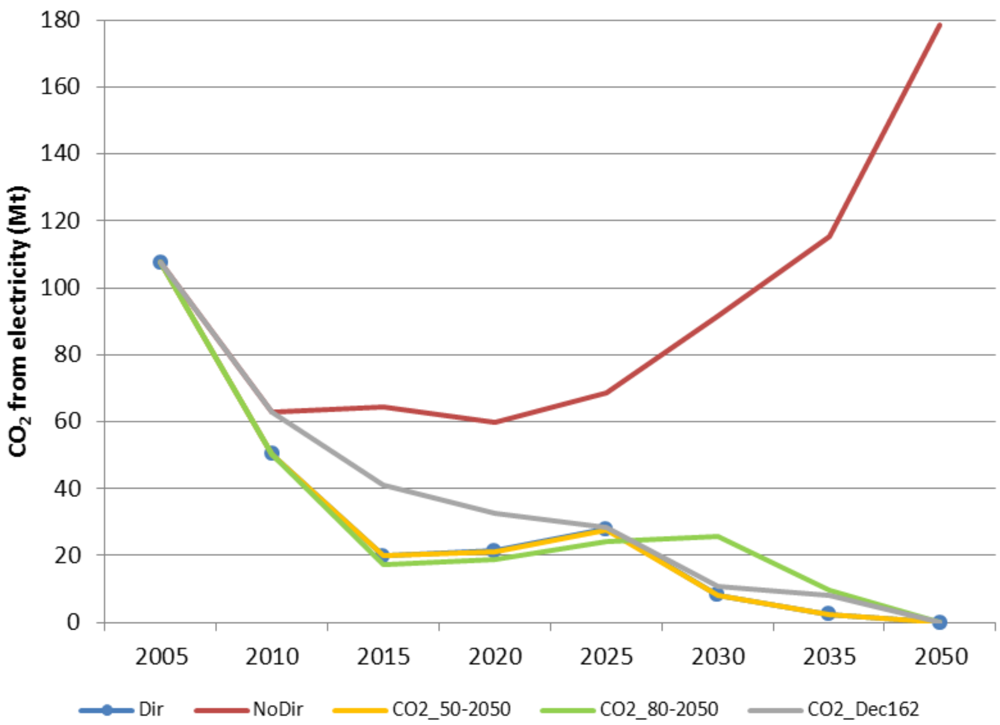


Figure 51. CO_2 emissions of the Spanish electricity production under several CO_2 limits

Results (Figure 51) show that CO_2 emissions coming from electricity production goes to zero at the end of horizon in all the scenarios except for the NoDir one. The CO2_50-2050 scenario has almost the same emissions than Dir scenario. On the other hand, the CO2_80-2050 scenario has higher emissions than Dir and CO2_50-2050 in 2030. The stricter CO_2 limits lead to a CO_2 emissions reduction in the industry sector shifting from fossil fuel direct consumption to electricity consumption. This increase in electricity demand causes the origin of the delay in the electricity sector to reduce its emissions. The increase in the emissions in the CO2_80-2050 scenario in 2030 comes from NGCC, natural gas solid oxide fuel cells and a remnant contribution of coal power plants.

The CO2_Dec162 scenario entails the transitory 2013-2020 period, which only affects to ETS sectors and gives more flexibility to the electricity production sector. Until 2025, results show that CO_2 emissions from electricity linked to the CO2_Dec162 scenario are higher than in the Dir scenario because stronger efforts are made in other sectors.

1.5.4. NO_x emissions

One of the main purposes of this work is to assess the application of Directive 2001/81/EC in Spain. In particular, NO_x emissions coming from the electricity production sector has been evaluated with and without the Directives.

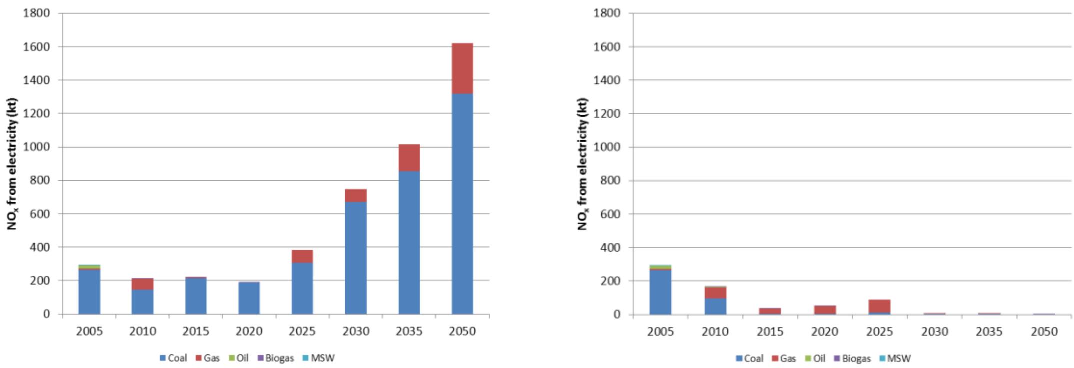


Figure 52. NO_x emissions of the Spanish electricity production by fuel wo/w the Directive scenario

Similarly to the CO_2 emissions from electricity, results highlight the coal contribution to the NO_x released. In the NoDir scenario (Figure 52 left), coal-related emissions remain at 200 kt up to 2020 and grow up to 1,300 kt in 2050. It is also remarkable the gas-related emissions from 2025. In the Dir scenario, NO_x emissions come from natural gas processes and disappear in 2030.

To summarise, meeting Directive 2001/81/EC ceilings leads to the NO_x emissions exhaustion in the Spanish electricity generation sector in 2030 by installing renewable technologies (wind and solar mostly) and natural gas CHP plants with low NO_x emissions in industry.

1.5.5. SO_2 emissions

SO_2 emissions are associated to the use of coal. Sulphur content of the hard coal and lignite is the basis of the SO_2 released in combustion processes both for producing electricity or heat. In the Spanish electricity sector, it is expected that coal contribution goes down progressively and disappears in the proximity of 2020. This contribution is fundamentally based on national political decisions.
Under the hypothesis of not accomplishing with the Directives, the coal, which is the cheapest option for producing electricity once hydro and nuclear technologies reach their maximum potentials, would grow enormously. Thus SO_2 emissions would grow accordingly. This can be observed in Figure 53 (left) where SO_2 in 2050 would reach up to 2,500 kt/yr.

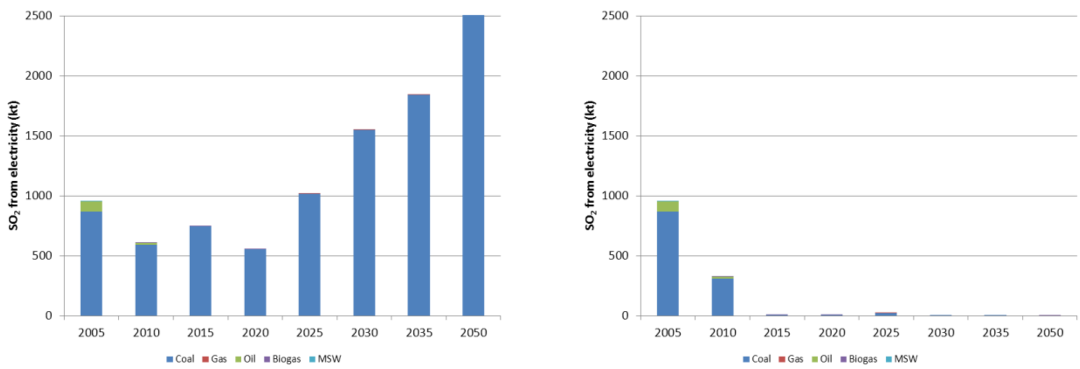


Figure 53. SO_2 emissions of the Spanish electricity production by fuel wo/w the Directive scenario

In the Dir scenario (Figure 53 right) SO_2 emissions coming from the electricity production sector disappear from 2015 due to the phase out of the coal power plants.

In the NoDir scenario, end-use services demands from residential and commercial sectors are satisfied using electricity which comes from coal and natural gas. Under the Dir scenario, residential and commercial demands are met using biomass combustion processes so a considerable amount of SO_2 is released due to the sulphur derived from the biomass.

1.5.6. Internalisation of external costs

The internalization of the external costs has been carried out by updating the variable operation and maintenance costs of the electricity production technologies included in TIMES-Spain. As the contribution of CHP plants to produce industrial electricity is significant (ACOGEN, 2013) – the external costs of those technologies have also been included using CASES project data.

The integration of the external costs of the electricity production technologies penalises those whose damage costs are higher. In this work, external costs included are those derived from CO_2, NO_x and SO_2 emissions.

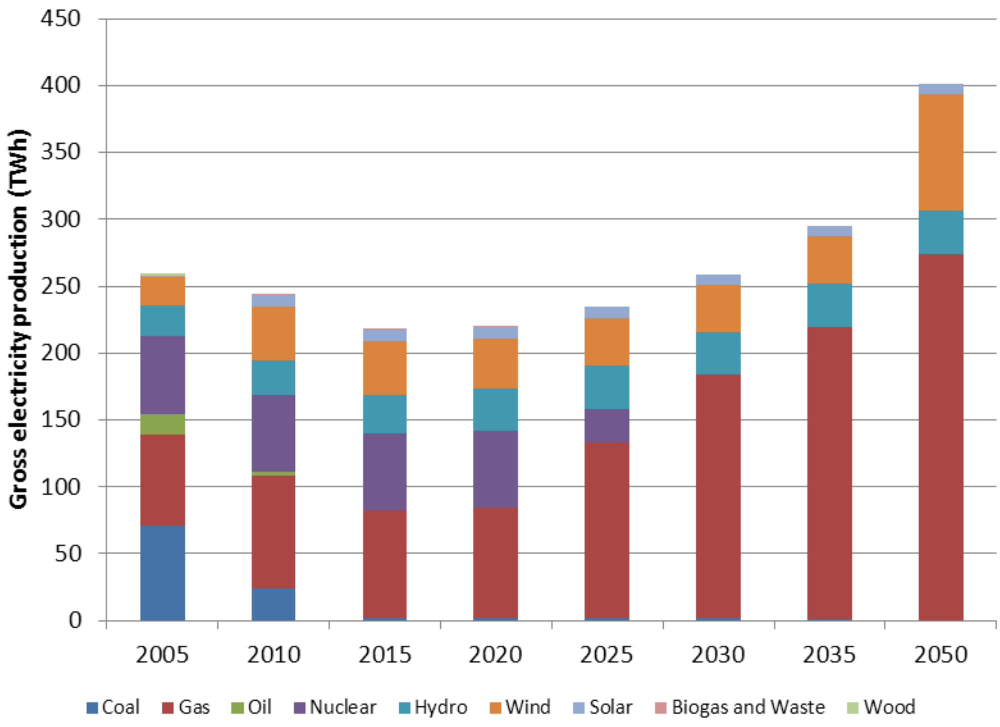


Figure 54. Gross electricity production in Spain by source considering external costs

Results (see Figure 54) show that the implementation of external costs leads to a rise in the use of gas in the electricity system, especially from 2025. Natural gas CHP plants are massively installed in industry. Another result from the internalisation is the increase in the production from wind in 2050. In addition, the electricity production is significantly higher than in the Dir scenario due to the electrification of the system, a consequence of the environmental restrictions imposed.

The internalisation of external costs involves an increase in the natural gas consumption. Consequently, there is also an increase in the CO_2 emissions resulting from this sector. This may be seen in the following Figure 55.

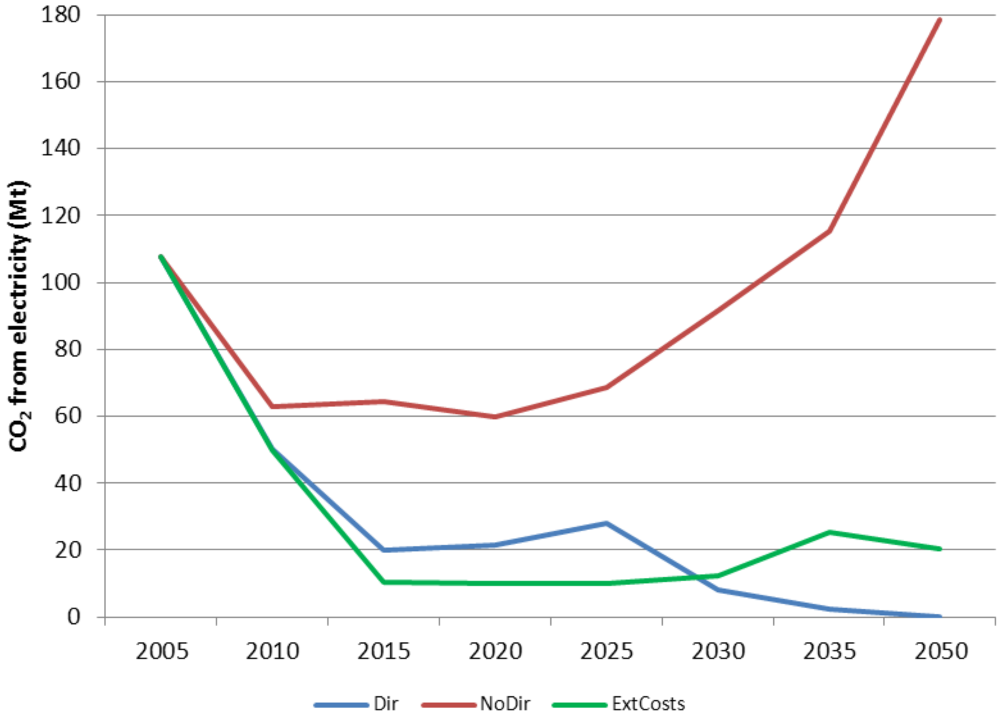


Figure 55. CO_2 emissions of the Spanish electricity production considering external costs

Internalising external costs is a good solution for reducing CO_2 emissions in the electricity sector until 2030. From then on, the system would rather install new natural gas CHP plants than renewable facilities. It is observed in Figure 55 that internalisation of external costs considered is not enough beyond 2030 to meet the Directive targets. Nevertheless, CO_2 emissions for the periods 2035 and 2050 are 6% and 5% of the total Spanish CO_2 emissions, respectively.

Finally, the effect of internalising the environmental externalities of the electricity generation sector in the CO_2 total emissions is shown in the Figure 56.

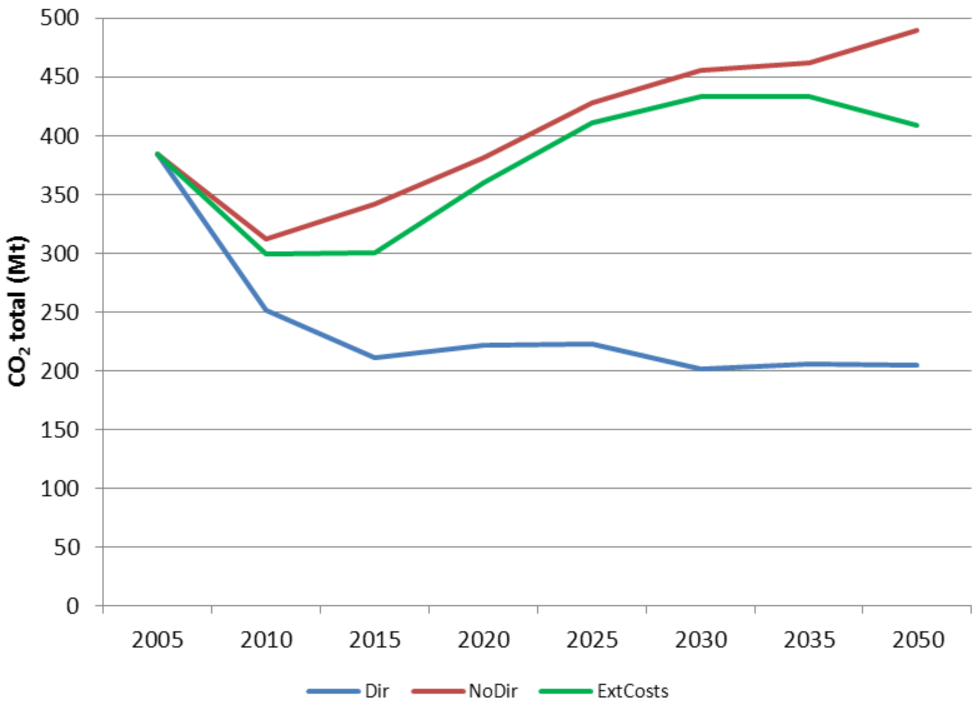


Figure 56. Total CO_2 emissions considering external costs

In general terms, the internalisation leads to approximately 10% CO_2 emissions reduction respect to a case without Directives. While Directive 2009/29/EC applies over all the ETS sectors, the internalisation only applies on the electricity production processes so those scenarios cannot be compared.

In summary, the internalisation of external costs in the electricity production sector has a significant effect in the reduction of the sectorial CO_2 emissions but it is not enough to reach the Directive's targets.

1.5.7. Emission taxes

Taxes have been applied to CO_2, NO_X and SO_2 emissions. Therefore CO_2 taxes have been implemented in TIMES-Spain trough two scenarios: CO2_Tax scenario (Figure 57 left) and CO2_Tax_High (Figure 57 right) scenario by means of considering Table 68 and Table 69, respectively. The effect of introducing CO_2 taxes into the system has the following consequences on the electricity generation.

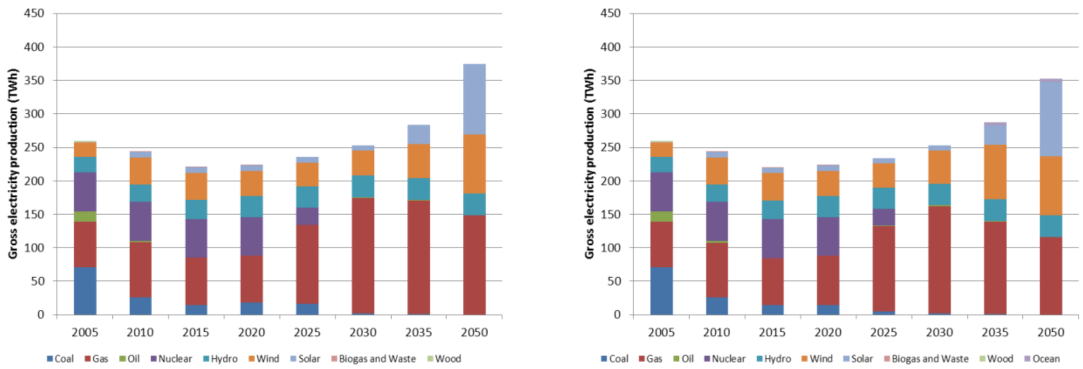


Figure 57. Gross electricity production in Spain by source under several CO_2 taxes

Compared to the Dir scenario, electricity produced in those scenarios is higher. In the CO2_Tax scenario, with taxes of 17.6€/t CO_2 in 2030 and 31.4€/t CO_2 in 2050, contribution of natural gas is above 150 TWh from 2030 until the end of horizon. If the taxes are increased significantly, reaching 30€/t CO_2 in 2030 and 50€/t CO_2 in 2050, a change in the electricity production happens, natural gas contribution diminishes from 2030 and electricity coming from solar plants grows.

In the following Figure 58, the effects of CO_2 taxes are observed in the total Spanish CO_2 emissions.

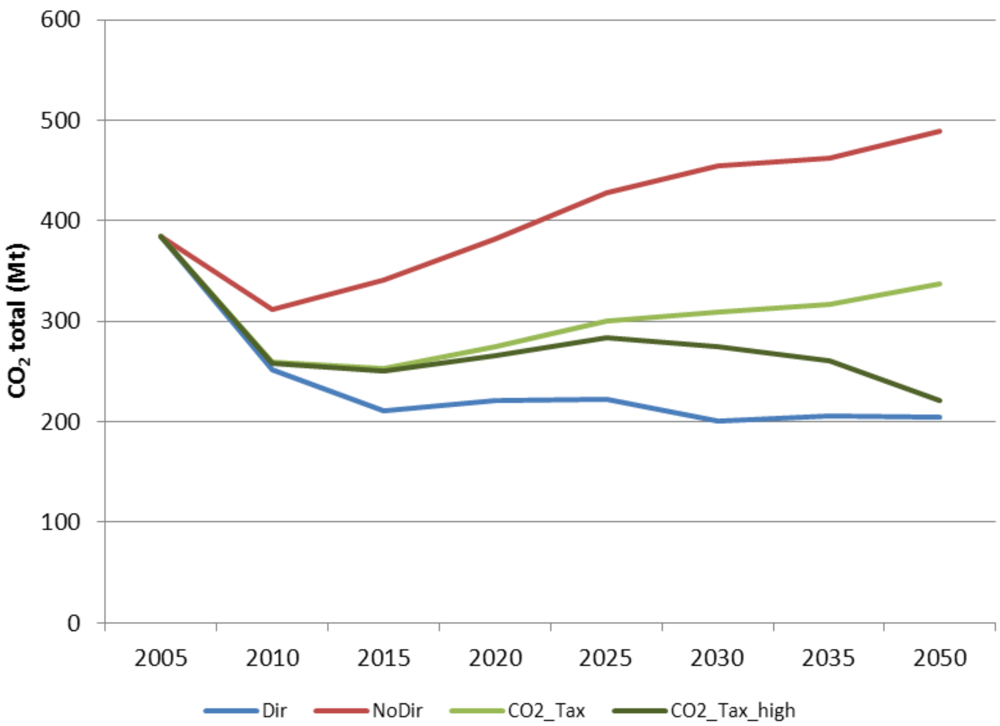


Figure 58. Total CO_2 emissions under several CO_2 taxes

The consideration of a conservative CO_2 tax (31€/t CO_2 in 2050) leads to a 150 Mt CO_2/yr reduction respect to the NoDir scenario but it is not enough to reach the bounds imposed by the Directive: CO2_Tax scenario deviates up to 133 Mt CO_2 above Dir scenario in 2050. On the contrary, the imposition of high CO_2 taxes shows a positive effect from 2030 when total CO_2 emissions decrease and converge to the Directive scenario in 2050.

In conclusion, a CO_2 tax of 30€/t CO_2 in 2030 helps to counteract the global emissions growth resulting from the increase in the use of gas and a tax of 50€/t CO_2 in 2050 favours meeting the Directives target.

Attending to the CO_2 emissions from electricity production, the effect of CO_2 taxes is quite different.

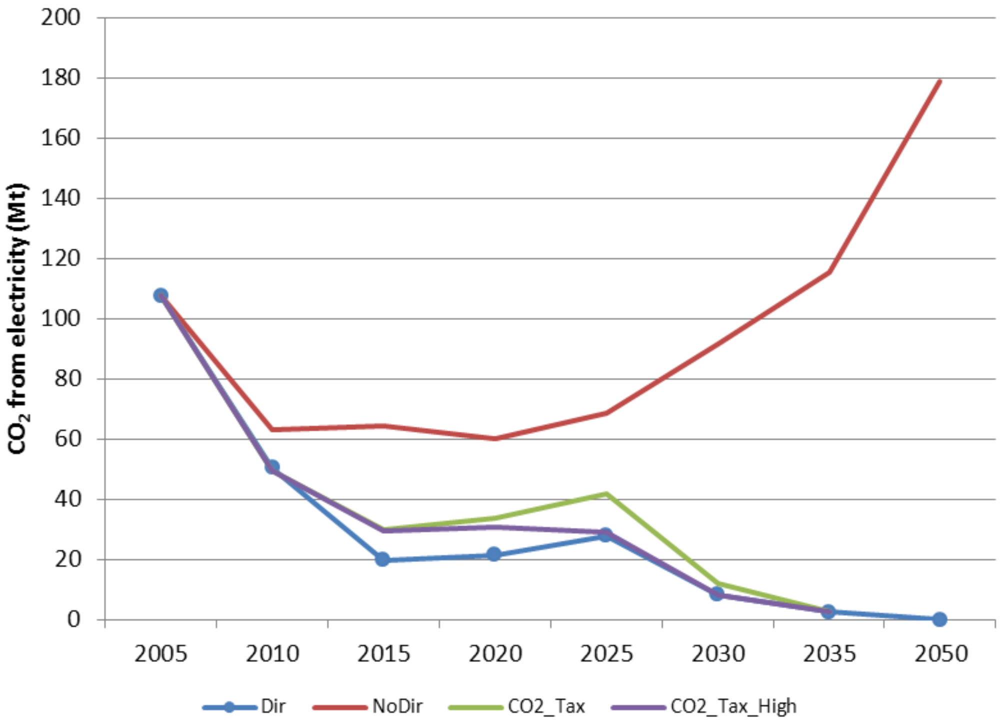


Figure 59. CO_2 emissions of the Spanish electricity production under several CO_2 taxes

Applying CO_2 taxes leads to the decarbonisation of the electricity production sector in 2035. Figure 59 shows the extinction of the CO_2 emissions in the Dir, CO2_Tax and CO2_Tax_High scenarios. The Directive scenario is the strictest one (blue spotted line) whereas lower CO_2 taxes entail 10-12 Mt CO_2 above in the mid periods (2015-2025) and converges to Dir in 2035. Finally, results from imposing high CO_2 taxes show a convergence with the Dir scenario from 2025.

To summarise, CO_2 taxes begin to have effect over the sectorial CO_2 emissions from 20€/t CO_2 in 2020 and make possible to keep the Directive's limits from 25€/t CO_2 in 2025.

Apart from the CO_2, also NO_x and SO_2 taxes have been imposed in order to assess Directive 2001/81/EC. Hence the NOX-SO2_Tax scenario has been built introducing different taxes for NO_x and SO_2 (Table 70).

The consequences of introducing these taxes on the electricity production are shown in the following Figure 60.

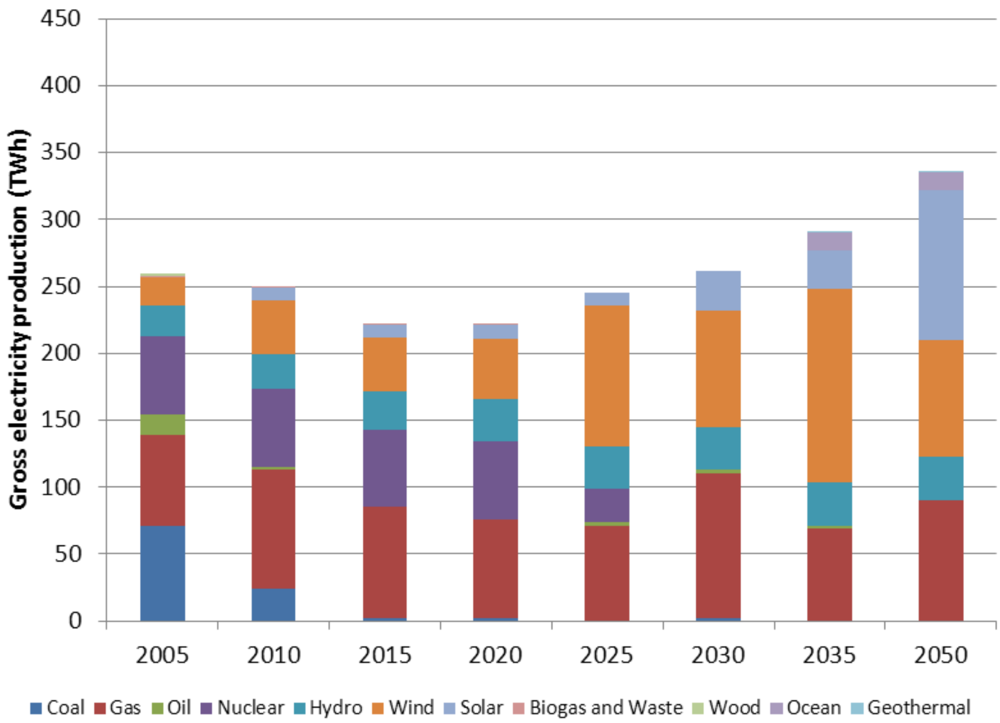


Figure 60. Gross electricity production in Spain by source considering NO_x and SO_2 taxes

In general terms, this scenario is similar to the Dir scenario, mainly looking at the amount of electricity produced in each period. On the contrary, the technology breakdown by source presents some changes respect to the Dir scenario. Natural gas contribution is lower, except in 2030 where 24 TWh come from NGCC plants instead of natural gas CHP plants used in Dir. The decrease in natural gas in 2020, 2025 and 2035 is compensated by the electricity coming from wind facilities. The introduction of natural gas CHPs in the Dir scenario is substituted by NGCC plants in 2030 in the NOX-SO2_Tax scenario. Results show that when taxes are applied, existing NGCC plants still work at the same time than new gas CHPs. This effect can be seen in the NO_x total emissions (see Figure 61).

Figure 61. Total NO_x emissions considering NO_x taxes

It can be concluded that taxes on NO_X entail a significant reduction on the emission levels respect to the Directive scenario from 2015 to 2025. Furthermore, the increase in the use of natural gas in 2030 causes an increase of the NO_x emissions. As a result, from 2030 and beyond, NO_x taxes do not help to meet the Directive's targets (from 8% above in 2030 to 45% more in 2050). Besides, NO_x emissions from transport grow (particularly in 2035 and 2050) under the NO_x taxes scenario.

In conclusion, using NO_x taxes up to 5,169 €/t NO_x in 2025 help to meet the Directive's targets but higher taxes are not enough to avoid the increase in the natural gas use from 2030.

Going further, the effect of the NO_x taxes in the electricity generation sector is very different than for the total Spanish NO_x emissions.

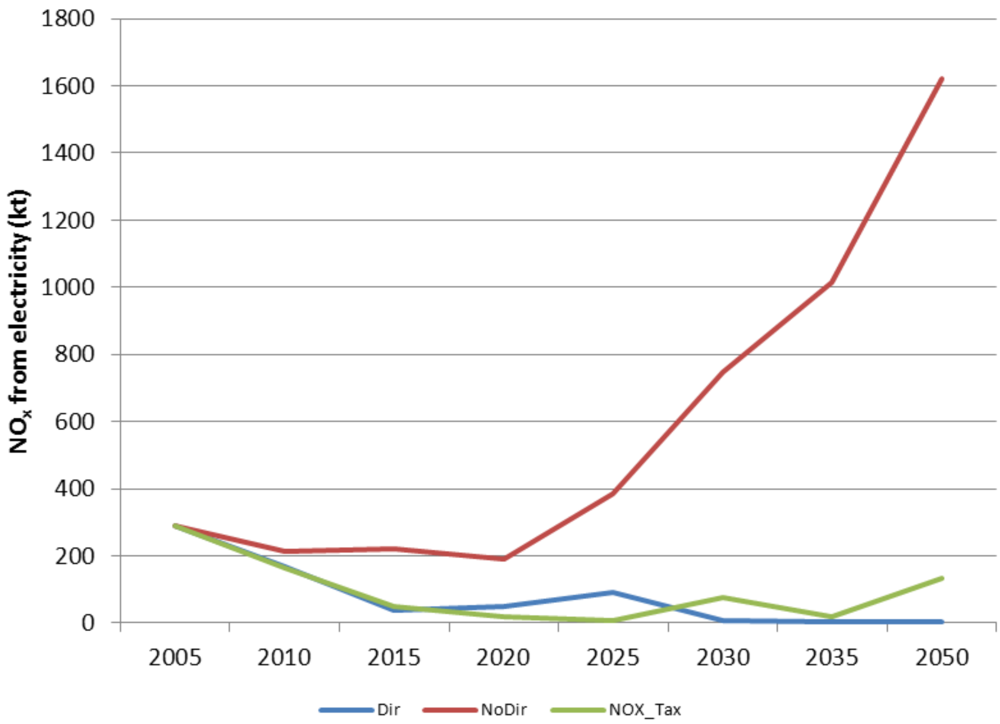


Figure 62. NO_x emissions of the Spanish electricity production considering NO_x taxes

Looking at Figure 62 and Figure 61, NO_x emissions from the electricity sector are low respect to the total (18.3% in 2005 and 14.3% in 2010).

In the Dir scenario, NO_x emissions from electricity mean less than 1% of the total in 2035-2050 while NOX_Tax scenario results in 8.4% (2030), 2.2% (2035) and 10.7% (2050). The unexpected increase in 2030 is due to the use of NGCC plants. In the Dir scenario, NO_x emissions linked to the natural gas come from CHPs (imputed to the industrial sector).

Finally, using the NOX-SO2_Tax scenario, the results of the SO_2 emissions in Spain considering SO_2 taxes have been obtained.

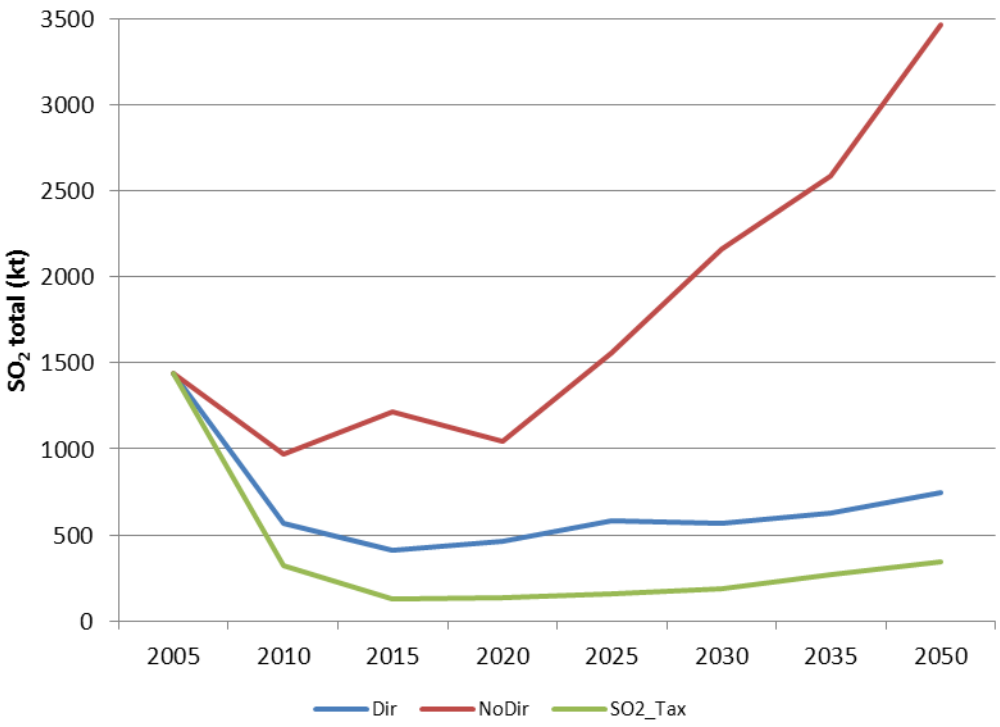


Figure 63. Total SO_2 emissions considering SO_2 taxes

Applying SO_2 taxes over the entire energy system in Spain leads to lower emissions than in the Directive scenario. SO_2 emissions in 2050 in the SO_2 taxes scenario are half the emissions in the Dir (see Figure 63).

Regarding the different sectors, SO_2 emissions are similar in both scenarios, Dir and SO_2 taxes, for the agricultural, industrial, transport and electricity production sectors. Changes take place in the commercial and residential sectors due to the use of biomass (wood-pellets) boilers, higher in Dir scenario than in SO_2 taxes scenario.

In summary, SO_2 taxes help to go further the Directive's targets reducing SO_2 emissions significantly. It is recommended a wide discussion about setting a tax to SO_2 emissions of biomass boilers in the future, both in residential and commercial sectors.

Finally, the effect of SO_2 taxes over the SO_2 emissions from the electricity production are presented next.

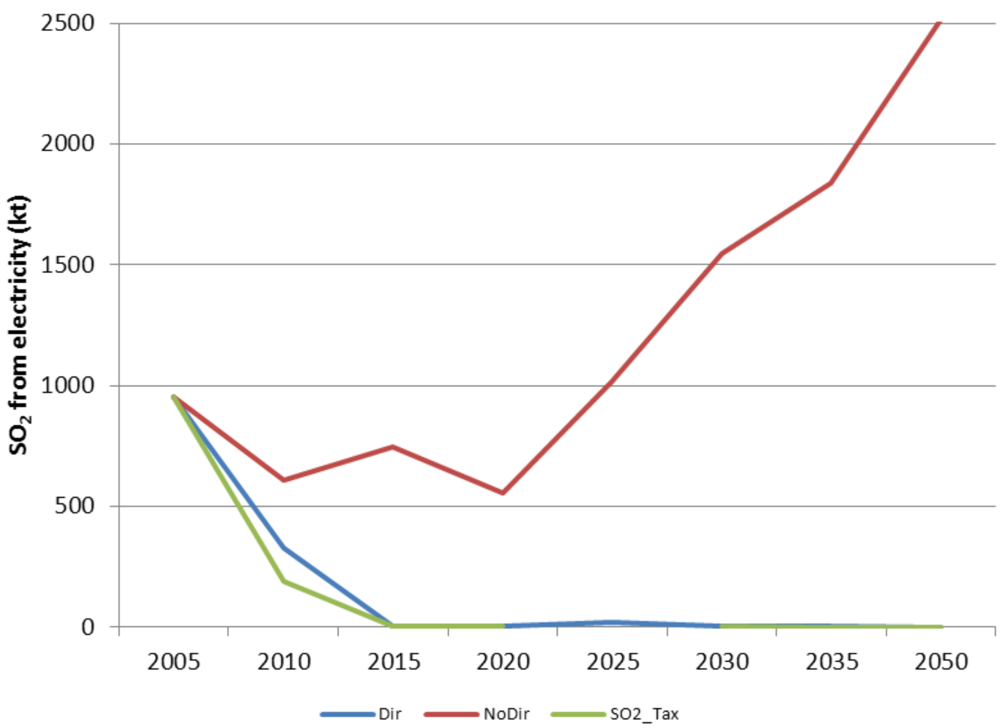


Figure 64. SO_2 emissions of the Spanish electricity production considering SO_2 taxes

SO_2 emissions from electricity production show a common result in Dir and SO2_Tax scenarios, the exhaustion of the SO_2 from 2015 due to the coal technologies phase out observed in both (see Figure 64). The difference amongst them is small; SO_2 taxes achieve major reductions in SO_2 emissions from electricity production but only in 2010 since extinction takes place from 2015 in both scenarios. It is then concluded that implementing SO_2 taxes forces the electricity system toward a fuel shift going from coal to natural gas.

1.5.8. System costs

The analysis of the system costs provides the economic effort of the energy system to achieve the targets proposed. From the system costs comparison of the Dir scenario with the NoDir scenario (see Table 71), it has been seen that Directive's compliance entails an extra cost of 1.9%.

Table 71. System costs comparison

Scenario	**System costs** (%)
NoDir	-
Dir	1.9
CO2_50-2050	2.1
CO2_80-2050	3.3
CO2_Dec162	0.6
CO2_Tax	2.6
CO2_Tax_High	3.7
NOX-SO2_Tax	4.2
ExtCosts	0.7
Coal+10%	2.0
Gas+10%	2.5
Oil+10%	2.7

In addition, when a CO_2 tax is set, the extra costs of the energy system go from 2.6% for the CO2_Tax scenario to 3.7% for the CO2_Tax_High scenario.

From the assessment of applying different CO_2 caps, it results that a CO_2 reduction by 50% in 2050 means +2.1% while a CO_2 reduction by 80% in 2050 entails an extra cost of 3.3%. Furthermore, the application of Decision 2013/162/EU means an extra system cost of 0.6%.

The introduction of taxes on NO_x and SO_2 means 4.2% extra costs. In this case, as observed previously, imposition of taxes allows accomplishing with the Directive 2001/81/EC ceilings obtaining better emission results than in Dir scenario.

The internalisation of the external costs of the electricity system and industry CHP plants means an extra cost of 0.7%. This value is lower than Directive's because this adjustment only takes place for the electricity production sector.

Finally, when the fuel prices are increased the system responds with a similar effect for every fossil fuel (2% approx.), but the higher costs correspond to the oil, 2.7%, followed by gas, 2.5%, and coal, 2.0%.

1.6. Summary

In this chapter, the Spanish electricity production sector has been analysed in detail. The main purpose of applying energy optimisation modelling to the Spanish energy system, and particularly to the electricity generation sector, has been to evaluate the Directives 2009/29/EC and 2001/81/EC.

TIMES-Spain modelling results have been obtained for different scenarios: CO_2 emissions, fuel prices, internalisation of external costs and taxes on emissions. Results on gross electricity generation, final energy consumption by fuel and CO_2, NO_X, SO_2 emissions have been assessed.

Electricity production

The main effects of applying Directive 2009/29/EC are the phase out of the coal power plants from 2015, the continuation of the NGCC plants and their substitution by new natural gas CHP plants in 2030. From then on, an increase in the renewable contribution takes place coming from the wind technologies and the emergence of ocean (waves) technologies in 2035. The solar PV plants produce electricity massively in 2050 and the solar thermal technologies have a noteworthy contribution from 2030. In addition, nuclear fission plants phase out in 2030 and hydropower is used at maximum capacity without installing new dams.

Looking at the sensitivity to CO_2 caps, results from 50% total CO_2 emissions reduction in 2050 respect to the 2005 levels are close to those from the Dir scenario so this target seems to be reasonable as a conservative option. In the case of an 80%-reduction of the CO_2 emissions, results show that there is a shift in the energy carriers in 2050, producing more heat for industrial processes and district heating plants and less electricity. This shift causes a major participation of biomass IGCC plants and biofuels in transport. Additionally, the application of the most recent Decision 2013/162/EU on national emission allocations for the period 2013-2020 (ETS - Phase III) involves a higher production of electricity from natural gas.

Sensitivity to the fuel prices in the electricity production is low and minor changes take place in the technology breakdowns. Considering 10% increase in the natural gas prices, a slight shift to coal happens in 2015 until it disappears in 2030 and wind power contribution grows. Electricity production seems to be irrelevant to 10% increases in oil and coal.

Directive 2009/28/EC (RES Directive) compliance

The effect of applying Directives 2009/29/EC and 2001/81/EC on the RES Directive 2009/28/EC has been evaluated. This Directive establishes 20% contribution of gross final energy consumption coming from renewable sources by 2020 in Spain. Considering the Directives, results have shown that Directive 2009/28/EC targets are met meaning the renewable contribution to the final energy consumption 32.1% in 2020, 43.5% in 2030 and 52.9% in 2050.

CO_2 emissions

Attending to the CO_2 caps scenarios, a long-term reduction by 50% of the total CO_2 emissions follows almost the same trend than the one derived from Directive 2009/29/EC. Increasing the target to 80% CO_2 emissions reduction, there is a fall in the total amount of CO_2 from 2035 to 2050 due to the energy carrier shift from electricity to heat.

The application of Directive 2009/29/EC on GHG targets involves the disappearance of CO_2 emissions from the electricity production sector in 2035.

NO_x emissions

The compliance of Directive 2001/81/EC on SO_2 and NO_X ceilings leads to the extinction of the NO_x emissions of the Spanish electricity generation sector in 2030. This is achieved by means of renewable energy technologies (wind and solar mainly) and the installation of natural gas CHP plants with low NO_x emissions in the industry sector.

SO_2 emissions

The disappearance of the SO_2 emissions coming from the electricity production sector takes place in 2015 as a result of the Directive 2001/81/EC application. As the main source of SO_2 is the sulphur contained in the hard coal and lignite, its extinction from the electricity generation mix makes possible the elimination of the SO_2 emissions.

Internalisation of external costs

The internalisation of the external costs associated to the electricity production technologies and industrial CHP plants has been carried out.

It favours the increase of the natural gas, especially from 2025. Natural gas CHP plants are massively installed and there is no more new capacity of renewable technologies. A consequence of the environmental restrictions imposed is the higher degree of electrification.

Internalising the external costs seems to be a good solution to reduce CO_2 emissions in the electricity sector until 2030. However, this sectorial effect is not enough looking at the entire energy system in order to reach the Directive 2009/29/EC targets.

Emission taxes

CO_2 taxes have been implemented through two scenarios: one establishing 17.6€/t CO_2 in 2030 and 31.4€/t CO_2 in 2050 and other with higher taxes of 30€/t CO_2 in 2030 and 50€/t CO_2 in 2050.
Imposing a CO_2 tax of 30€/t CO_2 in 2030 has effect on the global emissions growth resulting from the higher natural gas consumption and a tax of 50€/t CO_2 in 2050 makes possible to accomplish the Directive 2009/29/EC target.

Furthermore, CO_2 taxes involve the decarbonisation of the electricity production sector in 2035. Taxes on CO_2 have an effect on the CO_2 emissions reduction resulting from the electricity sector from 20€/t CO_2 in 2020 and help to meet the Directive target from 25€/t CO_2 in 2025.

The effect of the NO_x and SO_2 taxes respect to Directive 2001/81/EC have also been assessed. Electricity production results have shown that NO_x and SO_2 taxes imposition entails the system continuing using NGCC plants at the same time than using more natural gas CHP plants from 2030. This causes a significant NO_x emissions increase beyond 2030. In particular, taxes on NO_x emissions have a similar effect than the Directive. In the same manner, SO_2 taxes implementation allows going further the Directive targets reducing SO_2 emissions. It is recommended a wide discussion about how to tax the biomass boilers in the future, both in residential and commercial sectors.

6 CONCLUSIONS

1. Summary

This research work is based on assessing the European Directives concerning the main pollutants released to the atmosphere in the European Union member states. Directive 2009/29/EC improves and extends the GHG emission allowance trading scheme of the Community whereas Directive 2001/81/EC establishes national emission ceilings for the SO_2, NO_X, VOC and NH_3 gases. In particular, the analysis has been focused on Spain.

To evaluate the application of the Directives as well as their consequences in the Spanish energy system, several analyses have been carried out.

Firstly, the Spanish cement production industry has been analysed in depth by means of a complete LCA study and using TIMES energy optimisation modelling. The choice of this industry is not arbitrary. During the last decade, Spanish cement production has become one of the main industrial emitters, reaching 7% of the total CO_2 emissions. Furthermore, it is quite difficult to reduce CO_2 emissions of the cement manufacture since most of them are not linked to the combustion but come from the limestone calcination. Besides, cement making requires huge amounts of heat which means an additional problem for the future of the industry.

Once the LCA of the Spanish cement production has been done, technical solutions to improve the energy consumption and reduce the emissions have been implemented in the TIMES-Spain model. Using TIMES optimisation modelling, it has been possible to develop scenarios for exploring the cement industry up to the 2050. Moreover, several CO_2 caps, cement demands projections and investment costs of the CO_2 capture technologies scenarios have been considered with and without the Directives.

Secondly, the Spanish electricity generation sector has been studied using the TIMES-Spain model. The effect of the Directives has been compared with several scenarios imposing taxes on CO_2, NO_x and SO_2. Furthermore, internalisation of externalities derived from production of electricity has been assessed. In addition, a sensitivity analysis of the electricity production concerning the fossil fuel prices and also with different CO_2 bounds has been done.

2. Meeting the objectives

The three main objectives of the work have been successfully met.

a. The assessment of the environmental impacts of the cement manufacturing technologies in Spain in order to identify hotspots and to apply environmental-friendly solutions using LCA method.

The LCA of the cement production has made possible to identify the production hotspots and evaluate the technological improvements proposed by the cement industry (Chapter 4 Section 1). A brief set of conclusions answering this item is presented in the following Section 3.1 and Section 4 of this chapter.

b. The evaluation of the application of Directive 2009/29/EC and Directive 2001/81/EC in the framework of the Spanish cement production from 2010 to 2050.

By means of the environmental study and the TIMES energy optimisation model, the effect of the Directives on the cement sector in Spain has been assessed (Chapter 4 Section 2). Main conclusions and recommendations have been listed in the following Section 3.2 of this chapter.

c. The evaluation of the application of Directive 2009/29/EC and Directive 2001/81/EC in the framework of the Spanish electricity production from 2010 to 2050.

Analogously to the modelling of the cement industry, this work has answered questions concerning the application of the emissions Directives in the electricity production sector. This assessment is detailed and discussed in depth in Chapter 5. Main conclusions and recommendations have been listed in the following Section 3.3 and Section 4 of this chapter.

3. Conclusions

3.1. LCA of the Spanish cement production

This work has addressed both human and environmental impact improvements applied to the Spanish cement making industry, implementing BAT measures and considering other prospective solutions suggested by the European Commission.

- The main hotspot of the cement making is fossil fuel combustion at the kiln.

- Both material and fossil fuel substitution are the best options to reduce the majority of human and environmental impacts. The substitution of fossil fuels by alternative fuels achieves the highest reductions in most of the categories but eutrophication worsens due to the phosphates emissions of the alternative fuels.

- Material substitution is a good solution for the industry in terms of impacts, but it requires a shift in the cement types demand and further research to keep the properties.

- The need of steam from a CHP plant when CO_2 capture is implemented is extremely high. This is the basis of the 'energy penalty'. The weight of the CHP plant, in terms of impacts, is at the same level than the cement production plant. Results of the present work, in line with recent literature, show that using a natural gas-fired CHP plant entails a significant reduction in most impact categories compared to the case of using a coal-fired CHP plant. Besides, the consideration of this solution is supported by the expected coal phase-out of the Spanish electricity mix.

- CO_2 capture technologies applied to the cement industry contribute to reduce the climate change, while the rest of the impact categories grow by several times. In order to make this technology more competitive to reduce CO_2 emissions, more research is needed. Consequently, it is recommended that further studies take into account both the substitution of the hard coal in the CHP plant by alternative choices such as natural gas and biomass, as well as the consideration of different CO_2 capture technologies, e.g. OCC and/or other PCC options.

3.2. Modelling the Spanish cement industry with TIMES-Spain

Once the LCA method had been applied, several solutions and scenarios were implemented in TIMES-Spain in order to analyse the Spanish cement industry under the framework of Directives 2009/29/EC and 2001/81/EC.

- Directive 2009/29/EC involves reducing the CO_2 emissions of the cement production considerably respect to the case without Directive. When the Directive is applied, sectorial emissions go from 16 to 18 Mt CO_2 per year from 2020 and beyond whereas without Directive emissions reach up to 30 Mt CO_2.

- As a result of the CO_2 reduction in other sectors, there is an increase in the share of the sectorial CO_2 emissions respect to the total CO_2, going from 6% in 2010 to 9% in 2050. This is a problem that Spanish cement industry will have to deal with in the future.

- Besides, by implementing the BAT measures and substitution scenarios, it has been concluded that the reduction of the clinker content in cement is the best option to reduce the CO_2 emissions, achieving to diminish 2-2.4 Mt CO_2 per year from 2030.

- When all BAT measures and substitution scenarios are considered, energy consumption in cement industry reduces up to 21% in 2050.

- The SO_2 ceiling of Directive 2001/81/EC is too high compared with the historical data. Consequently, Directive 2001/81/EC should be updated to establish a stricter SO_2 ceiling. In the cement production sector, SO_2 emissions disappear when the petroleum coke is substituted by alternative fuels.

- CO_2 capture technology only emerges when cement demands are high, the CO_2 sectorial limits are stringent and the rest of cement-making technologies do not achieve meeting the CO_2 emissions targets. In such a case, the dry-route clinker production with post-combustion CO_2 capture using MEA appears in 2050 slightly.

3.3. Modelling of the Spanish electricity generation sector with TIMES-Spain

Several scenarios were implemented in TIMES-Spain in order to analyse the Spanish electricity generation sector under the framework of Directives 2009/29/EC and 2001/81/EC.

- The application of the emissions Directives 2009/29/EC and 2001/81/EC involves a high natural gas contribution in the production of electricity with NGCC plants. Those installations are substituted by new natural gas CHP plants beyond 2030. From then on, an increase in the renewable energy technologies contribution takes place.

- When Directives are applied, the long-term contribution of the renewable energies is relevant. It is based on wind, wave and solar thermal (parabolic troughs) technologies in 2035, and the massive installation of solar photovoltaic (plant type) in 2050.

- Nuclear fission plants phase out in 2028 and hydropower plants are used at maximum capacity without installing new dams.

- The application of Directive 2009/29/EC on GHG emissions has a significant effect in terms of CO_2 emissions reductions. CO_2 emissions of the electricity production sector disappear in 2035 due to the coal power plants phase-out and the shift to natural gas from 2015.

- Results of setting a target of 50% reduction in CO_2 emissions by 2050 respect to the 2005 levels are very close to those from applying Directive 2009/29/EC. Using a more ambitious reduction target of 80%, a shift in the main energy carrier, from electricity to heat, takes place.

- Results have shown that when considering a reduction of 80% in the CO_2 emissions in 2050, the major consumption of heat involves a major introduction of biomass IGCC plants and biofuels in transport.

- The effect of Directives 2009/29/EC and 2001/81/EC on the RES Directive 2009/28/EC is relevant. RES Directive establishes 20% contribution of gross final energy consumption coming from renewable sources by 2020 in Spain. Considering the emissions Directives, the objective of the RES Directive is completely satisfied.

- Applying the NO_x ceiling of Directive 2001/81/EC leads to the extinction of the NO_x emissions resulting from the electricity production from 2030. Besides, a major contribution of renewable technologies - mainly wind and solar - and new natural gas CHP plants takes place.

- Applying Directive 2001/81/EC causes the disappearance of the SO_2 emissions associated to the electricity production system from 2015. This is due to the coal power plants phase-out.

- The internalisation of the external costs of the electricity production favours the use of natural gas. New natural gas CHP plants are installed whereas the existing renewable capacity does not grow. A consequence of the environmental restrictions imposed is the high degree of electrification.

- Imposing a tax of 30€/t CO_2 in 2030 would stop the emissions growth resulting from the progressive natural gas contribution and a tax of 50€/t CO_2 in 2050 would achieve the Directive target. In particular, CO_2 taxes have effect on the CO_2 emissions resulting from the electricity sector from 20€/t CO_2 in 2020 and make possible reaching the Directive from 25€/t CO_2 in 2025.

- NO_X and SO_2 taxes imposition leads to continue using NGCC plants at the same time than new natural gas CHP plants are installed from 2030. The application of NO_x taxes favours the accomplishment of Directive 2001/81/EC until 2030, when the new natural gas CHP plants hinder achieving the NO_x ceiling. The application of SO_2 taxes allows going further the Directive targets reducing SO_2 emissions.

4. Final remarks and recommendations

In each chapter, recommendations for further research have been formulated to provide a better understanding of technologies, restrictions and measures evaluated. Key recommendations are summarised below:

4.1. Political recommendations

Political recommendations are mainly related to Directives 2009/29/EC and 2001/81/EC.

- It is recommended to reduce the CO_2 emissions limits to the cement manufacturing sector in Spain assuming that 2013-2020 allowances allocation does not force the cement producers to make new investments since the expected cement demands are too low, i.e. going further Decision 2013/448/EC beyond 2020.

- It is necessary to update Directive 2001/81/EC for establishing new ceilings. In particular, the 2010 SO_2 ceiling for Spain was achieved so it is recommended to set a new limit below 450-500 kt SO_2 per year.

- It is suggested to extend the 20% GHG reduction in 2020 respect to the 1990 levels (Directive 2009/29/EC) to 50% in absolute CO_2 in 2050 respect to the 2005 level. Furthermore, 80% reduction target by 2050 has shown to be achievable.

4.2. Technical recommendations

- In cement production, it is necessary to carry out more technical studies on keeping the chemical and mechanical properties of the cements when the clinker content is reduced introducing calcined secondary materials (material substitution scenarios).

- Other technical solutions for solving the so-called energy penalty linked to the flue gases purification of the post-combustion CO_2 capture should be evaluated. Looking at the results obtained both in LCA and modelling exercises, it is suggested to carry out a detailed study concerning the substitution of coal CHP plants by biomass CHP plants in cement production with CO_2 capture.

- To build synergies between cement industry and natural gas combined cycle power plants in order to use their residual heat to face the energy penalty linked to the post-combustion CO_2 capture processes.

4.3. Specific recommendations

Focusing on very specific matters observed both in cement and electricity production in Spain, some recommendations are remarked:

- More environmental impact categories should be considered in the LCA of the cement production, especially when CO_2 capture is implemented. Apart from impacts derived from CO_2 emissions, other categories such as human toxicity, eutrophication, ecotoxicity and acidification, have relevant contributions.

- In particular, it is interesting to analyse more deeply the environmental consequences of using amines as membranes in the post-combustion CO_2 capture, by extending the limits of the system upwards.

5. Publications

The list of publications derived from the present work is listed below:

Scientific papers

García-Gusano D., Garraín D., Herrera I., Cabal H., Lechón Y. *Life Cycle Assessment of applying CO_2 post-combustion capture to the Spanish cement production*. Journal of Cleaner Production. doi: 10.1016/j.jclepro.2013.11.056. To be published in 2014.

García-Gusano D., Herrera I., Garraín D., Lechón Y., Cabal H. *Explorative analysis of the Spanish cement production from a Life-cycle Assessment approach* (submitted to journal).

García-Gusano D., Cabal H., Lechón Y., Alonso-Ayuso A. *Long-term analysis of the Spanish electricity production considering environmental policies* (foreseen).

Conferences and other research works

García-Gusano, D., Garraín D., Herrera, I., Lechón Y., Cabal, H. *Efectos medioambientales derivados de la sustitución de combustibles fósiles en la producción de cemento en España*. I Simposio de la Red Española de ACV: "ACV y Bioenergía". October 15th 2013. Madrid (Spain).

García-Gusano D., Cabal H., Lechón Y., Garraín D., Herrera I. *Modelling future solutions for the Spanish cement industry*. WC-54: Simulation in Environmental Management and Optimisation in Energy Consumption. Stream: Energy, Environment and Climate. 26th European Conference on Operational Research (EURO-INFORMS). July 3rd 2013. Rome (Italy).

García-Gusano D., Cabal H., Van Den Broek M., Lechón Y., Alonso-Ayuso A. *Role of carbon capture technologies in the Spanish industry in 2030 under a CO_2 reduction scenario using the TIMES-Spain energy optimisation model.* WD-38 (moved to session WD-33). 25th European Conference on Operational Research (EURO). July 11th 2012. Vilnius (Lithuania).

García-Gusano, D. *Energy models, tools for developing energy plans*. Cantabria Campus Nobel. Water, Energy and Climate Change Workshop. Magdalena Palace Ballroom. June 12nd 2012. Santander (Spain).

6. Future works

Main future research is related to the TIMES model.

During the development of this work, numerous things have been identified as possible future research lines:

- LCA of other CO_2 capture technologies applied to cement-making such as oxyfuel or calcium looping.

- To carry out the same analysis as for the cement-making developed in the present work for the shale gas extraction, transformation and use in Spain.

- The development of an integrated tool including the LCA method and the TIMES energy model.

- The extension of the internalisation of the environmental external costs to other sectors in the TIMES-Spain model.

- To consider environmental externalities related to other pollutants such as particulate matter, dioxins and heavy metals.

- The introduction of not only the environmental externalities of the electricity production but also the socioeconomic external costs.

- The implementation of new technologies related to the transport sector (electric vehicles, hydrogen cars, motorbikes, planes, etc.) and a further analysis of the existing Directives concerning not only CO_2 emissions but also NO_x emissions. In addition, it would be interesting to assess the Spanish transport sector under several taxation policies as well as going beyond the current Decision No 406/2009/EC by imposing stringent restrictions to these sectorial emissions.

- The consideration of the recent Acuerdo Marco de Actuación de la Minería del Carbón 2013-2018 (Framework Agreement concerning the Coal Mining Sector 2013-2018) in TIMES-Spain.

- Cost-Benefit Analysis of the different technological solutions to reduce emissions in the cement production is recommended. This study should take into consideration the energy consumption and the compliance of the policies and regulations subscribed.

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APPENDIXES

Appendix I

LCI of the pre-treatment, transport and combustion of 1 kg of each alternative fuel used in the Spanish cement production in 2010

		01	02	03	04	05	06	07	08	09	10	11	12	13	14
Input	kg	1	1	1	1	1	1	1	1	1	1	1	1	1	1
LHV(1)	MJ/kg	18.88	13.29	20.14	12.4	15.17	12.94	17.13	12.48	31.34	27.04	14.81	29.84	12.73	24.67
Materials/fuels															
Transport, lorry >28t (2)	tkm	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05
Electricity/heat															
Electricity, medium voltage (2)	kWh	0.008	0.251	0.003	0.008	0.033	0.033	0.092	0.003	0.045	0.003	0.033	0.066	0.003	0.003
Heat from incineration plant (2)	MJ		6.265					0.23							
Output															
Emissions to air															
Carbon monoxide, biogenic	kg	1.35E-04	4.00E-05		2.23E-04	2.23E-04	2.23E-04	1.35E-04	2.23E-04						
Carbon monoxide, fossil	kg	8.82E-05						8.82E-05		2.23E-04	1.21E-05	1.21E-05	2.23E-04	1.21E-05	1.21E-05
Carbon dioxide, biogenic	kg	7.23E-01	7.26E-02		1.46E+00	1.46E+00	1.45E+00	7.23E-01	1.25E+00						
Carbon dioxide, fossil	kg	4.74E-01						4.74E-01		3.09E+00	1.10E+00	1.73E+00	2.30E+00	1.80E+00	1.10E+00
Methane, biogenic	kg	3.86E-06	1.14E-06		6.38E-06	6.38E-06	6.38E-06	3.86E-06	6.38E-06						
Methane, fossil	kg	2.53E-06						2.53E-06		6.38E-06			6.38E-06		
Sulfur dioxide	kg	4.46E-06	3.97E-06		5.99E-06	5.35E-07	8.44E-07	4.46E-06	6.19E-05	1.58E-05	7.70E-06	7.70E-06	5.99E-06		7.70E-06
Nitrogen oxides	kg	9.94E-05	6.75E-05		1.20E-04	3.14E-05	3.14E-05	9.94E-05	2.25E-03		2.66E-04	2.66E-04	1.94E-04		2.66E-04
Ammonia	kg	2.48E-06	1.68E-06		2.98E-06	7.82E-07	7.81E-07	2.48E-06	5.61E-05		1.02E-05	1.02E-05	4.84E-06		1.02E-05
Dinitrogen monoxide	kg	1.32E-05	9.79E-06		1.59E-05	4.17E-06	4.16E-06	1.32E-05	2.99E-04		3.69E-05	3.69E-03	2.58E-05		3.69E-05
Cyanide	kg	2.81E-06	1.91E-06		3.38E-06	8.88E-07	8.87E-07	2.81E-06	6.38E-05		9.22E-06	9.22E-06	5.50E-06		9.22E-06
Phosphorus	kg	8.94E-07	1.01E-06		1.13E-07	1.09E-07	1.09E-07	8.94E-07	3.75E-08		7.00E-07	7.00E-07		5.25E-07	7.00E-07
Boron	kg	8.63E-07			2.06E-06	2.53E-07	3.28E-06	8.63E-07							
Hydrogen chloride	kg	6.64E-08			2.04E-08	3.67E-09	3.67E-09	6.64E-08	1.99E-08	2.22E-07	7.54E-06	7.54E-06	2.01E-07		7.54E-06
Bromine	kg	4.07E-08						4.07E-08			5.01E-07	5.00E-07	1.96E-07		5.01E-07
Hydrogen fluoride	kg	2.97E-08			1.02E-08	1.11E-08	1.11E-08	2.97E-08			1.13E-08	1.00E-08	7.22E-09		1.13E-08
Iodine	kg	1.31E-13						1.31E-13			2.00E-08	2.00E-08			2.00E-08
Silver	kg	9.28E-12			6.20E-13			9.28E-12							
Arsenic	kg	6.38E-15	9.33E-16		2.09E-14	4.31E-15	2.75E-15	6.38E-15	6.12E-16				1.81E-14	1.22E-14	
Barium	kg	3.60E-08			1.14E-07			3.60E-08					1.74E-07		
Cadmium	kg	6.37E-10	3.58E-12		9.16E-11	1.10E-11	7.49E-11	6.37E-10	2.20E-12	4.41E-10			4.17E-09	4.41E-11	
Cobalt	kg	4.27E-14	1.19E-14		2.34E-14	2.76E-15	2.59E-09	4.27E-14			2.87E-09	2.00E-09	9.36E-13		2.87E-09
Chromium	kg	4.10E-12	2.09E-13		1.07E-12	4.86E-14		4.10E-12	4.14E-14				2.82E-12	8.28E-13	
Copper	kg	4.88E-09	9.62E-11		4.50E-10	3.06E-11		4.88E-09	3.30E-10		3.60E-09	3.00E-09	2.19E-09	7.00E-08	3.60E-09
Mercury	kg	4.07E-14	2.24E-15		4.80E-15	1.10E-14	1.10E-14	4.07E-14	2.07E-18	3.45E-17			2.74E-14	4.14E-17	
Manganese	kg	1.41E-12	6.68E-14		2.19E-13	2.89E-13	2.89E-13	1.41E-12					4.06E-13		
Molybdenum	kg	3.91E-09	4.43E-10		8.60E-09	1.66E-09	1.66E-09	3.91E-09							

Nickel	kg	2.35E-12	5.26E-14		4.08E-13	2.40E-14	2.39E-14	2.35E-12	6.91E-15		2.98E-09	2.00E-09	8.30E-13	2.24E-09	2.98E-09
Lead	kg	1.13E-08	1.34E-10		2.98E-09	1.03E-09	1.03E-09	1.13E-08	9.50E-10	2.60E-09			1.62E-08	6.83E-09	
Antimony	kg	5.48E-14			2.76E-15			5.48E-14					1.56E-13		
Selenium	kg	1.16E-15			1.30E-14			1.16E-15					9.85E-15		
Tin	kg	7.46E-08	1.23E-09					7.46E-08					3.24E-08		
Vanadium	kg	9.21E-10						9.21E-10					2.69E-08		
Zinc	kg	1.61E-08	5.80E-10		2.04E-09	2.91E-10	2.90E-10	1.61E-08	1.72E-09	2.61E-07	2.93E-08	2.90E-08	8.52E-09	4.76E-07	2.93E-08
Silicon	kg	3.63E-05	3.22E-06		4.95E-05			3.63E-05			7.29E-05	7.29E-05			7.29E-05
Iron	kg	2.80E-07	2.08E-07		3.97E-08	5.17E-10	5.16E-10	2.80E-07			5.93E-08	5.90E-08	1.16E-07		5.93E-08
Calcium	kg	1.47E-05	3.91E-06		5.73E-06	2.18E-07	2.18E-07	1.47E-05							
Aluminium	kg	1.19E-05	1.08E-06		1.94E-05	9.89E-09	9.88E-09	1.19E-05					2.92E-07		
Potassium	kg	6.19E-06			4.00E-06	1.97E-07	1.97E-07	6.19E-06							
Magnesium	kg	3.44E-06	3.62E-07		5.92E-06	2.72E-07	2.72E-07	3.44E-06							
Sodium	kg	8.92E-06			8.65E-06	1.32E-07	1.47E-06	8.92E-06					1.29E-05		
Emissions to water															
COD (r)	kg	4.02E-05	2.34E-04		2.70E-05	2.68E-05	2.68E-05	4.02E-05	2.31E-05	5.70E-05	2.40E-05	2.40E-05	4.23E-05	3.91E-05	2.40E-05
Nitrate (r)	kg	4.00E-05	1.28E-03		4.81E-05	1.26E-05	1.26E-05	4.00E-05	9.06E-04		1.33E-04	1.33E-04	7.82E-05		1.33E-04
Phosphate (r)	kg	1.75E-07	1.44E-05		2.21E-08	2.13E-08	2.13E-08	1.75E-07	7.33E-09		4.80E-05	4.80E-05		3.60E-05	4.80E-05
COD (g)	kg	1.82E-02	4.92E-04		9.97E-03	9.91E-03	9.89E-03	1.82E-02	8.52E-03	2.11E-02	7.75E-03	7.75E-03	1.56E-02	1.26E-02	7.75E-03
Nitrate (g)	kg	1.12E-04	7.62E-05		1.35E-04	3.55E-05	3.54E-05	1.12E-04	2.55E-03		3.72E-04	3.72E-04	2.20E-04		3.72E-04
Phosphate (g)	kg	1.05E-04	1.18E-04		1.32E-05	1.28E-05	1.27E-05	1.05E-04	4.39E-06		6.74E-04	6.74E-04		5.06E-04	6.74E-04
Ammonium, ion	kg		2.76E-04												
Nitrogen	kg		1.89E-05												

Nomenclature:

01. Meat and bone meals. 02. Municipal sewage sludge. 03. Other liquid fuels (bio). 04. Pulp, paper and paperboard. 05. Wood. 06. Impregnated sawdust. 07. Refuse-derived fuel MSW. 08. Textile waste. 09. Used tyres. 10. Hydrocarbon residues. 11. Others no biomass. 12. Plastics. 13. Used oils. 14. Varnishes and solvents. // COD = Chemical Organic Demand. // r = river. g = groundwater.

Notes: (1) Energy output (usable) refers to the low heating value (LHV) of each fuel according to CEMA (2010). (2) Both transport, electricity and heat required drag burdens from transportation and material pre-treatment. These values were obtained from Boesch and Meister (2011). (3) Emissions to air and water come from Ecoinvent (2010). In some vague cases, LHV was used for approaching factual fuel to an existing one in Ecoinvent database.