Power sector decarbonisation: Metastudy

WP 1.2 Comparison Methodology

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Content

1 Scope

Energy scenarios are an important and frequently used tool for decision makers to visualise the necessary changes towards a low carbon economy in the future. They demonstrate (alternative) paths for the possible mid- or long-term development. Backcasting approaches indicate what political decisions need to be taken today or within the short-term future to make the outlined paths feasible. Energy scenarios should not be equated with concrete projections, as they do not aim to continue developments from the past into the future. They rather try to develop a range of possible future paths, based on a set of assumptions.

In particular the range of paths and various sets of scenarios in the different studies make it difficult to compare them. Different assumptions, combined with a lack of transparency and the missing disclosure regarding the underlying data, hamper the comparison of the scenario studies and single scenario paths in particular. Given these limitations it is currently difficult for policy makers to decide upon a particular scenario to use as the basis for setting environmental policy in order to decarbonise the economy.

The scope of the research project *Power Sector Decarbonisation: Metastudy* is to provide a scenario overview which helps to overcome the difficulties outlined above. Having such an overview will be necessary when the European institutions and Member States start their debates on a Roadmap 2050 during the year 2011. Decisions shall be based on robust evidence from modelling exercises and other analytical work – therefore, it is necessary to analyse the existing and emerging analytical work on decarbonisation strategies for the power sector with a metastudy approach. The purpose of this metastudy is to identify:

- similarities and robust elements of decarbonisation strategies for the power sector;
- key differences and their determinants;
- key issues on implementation.

The scope of this work package (WP 1.2) is to provide an analytical framework for a systematic comparison of decarbonisation studies focusing on the power sector. The methodology involves the systematic disaggregation of emission reductions into the underlying causal factors (or components) that cause emission reductions in the power sector. By decomposing CO_2 emissions into causal factors the present methodology provides value added in increasing the transparency of modelling exercises completed in various studies. The studies considered in the course of this project include for example (Greenpeace International & European Renewable Energy Council 2010; WWF 2009; European Climate Foundation 2010; eurelectric 2010). All of these studies consider several scenarios regarding the future development of CO_2 emissions of the power sector in view of decarbonisation goals and provide a more or less detailed overview of future power generation. However, the assumptions underlying these studies and the scenarios they consider differ, and the specific analysis of the underlying structure of the emission reductions was not among their main goals.

In (WWF 2009) decomposition analysis is applied to attribute emission reductions to a range of underlying causal factors (or components) for a number of sectors. In this paper the decomposition methodology applied in the (WWF 2009) study is adapted for the power sector and expanded to include various causal factors, including for example efficiency improvements of traditional appliances. The methodological framework presented in Section 2 provides the means to disaggregate power sector CO_2 emission reductions into the contributions arising from demand side effects, energy efficiency improvements, renewable energy shares, nuclear shares, CCS shares, storage, and imports and exports. The methodological framework outlined in the following section is described in a clear and transparent manner to enable the approach to be replicated in the future to compare different scenarios for the decarbonisation of the power sector.

2 Methodology

2.1 Methods of decomposition analysis

A decomposition analysis can be used to explain a variable of interest in terms of a whole set of factors/activities that actually determine the value of this variable. Each decomposition analysis starts with defining a governing function relating the variable of interest (i.e. CO_2 emissions) to a number of causal factors (Ang 2004).

There are several ways of approaching a decomposition analysis. The most notable difference is the distinction between methods that produce a full decomposition and do not yield a residual term and those that yield a residual term.

Let us assume that the variable of interest to be decomposed is CO_2 emissions. The Laspeyres method of decomposition measures the isolated contribution of the change of one causal factor to the total change of CO_2 emissions, assuming all the other causal factors remain the same. Each factor playing a role in defining emissions is therefore modified individually while all the others are held at base year values. See for example (Ang 2000) . This can be interpreted as a prospective view (Albrecht et al. 2002) .

In contrast, when applying the Paasche method of decomposition, the contribution of the change of one activity is measured compared to the total change of emissions assuming the end year values of all other causal factors while keeping the element to be considered at base year values. This can be interpreted as a retrospective view (Sun 1998).

Both of these decomposition methods account for the *isolated effects* of each activity considered. As such they produce a residual – an amount that cannot be attributed to those individual effects. This residual is the difference between the total change as observed (e.g. emissions change between *t=0* and *t=1*) and the value to which the integrals of the activities add up to after the approximation[1].

This *residual term* accounts for the mixed effects, i.e. of changes that are triggered by joint changes of causal factors. Thus it reflects the lack of knowledge about the actual underlying functions (Muller 2006). The decomposition is thus not full and the modeller needs to decide on how to proceed with the residual term. Possibilities include neglecting it (if the value is sufficiently small), explicitly considering it, and distributing it among the different isolated effects (Seibel 2003).

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[1] Ideally, these would be integrals; in practice, however, they are sums because observations are only available for discrete time steps.

There are several methods providing a full decomposition without residual terms, for example the LMDI approach as described in (Ang 2005) and the Shapley decomposition described in (Albrecht et al. 2002). These methods account for the residual endogenously.

However, having a residual can be considered as accounting transparently for individual and mixed effects (Muller 2006). It is thus the choice of the modeller to decide which method is appropriate for the given context.

2.2 The implemented decomposition approach

The decomposition approach implemented in this study is based on the Laspeyres method where each causal factor of interest is modified to its future value while all other factors remain at base values. Data for base year and future values are retrieved from the corresponding scenario data documented by the considered studies.

We determine what would happen if the separated factor changed under the assumption that the rest of the power sector remained at base year values, i.e. no change would happen. This is repeated once for each of the factors in question.

The individual contributions (isolated contributions) to emission reduction are then aggregated and the *residual term* which corresponds to the mixed effects triggered jointly by more than one of the causal factors is distributed to each causal factor based on a specified method, explained in Section 2.3.8.

The decomposition methodology includes the means to calculate the traditional Laspeyres index decomposition with attributing the mixed effects proportionally to the calculated contributions of the causal factors. In this sense the methodology provides a refined Laspeyres approach yielding a full decomposition.

In the present study, we are interested in disaggregating CO_2 emission reductions of the power sector into the contributions from the effects summarised in Table 1.

Table 1: Contributions of different effects to be analysed with the decomposition approach for this metastudy

Type of effect	Effects	Sectors considered (if applicable)
Demand side	Energy efficiency changes via traditional appliances	Transport, residential, industry, tertiary
	Demand side effect via new appliances	Road transport, heat market
	Demand side effects via storage input	
	Export share [1]	
Production side	Renewable energy share	Hydropower, wind onshore, wind offshore, solar PV, solar CSP, biogas, biomass, geothermal, other
	CCS share	
	Nuclear share	
	Import share [2]	
	Fossil production share	
Structure / Intensity	Fuel input intensity	
	Overall emission factor of fuel mix	

Note: [1] Exports are accounted for on the demand side under the following assumption: exports relate to electricity consumed by consumers abroad.

[2] Imports are accounted for on the production side: the imports reflect electricity produced abroad.

2.3 Equations

2.3.1 CO_2 emissions (base equation)

The governing function of CO_2 emissions in the power sector is assumed to be composed of the consumption of electricity from various areas C, the share of production from CO_2 emitting electricity generation technologies $(1-\pi^{free})$, fuel input intensity (I^{fos}/P^{fos}), and the overall emission factor of the fuel mix, E/I^{fos}. Equation 1 reflects this equation for time step *t*.

Equation 1

$$E_t = C_t(1-\pi_t^{free})\frac{I_t^{fos}}{P_t^{fos}}\frac{E_t}{I_t^{fos}}$$

with[2]

E_t CO_2 emissions at time *t* (Mt),

C_t total electricity consumption at time *t* (TWh),

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[2] The share of production from zero carbon electricity generation technologies is calculated by dividing the production of zero carbon electricity generation (Equation 2) by the total production of electricity.

π_t^{free} share of electricity generation from non CO_2 emitting generation technologies at time *t*,

I_t^{fos} input of fossil fuel at time *t* (PJ),

P_t^{fos} production of electricity from CO_2 emitting generation technologies (TWh)

The share of CO_2-free electricity production is determined through Equation 2:

Equation 2

$$\pi_t^{free} = \sum_{i=1}^{n} \frac{P_t^i}{P_t}$$

where:

$i = 1,...,n$	non-CO_2 emitting generation technologies,
P_t^i	electricity generation from the non-CO_2 emitting generation technology i in time step *t* (TWh),
P_t	total electricity generation in time step *t* (TWh).

2.3.2 Consumption

Consumption, measured in TWh, is assumed to originate from various sources reflecting contributions to emission reductions via electricity demand side effects. $C_0 \sum_{j=1}^{m} \mu_0^{old,j}(1-\varphi_t^{old,j})$ represents the electricity consumption of traditional appliances (i.e. ventilation systems) at time *t*, $C_0\gamma_t^{new}$ represents the electricity consumption of new appliances (i.e. electric vehicles) at time *t*, while $C_0\gamma_t^{store}$ represents the electricity consumption of storage inputs (i.e. electricity storage) at time *t*. Thus, the overall consumption at a given period, *t*, in a scenario can be expressed by the following equation:

Equation 3

$$C_t = C_0 \sum_{j=1}^{m} \mu_0^{old,j}(1-\varphi_t^{old,j}) + C_0\gamma_t^{new} + C_0\gamma_t^{store}$$

with

C_t	electricity consumption at time *t* (TWh),
C_0	total consumption of electricity at base year (TWh),
φ_t^{old}	efficiency gain of traditional appliances at time *t* compared to the base year,
μ_0^{old}	share of the electricity consumption of old appliances at base year,

γ_t^{new}	electricity consumption share of new appliances at time *t*, compared to the total base year electricity consumption,
γ_t^{store}	electricity consumption from storage input at time *t*, compared to the total base year electricity consumption.

The efficiency of traditional appliances in time step *t* is determined via:[3]

$$\varphi_t^{old,j} = \frac{C_0^{old,j} - C_t^{old,j}}{C_0^{old,j}}$$

and the share of the electricity consumption of old appliances at the base year via:

$$\mu_0^{old,j} = \frac{C_0^{old,j}}{C_0},$$

where

old	traditional appliances,
$C_t^{old,j}$	consumption of electricity from traditional appliance *j* at time *t*,
j = 1, …, m	consumption areas of traditional appliances (residential, tertiary, transport, industry).

The electricity consumption share of new appliances (compared to the total base year electricity consumption) in time step *t* is expressed as:[4]

$$\gamma_t^{new} = \sum_{k=1}^{x} \gamma_t^{new,k}$$

with

$$\gamma_t^{new,k} = \frac{C_t^{new,k}}{C_0},$$

where

new	new appliances
$C_t^{new,k}$	consumption of electricity from new appliance *k* at time *t*

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[3] The electricity consumption of traditional appliances in time step *t* is calculated by multiplying the total electricity consumption in the base year with the change in electricity consumption of all the traditional appliances in the industrial, tertiary, residential, and transport sectors between time step *t* and the base year. This value is subsequently converted into a share of electricity consumption for the traditional appliances.

[4] The electricity consumption share of new appliances in time step *t* is expressed as the change in electricity consumption of all the new appliances for road transport and heat between time step *t* and the base year.

k=1, …, x	consumption areas new appliances (road transport, heat)

with the electricity consumption share of storage (compared to the total base year electricity consumption) in time step *t* expressed as:[5]

$$\gamma_t^{store} = \sum_{l=1}^{y} \gamma_t^{store,l}$$

with

$$\gamma_t^{store,l} = \frac{C_t^{store,l}}{C_0},$$

where

store	storage input
$C_t^{store,l}$	consumption of electricity from storage input *l* at time *t*
l=1, …, y	consumption areas storage input.

2.3.3 CO_2 emissions at a given point in time

Substituting π_t^{free} in Equation 1 by Equation 2 yields the CO_2 emissions of the power sector based on the causal factors at time *t*, E_t:

Equation 4

$$E_t = \left(C_0 \sum_{j=1}^{m} \mu_0^{old,j} (1 - \varphi_t^{old,j}) + C_0 \gamma_t^{new} + C_0 \gamma_t^{store} \right) \left(1 - \sum_{i=1}^{n} \frac{P_t^i}{P_t} \right) \frac{I_t^{fos}}{P_t^{fos}} \frac{E_t}{I_t^{fos}}$$

Generally speaking, emissions at a given point in time are determined via consumption, production, energy productivity, and overall emission factor of the fuel mix.

Emission changes from one time step to another (e.g. from *t=0* to *t*) can thus be expressed as the difference between emissions at time *t* and emissions at time *t=0*:

$$\Delta E = E_t - E_0 = \Delta E_C + \Delta E_P + \Delta E_I + \Delta E_E + \varepsilon \,,$$

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[5] The electricity consumption share of storage appliances in time step *t* is expressed as the change in electricity consumption of all the storage appliances between time step *t* and the base year.

with

ε residual.

The emissions change can be decomposed into changes of consumption activities ΔE_C, production activities ΔE_P, fuel input intensity ΔE_I and overall emission factor of the fuel mix ΔE_E. These again are caused by different factors as shown by the equations documented in 2.3.4, 2.3.5, 2.3.6, and 2.3.7.

2.3.4 Contribution to emission reductions from electricity consumption changes

The isolated contribution of each of the different sub-categories of electricity consumption *h* (e.g. electricity consumption from traditional appliances, electricity consumption from new appliances and electricity consumption from storage input) to emission reductions can be determined as shown in Equation 5

Index *sec* refers to the sectors considered within the different sub-categories of consumption *h*.

Equation 5

$$\Delta E_c^{h,\sec} = (C_t^{h,\sec} - C_0^{h,\sec})(1-\pi_0^{free})\frac{I_0^{fos}}{P_0^{fos}}\frac{E_0}{I_0^{fos}}$$

Equation 5 is derived from the following (generally formulated)[6]:

$$\Delta E_c = C_t\,(1-\pi_0^{free})\frac{I_0^{fos}}{P_0^{fos}}\frac{E_0}{I_0^{fos}} - C_0\,(1-\pi_0^{free})\frac{I_0^{fos}}{P_0^{fos}}\frac{E_0}{I_0^{fos}}$$

2.3.5 Contribution to emission reductions from electricity production shares of zero carbon electricity generation technologies

The production share from CO_2 emitting electricity generation technologies is given by $(1-\pi_t^{free})$. To determine the contribution of zero carbon electricity production technologies to emission reduction Equation 6 can be used. Index *i* refers to zero carbon electricity production technologies in the equation.

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[6] In order to determine the emissions change from changes to consumption activities between the base year and time step *t*, it is necessary to input the consumption activity at time step *t* into Equation 1 and then subtract this from an Equation 1 where the consumption activity is set at the base year. The remaining causal factor activities are always set at the base year as required by the Laspeyres method.

Equation 6

$$\Delta E_p^{free} = \sum_{i=1}^{n} C_0 \left(-\frac{P_t^i}{P_t} + \frac{P_0^i}{P_0} \right) \frac{I_0^{fos}}{P_0^{fos}} \frac{E_0}{I_0^{fos}} \ ,$$

Equation 6 is derived from the following (e.g. for electricity generation from hydro power):[7]

power): $\Delta E_p^{hy} = C_0 \left(1 - \frac{P_t^{hy}}{P_t} - \frac{P_0^{nonhydro}}{P_0} \right) \frac{I_0^{fos}}{P_0^{fos}} \frac{E_0}{I_0^{fos}} - C_0 \left(1 - \frac{P_0^{free}}{P_0} \right) \frac{I_0^{fos}}{P_0^{fos}} \frac{E_0}{I_0^{fos}} \ ,$

with

$$P_0^{free} = P_0^{hydro} + P_0^{nonhydro}$$

2.3.6 Contribution to emission reductions from fuel input intensity variation

Energy-related statistical conventions for evaluating the electricity generation of nuclear power plants, wind-, water, solar- and geothermal plants and regarding the import of electricity can lead to a distortion of the energy-input variable. An extension of electricity generation from wind-, water-, or solar power and from imports would thus lead to a massive decrease of the energy input for electricity generation. This would lead to an underestimation of the contribution of renewable energies to emission reductions and to an overestimation of the contribution of energy efficiency. The opposite effect would be observed with respect to nuclear and geothermal electricity generation. To account for these statistical conventions fuel input intensity, I^{fos}/P^{fos} , is measured solely on the base of changes in the fossil part of the power plant fleet. This prevents the occurrence of the distortions described above. To determine the contribution of fuel input intensity changes to emissions reduction we apply Equation 7:

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[7] The emissions change due to changes in production activities between the base year and time step *t* is calculated by determining the change in the share of zero carbon electricity production. The activity level at time step *t* for every production technology (i.e. hydro power) is individually put into Equation 1 while the activity of the remaining production technologies is set at the base year. This result is then subtracted from an Equation 1 where the production activities for all technologies are set at time step *t*. In doing so it is possible to attribute the change in emissions associated with a change in the activity of a specific production technology between the base year and time step *t*.

Equation 7

$$\Delta E_P^{fos} = C_0(1-\pi_0{}^{free})\left(\frac{I_t^{fos}}{P_t^{fos}} - \frac{I_0^{fos}}{P_0^{fos}}\right)\frac{E_0}{I_0^{fos}}$$

Equation 7 is derived from the following:[8]

$$\Delta E_P^{fos} = C_0(1-\pi_0{}^{free})\frac{I_t^{fos}}{P_t^{fos}}\frac{E_0}{I_0^{fos}} - C_0(1-\pi_0{}^{free})\frac{I_0^{fos}}{P_0^{fos}}\frac{E_0}{I_0^{fos}}$$

2.3.7 Contribution to emission reductions from overall emission factor of fuel mix variation

To determine the contribution of changes in the overall emission factor of the fuel mix to to emissions reduction we apply Equation 8.

Equation 8

$$\Delta E_E = C_0(1-\pi_0{}^{free})\frac{I_0^{fos}}{P_0^{fos}}\left(\frac{E_t}{I_t^{fos}} - \frac{E_0}{I_0^{fos}}\right)$$

Equation 8 is derived from the following:[9]

$$\Delta E_E = C_0(1-\pi_0{}^{free})\frac{I_0^{fos}}{P_0^{fos}}\frac{E_t}{I_t^{fos}} - C_0(1-\gamma_0^{free})\frac{I_0^{fos}}{P_0^{fos}}\frac{E_0}{I_0^{fos}}$$

2.3.8 Accounting for mixed effects

Mixed effects are accounted for by distributing the residual term proportionally to the individual causal factors according to their contribution to emission reductions. Thus, the isolated contribution of a factor including the mixed effects is determined via the following equation:

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[8] In order to determine the emissions change from changes to energy intensity (i.e. fossil fuel input divided by fossil fuel based production) between the base year and time step *t*, it is necessary to input the energy intensity at time step *t* into Equation 1 and then subtract this from an Equation 1 where the energy intensity is set at the base year. The remaining causal factor activities are always set at the base year as required by the Laspeyres method.

[9] In order to determine the emissions change from changes to emission intensity (i.e. CO_2 emissions divided by fossil fuel input) between the base year and time step *t*, it is necessary to input the emission intensity at time step t into Equation 1 and then to subtract this from an Equation 1 where the emission intensity is set at the base year. The remaining causal factor activities are always set at the base year as required by the Laspeyres method.

$$\Delta E_{t_{incl}}^{factor} = (E_t^{fos} - E_o^{fos}) \frac{\Delta E_t^{factor}}{\sum_{factor} \Delta E_t^{factor}} ,$$

with

factor	causal factor.

3 Summary

The present document provides the suggestion for an analytical framework to decompose emission reductions in the power sector based on data retrieved from studies which provide scenarios of power sector decarbonisation. With the given approach and under sufficient data availability it will be possible to reveal the contributions of demand side effects such as changing consumption patterns in traditional and new appliances and increased electricity demand of new appliances and storage inputs. At the same time a changing power generation structure also contributes to emission reductions and can be explicitly considered. Electricity generation from CCS can be considered if data availability if sufficiently documented and the analysis proceeds as laid out in the Appendix.

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5 Appendix I: Completely considering electricity production from CCS

Electricity generation from CCS plays a hybrid role in decomposition analysis. This is due to the fact that a share of electricity generated from CCS can be viewed as being CO2-free, while the other share of electricity generation from CCS technology produces emissions. The emission capture rate provides insights into the shares (usually in the range of 90% of the emissions being captured). CCS production thus needs to enter the decomposition analysis at two locations: twice on the production side of electricity (once at the CO2 neutral part and once at the fossil part) and fuel used for CCS production and causing emissions (determined by *1-capture rate*) needs to be attributed to the fossil fuel input, I^{fos} . As documentation standards of studies vary, this attribution may not be easily addressed and several procedures are viable, which are shortly documented here:

1. Primary energy input is documented in a CCS plant specific manner:

   Attribution of that share of electricity production from CCS technology that can be viewed as CO_2 emission free to P^{CCS}. Attribution of the remaining production to the fossil fuel part of production P^{fos}. Attribution of the amount of primary energy input used in CCS plants and where emissions are not captured (*1-capture rate*) to the fossil fuel input variable, I^{fos}.

2. Primary energy input is not documented CCS specific, but plant specific efficiencies are documented:

   Attribution of the electricity production of CCS to P^{CCS} that is emission free (determined by capture rate). Attribution of the remaining production to the fossil fuel part of production, P^{fos}. Utilisation of information on total primary energy input of a specific plant type, information on generation by conventional and CCS plants of this type to calculate the primary energy input for the CCS plants. Attribution of 1-*capture rate* to fossil fuel input

3. If 1. and 2. are not viable, due to data insufficient documentation problems, there are several alternative ways of approaching the decomposition analysis:
   a. make meaningful assumptions and then proceed as documented in 2.
   b. attribute all fuel input to I^{fos}, keep interpretability of P^{CCS} but lose the interpretability of E/I^{fos} and I^{fos}/P
   c. do not decompose the scenario
   d. do not decompose the CCS part of the scenario