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Which decarbonisation pathway for China ?

Insights from recent energy-emissions scenarios

Elie Bellevrat (IDDRI)

MAKING BETTER USE OF ENERGY EMISSIONS LONG-TERM SCENARIOS FOR CHINA

Scenarios should be used more extensively to prepare for the future Chinese economic transformations and their energy-environment implications. In particular, they are helpful to better assess the necessary milestones (e.g. objectives at 2020 or 2030) to set the country on a low-carbon development path (at 2050 and beyond), and shift from the current overwhelming coal paradigm. Unfortunately, the difficulties to understand and compare scenarios are preventing their appropriation. A post-treatment methodology can enhance their reading, which seems necessary to draw the lessons for the future Chinese policy and economic orientations.

A DIVERSITY OF PROJECTED EMISSIONS PATHS: LESSONS FROM THEIR COMPARISON

Different modelling approaches and underlying scenario storylines lead to sometimes contrasted supply or demand-side emissions abatement potentials. In particular the wide uncertainty on the Chinese economic growth has huge implications on future emission profiles. Energy intensity improvement is a crucial factor for driving down future CO_2 emissions in the short term, in all scenarios (including Business as Usual). But the decarbonisation of overall energy inputs, much constrained by the energy system inertia, is the only factor capable to set China on a low-carbon development path in the longer term. However, the relative weights and magnitudes of those factors widely differ across scenarios. If mitigation policies should better drive a smooth transition toward a low-carbon economy, delayed action usually require more aggressive decarbonisation effort in the long term.

THE NECESSARY TRANSFORMATION OF THE CHINESE ECONOMY IN A GREEN GROWTH PERSPECTIVE

Beyond the improvement of the energy and carbon intensities, the Chinese economy will have to shift from the current paradigm. In such perspective, structural transformations will act as a catalyst for the low-carbon development processes. In particular the interactions between the macro and sectoral levels will define the possible mitigation options and abatement potentials over time. At the centre of this transformation are the technological, societal and organizational innovation capacity, the urbanization process and related urban-transport nexus, etc. There is a lack of representation of those processes in current models and scenarios, which now needs to be addressed in the perspective of stimulating a new China-tailored model of development.

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Context of the working paper
This paper was developed in the framework of IDDRI's Global Learning Platform on Climate Policies. This programme has been initiated in 2011 with China, with the support of the European Commission (DG Climate Action). This piece of work complements already published materials on the Chinese medium-term climate policy and will be complemented with further materials to support decision-making for long-term transition of China toward low-carbon economy.

☆☆☆

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INTRODUCTION

It Copenhagen, late 2009, China has pledged to reduce its carbon intensity by 40% to 45% by 2020 compared to 2005 levels. The country is seriously committed in climate change mitigation, which materialize into the carbon intensity reduction objective of 17% in the XII[th] FYP (2011-2015). A wide array of policies and measures are progressively introduced, from regulatory to market-based instruments to shift the country from a carbon-intensive path with the objective to meet these short-medium term targets. To date, there are no official projections or roadmap beyond 2020, though several long-term scenarios do exist at the 2050 horizon, in an attempt to fill this gap.

Forward-looking studies are crucial to develop consistent long-term visions of the national economy, in particular in a decarbonisation perspective. Scenarios are helpful for domestic policy-making purposes, in order to take the right policy decisions today to set the country on a realistic, sustainable and ambitious development path, with consistent intermediate milestones. Elaborating on long-term energy and emissions scenarios for China is also very important internationally, because this country has an increasing geopolitical role worldwide and will certainly remain one of the most, if not the most, influential players in the world economy (e.g. role on energy and raw materials prices, role in setting norms and standards, etc.) in the next decades. In addition, the weight of China in global environmental issues will continue to increase dramatically. It already represents around 25% of global energy needs (2010) and could even grow in the future to reach 30% of total emissions in a Reference scenario by 2050, according to Enerdata (2010). It is thus crucial for both domestic analysts and the international community to better assess the Chinese emission abatement potentials over the long run, and to qualify its possible contribution to global climate change mitigation.

However, existing long-term emission scenarios for China are difficult to assess (separately and together), with a full understanding of the implications of the different assumptions. Nor do the already published comparative studies provide a clear vision of the underlying decarbonisation processes and transformational drivers of the Chinese economy. Indeed, direct quantitative comparison of key models outputs is usually not sufficient to obtain a good understanding of the possible futures and their implications for a country like China. Modelling results often focus on specific, sectoral, comparable variables only, detached from the overall context, and as such they do not succeed in bringing the systemic understanding of the energy-economy processes at play (even though the models themselves sometimes use systemic approaches). The overall understanding is supposed to come from the addition of the single elements of analysis, which can be compared among different scenarios.

To cope with these difficulties, our paper proposes to add an original analytical layer above the already published scenarios, based on a simple decomposition analysis, mixing a logarithmic mean Divisia index (LMDI) method with a Kaya identity approach. This will allow comparing long-term scenarios on a homogenous basis, while clarifying the explicit or implicit underlying storylines and their temporality. In this respect, the method developed in this paper is important in order to translate the many long-term modelling and scenario outputs for China into an intelligible language, but more practically for policy-makers and analysts, so that they can draw some conclusions and take valuable lessons from existing forward-looking exercises.

A first section presents the most relevant forward-looking studies for Chinese energy and emissions, and makes the review of recently published comparative papers. The national emissions pledge at 2020 is assessed with regards to the medium-term emissions trajectories of the selected scenarios. In addition, a possible way for improvements of such a comparison works in terms of methodology is identified, factoring in the poor set of comparable numerical series across studies. The comparison method developed in this paper is detailed in a second section, before being applied to the Chinese historical emissions trends. The analysis of historical emissions serves as a proof of the usefulness of the method to compare emissions projections at 2050. Section 3 provides the results of the comparison work applied to the selected Chinese emissions profiles for two sets of scenarios: the "Reference" and "Alternative" scenarios. Scenarios are compared across the two categories, using the Reference cases as counterfactual scenarios, and within the two categories, in order to identify the implicit key features of the long-term decarbonisation processes in China. The final section focuses on the key drivers for long-term decarbonisation in China from the scenarios analysis, using some sectoral insights as a matter of illustrations. The paper does not aim at going much in details on the sectoral drivers, which could be further developed by additional research and application of the method at more detailed levels. Finally, a stylized representation is used to summarize the main outcomes from the study.

1. RECENT FORWARD-LOOKING EXERCISES FOR CHINA

1.1. Presentation of recent studies and existing comparative papers

This paper compares energy and emissions scenarios for China from six recent forward-looking studies. None of them was published before 2009:

- The latest International Energy Agency (IEA) scenarios come from the yearly publication World Energy Outlook or WEO (IEA, 2011), released in November 2011. This is certainly the most famous global energy projections publication, presenting detailed quantitative results to 2035, including three policy scenarios for the main world regions, including a detailed energy and emissions balance for China.
- Scenarios from the Energy Research Institute (ERI) are the only "official" energy and CO_2 emissions forecasts compared in this study (ERI, 2009a). ERI is a think tank linked to the National Development and Reform Commission (NDRC), the most powerful Chinese Minister in charge of the national economic planning. Scenarios were published in Chinese, together with an official report on energy and CO_2 emissions in China (ERI, 2009b). To date, those scenarios still constitute a reference in China.
- The China Energy Group of the American Lawrence Berkeley National Laboratory (LBLN), has developed national energy and emissions projections for China from 2010 and published the main results of the analysis of three scenarios (Zhou *et al.,* 2011), including a strong focus on the 2050 low-carbon perspective for the country.
- The Tyndall Center for Climate Change Research with the Sussex Energy Group and SPRU of the University of Sussex from the UK (later called Tyndall study), have released four original low-carbon scenarios for China (Wang and Watson, 2009). Wang and Watson (2010) published the main outcomes of this prospective exercise, out of which only two scenarios (Tyndall S3 and S4) are judged credible with regards to recent emissions development in China, and thus retain our attention (S1 and S2 scenarios show very diverging emissions trends as early as 2010 compared to already measured emissions path).
- The China Development Report 2009/2010, commissioned by United Nations Development Program (UNDP) in China and coordinated by Renmin University of China proposes a state of the art of China's carbon footprint and three exploratory scenarios, including low-carbon ones (UNDP, 2010), quantified using the in-house PECE model to 2050.
- The EnerFuture information service by Enerdata, a French consultancy, provides a global energy and emissions outlook on a regular basis (Enerdata, 2010). The dataset to 2035 includes four contrasted scenarios, quantified by the POLES model, also used by the European Commission for its economic and policy assessment over the long-run (see for instance the WETO-H2 study (EC, 2006) and the European Roadmaps at 2050 (EC, 2011a and 2011b). World projections to 2050 have been made available by Enerdata for the purpose of this study, including China as a detailed region.

Existing comparison papers

Two already published papers compare the main outputs from most of these listed studies (Zheng *et al.* (2010) and Li and Qi (2011)). Both papers describe and compare the models, approaches and scenarios from each study. Li and Qi (2011) compare ERI (2009), IEA (the Energy Technology Perspectives 2010, instead of the 2011 WEO edition in this paper), Wang and Watson (2009), Zhou *et al.* (2011), UNDP (2010) and McKinsey&Company (2009).

Table 1. List of institutions, models and scenarios compared in the different studies

	IEA, WEO, 2011	ERI, 2009	LBNL, 2011	Tyndall, 2009	UNDP, 2010	Enerdata, EnerFuture, 2010
Institution	International Energy Agency (IEA), World Energy Outlook publication	Energy Research Institute (ERI) of the Chinese National Development and Reform Commission (NDRC)	Lawrence Berkeley National Laboratory (LBNL), China Energy Group	Tyndall Centre for Climate Change Research and the Sussex Energy Group, SPRU, University of Sussex	United Nations Development Programme (UNDP) China Report coordinated by Renmin University of China	Enerdata (consultancy), Global Energy Forecasting Group, EnerFuture service*
Model	World Energy Model (WEM) and complementary models	Integrated Policy Assessment Model for China (IPAC-SGM, IPAC-AIM, IPAC-Emission, etc. modelling framework)	China End-Use Energy Model, based on a LEAP platform (Long range Energy Alternatives Planning System)	Tyndall Centre's scenario analysis tool and ad-hoc calculation	Programme of Energy & Climate Economics (PECE) Model	Prospective Outlook on Long-term Energy Systems (POLES)
Approach	Bottom-up, global technical-economic, incl. China individually	Hybrid Top-down (CGE) and Bottom-up, technical-economic using input-output table	Bottom-up, national accounting technical-economic	Top-down, based on national cumulative carbon budget (mixed normative and backcasting)	Bottom-up, national technological optimization	Bottom-up, global technical-economic, incl. China individually
Period	2009**-2035	2005-2050	2005-2050	2005-2050	2005-2050	2009***-2050
References scenarios	IEA Current Policies IEA New Policies	ERI Baseline ERI Low Carbon (LC)	LBNL Continued Improvement (CI) LBNL Continued Improvement (CI) with CCS		UNDP Reference UNDP Emissions Control (EC)	Enerdata S1 – Recovery Enerdata S2 – Depression
Alternative scenarios	IEA 450	ERI Accelerated Low Carbon (ALC)	LBNL Low Carbon (LC)	Tyndall S3 Tyndall S4	UNDP Emissions Abatement (EA)	Enerdata S3 – Renewal Enerdata S4 – Struggle

Source: From all references quoted (one per column) and from Zheng *et al.* (2010) and Li and Qi (2011)

* http://www.enerdata.net ** Last year available data. *** Last year available data.

Zheng *et al.* (2010) compares ERI (2009), IEA (but 2009 WEO edition, instead of 2011 in this paper), Wang and Watson (2009), Zhou *et al.* (published a few months later in 2011, even if they were already able to make use of in-house quantitative outputs to perform the comparative study) and McKinsey (2009).

In addition to studies already compared in those two papers, we newly introduce the EnerFuture scenarios by Enerdata (version December 2010) as they provide all the necessary quantitative and story-telling materials to 2050. On the contrary, we do not compare the McKinsey scenarios (McKinsey&Company, 2009) as the two previously mentioned comparison papers did, because of incompleteness of data availability for this study, in addition to a too short-term horizon under consideration in this study (2030), not completely in line with our needs.

Table 1 reports and summarizes the main features that can explain differences across the studies and scenarios. It builds on and expands the analysis provided by the two previous comparison papers.

Emissions paths in the "Reference" scenarios

The above-mentioned "Reference" scenarios in Table 1 are those used as counterfactual scenarios. They usually reflect a continuation of the historical trends for the Chinese energy consumption and CO_2 emissions and their macro-economic and demographic drivers. In almost all studies, they allow identifying the necessary efforts to drastically reduce future energy consumption and CO_2 emissions and measure the quantitative mitigation potentials, future abatement costs, etc. Reference scenarios include Business and Usual (BAU) or Baseline scenarios like the IEA Current Policies, Enerdata S1 – Recovery scenarios, etc., as well as scenarios reflecting a slightly deviating policy context (e.g. IEA New Policies, ERI Low Carbon scenarios).

Figure 1. Total emissions projections for China in the "Reference" scenarios

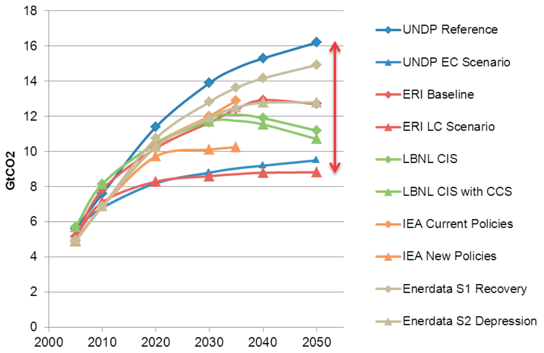
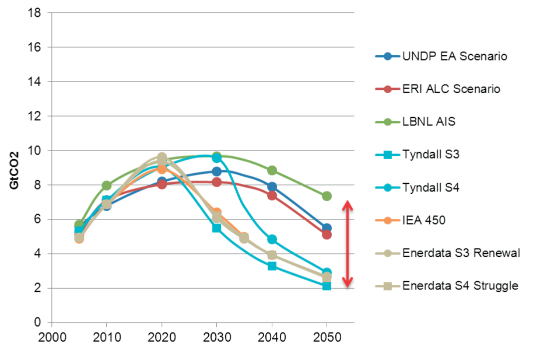


Figure 2. Total emissions projections for China in the "Alternative" scenarios



They may consider some limited additional policies and measures compared to history (like those already in debate today), but are not introducing a real acceleration of energy or climate policy reforms.

Emissions paths in the "Alternative" scenarios

"Alternative" scenarios consist in the most voluntary scenarios for long-term emissions reductions in China, as opposed to the "Reference" scenarios. They usually contain specific breakthrough hypotheses (technological, political, social, organizational, etc.), either modelled through equations or translated into new sets of parameters. They are often based on determined storylines that usually reflect clear switch from past trends for energy consumption and CO_2 emissions. Vigorous additional policies and measures to those already existing are introduced, which delivers the necessary signal for reducing the country's footprint (e.g. strong carbon pricing, significant additional regulation, etc.). Low-carbon and green growth concepts are at the basis of some Alternative scenarios, including those explicit or implicit policies to curb long-term trajectories of domestic CO_2 emissions and/or to change of development paradigm of China.

"Reference" vs "Alternative" scenarios

Of course, setting up a clear separation between the "Reference" and "Alternative" scenarios is not so obvious (e.g. for ERI and UNDP scenarios, but also for IEA scenarios), and what has guided our choice relates to the emissions profiles and the long-term emissions levels, with two main criteria for the scenarios to be considered "Alternative":

1) Emissions in 2050 should be below 2010 levels;

2) Emissions peaking year should not be later than 2030;

Another set of scenarios could have been identified to include some intermediate scenarios: those not really Alternative with regards to the criteria we have defined or those not so close to BAU scenarios because they include some novelty from past paradigm (i.e. not just continuing former trends). This category would have included the IEA 450, ERI Low Carbon or UNDP Emission Control scenarios for instance, but what about the two LBLN CIS scenarios? As it proved difficult to define consistently such an intermediate category, and because it is not really useful to our study, we decided to merely remain with the two Reference and Alternative scenarios categories.

A particular case regards the two scenarios from Tyndall which are both Alternative ones and as such cannot compare with any Reference from the same study. The Tyndall S1 and S2 scenarios, not considered in this study, would also be two Alternative scenarios according to our definition. This leaves us without any possible counterfactual scenario for the Tyndall study, due to methodological choices.

Main insights from the comparison papers

The final amount of CO_2 emissions in absolute value in 2050 is a clear characterization of the different scenarios and already brings valuable lessons from the scenarios comparison exercise. For instance, emissions from the different Reference scenarios show that Chinese CO_2 emissions could still double from now to 2050, as in the UNDP Reference scenario. Another scenario from Enerdata, S1 Recovery, confirms the threat of the rising Chinese emissions if nothing else is done than what already in place (Figure 1). The published comparison papers both mention the role of the industrial and power sectors in the continuation of the very coal-based development style in such dramatic scenarios.

On the contrary, the most CO_2 constrained scenarios tend to prove that turning back to 2005 emissions levels by 2050 is feasible in China. The ERI ALC and UNDP EA scenarios both reach that outcome (Figure 2). Even more voluntary scenarios are designed by Tyndall, cutting by around a factor two the CO_2 emissions in 2050 compared to 2005 levels (-60% in S3 and -45% in S4), while the EnerFuture S3 and S4 scenarios also achieve a huge reduction of CO_2 emissions at 2050 compared to 2005 level (over a factor two for emissions abatement in both cases). In addition, the IEA scenario compatible with the long-term target of CO_2-eq concentration stabilization of 450 ppmv, seems to confirm this, even if its projections stop in 2035. The two comparison papers already portray common features and both point out that energy efficiency and decarbonisation of the Chinese energy system, especially on the power sector, are key drivers for long-term transition of China toward a low-carbon economy.

One striking result of this direct emissions paths comparison is the range of emissions levels by 2050 obtained in the two set of scenarios: from slightly over 8 $GtCO_2$ to 16 $GtCO_2$ for the Reference scenarios, and from 2 $GtCO_2$ to a little below 8 $GtCO_2$ for the Alternative scenarios (see Figures 1 and 2). That range is thus around 8 $GtCO_2$ in the former category of scenarios compared to 6 $GtCO_2$ in the latter, which is largely explained by the ad-hoc definition of what is "Reference" and what is "Alternative". However, the main lesson relates to the level of uncertainty about the future Chinese emission trends, for hardly four decades ahead. With no surprise, uncertainty is high regarding low-carbon scenarios (even though the maximum effort scenarios seem to converge to less than 5 $GtCO_2$ by 2050), but more surprisingly it is higher for what could be considered BAU scenarios, ranging from around 12 $GtCO_2$ to 16 $GtCO_2$. This shows how it is far from being a single vision of what could be the worst continuation case.

Limits of the existing scenario comparisons

The two comparative papers (Zheng *et al.* (2010) and Li and Qi (2011)) stress the existing potentials for CO_2 emissions reduction with the introduction of climate-related policies. They quantify and compare the possible abatement potentials for the whole Chinese economy, within each study.

As mentioned, the estimated range for absolute CO_2 emissions in 2050 in the Reference scenarios is larger than the Alternative cases'. Therefore dealing with abatement potentials is too simplistic and sometimes meaningless, without having a clear view on how the References scenarios themselves do compare. In particular, their underlying assumptions (e.g. demography, macro-economic backgrounds, policy content, etc.) are very influential to this metric of "abatement potentials", and those are sometimes more important than the assumptions retained for the definition of the Alternative scenarios themselves.

Both studies recognize the difficulty to compare different sets of data from different sources because methodologies, macro-economic drivers, various assumptions and parameters and the underlying storylines are often quite different. The perception of modellers and their personal approach and attitude towards modelling also contribute to the scenarios' outcomes.

Though they bring valuable comparison materials concerning the main scenario assumptions and results, including some details in terms of key variables development, the two published studies fail to clearly state what the key underlying drivers of future domestic CO_2 emissions development are, and how they do compare on an homogenous analysis basis.

In particular, they fail to explain the main differences across the Reference scenarios emissions and they fail to figure out what the underlying storylines are for the alternative scenarios, in particular with regards to the development of ambitious decarbonisation processes over the long run. What does this mean for energy efficiency and the decarbonisation of energy inputs? How do population or economic growth assumptions play in the story? What could we imagine in terms of new and additional policies, over the long run to follow such low-carbon development paths? How does all this integrate into energy-economy systemic visions for China?

Those are key questions to be addressed so that the results of those exercises be useful for policy-making purposes in China. If not, it will remain very difficult to decipher what the key differences between these scenarios are and what is supposed to be playing most in all them. So far, they are difficult to use effectively for shorter-term policy design and implementation issues, by relying on an integrated vision of possible implications for the long-term development of the Chinese economy.

1.2. Ensuring comparability of the scenarios and their key variables

When comparing various sources, it is often difficult to perform immediate confrontation of data because of the many heterogeneity issues that may occur both in the approach and hypotheses but also in the presentation of the scenarios. In order to ensure that the comparison is legitimate, relevant and accurate, it is crucial to check that the units used for the main variables are comparable across the studies and that the system boundaries are homogenous (e.g. the definition of the power sector within the energy balances, etc.).

Energy units are usually easy to convert across studies. But in reality, discrepancies across the

Table 2. Ensuring units and system boundaries comparability across studies

	IEA, WEO, 2011	ERI, 2009	LBNL, 2011	Tyndall, 2009	UNDP, 2010	Enerdata, EnerFuture, 2011
Energy Units	Mtoe (all IEA sources)	Mtce (all ERI sources)	Mtce	Mtoe	Mtce	Mtoe (all Enerdata sources)
Monetary Units (GDP)	Constant $2010 at Power Purchase Parity (PPP)	Constant ¥2005 at Market Exchange Rate (MER) by definition, Growth rates provided	Growth rates provided (%)	Constant $2000 at Market Exchange Rate (MER)	Constant $2005 at Market Exchange Rate (MER), Growth rates provided	Constant $2005 at Power Purchase Parity (PPP)
Emissions Units	CO_2-Energy	CO2-Energy, even though IPAC Model suite is able to handle all GHG emissions	CO_2-Energy (Process included?)	Carbon-Energy (sources: CDIAC* for historical emissions, IEA and ERI for future emissions budgets)	CO_2-Energy (historical emissions from IEA and WRI- CAIT database), but presumably includes CO_2 process emissions**	CO_2-Energy

* CDIC: Carbon Dioxide Information Centre, U.S. Department of Energy (DOE).

** According to the UNDP Reference, CO2 emissions projections are energy-related, but the value given for year 2005 (5600 MtCO2) corresponds to the total CO2 emissions (including process emissions) from the quoted Climate Analysis Indicators Tool of the World Resource Institute, (WRI-CAIT).

historical level of total energy demand may remain and are difficult to explain. It was the case in the two previous comparative studies, where starting points for comparison of energy demand were sometimes different among studies, which was not explained. This usually relates to statistical debates and/or energy system boundaries. This paper proposes a methodology which allows overcoming this particular barrier in the scenario comparison (see Section 2).

The discussion on emissions and monetary units is maybe even more important. Table 2 shows that all studies forecast economic variables expressed in constant prices. But the reference years are often different and GDP are expressed either in Power Purchase Parity (PPP) or in Market Exchange Rate (MER). This does not influence the comparability across studies as long as the reference years are fixed and the time series that is reported here for GDP represents the macro-economic driver for future energy demand (e.g. wealth effect in econometric functions). Indeed, exchange rates are supposed to be constant over time and as we are working in variations in the methodology developed, direct comparability of monetary parameters (i.e. absolute values) do not matter. There is also an issue for carbon emissions boundaries (e.g. CO_2 or GHG, including or not including CO_2 process emissions). In order to perform a direct comparison, we check that emissions under consideration are CO_2 emissions from fossil fuel combustion. Most studies clearly state that they assess CO_2 emissions from fuels combustion (i.e.energy-related emissions). However, there might be differences in the historical data sources, sometimes making differences in the starting point (usually year 2005 as mentioned in Table 1). For instance, LBLN focuses on CO_2-energy emissions but the emissions levels in 2005 seem to include also CO_2 emissions from industrial processes. Other greenhouse gases are not concerned by any of the studies compared in this paper.

Quality of data recovered so far can be considered satisfactory to perform the scenario comparison analysis proposed in this paper. Difficulties experienced in collecting data and the possible differences in units and system boundaries that are observed eventually do not appear to be so crucial, because:

1) All calculations, for all variables and intermediate ratios, are based on variations per periods over time. This is why the possible differences in boundaries, as far as they remain small, do not matter so significantly. For each study it is assumed that the time series boundaries do not vary over time, and that trends are always originated by the bulk of the variables across the studies. So discrepancies are supposed to remain at the margin when looking at tendencies over the long-term.

2) We compare very general trends, which already provide substantial insights. This is why giving too much importance to details would certainly be counter-productive and not relevant in such a comparison paper. The work done in this section is here to ensure that we are theoretically authorized to compare the different scenarios using the methodology that we develop in the next section.

1.3. Deciphering national targets with the 2020 scenarios milestone

Understanding the Chinese carbon intensity targets by 2020

The Chinese economic planning is established by the National Development and Reform Commissions (NDRC) through the Five Years Plans (FYP) process. The XI[th] FYP (2006 to 2011) and the current XII[th] FYP (2011 to year 2015 included) both contain energy intensity targets, respectively 20% and 16% reduction over the five-year periods. The XII[th] FYP is the first to also introduce a carbon intensity target, which is one percentage point higher than the energy intensity target with 17% reduction in five years.

In Copenhagen (2009) and Cancun (2010), China has pledged a -40% to -45% carbon intensity reduction in 2020 compared to 2005 levels. It is a strong commitment with regards to the historical trend of carbon intensity in China. Whereas the country has been close to reach its energy intensity target of 20% reduction over the XI[th] plan, with a 19% reduction, the carbon intensity has improved only a little, around 2.7% each year on average, or -13% in 2010 compared to 2005 levels (Guérin and Wang, 2012). As a consequence, the carbon content of the primary energy consumed in China has slightly increased over the period, which is the opposite of the prospect of decarbonising the economy over the long run (see next Section 2.3 for an in-depth explanation of recent trends in energy demand and carbon emissions).

Several existing studies aim at assessing the level of efforts required by the Chinese commitment to 2020, as summarized by Zhang (2011). The Grantham study (Hirst *et al.,* 2011) states that while the low end of the Chinese target would be reached by simply developing further profitable actions compared to a Business as Usual scenario, the high end target would require much more effort and an implicit carbon price of 50 $/tCO_2$. Guérin and Wang (2012) qualitatively argue that even reaching the low end of the Chinese target will be challenging, whereas it would not be impossible for the country to reach its high end target, under the necessary condition that public policy provisions are taken. Our analysis is quite in line with this general result, as developed below.

Assuming that carbon intensity has improved by 13% over the 2005-2010 period, the carbon intensity target of the XII[th] FYP as well as the 2020 target would introduce a progressive shift in the Chinese development pattern, roughly translating into 31% to 37% of energy intensity improvement between 2010 and 2020 (see Table 3). The pace of carbon intensity improvement would increase from -3,7%/year on average over 2011-2016 to -3.6%/year to -4.5%/year on average until 2020. More precisely, those targets would entail a decarbonisation of the energy inputs fuelling the Chinese economy, and thus reverse past trends.

How do scenarios compare with official targets?

Tavoni (2010) reports wide discrepancies as regards to the 2020 emissions levels in China among Reference scenarios depicted by the participating model of the EMF22[1] study. Around half of the carbon intensity results are below the Chinese low end carbon intensity target (<40%), and around half are higher than the high end target (>45%), with very few results being in the range. This confirms how it is difficult to assess the Chinese pledge, even though most of the models used in this study are global models and as such not very precise on China. In Table 3, results from the various scenarios considered in our paper are compared to the official Chinese targets at 2020. Although this time most of the models focus on China, the comparison offers the same kind of discrepancies than the EMF outputs. Nevertheless, some interesting points of comparison can be drawn.

The IEA forecasts optimistic decarbonisation in the short term in all scenarios, including in the Current Policies scenario that reflects a continuation of past trends. This scenario is very close to the low end of China's official carbon intensity target, implying that the Chinese commitment would be rather conservative.

ERI scenarios are even more optimistic by 2020, with a Baseline scenario as optimistic as IEA's most stringent scenario. The underlying efforts for the CO_2 emissions control over the next decade is thus far beyond what would be required by the official objective. ERI's alternative scenario even shows more than a doubling of the emissions intensity reduction by 2020 compared to the most recent trends. This scenario shows the quickest decline of CO_2 emissions in the short term and, interestingly, it is an official Chinese scenario. But this should not prevent us from questioning its credibility.

LBLN scenarios are quite in between IEA and ERI in terms of carbon intensity reduction by 2020, respectively for the Reference and Alternative scenarios. But it should be noticed that LBLN certainly overestimates the Chinese 2010 emissions, which is not without consequences on the level of efforts (higher emissions reduction potential for

1. Energy Modelling Forum (EMF) model comparison exercise aiming at comparing international climate change policy architectures (Clarke *et al.*, 2009)

Table 3. Carbon intensity improvement over 2010-2020, comparison across studies and with the official target

	References scenarios			Alternative scenarios		
		10/20 change	CAGR (10/20)		10/20 change	CAGR (10/20)
National target		-31,0%	(-3,6%)		-36,8%	(-4,5%)
IEA, WEO, 2011	Current Policies	-34,1%	(-4,1%)	450	-42,2%	(-5,3%)
	New Policies	-37,5%	(-4,6%)			
ERI, 2009	Baseline	-41,8%	(-5,3%)	Accelerated Low Carbon (ALC)	-49,5%	(-6,6%)
	Low Carbon (LC)	-47,9%	(-6,3%)			
LBNL, 2011	Continued Improvement (CI)	-39,2%	(-4,9%)	Low Carbon (LC)	-43,9%	(-5,6%)
	Continued Improvement (CI) with CCS	-39,4%	(-4,9%)			
Tyndall, 2009				Scenario 3	-22,0%	(-2,4%
				Scenario 4	-21,1%	(-2,3%)
UNDP, 2010	Reference	-20,8%	(-2,3%)	Emissions Abatement (EA)	-36,4%	(-4,4%)
	Emissions Control (EC)	-36,4%	(-4,4%)			
Enerdata, EnerFuture, 2010	S1 – Recovery	-27,1%	(-3,1%)	S3 – Renewal	-34,7%	(-4,2%)
	S2 – Depression	-26,4%	(-3,0%)	S4 – Struggle	-32,6%	(-3,9%)

the same abatement cost) to obtain the required carbon intensity reduction by 2020. In addition, it should be noticed that the results translated in absolute levels of carbon emissions cannot compare with official targets at 2020, because of those differences in the starting point.

Tyndall S3 and S4 scenarios are very ambitious in the long term, but look quite pessimistic in the short term compared to other studies, contrary to Tyndall S1 and S2 scenarios that are not directly compared in this study.[2] Indeed, the S3 and S4 emissions paths are exogenous and based on projections to 2015 from a former release of the IEA's *World Energy Outlook* (IEA, 2007). Even though this IEA scenario was considered as "Alternative" at that time, as it included some gradual transition in the medium term, it can now be considered as quite conservative compared to the recent Chinese announcements for 2020. Tyndall scenarios are based on carbon budget assumptions over the XXI[th] century (90 GtC and 111 GtC respectively for the S3 and S4 scenarios), and the fact that short-term emissions continue to soar by 2020 entails that post-2020 emissions decrease dramatically. The necessary medium-term shifts for those two scenarios, in order to comply with the total carbon budget by 2100, are illustrated into more details in a following section.

The UNDP Reference scenario forecasts a carbon intensity reduction below the low end of 2020 Chinese target, which seems quite conservative. That would mean that the official target is missed, and maybe neither the XII[th] FYP nor the future XIII[th] FYP targets will be met, in line with the underlying assumption that no mandatory emissions reduction measures are undertaken in this scenario. On the contrary, the Emission Control and the Emission Abatement scenarios have the same emissions path to 2020, showing a substantial carbon intensity reduction over the next decade corresponding to the high end official target. Those three scenarios explore a credible range of possible short-term emissions trajectories, even if the classification that we are operating may look unsuitable for this case. As previously said, scenarios are not classified in the Reference and Alternative categories depending on their emission trajectories to 2020, but rather on their latter emission developments. This is why we have both the UNDP Reference and Emission Control scenarios classified as "Reference", although there is a huge contrast in their efforts to effectively reduce carbon intensity

2. The Tyndall S1 and S2 scenarios would be much more optimistic in the short-term but really not credible as the level of CO_2 emissions assumed in 2010 is far too low compared with the recently observed evolutions (as given by the IEA up to 2009 or Enerdata to 2010. In those S1 and S2 scenarios, Tyndall uses exogenous emissions paths to 2020 from a former ERI scenario (Dai *et al.*, 2004), which strongly underestimates short-term emissions for China. That scenario would be considered as "Alternative" because it supposes radical transformation of the Chinese economy and its energy system.

by 2020; and this is why the UNDP Emission Control and Emission Abatement scenarios are separated in two different categories even though their emission paths are strictly identical to 2020.

Enerdata scenarios are quite in the range of the Chinese official objectives at 2020. The S1 and S2 Reference scenarios (Recovery and Depression) are just below the low end carbon intensity reduction, while the S3 and S4 Alternative scenarios (Renewal and Struggle) just below the high end target.

Meaning for the longer-term emission projections

As explained above, the classification of scenarios does not completely match short/medium-term considerations. On the contrary, it is rather related to long-term emissions trajectory, the emissions peak story, etc. This is particularly true when trying to decipher the emissions projections in 2020 in relation with the official Chinese target. If for most of the scenarios, the "Reference vs Alternative" terminology is relevant at 2020, this is not the case for some others like, for instance, the Tyndall S3 and S4, the ERI Baseline or the UNDP Emissions Control scenarios. But the short-term prospect for emissions development allows anticipating what could be the first elements of the storylines for some Alternative scenarios in the post-2020 era:

- Low-carbon scenarios underestimating short-term emissions reduction will show a big shift in their emission trajectories triggered in the medium term. This is the case for the Tyndall scenarios that make the assumption of a stringent decarbonisation process starting after 2020.
- Low-carbon scenarios which are optimistic in the short-term, possibly overestimating the initial abatement potentials, will describe smooth transition paths for a sustained decarbonisation effort over time. This is the case of the IEA, ERI and LBLN Alternative scenarios with a loosen carbon reduction effort in the long term.
- Low-carbon scenarios with a 2020 milestone in the range of the Chinese target (UNDP and Enerdata) will set the country on a trajectory in line with official announcements. Depending on the stringency of the long-term target, that would necessitate either to maintain the level of efforts by 2050 (UNDP) or rather to increase it and possibly introduce a real paradigm shift by 2050 (Enerdata).

These long-term processes (sustained/loosen efforts, paradigm shifts, etc.) will be detailed in Section 3 using a dedicated methodology (as presented in Section 2), much attention being paid to the underlying drivers of those processes.

It is difficult to compare short-term emission projections with the official Chinese pledge at 2020, because the emissions levels at this time horizon are very much linked to the starting points that show discrepancies across scenarios. Indeed in Table 3, the starting year is 2010 and is a result from the models in all studies under consideration. Those difficulties decrease as the time horizon that is considered slips forward. This advantage is even stronger when using a methodology that only considers variations, not absolute terms, over the future decades to 2050, for both CO_2 emissions and their drivers.

2. METHODOLOGY ADOPTED FOR SCENARIOS ANALYSIS

2.1. Decomposition of key drivers for CO_2 emissions

We propose to develop a method that allows comparing emissions trends (especially CO_2-energy emissions) across the various scenarios under consideration, and to better understand their key drivers. The method described in this section is used to assess both historical emissions developments for China and their future trends. More particularly, it is useful to compare the differences in the underlying storylines and in the forward-looking approaches across studies.

The proposed method has the advantage to make comparable studies that have different starting years, because we focus on the variations of CO_2 over time and the reasons for those variations, rather than absolute terms. Even though all studies considered in this paper are recent (the oldest being published in 2009), 2005 is usually the starting year. There may be already significant deviations from the actual energy consumption and CO_2 emissions in year 2010, compared to the reality, which of course advocates for our approach. Scenarios showing a sizeable short-term deviation have been disregarded in order to ensure the necessary consistency and credibility of our comparison. This is the case for the Tyndall scenarios S1 and S2, not considered in this study as already mentioned.

The numerical method adopted in this paper comes from the combination of the decomposition principle by Ang *et al.* (1998), also called Logarithmic Mean Divisia Index (LDMI), with a very simple decomposition analysis using the Kaya formula for the various long-term energy and emissions forecast studies for China as detailed in the previous section. This method is considered to be adapted to our objectives in that it is both highly illustrative for a quick understanding of the scenarios and their main differences, and easy to implement as it necessitates only a few homogenous and comparable data—data availability often being a limit for scenario comparisons. Using the Kaya formula as in equation (1) (Kaya, 1989), our method thus merely necessitates four time series for each publication in consideration: Population, GDP, Total energy consumption (i.e. primary energy) and Total CO_2-energy emissions.

The Kaya formula is common and consists in a very simple way to decompose the CO_2 emissions related to fossil fuel consumption. They are as in equation (1), where Pop is the country population, GDP/Pop represents the average per capita GDP, Ene/GDP is the energy intensity of the national economy and CO_2/Ene represents the average carbon content of the energy consumed within the country. Each of the factors in the Kaya formula represent an aggregated factor for domestic CO_2 variations over time, thus allowing a better understanding of the underlying reasons for the overall emissions variations.

$$\mathrm{CO2} = Pop \times \frac{GDP}{Pop} \times \frac{\mathrm{Ene}}{GDP} \times \frac{\mathrm{CO2}}{Ene} \quad (1)$$

The LMDI formulation provided by Ang allows decomposing the emissions variations of the Kaya formula over time in a proper mathematical manner, i.e. eliminating residuals unlike a too simplistic logarithmic-integration method. Under its additive form and following the practical guide by Ang (2005), the LMDI is given as follows:

$$\mathrm{V} = \sum_i x_{1,i} \times x_{2,i} \times \ldots \times x_{n,i} \quad (2)$$

$$\Delta V_{tot} = V_T - V_0 = \sum_k \Delta V_{x_k}$$
$$= \Delta V_{x_1} + \Delta V_{x_2} + \Delta V_{x_3} + \cdots + \Delta V_{x_n} \quad (3)$$

$$\Delta V_{x_k} = \sum_i \frac{V_i^{\,T} - V_i^{\,0}}{\ln V_i^{\,T} - \ln V_i^{\,0}} \times \ln \frac{x_{k,i}^{\,T}}{x_{k,i}^{\,0}} \quad (4)$$

As this paper considers CO_2 energy-related emissions aggregated at the country level for China as a whole, the index i is no more useful and vector V (i.e. CO_2) is decomposed according to the Kaya factors x_k, which finally gives a simplified equation for the overall CO_2 emissions variation (5):

$$\Delta CO2 = \sum_k \Delta CO2_{x_k}$$
$$= \Delta CO2_{Pop} + \Delta CO2_{\frac{GDP}{Pop}} + \Delta CO2_{\frac{Ene}{GDP}}$$
$$+ \Delta CO2_{\frac{CO2}{Ene}} \quad (5)$$

The variation of CO_2 emissions over a given period of time (period 0 to T in the equation) is finally calculated as follows (6):

$$\Delta CO2_{x_k} = \frac{CO2^T - CO2^0}{\ln CO2^T - \ln CO2^0} \times \ln \frac{x_k^{\,T}}{x_k^{\,0}} \quad (6)$$

The final equation (7) decomposes the overall CO_2 growth rate per period into additive contributions, based on the previous decomposition in absolute emissions variations:

$$dCO2_{x_k} = \frac{\Delta CO2_{x_k}}{\Delta CO2} \times dCO2 \quad (7)$$

In this paper, the calculation is performed for historical Chinese emissions based on five-year time periods, which broadly compares to the official FYP periods, with a one-year time lag only. In the next scenarios comparison section (Section 3), the periods considered usually correspond to the decades to 2050 starting in 2010, with an exception for the IEA scenarios which only consider the periods 2009-2020, 2020-2030 and 2030-2035.

2.2. Combining a decomposition analysis with emissions projections

Decomposition analyses of past CO_2 emissions trends are common and this is not the purpose of this paper to mention all. A wide array of technics has been developed, amid which the LMDI is only one example of the main Index Decomposition Analysis (IDA) methods. There are several studies analysing past CO_2 emissions trends for China, for instance Wang *et al.* (2005) and Liu *et al.* (2007) using an LMDI method. The former deals with CO_2-energy emissions from 1957 to 2000, while the latter focuses on industrial CO_2-energy emissions over the 1998-2005 period. More recently, Zhang *et al.* (2009) proposed an interesting decomposition of the Chinese CO_2 emissions between 1991 and 2006 period, taking the sectoral dimension into account. Studies of past CO_2 emissions decomposition have been realized for other countries, for instance in Brazil (Charlita de Freitas and Kaneko, 2011) or India (Narayanan and Sahu, 2012).

If decomposition analyses have been mostly used to better understand past CO_2 emission trends, as in all the previously quoted references, or merely the past energy demand trends (intensity *vs.* structural effects), such combinations can be used to build Marginal Abatement Cost curves (MAC), as illustrated by Kesicki (2010) for the United Kingdom.

There have been only a few attempts to combine emissions projections and decomposition analysis. For instance, Kesicki and Anandarajah (2011) assess the mitigation potentials from energy demand reduction using their own long-term energy model. Their methodology, close to the one developed in this paper, also includes a sectoral dimension. They compare the contributions of energy demand reduction to overall CO_2 emission reduction, in different sensitivity cases, among the main world regions (including China, but also the USA, Western Europe, India). So they focus on very specific issues, like energy demand-related mitigation potentials in the residential and transport sectors, using a single prospective model and several scenarios. Guan *et al.* (2008) also analyses past and future CO_2 emission trends for China using an original decomposition analysis.[3] He builds and compares three simple forward-looking scenarios, a Reference, a "Lifestyle" scenario (westernization of the consumption patterns in China) and a carbon capture and storage (CCS) scenario, and he looks at the driving forces of emissions increase by 2030. In this study, total CO_2 emissions in 2030 would increase by 80% to almost 450% compared to 2002 levels (from 6 $GtCO_2$ in the "CCS" scenario to 21 $GtCO_2$ in the "Lifestyle" scenario, twice as much as the Reference scenario). While the "CCS" scenario provides an estimation of emissions levels in 2030 close to the Alternative scenarios that we are comparing in this study, the "Lifestyle" scenario looks quite pessimistic, assuming a quick convergence of Chinese lifestyles (certainly for a very large part of its population) with that of Western regions.

Decomposition methods have been scarcely used to understand future CO_2 emissions scenarios for China. In addition, to our knowledge, such methods are not so commonly used to compare emissions forecasts scenarios, even in a very simplistic manner as it is done in this paper. One example is the work done by Luderer *et al.* (2009) in the framework of the European RECIPE project, which compares global CO_2 emissions projections in two contrasted scenarios (BAU and 450ppm) by three models (IMACLIM-R, REMIND-R and WITCH), resulting in six scenarios in total. Decomposing future emissions was an interesting way to compare the overall dynamics of CO_2 emissions between models and scenarios, even though the method is described in the study. Another example for Europe is the SEFEP meta-study (Smart Energy For Europe Platform) by the Öko-Institut and the Wuppertal Institut (Förster *et al.* 2012), which analyses the most recent emissions scenarios, to support the preparation of the official European Roadmaps 2050 (EC, 2011a and 2011b). Our paper will be the first attempt to compare all the most recently published scenarios for China, mixing all sorts of models (partial equilibrium of the energy sector, pure bottom-up, macro-economic top-down, etc.) using such kind of methodology.

3. Referred as IO-IPAT structural decomposition method

2.3. Application to historical Chinese emissions

Current state of energy demand and CO_2 in China

China has been the largest energy consumer in the world since 2009. Its total emissions overpassed the US in 2007 and are now already 45% higher (reference approach for CO_2-energy emissions[4]), and China accounts for almost a quarter of global CO_2 emissions (from fuel combustion) in 2010.

China's high energy intensity (more than twice that of Brazil, the EU or Japan, over 60% higher than the USA's) is very much linked to its highly industrialized context with the industry sector accounting for 47% of GDP, far beyond any other country[5], except maybe Indonesia. It has decreased a lot over the last decades, at a yearly pace of 3.8%/year on average over the 1971 to 2011 period due to huge economic reforms and industrial development relying on more recent technologies. The trend has been reversed for a while in the early 2000s (2002-2005) to decrease again since 2006 as shown on Figure 6 (NBS, 2012).

In its modern history, Chinese economic development has been driven by coal consumption, made possible thanks to its huge resources. In 2011, 80% of the Chinese power production came from steam coal, and that source of energy accounts for 68% of primary energy supply. Coal consumption in industry represents just one third of total final energy demand in the country, which is more than three times the energy demand in transport and more than the total energy demand arising from buildings.

4. In this section, not referenced data come from the Enerdata Global Energy&CO_2 database (2012)

5. 26% in the EU, Japan and India equal to the World average, against 20% in the USA and 37% in Russian Federation, etc. according to the World Bank (2012)

Per capita emissions have recently overpassed the world average (in 2007), approaching very quickly the EU average (according to Enerdata, CO_2 from fuel consumption per capita reached 5.9 tCO_2/cap in China in 2011, against 4.2 tCO_2/cap for the world average and 7.1 tCO_2/cap on average in the EU for year 2010). But the Chinese per capita emission ratio remains far from the US levels (about one third of the US levels).

Historical CO_2 emissions decomposition for China

In this section we describe past trends in Chinese CO_2-energy emissions and provide interpretations of the variations and sometimes the "shifts" identified over time using our original analytical method.

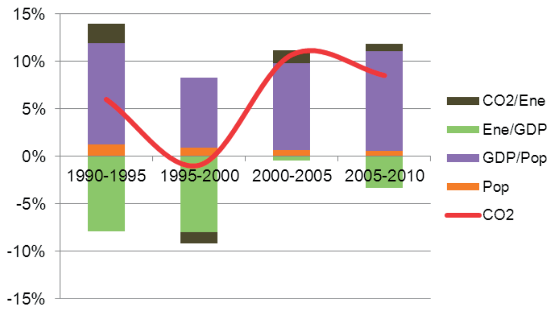
Huge concerns about the Chinese statistical body cannot be evaded, both concerning macro indicators and energy and emissions reporting, even though it is often considered to have improved substantially in recent times. In particular, there are concerns related to GDP growth figures, often considered to be overestimated mainly due to widespread falsification during the 1990s, sometimes as much as a 3 percentage point exaggeration (Zhang, 2003). More problematic, total energy supply figures seem to remain quite approximate, especially before year 2000. But it has not been possible so far to estimate the extent of the deviation from real figures. The transparency and comprehensiveness of energy intensity figures, updated on a regular basis by the Chinese authorities, are also questioned by Wang (2011), in particular with respect to changes in the statistical classification.

The analysis of historical CO_2 emissions development is used as an illustration of the possible trends, as a reference for the work of prospective scenarios comparison. This is why we remain focused on broad trends, at a level of precision that does not require questioning the official Chinese statistics. In addition, Zhang (2003) demonstrated that even taking a lower historical GDP growth rate, his conclusions from the decomposition analysis remain.

Figure 3 shows that Chinese emissions have fluctuated a lot during the last two decades, demonstrating different and moving patterns for energy demand, macro-economic features, etc. Recent data from the International Monetary Fund (IMF) are used for GDP growth estimation; past CO_2 emissions as well as total Chinese energy demand data come from the *Global Energy and CO_2 database* by Enerdata; finally the population time series comes from the UN Population Division.

The hectic historical CO_2 emissions profile in China has no trivial explanation. Their drivers

Figure 3. Historical Chinese emissions and their drivers from 1990 to 2010



have changed, sometimes in very different directions, in almost each five-year periods. The only constant driver over the whole period (1990-2010) is the population. It is one if the easiest parameter to monitor and anticipate because of its strong inertia compared with other socio-economic variables in China. Nor has it been so crucial to explain historical CO_2 emissions trends because of its marginal weight. Population growth has steadily decreased during the recent Chinese history, thus slightly relaxing the pressure on energy consumption and CO_2 emissions. This is of course much linked to the Chinese family planning policies, like the one-child policy introduced in 1978.

More sensitive than mere population size is the role of other demographic parameters like the transformation of the age pyramid, the rural exodus trends, the increase of inequalities, the reduction of household's size, etc. Those parameters which are not assessed in detail in this paper have strong impact on energy consumption patterns due to the revenue effects, the developing standards of living, the actual number of households, etc. They may thus have huge but somehow indirect consequences on CO_2 emissions.

The historical variations of the Chinese emissions are analysed below for each five-year time period, thanks to our decomposition analysis. The key explanation factors are: the energy intensity of the Chinese economy, the CO_2 content of the energy inputs and the GDP per capita growth.

1990-1995

Emissions were substantially boosted by the high economic growth, and were not fully compensated by the reduction of energy intensity even though it strongly improved during that period. Demography played a little direct role in emissions increase, but less than the changes in the primary energy mix, which saw the role of coal increase during this period.

1995-2000

As a consequence of the 1997 Asian economic crisis, the Chinese economic slowed down in, 1998 and 1999 reflecting internal structural weaknesses. This led to a zero or even negative trend of the Chinese CO_2 emissions for a short period. As shown on Figure 3, that inflection in CO_2 emissions trend is visible compared to the previous period, even though the GDP growth rate remained above 7,6% over this five-year period (minimum growth rate reached in 1999 according the IMF). The 1997-2002 period also corresponds to a period when the share of industry in the Chinese GDP has lost 3% points according to the World Bank, thus improving the overall energy efficiency of the economy by a structural effect. In addition, the industrial activity became more export-led than pushed by the domestic infrastructure development. That facilitated the energy intensity improvement by a structural effect within the industrial sector itself, with the relative development of the manufacturing branch compared to the construction one. The power production also increased at a slower pace than the average GDP growth over this five-year period, at an average rate of 6%/year according to Enerdata, which also contributed to a substantial decrease of energy intensity and to substantial coal savings.

2000-2005

The first decade of the 21st century has been a period of huge economic growth for China. This is broadly explained by a continuous industrialization pulled by new vigorous exportations starting after China became a Word Trade Organization member in late 2001. But the infrastructure-led energy-intensive growth was also an important trend, thus explaining why the energy intensity improvement has been almost insignificant. This macro-economic trend was accompanied by an important rural exodus toward the Eastern and coastal provinces, thus sustaining the heavy industrialization process of the country. During this period, the average GDP per capita increased by over 55% in power purchase parity value, but was accompanied by huge inequalities. The related urban development finally induced a soaring demand for coal (11.5%/year on average according to Enerdata), from both the power and the industrial sectors (respectively 13.1%/year and 10.4%/year). Energy efficiency improvement was quite reduced overall with even an increase of energy intensity observed over the period from 2002 to 2005 (see Figure 6).

2005-2010

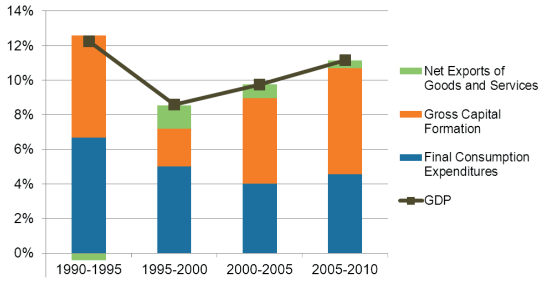
Over the most recent five-year period, a steady electrification of the country at an average pace of 13%/year contributed a lot to the increase of domestic coal demand, and thus to the increase of CO_2 content of the energy consumed. Total domestic CO_2 emissions thus soared, sustained by the growing economic activity. However this upward trend slightly decreased because of renewed and more stringent energy efficiency measures taken during the XIth FYP. The official target of 20% energy intensity reduction has been almost reached with 19% as show on Figure 6 (NBS, 2012). If the outcome in terms of energy intensity reduction is sizeable, it remains below the pace achieved during the last decades of the 20th century. It is also far from compensating the revenue effect (i.e. GDP per capita) over the period, following the export-led industrialization process and the development of heavy domestic infrastructures.

Main lessons from the analysis of past Chinese CO_2 emissions

The key factors with regards to historical development of the Chinese CO_2-energy emissions can be summarized in three aspects:

- *The economic growth and its content* have huge consequences in term of overall energy demand and related emissions trends. This is a key issue for China, which used to deliver guides on the role of industrial development in the national economy. In this respect, the recent announcements that the share of industry in the GDP would increase by two percentage points over the XIIth FYP looks rather counterproductive, even if it is justified by the Chinese authorities as resulting from the switch from heavy industry to high value and leading-edge technology. Another structural change which seems to be neglected in the Chinese case is the switch from the industry to the tertiary sector, pushed by the growing domestic demand for services which are usually low energy-intensive. During the past decades the role of industry in GDP growth has prevailed, with the subsequent issues of massive public investments and exports of manufactured goods driving this growth. On Figure 4, it is clear that exports have starting to contribute to GDP growth as from the mid-1990s. But over the 1990s, the contribution share of consumption was still dominating (over 50% growth share), which has been reversed during the last decade when consumption contribution to GDP growth has been reduced (around 40% contribution on average). Further research would be necessary to better identify the role industrial investments *vs.* investments in the other sectors have played, and more particularly within the industrial sector how the various branch have developed

Figure 4. Contribution of the three components of GDP, by expenditure approach, to the growth of GDP, 1990-2010

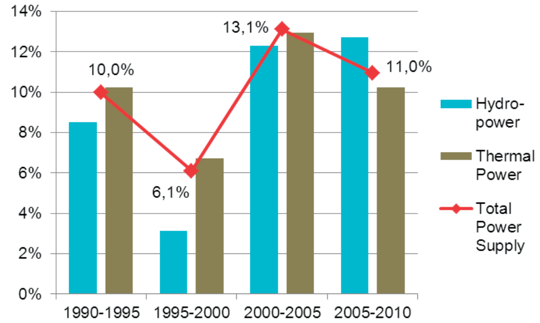


Source: author's calculation, based on yearly data from (NBS, 2012) for data 2000-2009, (NBS, 2005) for data 1990-2000 and (ADB, 2011) for estimation year 2010

(manufacturing *vs.* construction, etc.). Kahrl and Roland-Holst (2009) and Guan *et al.* (2008) provide more insights on those structural issues.

- *The power sector development and its capacity mix* is of course very much linked to the economic growth, but also to the content of this growth (industry-led, households consumption-led, etc.) as well as to the dynamics of energy consumption and the electrification rates of every sectors. The power mix constitutes both an opportunity and a risk for future CO_2 emissions development: power production may be heavily emitting in a business as usual as coal is the easiest way to produce very quickly new power plants to satisfy the new demand, as it used to be in the past. On the other hand, decarbonising the power sector is certainly one major mitigation option, with the best potential both in terms of volume and cost for long-term CO_2 emissions control in China. Figure 5 illustrates how two electricity production routes only, namely thermal coal and hydropower, were able to supply and satisfy the soaring power demand since 1990. The question is now about finding new power generation technologies capable of substituting for coal-based production at such wide scale of development in the future.
- *Efficiency policies and measures* mainly taken in the industry sector, as those introduced during the XIth FYP, have demonstrated their effectiveness even if their economic and social efficiency is still subject to debate. Together with the structural change of the Chinese economy, energy efficiency is the main factor of improvement of the overall energy intensity. The weight of the industrial sector in the Chinese economy explains by itself how the overall energy intensity change simply follows the energy intensity trend of the industrial sector (Zhang *et al.*, 2009). The decline in industrial energy intensity

Figure 5. Thermal and hydro power contribution to total power supply growth in China, 1990-2010 (NBS, 2012)

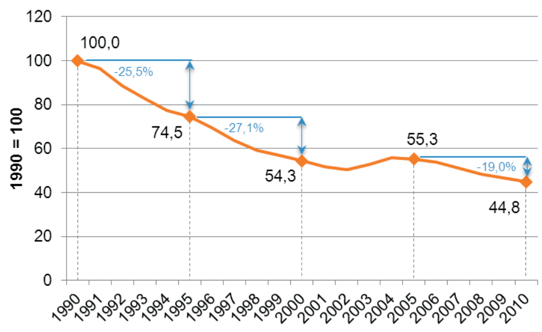


Note: From 2000 to 2005, unlike over the other periods, nuclear contribution is not insignificant because of the completion of 6 nuclear reactors (from 17 to 53 TWh produced from nuclear) in addition to 2 existing reactors, explaining why total power supply growth is above both thermal and hydro power growth. Wind power contribution has no visible impact on this graph even if it reaches 45 TWh in 2010 according to the NBS.

over the 1990 decade is not attributed to structural factors but to a real intensity decrease as shown by Zhang *et al.* (2003), while Teng and Yang (2011) confirm that result at the provincial level. Low-carbon scenarios are expected to rely as much as possible on the remaining energy efficiency potentials in the different sectors of the economy, in order to maintain and increase the beneficial trends observed during the XIth FYP period. After the average country energy intensity has seen a reverse trend in early 2000, it was necessary to restore the historical improvement dynamics of the Chinese overall energy intensity by implementing dedicated policies (top-1000 enterprises policy, small inefficient facilities closing programme, etc.). But future decrease of the energy intensity will be difficult to reach due to decreasing returns. Indeed, technologies in use in China today are close to OECD's, which leaves much less room for improvement than during the 1980's. Efficiency improvement will also be requested in the transport and building sectors, those two sectors constituting the future huge energy-related challenges in China.

The persistent historical failure to drive down the carbon content of the overall country energy supply, as illustrated by our analysis, seems contrary to the international commitment taken by China in Copenhagen in 2009 (i.e. reduction of 40 to 45% of the carbon intensity compared to 2005 levels). Indeed, the Chinese pledge in carbon intensity is certainly higher than what the country will be able to achieve in terms of energy intensity reduction, thus entailing a necessary decarbonisation of the average Chinese energy inputs. Recently, a carbon intensity target has been introduced

Figure 6. Overall energy intensity trend in China and five-year lags improvement, 1990-2010 (NBS, 2012)



for the XII[th] FYP, higher than the energy intensity target. This new policy development shows that the necessary development shift is acknowledged by the government.

The next two sections assess the possible factors participating to long-term CO_2 emissions trends in the different scenarios listed in Section 1. The conditions for reaching low-carbon development objectives in China are discussed and compared. The focus is put on the identification of possible paradigm shifts and their timing, and on the various strategies identified by the studies. For both sets of Reference and Alternative scenarios, we identify the common features and the main differences across the studies, as well as their quantitative outputs.

3. LONG-TERM EMISSIONS SCENARIOS COMPARISON FOR CHINA

3.1. CO_2 emissions decomposition of Reference scenarios

Comparing Reference scenarios for China is a very fruitful exercise with regards to the understanding of the probable natural development of Chinese emissions, unless any further stringent energy and climate measures are taken. In particular, it is interesting to understand how models continue historical trends or, on the contrary, already anticipate changes in the future emissions development. In this section, we focus on the comparison of two elements: CO_2 emissions trend for China, and the decomposition of their underlying evolution factors. Figure 7 provides their graphic representations in the different scenarios. First, we isolate the common features in all scenarios and then we identify and explain the main differences in the underlying visions for China.

Detailed figures are provided in Annex of this paper.

Common features of the Reference scenarios

Reference scenarios reflect a continuation of past trends with possible smooth changes over time, but nothing brutal. Projections are not much different in structure from the average historical developments of Chinese emissions, as analysed in the previous section. And it should be noticed that projections usually fluctuate much less in time than historical trends. This is linked to the representation that models make of the energy systems or the economy in general, relying on "fundamentals" that are not able to represent brutal changes unless they are explicitly specified. And by definition, those "shifts" are usually not represented in Reference scenarios, for any of the forecast periods.

There are some robust common features coming out of the Reference scenarios. In all scenarios, future CO_2 emissions growth decreases progressively over time, which has not been the case historically. But as it used to be in the past, in all scenarios we can observe that:

- GDP growth clearly remains the main driver for future CO_2 emissions, even though tending to decrease in magnitude;
- Demography really weakly drives future CO_2 emissions, even less than historically;
- Energy efficiency and sobriety, used as a proxy for energy intensity improvement, is almost the only option that really smoothes future CO_2 emissions;
- The reduction of the carbon content of total Chinese energy inputs only plays a little role, if any, to contain future CO_2 emissions growth;

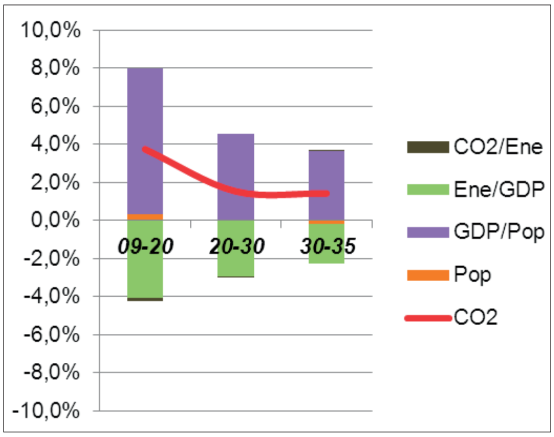
Generally speaking, the energy intensity factor tends to decrease in importance over time, which does not apply to the carbon content of energy inputs. On the contrary, this latter factor seems really sensitive to the additional policies and measures that are assumed in the different scenarios. It appears quite clear already that its role may increase over time, depending on the political effort assumed in the scenarios. The effort is generally weak in the Reference scenarios, but the relative differences concerning the underlying assumptions of policies and measures implemented in the scenarios are already sensitive for this driver (e.g. UNDP EC Scenario *vs.* UNDP Reference).

Main differences across the Reference scenarios

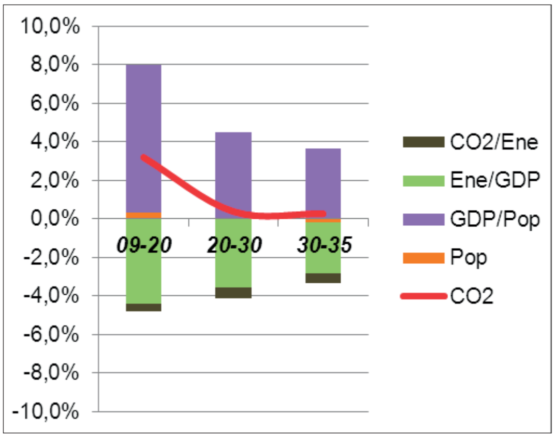
CO_2 emissions trends

Emissions levels at 2050 range from around 9 $GtCO_2$ to 16 $GtCO_2$. CO_2 emissions dynamics are very different across scenarios (see Figure 1),

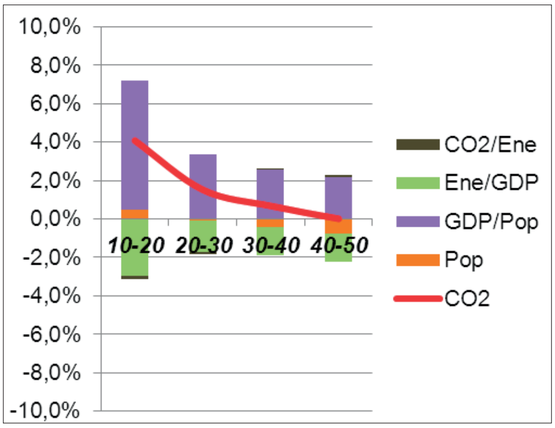
Figure 7. CO_2 emissions decomposition analysis for Reference scenarios



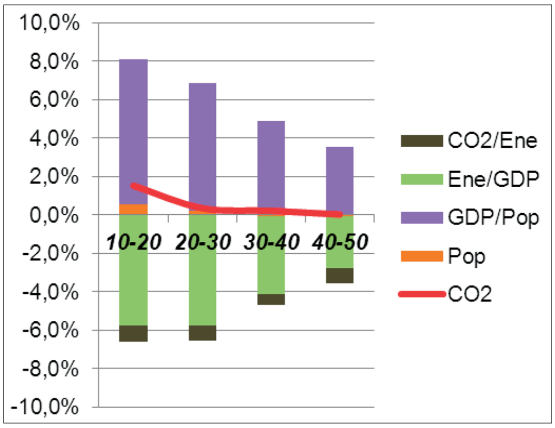
IEA Current Policies



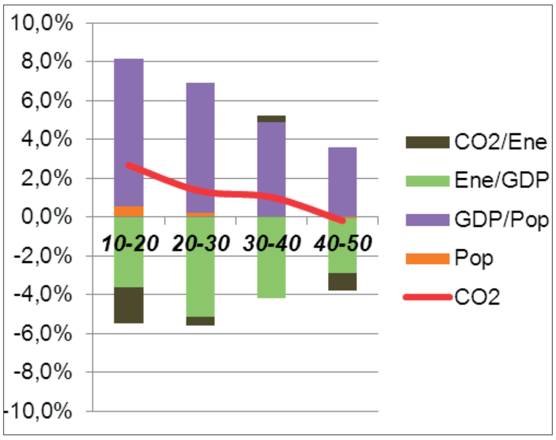
IEA New Policies



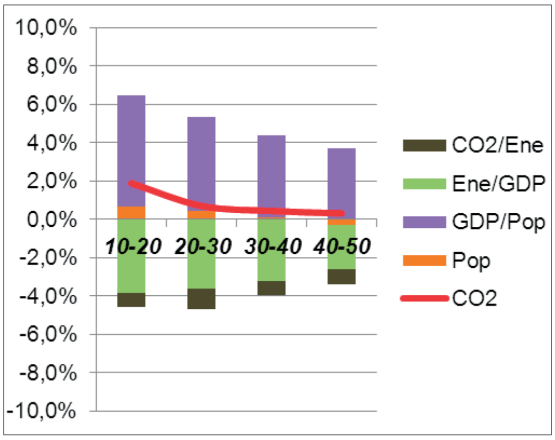
ERI Baseline



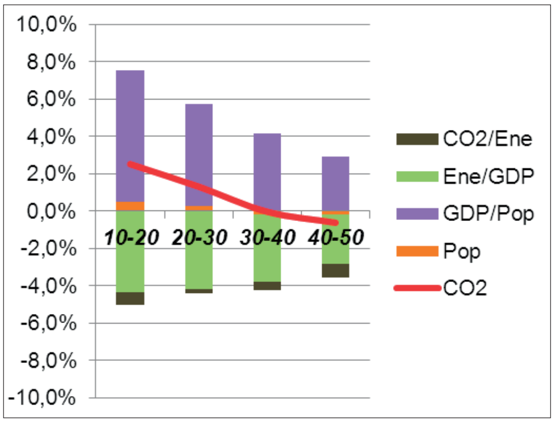
ERI Low Carb



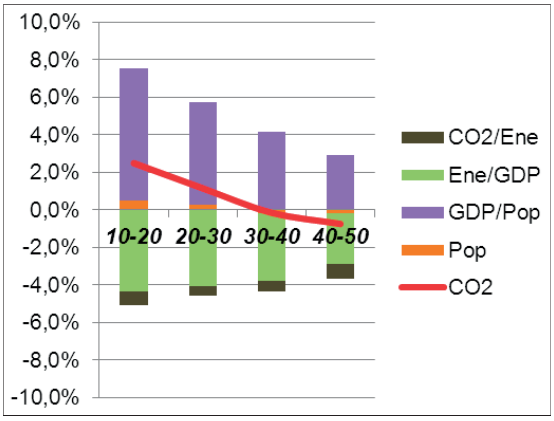
LBLN CIS



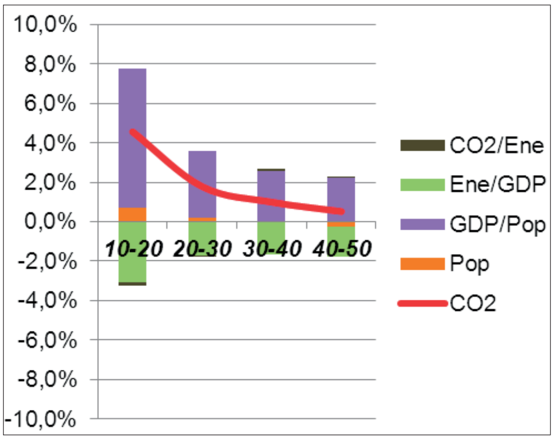
LBLN CIS with CCS



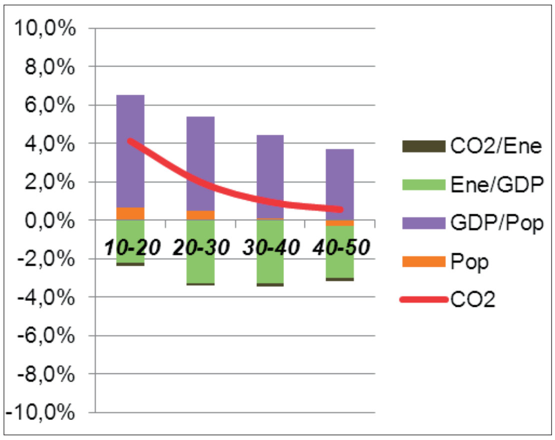
UNDP Reference



UNDP EC Scenario



Enerdata - S1 Recovery



Enerdata – S2 Depression

which translates on Figure 7 with different growth rates profiles. This is due to much different underlying policies and measures, socio-economic assumptions, and models parameters, as illustrated by the different indicators of the following decomposition analysis. Future emissions trends can be flat (IEA) or decrease steadily over time (ERI, Berkeley, UNDP, Enerdata), meaning that emissions would decelerate in the future. One scenario even shows a negative growth rate in the long term (Berkeley).

The previous section showed that during the XI[th] period, the national CO_2 emissions trend was 8.5% (see Figure 3). For all the studies under consideration, the average trend for the first simulation period is clearly reduced, ranging from 4,5% (Enerdata S1) to 1,5% (ERI Low Carbon) over the 2010-2020 period.

Revenue effect (GDP per capita)

The revenue effect is the major driver for future CO_2 emissions increase, as it used to be in the past. But as GDP growth is expected to decrease as from the next decade in all the Reference scenarios, revenues will also drive future emissions at a slower pace. In addition, future GDP growth assumptions are much different across the scenarios, explaining some of the main differences in energy and emissions projections. For a more detailed comparison of macro-economic (GDP growth) assumptions, refer to Table 4, in Section 4.1. Though future economic growth is clearly the most significant parameter driving up CO_2 emissions in China, it remains very uncertain as illustrated by the wide range of assumptions adopted by the various studies.

Energy intensity improvement

There is a general decreasing trend of energy efficiency improvement over time, but levels can be much different across scenarios. Some projections also assume an increasing trend in the short-medium term before resuming to a decreasing trend (UNDP Reference and ERI Baseline). Almost all studies thus implicitly reflect decreasing returns of energy efficiency measures in the long run. Potentials for energy intensity improvement have different magnitudes across scenarios, displaying various underlying storylines and identified potentials for energy efficiency and conservation in the models. It ranges from 2,2%/year (UNDP) to 4,3%/year (LBLN) improvement in the short term to 1,5%/year (Enerdata) to 2,8%/year (ERI) in the long term.

Generally speaking, the level of energy intensity improvement can be important when the GDP per capita driver is high and *vice versa*, as if storylines were possibly incorporating more efforts to control energy consumption when the economic conjuncture was good. In reality, the explanation is related to a structural effect due to the dynamics of the growing stock of assets in the economy: a rapidly growing economy gives further opportunities to improve energy intensity building on the stock effect and its technical renewal speed. Some perverse behaviour related to this phenomenon has been observed during the XI[th] FYP, as the best way to achieve the energy efficiency targets (e.g. building many new efficient facilities close to old inefficient ones, thus quickly improving the average). But this asymmetric evolution might also be explained by an underlying assumption of increasing focus put on energy security issues in case of high economic growth and thus higher energy demand trends to be kept under control.

Decarbonisation of energy inputs

Reference scenarios generally show not much improvement of the carbon content of the energy inputs, but also no real deterioration of it. Two factors explain this: first, given the inherited energy mix of China, with an overwhelming share of coal both in primary energy supply and in the power sector (see Section 2.3 for a brief energy profile of China), the market share of coal cannot really increase or at least not at significant levels; second, historical trends have seen both decrease and increase of the carbon content of Chinese primary energy supply. This is why the assumption of a constant evolution of the carbon intensity of energy consumption over the next decades may look like a reasonable in-between for a Reference scenario.

Usually, scenarios which add some policies and measures have more decarbonisation of energy inputs than their counterfactual Baseline scenarios, even though the effects on CO_2 emissions trend remain quite marginal in all Reference scenarios. For instance, UNDP EC scenario *vs.* UNDP Reference, IEA New Policies *vs.* IEA Current Policies and LBLN CIS with CCS *vs.* LBLN CIS. In this last study, it is very clear that the additional decarbonisation in the LBLN CIS with CCS scenario is due to the introduction of Carbon Capture and Storage technologies (CCS) in the power sector (4% of total power installed capacity in 2050, or 84 GW of capacity capturing 500 $MtCO_2$ by 2050).

The ERI Baseline scenario looks more complex in this regards. Indeed, this scenario is the only assuming a small decarbonisation trend of energy supply during the early times of the simulation (at almost 2%/year improvement on average), thus playing significantly for the total CO_2 emissions development by 2020. But this seems much linked to the energy intensity improvement and there may be some compensation between the two, especially over this first simulation decade. Finally, the effect is much reduced and almost disappears in the post-2020 era.

3.2. CO_2 emissions decomposition of Alternative scenarios

The meaning of "low-carbon" is investigated in the various Alternative scenarios, focusing on the underlying storylines and "pathways", or sometimes what can be considered "paradigm shifts" that those scenarios are assuming. As for the Reference scenarios, we firstly identify the common features across the Alternative scenarios and then try to analyse their main differences and specificities in terms of approach and storyline. New elements only are analysed in this section compared to the previous assessment of the Reference scenarios.

Detailed figures are provided in Annex of this paper.

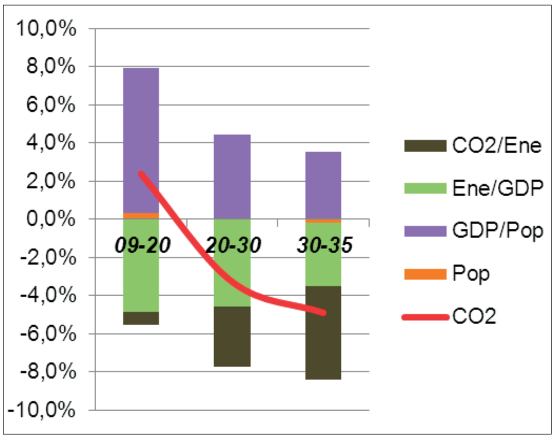
Common features across Reference and Alternative scenarios

- First there is not much influence of the demographic drivers on the overall CO_2 emissions, except maybe in Enerdata S4 (respectively S2 in the Reference scenarios) where the population trend is negative, unlike Enerdata S3 (respectively S1), with only a -0,3%/year on average of difference in 2030 and -0.5% in 2050. In all studies, demographic assumptions are the same across the Reference and the Alternative scenarios.
- Second, there is not much difference across the Reference and Alternative scenarios regarding the overall GDP drivers, except in the Tyndall study where there is no Reference counterpart (mainly due to the specific modelling approach). However, there is still a great diversity of macroeconomic assumptions among studies, as shown in the comparison of the average GDP per capita growth in Table 4. Note the particularly hectic GDP per capita growth of the Tyndall scenarios compared to steady decreasing growth rates in the other Alternative scenarios.

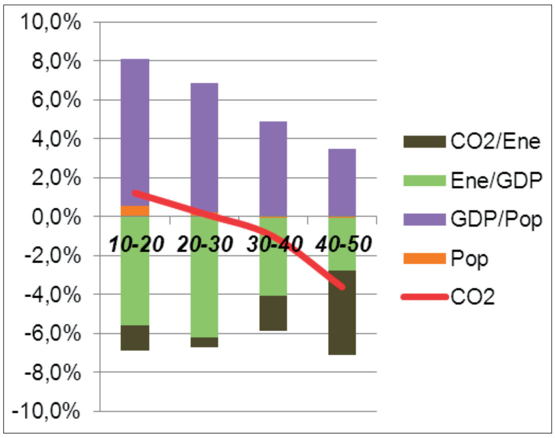
Main differences with the Reference scenarios and across the Alternative scenarios

Two main factors contribute to deliver further CO_2 abatements in the Alternative scenarios: first there is further energy intensity improvement, and

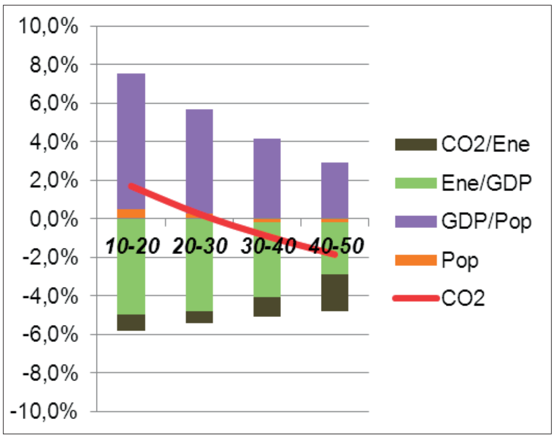
Figure 8. CO_2 emissions decomposition analysis for Alternative scenarios



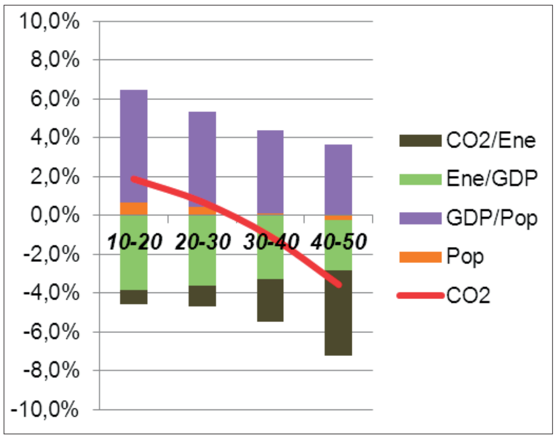
IEA 450



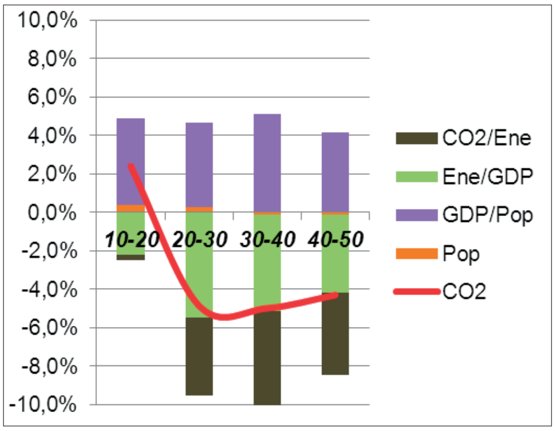
ERI Accelerated Low-carb



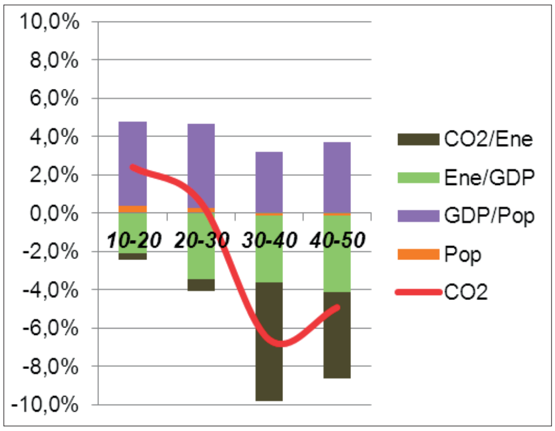
LBLN Low Carb



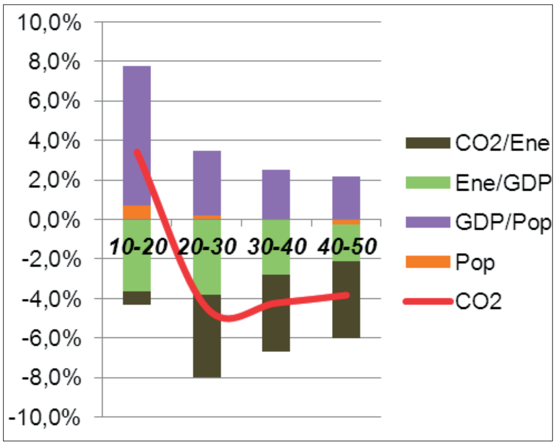
UNDP EA Scenario



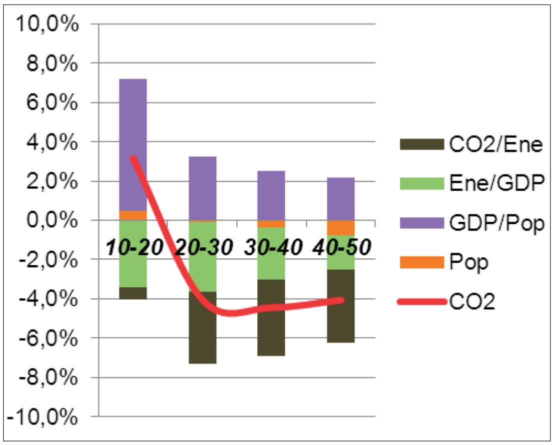
Tyndall S3



Tyndall S4



Enerdata - S3 Renewal



Enerdata – S4 Struggle

second is the decarbonisation process of energy inputs. While the former already plays in the Reference scenarios, the latter is a new contributor to CO_2 emissions containment or even decrease over the long run. Both have different timing and magnitudes across scenarios.

Energy efficiency improvement

Historically, energy intensity improvement used to be the only factor for CO_2 emissions containment, although with significant fluctuations over time. In all Reference scenarios, energy intensity is improving in the future, though at different paces. In the Alternative scenarios, this contribution is clearly amplified compared to their counterfactuals, even if the contributions to CO_2 emission abatements may be quite different among the studies. As already mentioned for the Reference scenarios, the magnitude of energy intensity improvement is often indirectly linked to the overall economic growth.

Interestingly, the additional contribution of energy intensity improvement compared to the Reference scenarios is high in the short-medium term (by 2030), and tends to reduce—or even disappear—in the long term in almost all studies (from 2030 to 2050), as if the remaining potentials for technological energy efficiency improvements and energy conservation were to be tapped soon. It is not surprising as recent Chinese policy developments were focused on energy intensity, a rather short-term mitigation option with many potential co-benefits. Compared to ERI's Baseline scenario, the Low-Carbon and Accelerated Low-Carbon scenarios both show early additional energy intensity decrease, of the same order of magnitude. But due to our methodology, ERI's Low-Carbon scenario is classified as Reference instead of Alternative, even though on this specific issue it closely follows the short-term features of Alternative scenarios.

The magnitude of additional energy intensity contributions provided by the Alternative scenarios, especially over the 2010-2020 period, is wide: from around 0.3 to 0.7%/year in Enerdata/IEA/LBLN, to around 1.6 to 2%/year in ERI/UNDP. The timing is also different: additional energy intensity improvement potentials survive longer in Enerdata and IEA than in ERI, UNDP and even LBLN.

Decarbonisation of energy inputs

The carbon content of energy inputs has shown historically that it may fluctuate from a positive to a negative trend, so that policies and measures should very carefully look at this aggregated indicator in the future development of China. It has always been indirectly linked to the economic growth in the past, because 1) coal has been the only energy resource capable to feed such a strong macro-economic dynamics (mainly through the construction of coal power-plants as shown on Figure 5) and 2) because such a strong economic growth used to be driven by the (mostly heavy) industrial development, widely relying on domestic coal fuel supply.

Past demographic trends as well as the carbon content of energy inputs have not proved to be drivers of decarbonisation so far, nor would they be in the Reference scenarios as shown in the previous section. While the former is supposed to remain neutral, the latter is intended to play a key role in the future, as revealed by this assessment of the Alternative scenarios. More interesting is to compare the possible decarbonisation pathways, largely depending on the evolution of the carbon content of energy inputs and its timing: some scenarios rather follow early mitigation paths, like the Tyndall S3 or those by Enerdata; others are much delayed action scenarios, like in the ERI or UNDP studies. To this regard, the IEA 450 scenario could be considered as a progressive scenario, while the LBLN Low-Carbon scenario is certainly the least optimistic of all Alternative scenarios in terms of decarbonisation of the energy inputs. But it should be stressed that this scenario is also the least stringent carbon constrained over the long run.

All the scenarios do not really consider very short-term potentials with regards to the decarbonisation of energy supply. Indeed, the contribution from this factor is quite reduced over the 2010-2020 period: between 0.6 to 0.9%/year on average), contrary to energy intensity improvement. This can be explained by the inertia of the energy systems, taken into account in a quite realistic manner in the scenarios. Indeed, the time necessary to realize the potential by implementing the necessary actions (e.g. build new infrastructures, commission new low-carbon assets, etc.) and have those delivering (e.g. power capacity mix changed, CCS facilities installed, etc.) can be long. The last section (Section 4) will further describe the underlying possible actions, which usually correspond to heavy investments and organizational adaptation. As a consequence, benefits can hardly be obtained within a 10-year time span. On the contrary, the contribution may be really important in the longer term, as much as 6.2%/year improvement on average in the Tyndall S4 scenario (over the 2030-2040 period), but most scenarios can reach smaller but still significant rates, around 3.5 to 4.5%/year on average.

Two main lessons can be drawn from this scenario comparison:

- First, the higher the emissions trend in the short term, the sharper the emissions decline through decarbonisation of the energy inputs when actual emissions reduction starts. A delayed action requires a more aggressive action for a given level of carbon emissions mitigation effort, as perfectly illustrated by the Tyndall scenarios. Indeed, the Tyndall S3 scenario starts decarbonisation in 2020 against 2030 in the S4 scenario, with an average decarbonisation rate of the energy supply finally much smoother in S3 than in S4. Rates of decrease obtained in the S4 scenarios are as high as 6.2%/year on average over the 2030-2040 period, against 4 to 5%/year on average in S3 over the 2020-2040 period. That can be understood as a brutal shift in the development patterns in S4, certainly inducing heavy challenges in the country's economy to achieve such a paradigm shift, instead of smoother possible transition in other scenarios.
- Second, studies with high GDP growth or low energy intensity improvement in the short term usually require a greater shift in the longer term. This is the case in particular for the Tyndall and Enerdata scenarios (to a least extent the IEA 450 scenario) against the others. In those scenarios, short-term carbon emissions continue to increase due to macro-economic fundamentals and/or limited energy efficiency and conservation; this trend implies additional mitigation efforts in the medium or long-term in low-carbon scenarios.

In this section, we identified the main common features and differences explaining the CO_2 emissions trajectories in in both the Reference and Alternative scenarios. This was used to better understand the main abatement opportunities and strategies identified by long-term mitigation scenarios. In the next and last section, we propose to illustrate the underlying drivers and options identified by the studies, beyond the main possible contributing factors and macro-indicators. Our objective is to go into more in-depth understanding of the scenarios' storylines.

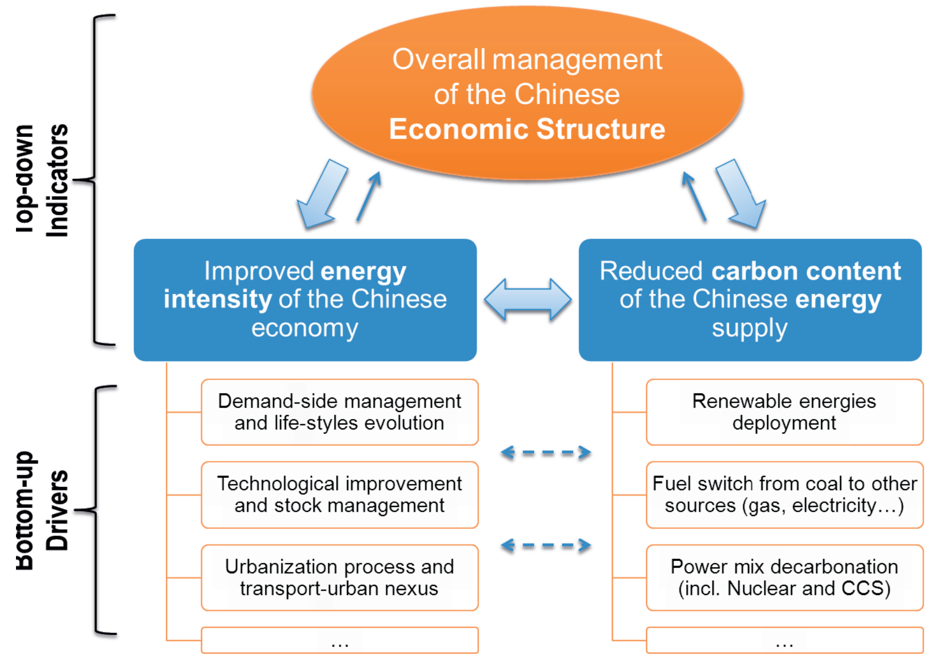
4. HIGHLIGHTING THE DECARBONISATION PROCESS OVER THE LONG RUN

First, needless to say, the method developed in this paper is neither perfect nor detailed enough to completely describe the decarbonisation process over the long run. It compares very general behaviours of the Chinese economy, while some dynamic analyses are still necessarily missing. The possibility to make direct assessment of the interactions in between the major decarbonisation processes remains quite limited with our method. However, based on a common and homogenous assessment methodology, it proved useful to draw the general picture and pinpoint the underlying narratives of possible long-term decarbonisation scenarios.

Figure 9 provides an analytical framework that describes the possible transition processes in China toward a low-carbon economy, as illustrated by the method used in the paper. Indeed, this comparison study has allowed to identify and frame the key levers for long-term decarbonisation in China and to assess their hierarchical organisation and possible interactions. This section aims at summarizing the key elements of the paper and going slightly further in analytical terms.

- First, the overall Chinese economic growth and structure management will be key in the future development of energy consumption and the associated emissions. It is in particular much linked to the evolution of the relative secondary and tertiary sectors shares within the economy,

Figure 9. Possible levers for the transition towards a low-carbon economy in China and their hierarchical inter-linked organisation



but also to the structural evolution of the industry itself with more or less heavy industry *vs.* high-tech industries;

- Second, the improvement of the energy intensity is framed by the macro-economic context. It is induced by pure energy efficiency improvement, energy conservation and other organizational drivers. In return, it may induce overall macro-economic evolutions by creating new opportunities and markets through new energy services and the evolution of lifestyles, by triggering learning effects through technological innovation and the deployment of new organizational systems, etc.
- Third, the major factor capable of triggering low-carbon transition in China, as analysed through the scenario comparison, is the long-term decarbonisation of the average energy supply (even though there may be different strategies). It is related to technical change in the demand and transformation sectors, and in particular the deployment of renewable technologies, nuclear and CCS. It is also driven by fuel switch, which possibilities are depending on the sectors (e.g. coal to gas in households, oil to electricity in transport, etc.). The improvement opportunities are much linked to the macro-economic context and more especially to the increasing demand of energy services in the various sectors. As for energy intensity, the other way round is also true.

Those interactions between the drivers of energy intensity and carbon content of energy are illustrated by Figure 9. Energy efficiency potentials are interlinked with renewable energy deployment and their respective targets cannot be completely separated but they both form a whole. It is the same between the urbanisation process and the fuel switch drivers, etc. Regarding this policy mix consistency issues and the overall macro-economic issues, the European experience (e.g. with its 20/20/20 climate and energy package and its associated *ex ante* and *ex post* assessments) is much valuable, even if certainly imperfect, as shown by Guerin and Spencer (2011).

The low-carbon transition in China will also entail important governance issues, necessitating huge coordination across the institutional political layers, from the Provinces to the State. In theory, the analysis should further take into account the regional contexts, in particular the disparities in the economic and social specificities across the provinces (Teng and Yang, 2011). This is not possible to go this far in this study as scenarios usually consider China as one homogenous single region, using averaged metrics for the whole country. Unfortunately, such level of simplification hides very different situations and thus possible evolutions and internal structural changes, like for instance threshold effects in technology adoption or behavioural changes.

There is no comparison of overall costs across the scenarios, because when available, the information is based on very different methodologies as there are no common approaches for costs and benefits calculation. Some use overall abatement cost in a very bottom-up perspective and others estimate GDP losses in a very macro-economic perspective. As the macro-economy is usually not central in the compared studies, this particular issue should require further research. Nevertheless, Tyndall already provides a really interesting and rather qualitative macro-economic perspective through storylines, while the UNDP makes an attempt to evaluate costs and benefits by analysing potential GDP loss, green jobs creations, etc.

4.1. Greening future economic development: managing the uncertainty on its level and content

Uncertainty on the future GDP growth

As already mentioned, one of the most important discrepancies across the scenarios is regarding future economic growth and the associated structure. Table 4 compares GDP per capita growth assumptions, which usually are identical between the Reference and the Alternative scenarios among studies. As a matter of comparison, the last CEPII projections using a global macro-economic model are also reported. These projections forecast that Chinese GDP would account for 33% of the world total by 2050 compared to 10% in 2011, including real appreciation (Four *et al.*, 2012). They stand at the high end of all other assumptions in scenarios under consideration in this study (except for ERI for the medium-term horizon). The CEPII assumes a convergence between Chinese and US standards of living by 2050, the average Chinese GDP per capita at that time horizon reaching 90% of the US levels. Such high economic activity would eventually entail higher Business as Usual projected levels of energy demand than the ones from the studies compared.

Table 4. Average yearly GDP per capita growth

	2010 – 2030	2030 – 2050
IEA	6.6%*	
ERI	7.3%	4.3%
LBLN	6.4%	3.6%
Tyndall (S3)	4.6%	4.9%
Tyndall (S4)	4.5%	3.6%
UNDP	5.5%	4.1%
Enerdata (S1 and S3)	5.3%	2.4%
Enerdata (S2 and S4)	5.1%	2.4%
CEPII, 2012	6.5%	4.4%

*data corresponding to the period from 2009 to 2030

GDP growth was 9.2% in 2011 according to recently published statistics from NBS, and initial forecast values of economic development are much below the recent observed values in all scenarios. But this seems in line with current Chinese official announcement of a deceleration of the economic growth in the years to come, from slightly over 8% in 2012 (according to recent governmental announcements and other international estimations[6]) to the objective of 7% on average by 2015 set by the XII[th] FYP. It should be noted here that objectives as formulated within the FYP are indicative only. For instance, while the XI[th] FYP objective was 7.5%/year on average (over the 2006-2011 period), the realized economic growth figure reached 11.2%/year.

Behind the overall economic figures and the aggregated GDP metric, other actual issues for Chinese energy demand and CO_2 emissions forecasts are: who gets richer and where are these people? What are the underlying societal changes? In particular, will the current huge inequalities in China continue to increase or is the gap between rich and poor getting progressively bridged?

How could macro-economic structural change help?

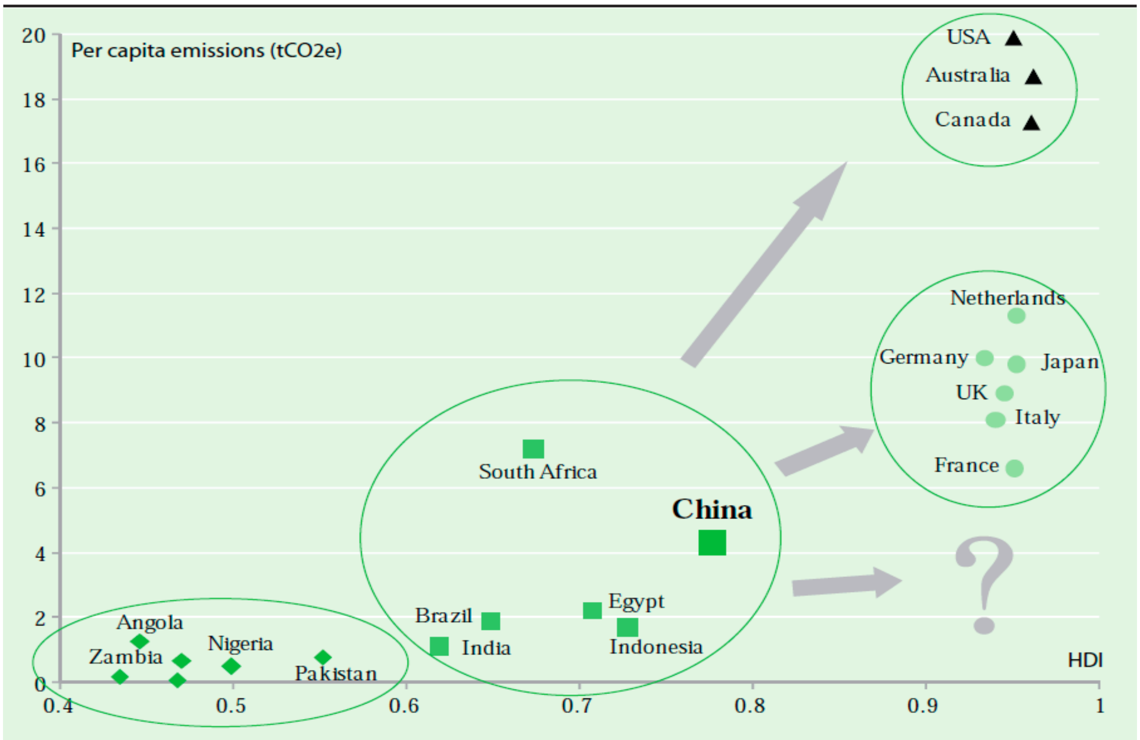
Vermander (2007) used the original concepts of "brown" or "green" China to illustrate two possible and contrasted pathways for its future development.

- The "brown" path corresponds to something like a "Business as Usual" scenario for China, as this is clearly a current trend in the Chinese development. The continuous westernization of the standards of living would lead to increasing tensions and instabilities in all the institutional, economic and social aspects and finally the system would meet its intrinsic limits.
- The "green" path would not necessary imply less growth, but a new China-tailored model of development implying the necessary adaptation and reforms of the energy and environmental governance. Such an "Alternative" scenario would induce fewer constraints on all the economic and social factors.

China is at a crossroad today. Figure 10 from UNDP (2010) illustrates the possible development paths for the next decades and the choice between following the examples of already developed

6. The last IMF World Economic Outlook (April 2012) forecasts 8.2% GDP growth in 2012 (8.8% in 2013 and 8.5% in 2017), The Economist forecasts 8.2% GDP growth in 2012 as well, the World Bank forecasts 8.4% % GDP growth in 2012 followed by 8.3% in 2013.

Figure 10. Possible development pathways for China with regards to existing configurations of developed countries (Source: UNDP, 2010)



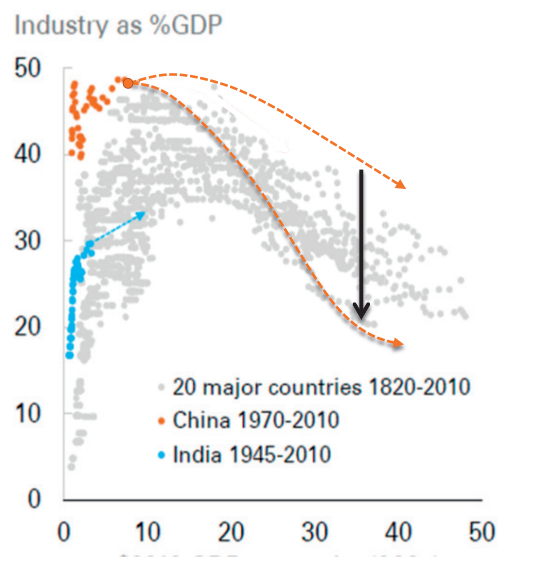
countries and inventing a new Chinese-related paradigm.

There are two categories of already developed countries which followed either a very high emission intensive trajectory, like the USA, Australia or Canada, or a more frugal development path, like Japan, Germany (European countries in general), etc… These two groups broadly correspond to regions with important energy resources endowments and regions without, independently of wealth considerations. In the former group, energy prices are usually low and/or with an important development of upstream energy industries, while countries from the latter group are usually supplied through the international energy markets which results in high energy prices for final consumers. Indigenous energy resources are wide in China, but it is still not clear whether China will manage to remain energy self-sufficient or not, in particular for coal supply and with respect to the possible development of new domestic resources like shale gas. The answer will certainly be much dependent on the very next strategic economic choices and the model of development that will be adopted. Among the emerging countries, China and India are naturally more likely to follow a frugal development over the long run because of the increasing resources constraints, unlike Brazil, South Africa or Indonesia which may base their development on their huge domestic energy resources (and could thus be threatened by the so-called "Dutch disease"). If China is supposed to provide the minimum necessary incentive through fiscal reforms, innovation policies etc., that may prove not sufficient to radically change the country's development path and invent an original Chinese low-emissions paradigm.

Figure 10 illustrates the fact that even with a similar GDP growth overall trend, the underlying macro-economic parameters might be much different according to the country key priorities. The main challenge for China in that regard will be the overall macro-economic rebalancing issue, in particular with regards to the reduction of the industrial share in the aggregated GDP and the relative development of the tertiary sector. It is crucial to understand how long-term scenarios may tackle such a structural shift from investment and export-driven to domestic consumption and tertiary-led growth. So far, it has not been a factor envisioned by the scenarios analysed in this study, for accelerating the decarbonisation of the Chinese economy. Only Tyndall makes a different and rather contrasted assumption between its S3 and S4 scenarios.

Figure 11 illustrates the current situation of China compared to existing paths followed by major developed countries. The market structure

Figure 11. Historical industrialization rates of major countries and possible development paths for China and India



Source: BP, 2012

is represented by the share of industry as a function of the per capita GDP: today's China industrialization rate is very high, the higher rate ever observed for a major economy indeed. And there is also evidence that in the longer term this rate will decrease. But the main question is at which pace would this be desirable and possible, from a sustainable economic and low-carbon development point of view? How to increase the speed of development of the service sector in the Chinese economy, without entailing drawback effects in other regions of the world (e.g. by inducing carbon emissions leakage in other developing countries), but rather use this paradigm shift in China as the driver for a global energy/environment transition?

It is essential to understand how this domestic structural shift in China could occur within the evolving international context. This is much linked of course to the international climate and trade regime, to the organisation of international energy markets, etc. This is why long-term macroeconomic scenarios should imply strategic visions of economic development, compatible with setting China on a low-carbon path in global environment. In such visions, both the demand and supply sectors would evolve, relying on new economic backgrounds, including new products and services. Without such a concomitant evolution, low-carbon scenarios may just rely on the externalization of energy-intensive and highly emitting industries, thus exporting emissions without allowing climate change mitigation globally.

Interestingly, the recent indicative objective of industrial value added share in GDP, announced in the Chinese XII$^{\text{th}}$ FYP (plus 2 percentage points over the 2011-2016 period) seems inconsistent with the generally accepted necessity to reduce the overall country industrialization rate. Of course, this official objective translates into an increasing share of the Strategic Emerging Industries (SEI) all related to emissions reductions (Clean energy technology, Alternative energy, Clean energy vehicles), at the cost of heavy industries. But this illustrates a real difficulty, or even limited political willingness, to really start to push and commit into the economic transition in China with less industry overall. Huge constraints to this shift are related to the path dependency effect, at all various levels (governance, education, cultural etc.).

In the same time, it should be noted that China is committed in developing its services sector. The XI$^{\text{th}}$ FYP objective to increase its share in the GDP by 3.5% points has been missed by 0.5% only (to finally reach 43.5%). A new objective to raise this figure to 47% by 2015 has been set by the XII$^{\text{th}}$ FYP (i.e. +4% points in 5 years), and there is great chance that China will deliver on this target as it usually does.

The ERI scenarios show a still increasing industrialization rate to 50% by 2020, rather in line with the most recent announcements by the Chinese government, before it steadily decreases at 38% by 2050. This reflects the idea of a smooth and somehow delayed transition. To this regard, the Tydall S3 scenario seems more progressive, with the share of industry in GDP representing 20% in 2050, the only scenario to reach a level below the current average of OECD countries (around 25% according to the World Bank). In the other studies, the industrialization rate does not constitute a source for a low-carbon storyline, because there is no difference in the GDP structure across scenarios (Reference vs. Alternative). Some scenarios do not even provide the share of industrial value added in GDP, and except for Tyndall, none precise the actual industrial content (i.e. high *vs.* low-value added industry). The share of industry in GDP in 2050 is reaching 37% in Enerdata, 38% in UNDP, as in ERI, and 33% in Tyndall S4 (20% in Tyndall S3 as already mentioned), showing that most of the scenarios are just aligned on what could be considered a natural trend, even in "Alternative" cases.

All scenarios thus forecast a reduction of the industrial weight in the overall Chinese economy, and the most interesting scenarios in this regard are clearly those produced at Tyndall, as they cross income disparities and innovation assumptions, as the most relevant challenge to describe a macroeconomic narrative for China over the long run.

Income disparities remain important in Tyndall S4 compared to S3, and both S3 and S4 show an increased rebalancing of the sources of economic growth compared to the other studies, even though S3 is much more aggressive.

Our paper thus calls for emphasizing evolution in GDP structure in prospective studies for China. Of course, some bottom-up models with low level of economic representation rather provide a vision of the economy in terms of physical flows like industrial outputs. That allows assessing the overall industrial economic activity with sometimes a detail on the breakdown between heavy, manufacturing and modern or high tech industry. But in our perspective, the direct comparison of key industrial outputs across scenarios does not provide many insights on the decarbonisation processes themselves. Indeed, they are almost always at the same level between the Reference and the Alternative various scenarios, except in ERI. However, levels of outputs are very different across studies as already shown by Li and Qi (2011). For instance, term ERI forecasts steel production in the long term (2050) at 360t (LC and ALC) against 1077t in LBLN (CIS and AIS) with UNDP in-between. For cement production in the long term, there are not so many disparities (around 1100Mt/year +/- 20%), even if there are large differences in the mid-term (2030) with 1005t for LBLN and 1720t for UNDP. This is mainly due to different assumptions across studies in sectoral strategic plans, and to the related policies and measures taken into account. But as already said, those are generally not different between BAUs and the low-carbon cases. Projections of industrial products could help in the storytelling process for decarbonisation scenarios and would require further research, in particular with regards to international trade economy and the future international climate regime.

Finally, the evolving economic structure is deeply interconnected with both energy efficiency improvement and the reduction of carbon intensity of energy supply, two factors which are detailed in the sections below. Indeed, energy efficiency and carbon intensity improvements are linked to structural effects because the developing tertiary sector (beyond a certain level of development, as shown on Figure 11) is usually more efficient and is consuming less fossil fuels, and proportionally more electricity, than industry. There are also many interesting possible macro-economic feedbacks of climate and energy policies focused on energy and carbon intensity reduction. This is not the purpose to cite them all in this paper, but it remains important to stress that the economic and policy processes are not only top-down but rely on a mix of top-down and bottom-up implications.

In addition, the acceleration of the electrification process of the economy is observed in most low-carbon scenarios (e.g. the share of electricity demand in total final energy consumption increases from 18% in 2010 to 28% in 2030 and 41% in 2050 in Enerdata S3 compared to 25% in 2030 and 32% in 2050 in Enerdata S1). The rational for this is that the marginal abatement costs are usually lower in the power sector than in the other sectors of the economy, because many mitigation options are generally considered to be available in this sector. When a carbon constraint is introduced in the system, the classic economy induces a shift from direct fossil fuel to power consumption. The energy efficiency and carbon intensity factors are thus deeply interlinked through this "natural" electrification process. Once again, this is much related to macro-economic factors, in both directions: an economy based on the development of second energy carriers would not look like an economy based on direct fuel consumption.

4.2. Enhancing energy efficiency as the flagship measure of current and future Chinese policy

Historically and unlike many other climate-related policies, energy efficiency used to be promoted in China because it generates much more benefits than simply reducing CO_2 emissions. Rather, CO_2 emissions reduction sometimes appears to be a co-benefit from energy efficiency dedicated policies, which have other primary objectives, such as: the overall country energy security (geopolitics), the affordable access to energy (social), the international competitiveness of domestic companies or domestic inflation control (economic), the reduction of local air pollution (environmental), etc.

The fact that most of energy efficiency potentials are no-lose measures bringing many benefits to the Chinese economy explains why energy efficiency is a factor of CO_2 emissions containment in all scenarios compared in this study, including the Reference ones. In addition, the autonomous technological improvement (i.e. efficiency improvement which is not induced by any specific policy or measure, or by a price or other economic chock) naturally induces a reduction of the energy intensity indicators, and this is even more pregnant in a fast growing economy where the stock effect and the inertia of averaged technical characteristics are limited.

In the low-carbon scenarios, energy efficiency is generally much increased compared to the Reference scenarios, because it brings additional benefits in terms of CO_2 reduction. Energy efficiency is measured as the reduction of the amount of energy per unit of economic output, or per household (person), and it is catalysed by the structural change of the Chinese economy as already mentioned. We identify the main drivers for energy efficiency improvement in the Chinese context and the main lessons from the scenarios compared in this study:

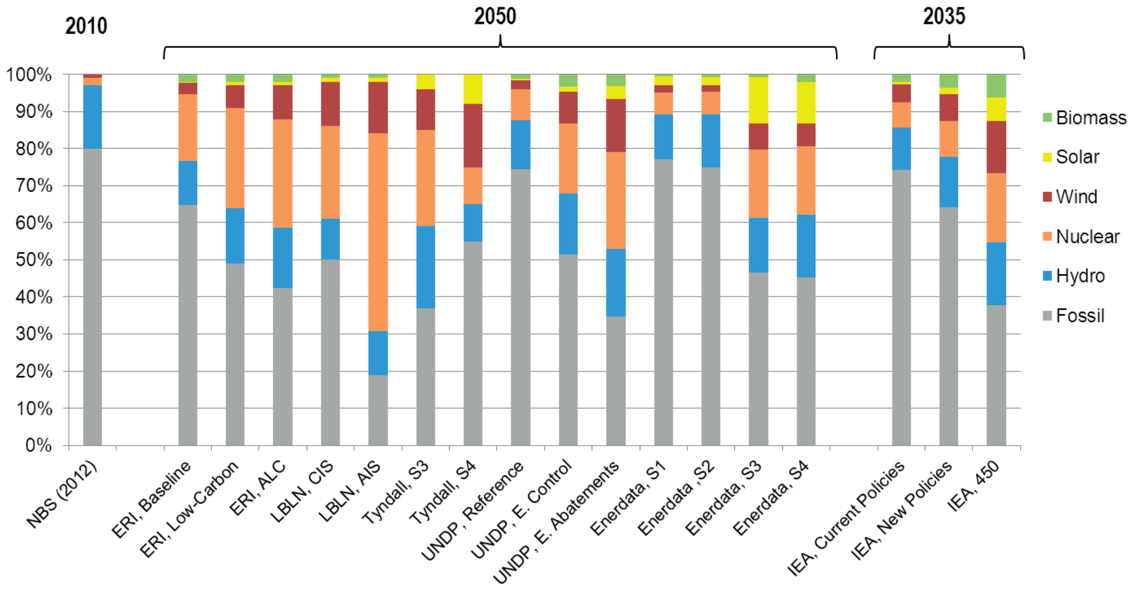
Incremental technological improvement
Technological improvement aims at upgrading the energy transformation efficiency of the whole economy. It requires a renewal of the existing stock of technologies already in place with more efficient technologies and the deployment of new, upgraded technologies. The inertia for improving the average technical efficiency may be strong, due to the stock effect and the difficulties to act on the already installed technologies. There may also be a lock-in effect if the efficiency-related policies and measures are not strict and/or anticipated enough for the new equipment. In China, the stock effect is quite limited in comparison with other regions because of the two-digit economic growth, but for the same reasons the risk of lock-in is more important. A reduced GDP growth in the next decades would also induce an increased inertia for overall technological improvement.

Energy conservation and frugal development
Demand-side management will participate in the decupling between energy consumption and the main economic drivers. Energy conservation measures would require a price signal to be applied in order to avoid the rebound effects. Doing this, people are forced to change their natural behaviour and adapt to the new constraint. But in the longer term, society's aspirations will determine how resources, in particular energy resources, will be consumed. The question of the standard of living and model of development are still important in China as households are accessing higher levels of revenue, *modulo* the inequality factors, which allows them to live in a new consumption society. To this regard, the continuous westernization of the Chinese economy would be detrimental to a resource-efficient economy, as shown by Guan *et al.* (2008). In a low-carbon perspective, China should invent its own way, a new model of development, or paradigm, not only relying on the usual technical possibilities to reduce emissions, but also on other socio-economic factors (i.e. how people will live, work, move, entertain themselves, etc.).

In connection with those two points, one of the biggest challenges for China in the next decades is the urbanization process, and more particularly the urban-transport nexus. Indeed, the urbanization rate is increasing in a comparable way in almost all studies from slightly below 50% in 2010 to 70-80% by 2050. Private and public mobility is supposed to soar in the same time. So what will really factor in is not whether or not people will go to the cities but how those cities will develop in terms of form, density, public transport, energy/transport networks, etc. Cars ownership in 2050 is quite different across the studies, but as shown in the ERI scenarios, the limitation of it is one factor for energy conservation: from almost one car per capita in the Baseline scenario to 0.8 in the low-carbon scenarios in 2050 (figures may also be even lower as in LBLN study for instance). Low-carbon strategies for urban planning should not be limited to the energy use from households, but requires an integrated vision of where people live, where they work and where they spend their leisure time. Urban planning has strong connections with the energy intensity improvement as it is an opportunity to reorganize more efficiently the building and transport systems altogether. It is a real leverage in China due to the fact that many new cities and growing urban centres will be created from scratch by 2050. Almost 40% of the expected urban population in 2050 does not yet live in a city. Teng and Yang (2011) recall that the urbanization trend is connected to the industrialization process and thus to economic growth through a S-type curve. The urbanization process is a real driver for economic development aspects, as a factor for the creation of activity in the tertiary sector, which can be enhanced in a green growth paradigm. When the urbanization rate exceeds 70% on average in China, which is the case in almost all the studies by 2050, the tertiary sector will become the first contributor to the economic growth. Teng and Yang (2011) draw some conclusions about the policy priorities according to the context at the provincial levels: structural shift from industry to service in already industrialized provinces and improvement of technological standards in provinces that are still in the second stage of this curve.

There is a connection between the electrification process and the energy efficiency induced by technological improvement and energy conservation measures. While energy efficiency policies and measures aim at reducing the amount of energy consumed by unit of economic production, the enhanced electrification process (related to the introduction of a carbon constraint) may work in the opposite direction: developing the transformation sector would induce larger overall losses in the national energy system. In turn, the intrinsic quality of electricity, as a final energy form, may induce

Figure 12. Power production mix in the long term in all scenarios



better efficiency of use at the final consumption point (e.g. electrical appliances are more energy efficient than thermal uses). In the end,the final energy efficiency effect in the Alternative scenario more than compensate the drawbacks of the enhanced electrification process (in all studies except in Tyndall for which detailed figures are not available). Indeed, the ratio of total power demand between the Alternative and the Reference scenarios is generally below 100% (86% in ERI, 83% in LBLN, 79% in UNDP and 72% in Enerdata in 2050, and 72% in IEA in 2035). Even though fuel switch effects toward electricity is maybe not well represented in these studies, this common result seems to prove the usefulness and potentials for electrical energy efficiency in a low-carbon perspective.

4.3. Improving carbon content of energy supply: the big shift from the coal paradigm

A great and necessary challenge for setting China on a low-carbon trajectory is the shift away from its current coal paradigm. As illustrated by all Alternative scenarios and as analysed in a previous section, the objective would be to reduce the carbon content of the country's energy supply, measured as the amount of carbon emitted per unit of energy consumed. Over half of total coal supply (56%) was consumed in the power sector in 2011, which makes it the key sector to be decarbonized, followed by the industry representing just one third of total coal consumption (Enerdata, 2012). As already mentioned, the electrification process is enhanced in low-carbon scenarios, which makes the necessity to decarbonize the power sector even more crucial.

Here are the main drivers for decreasing the carbon content of the overall country's energy supply, in particular the power sector:

Technical change and radical innovation

This includes the power sector decarbonisation, switching from coal-based power production to the deployment of renewable technologies like the hydro-power that has been historically co-developed with thermal plants in China. But renewables development may be accelerated in a low-carbon perspective (see discussion below), especially the already mature power technologies like wind, solar, biomass, but also the more radical innovation technologies like tidal and waves, or high temperature geothermal technologies. Low-carbon technical change also includes the deployment of conventional nuclear and maybe also new nuclear designs (IVth Generation and Fusion). Another radical technological innovation considered in most low-carbon scenarios is the CCS that may be used for both the power and the industrial sectors. Indeed, in the industry, a stream of technologies may be used to switch from coal to electricity-based processes, for instance in the steel and iron sector where blast-furnace may be replaced progressively by electric arc furnace, which is made possible by amounts of scrap available for recycling (e.g. toward the closed loop economy).

Fuel switch in final energy consumption

Fuel switch from coal and gas to renewables and electricity covers of course the industrial sector but also the much growing building and transport sectors. In the building sector, thermal needs may rely on fuels with a lower carbon-content than coal, using more natural gas, biomass, solar and even (decarbonized) electricity. Diffusion of domestic appliances like reversible heat pumps may be envisaged as well as domestic combined heat and power plants (i.e. micro CHP), solar thermal and photovoltaic panels, etc. In the transport sectors, the use of biofuels and the electrification of both private (e.g. electric cars and two-wheels) and public means (tramways, subways etc.) are both possible options. Beyond energy efficiency improvements, fuel switch options are possible in almost all sectors and should be considered on the basis of available local resources and capacities.

The possible rhythm for new technologies deployment and fuel switch depends on the technological learning process and the possible grid connection rate (power sector) or integration in the energy systems in general (other sectors), with the development of new low-carbon infrastructures. Most of the time radical technological changes require huge adaptation of governance/institutional, economic/market and grid/systems structures. Decarbonisation scenarios must therefore be accompanied by organizational policies and measures to facilitate the deployment of new technologies and avoid internal constraints including market failures, industrial inefficiencies, and social concerns that may overcome the benefits.

As one of the major decarbonisation options, we discuss hereafter the long-term power mixes as forecast in the scenarios compared in this paper (see Figure 12). The share of renewables in the Reference scenarios usually remains under 20% of the power generation mix by 2050. It may however represent from 25% to 40% of the production mix across the Alternative scenarios. If the quick development of renewables can be considered as a real means to decarbonize the power sector, this is not enough to reach very low-carbon paths in any of the compared scenarios. Indeed, in a context of huge electrification, it remains difficult to deploy renewables at rates that are high enough to really gain big shares in the power mix. Indeed in a scenario where power demand grows at an average 10% annual rate, renewables have to increase at an even higher rate for a long time in order to obtain a really significant weight in the mix. This is particularly true for the "new" renewables (like wind, solar or tidal and high-temperature geothermal, etc.), which almost start from scratch. They would not exceed 20% of the power mix by 2050 with two exceptions: the Tyndall S4 scenario where 25% are supposed to be reached through solar, wind and biomass quick diffusion, and more surprisingly and optimistic, the IEA 450 scenario which forecasts a possible 27% share for those technologies by 2035.

So what are the other main options considered by the scenarios for the long-term decarbonisation of the Chinese fast-growing power mix? Most of the studies consider two key technologies, nuclear and CCS, though with much different visions. LBLN is betting a lot on nuclear development, while Tyndall S4 is describing a huge development of CCS technologies. Most of the Alternative scenarios consider both technologies: Enerdata S3 and S4, ERI ALC, and the IEA 450 scenarios. The scale of development of those technologies is certainly vast and both technologies may quickly diffuse depending on the increase of domestic power demand, but their deployment still relies on the domestic capacity for nuclear and on the technical potentials for carbon storage. In addition, those technological routes are not without risks, both in terms of technical security and social acceptability of their development at wider scales.

What is clear though is that the development of alternative technologies in the power sector, and in the other economic sectors, will require huge support from the government, with dedicated development plans and carbon pricing policies that should facilitate their emergence. The estimation of the carbon value requested to trigger investments and changes in the merit-order of fuels/technologies is sometimes assessed in the studies compared, but not on a systematic basis, and this will certainly be far from being enough to induce the expected long-term developments. This is why it would prove useful to examine the required investments that may allow changing the energy mix in long-term scenarios, like this is done in the UNEP study in particular.

CONCLUSION

The method developed in this paper allowed comparing existing long-term emission scenarios for China, while considering the overall energy system. From this assessment, we have derived significant lessons and messages for the different communities interested in the long-term decarbonisation prospects: policy-makers, negotiators and the modellers themselves.

Ex-post assessment of existing scenarios must allow policy-makers to make better use of existing scenarios, understanding the underlying storylines and their socio-economic implications so as to establish innovative policy-framework that would allow setting the country on the desired development trajectory, while bridging short-term constraints with long-term expectations. This will require to better understand the usefulness (strengths and complementarity of the different approaches) and the limitations (domains of validity) of modelling exercises for policy-making purposes.

Negotiators could also gain from better appreciation of long-term potentials for CO_2 emissions abatement, especially in China. Assessing the possible long-term emissions trajectory over the next decades for China, in relation with the domestic constraints, would allow them to decipher past commitments and existing policy milestones with regards to low-carbon development prospects in China, and would help positioning Chinese mitigation potentials within the global 2°C ambition and the related necessary effort-sharing among countries.

A lesson to the modeller's community is that they should further develop macro-economic narratives for Chinese development, linking sectoral prospective studies with consistent socio-economic storylines compatible with a low-carbon future for China. They will have to replace those possible linkages within quantitative approaches, mixing 'bottom-up" and "top-down" assessments, through three possible channels: 1) Hybridation of models, or hard-link (endogenized "bottom-up" and "top-down" modules), 2) Modelling platforms, or soft-link (addition of models with different approaches and ad-hoc linkage), and 3) Mixing socio-economic qualitative storylines with bottom-up quantitative projections. In addition, China-focused studies should be more systematically connected with the international environment storylines: and more particularly the macro-economic and financial global context; the international energy markets and the related country-dependency to import/exports; the global climate regime and the climate policies in other regions, as well as the other global sectoral issues (e.g. trade policies and industrial strategies, etc.).

Finally, our method could be further applied at the sectoral level, detailing the structural effects in the low-carbon scenarios for China and thus the vision of the drivers for long-term decarbonisation. Lack of available and homogenous data across the studies remains a barrier, but research would gain from such developments. Interestingly, this method could be applied with higher regional details in China, as the future regional dynamics of energy consumption and CO2 emissions may be very inhomogeneous. But the literature currently suffers from the lack of prospective studies with such a provincial breakdown. Emissions dynamics in other important countries or regions, with regards to the challenges posed by climate change mitigation, could be analysed using the decomposition method, as it was done for Europe with the RECIPE project, (Luderer *et al.*, 2009) and the SEFEP study (Förster *et al.*, 2012). Nevertheless, we hope this paper is a first step to better assess the necessary processes for China's transition toward a green economy, including the reconciliation of the external constraints with the internal tensions for a long-term "Harmonious Society" in this country.

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ANNEX: DETAILED TABLES OF CO_2 DECOMPOSITION ANALYSIS – ABSOLUTE AND PERCENTAGE CONTRIBUTIONS TO VARIATION

Annex A: Direct comparison of factors variations for each period

	10-20					20-30					30-40					40-50				
(MtCO2)	CO2	CO2/Ene	Ene/GDP	GDP/Pop	Pop	CO2	CO2/Ene	Ene/GDP	GDP/Pop	Pop	CO2	CO2/Ene	Ene/GDP	GDP/Pop	Pop	CO2	CO2/Ene	Ene/GDP	GDP/Pop	Pop
Enerdata S1 – Recovery	3868	-119	-2616	5986	618	2078	-94	-2007	3920	259	1339	135	-2170	3438	-64	760	153	-2214	3203	-382
Enerdata S2 – Depression	3383	-156	-2438	5564	413	1672	-135	-1802	3696	-87	842	43	-1867	3153	-487	22	79	-1912	2815	-959
Enerdata S3 – Renewal	2742	-566	-2917	5643	583	-3540	-3296	-2987	2573	170	-2129	-1991	-1374	1260	-24	-1276	-1300	-611	721	-86
Enerdata S4 – Struggle	2514	-486	-2704	5313	391	-3179	-2895	-2791	2567	-60	-2267	-1994	-1351	1274	-196	-1338	-1224	-583	712	-243
ERI Accelerated Low Carbon (ALC)	921	-968	-4207	5663	433	124	-439	-5005	5401	167	-784	-1394	-3166	3803	-26	-2270	-2735	-1721	2207	-21
ERI Baseline	2365	-1659	-3182	6695	512	1466	-472	-5553	7266	225	1269	435	-5133	5968	0	-220	-1137	-3615	4620	-87
ERI Low Carbon (LC)	1170	-621	-4400	5752	440	304	-626	-4871	5626	174	195	-460	-3571	4255	-30	29	-688	-2398	3145	-30
IEA 450	2044	-615	-4126	6481	304	-2523	-2432	-3512	3389	33	-1419	-1426	-970	1026	-49					
IEA Current Policies	3437	-146	-3743	6997	328	1700	-88	-3235	4975	48	883	17	-1285	2258	-107					
IEA New Policies	2850	-333	-3918	6783	318	386	-580	-3505	4428	43	140	-261	-1358	1847	-88					
LBNL Continued Improvement (CI)	2311	-638	-3973	6453	469	1466	-281	-4610	6047	311	-31	-491	-4317	4982	-206	-708	-841	-3076	3413	-203
LBNL Continued Improvement (CI) with CCS	2280	-673	-3958	6443	468	1273	-546	-4468	5980	307	-166	-615	-4211	4860	-201	-825	-924	-2994	3289	-195
LBNL Low Carbon (LC)	1469	-740	-4274	6044	439	250	-593	-4589	5167	265	-826	-929	-3609	3872	-160	-1502	-1561	-2188	2389	-142
Tyndall S3	1914	-254	-1741	3616	293	-3538	-2951	-3987	3200	201	-2200	-2200	-2208	2268	-60	-1173	-1173	-1096	1134	-38
Tyndall S4	1914	-252	-1658	3531	293	532	-561	-3215	4046	262	-4730	-4459	-2483	2309	-97	-1916	-1762	-1550	1450	-54
UNDP Emissions Abatement (EA)	1400	-556	-2823	4300	479	600	-900	-3049	4148	401	-900	-1843	-2728	3563	109	-2400	-2942	-1738	2454	-174
UNDP Emissions Control (EC)	1400	-556	-2823	4300	479	600	-900	-3049	4148	401	400	-671	-2890	3843	118	300	-760	-2156	3462	-246
UNDP Reference	3800	-158	-2032	5389	601	2500	-149	-4101	6156	594	1400	-299	-4722	6231	191	900	-243	-4274	5831	-414
(%)	CO2	CO2/Ene	Ene/GDP	GDP/Pop	Pop	CO2	CO2/Ene	Ene/GDP	GDP/Pop	Pop	CO2	CO2/Ene	Ene/GDP	GDP/Pop	Pop	CO2	CO2/Ene	Ene/GDP	GDP/Pop	Pop
Enerdata S1 – Recovery	4,56%	-0,14%	-3,09%	7,06%	0,73%	1,78%	-0,08%	-1,72%	3,36%	0,22%	1,00%	0,10%	-1,62%	2,56%	-0,05%	0,52%	0,11%	-1,53%	2,21%	-0,26%
Enerdata S2 – Depression	4,08%	-0,19%	-2,94%	6,71%	0,50%	1,52%	-0,12%	-1,64%	3,36%	-0,08%	0,68%	0,04%	-1,52%	2,56%	-0,40%	0,02%	0,06%	-1,50%	2,20%	-0,75%
Enerdata S3 – Renewal	3,41%	-0,70%	-3,63%	7,02%	0,72%	-4,48%	-4,17%	-3,78%	3,26%	0,21%	-4,22%	-3,94%	-2,72%	2,50%	-0,05%	-3,82%	-3,90%	-1,83%	2,16%	-0,26%
Enerdata S4 – Struggle	3,16%	-0,61%	-3,40%	6,69%	0,49%	-4,05%	-3,69%	-3,55%	3,27%	-0,08%	-4,44%	-3,90%	-2,64%	2,49%	-0,38%	-4,06%	-3,71%	-1,77%	2,16%	-0,74%
ERI Accelerated Low Carbon (ALC)	1,22%	-1,29%	-5,59%	7,52%	0,58%	0,15%	-0,54%	-6,18%	6,67%	0,21%	-1,00%	-1,79%	-4,05%	4,87%	-0,03%	-3,61%	-4,34%	-2,73%	3,51%	-0,03%
ERI Baseline	2,68%	-1,88%	-3,60%	7,58%	0,58%	1,35%	-0,44%	-5,13%	6,71%	0,21%	1,04%	0,36%	-4,20%	4,89%	0,00%	-0,17%	-0,89%	-2,82%	3,60%	-0,07%
ERI Low Carbon (LC)	1,53%	-0,81%	-5,76%	7,53%	0,58%	0,36%	-0,74%	-5,78%	6,67%	0,21%	0,22%	-0,53%	-4,11%	4,90%	-0,03%	0,03%	-0,78%	-2,72%	3,57%	-0,03%
IEA 450	2,39%	-0,72%	-4,83%	7,59%	0,36%	-3,27%	-3,15%	-4,55%	4,39%	0,04%	-4,89%	-4,92%	-3,35%	3,54%	-0,17%					
IEA Current Policies	3,75%	-0,16%	-4,09%	7,64%	0,36%	1,54%	-0,08%	-2,93%	4,50%	0,04%	1,43%	0,03%	-2,08%	3,65%	-0,17%					
IEA New Policies	3,20%	-0,37%	-4,40%	7,62%	0,36%	0,39%	-0,59%	-3,54%	4,47%	0,04%	0,28%	-0,51%	-2,67%	3,63%	-0,17%					
LBNL Continued Improvement (CI)	2,53%	-0,70%	-4,34%	7,06%	0,51%	1,32%	-0,25%	-4,15%	5,44%	0,28%	-0,03%	-0,41%	-3,62%	4,18%	-0,17%	-0,61%	-0,73%	-2,66%	2,95%	-0,18%
LBNL Continued Improvement (CI) with CCS	2,50%	-0,74%	-4,33%	7,05%	0,51%	1,16%	-0,50%	-4,06%	5,44%	0,28%	-0,14%	-0,53%	-3,62%	4,18%	-0,17%	-0,74%	-0,83%	-2,68%	2,95%	-0,18%
LBNL Low Carbon (LC)	1,71%	-0,86%	-4,97%	7,03%	0,51%	0,26%	-0,62%	-4,81%	5,41%	0,28%	-0,89%	-1,00%	-3,88%	4,16%	-0,17%	-1,84%	-1,91%	-2,68%	2,93%	-0,17%
Tyndall S3	2,41%	-0,32%	-2,19%	4,55%	0,37%	-4,85%	-4,04%	-5,46%	4,38%	0,27%	-4,98%	-4,98%	-5,00%	5,13%	-0,14%	-4,30%	-4,30%	-4,02%	4,15%	-0,14%
Tyndall S4	2,41%	-0,32%	-2,09%	4,44%	0,37%	0,57%	-0,60%	-3,47%	4,36%	0,28%	-6,59%	-6,21%	-3,46%	3,22%	-0,14%	-4,91%	-4,52%	-3,98%	3,72%	-0,14%
UNDP Emissions Abatement (EA)	1,89%	-0,75%	-3,81%	5,80%	0,65%	0,71%	-1,06%	-3,60%	4,90%	0,47%	-1,07%	-2,20%	-3,25%	4,25%	0,13%	-3,56%	-4,36%	-2,58%	3,64%	-0,26%
UNDP Emissions Control (EC)	1,89%	-0,75%	-3,81%	5,80%	0,65%	0,71%	-1,06%	-3,60%	4,90%	0,47%	0,45%	-0,75%	-3,22%	4,28%	0,13%	0,32%	-0,81%	-2,31%	3,71%	-0,26%
UNDP Reference	4,14%	-0,17%	-2,21%	5,87%	0,65%	2,00%	-0,12%	-3,29%	4,93%	0,48%	0,96%	-0,21%	-3,25%	4,29%	0,13%	0,57%	-0,15%	-2,72%	3,71%	-0,26%

Annex B: Direct comparison of variations per period for each factor

	CO2				CO2/Ene				Ene/GDP				GDP/Pop				Pop			
(MtCO2)	10-20	20-30	30-40	40-50	10-20	20-30	30-40	40-50	10-20	20-30	30-40	40-50	10-20	20-30	30-40	40-50	10-20	20-30	30-40	40-50
Enerdata S1 – Recovery	3868	2078	1339	760	-119	-94	135	153	-2616	-2007	-2170	-2214	5986	3920	3438	3203	618	259	-64	-382
Enerdata S2 – Depression	3383	1672	842	22	-156	-135	43	79	-2438	-1802	-1867	-1912	5564	3696	3153	2815	413	-87	-487	-959
Enerdata S3 – Renewal	2742	-3540	-2129	-1276	-566	-3296	-1991	-1300	-2917	-2987	-1374	-611	5643	2573	1260	721	583	170	-24	-86
Enerdata S4 – Struggle	2514	-3179	-2267	-1338	-486	-2895	-1994	-1224	-2704	-2791	-1351	-583	5313	2567	1274	712	391	-60	-196	-243
ERI Accelerated Low Carbon (ALC)	921	124	-784	-2270	-968	-439	-1394	-2735	-4207	-5005	-3166	-1721	5663	5401	3803	2207	433	167	-26	-21
ERI Baseline	2365	1466	1269	-220	-1659	-472	435	-1137	-3182	-5553	-5133	-3615	6695	7266	5968	4620	512	225	0	-87
ERI Low Carbon (LC)	1170	304	195	29	-621	-626	-460	-688	-4400	-4871	-3571	-2398	5752	5626	4255	3145	440	174	-30	-30
IEA 450	2044	-2523	-1419		-615	-2432	-1426		-4126	-3512	-970		6481	3389	1026		304	33	-49	
IEA Current Policies	3437	1700	883		-146	-88	17		-3743	-3235	-1285		6997	4975	2258		328	48	-107	
IEA New Policies	2850	386	140		-333	-580	-261		-3918	-3505	-1358		6783	4428	1847		318	43	-88	
LBNL Continued Improvement (CI)	2311	1466	-31	-708	-638	-281	-491	-841	-3973	-4610	-4317	-3076	6453	6047	4982	3413	469	311	-206	-203
LBNL Continued Improvement (CI) with CCS	2280	1273	-166	-825	-673	-546	-615	-924	-3958	-4468	-4211	-2994	6443	5980	4860	3289	468	307	-201	-195
LBNL Low Carbon (LC)	1469	250	-826	-1502	-740	-593	-929	-1561	-4274	-4589	-3609	-2188	6044	5167	3872	2389	439	265	-160	-142
Tyndall S3	1914	-3538	-2200	-1173	-254	-2951	-2200	-1173	-1741	-3987	-2208	-1096	3616	3200	2268	1134	293	201	-60	-38
Tyndall S4	1914	532	-4730	-1916	-252	-561	-4459	-1762	-1658	-3215	-2483	-1550	3531	4046	2309	1450	293	262	-97	-54
UNDP Emissions Abatement (EA)	1400	600	-900	-2400	-556	-900	-1843	-2942	-2823	-3049	-2728	-1738	4300	4148	3563	2454	479	401	109	-174
UNDP Emissions Control (EC)	1400	600	400	300	-556	-900	-671	-760	-2823	-3049	-2890	-2156	4300	4148	3843	3462	479	401	118	-246
UNDP Reference	3800	2500	1400	900	-158	-149	-299	-243	-2032	-4101	-4722	-4274	5389	6156	6231	5831	601	594	191	-414
(%)	10-20	20-30	30-40	40-50	10-20	20-30	30-40	40-50	10-20	20-30	30-40	40-50	10-20	20-30	30-40	40-50	10-20	20-30	30-40	40-50
Enerdata S1 – Recovery	4,56%	1,78%	1,00%	0,52%	-0,14%	-0,08%	0,10%	0,11%	-3,09%	-1,72%	-1,62%	-1,53%	7,06%	3,36%	2,56%	2,21%	0,73%	0,22%	-0,05%	-0,26%
Enerdata S2 – Depression	4,08%	1,52%	0,68%	0,02%	-0,19%	-0,12%	0,04%	0,06%	-2,94%	-1,64%	-1,52%	-1,50%	6,71%	3,36%	2,56%	2,20%	0,50%	-0,08%	-0,40%	-0,75%
Enerdata S3 – Renewal	3,41%	-4,48%	-4,22%	-3,82%	-0,70%	-4,17%	-3,94%	-3,90%	-3,63%	-3,78%	-2,72%	-1,83%	7,02%	3,26%	2,50%	2,16%	0,72%	0,21%	-0,05%	-0,26%
Enerdata S4 – Struggle	3,16%	-4,05%	-4,44%	-4,06%	-0,61%	-3,69%	-3,90%	-3,71%	-3,40%	-3,55%	-2,64%	-1,77%	6,69%	3,27%	2,49%	2,16%	0,49%	-0,08%	-0,38%	-0,74%
ERI Accelerated Low Carbon (ALC)	1,22%	0,15%	-1,00%	-3,61%	-1,29%	-0,54%	-1,79%	-4,34%	-5,59%	-6,18%	-4,05%	-2,73%	7,52%	6,67%	4,87%	3,51%	0,58%	0,21%	-0,03%	-0,03%
ERI Baseline	2,68%	1,35%	1,04%	-0,17%	-1,88%	-0,44%	0,36%	-0,89%	-3,60%	-5,13%	-4,20%	-2,82%	7,58%	6,71%	4,89%	3,60%	0,58%	0,21%	0,00%	-0,07%
ERI Low Carbon (LC)	1,53%	0,36%	0,22%	0,03%	-0,81%	-0,74%	-0,53%	-0,78%	-5,76%	-5,78%	-4,11%	-2,72%	7,53%	6,67%	4,90%	3,57%	0,58%	0,21%	-0,03%	-0,03%
IEA 450	2,39%	-3,27%	-4,89%		-0,72%	-3,15%	-4,92%		-4,83%	-4,55%	-3,35%		7,59%	4,39%	3,54%		0,36%	0,04%	-0,17%	
IEA Current Policies	3,75%	1,54%	1,43%		-0,16%	-0,08%	0,03%		-4,09%	-2,93%	-2,08%		7,64%	4,50%	3,65%		0,36%	0,04%	-0,17%	
IEA New Policies	3,20%	0,39%	0,28%		-0,37%	-0,59%	-0,51%		-4,40%	-3,54%	-2,67%		7,62%	4,47%	3,63%		0,36%	0,04%	-0,17%	
LBNL Continued Improvement (CI)	2,53%	1,32%	-0,03%	-0,61%	-0,70%	-0,25%	-0,41%	-0,73%	-4,34%	-4,15%	-3,62%	-2,66%	7,06%	5,44%	4,18%	2,95%	0,51%	0,28%	-0,17%	-0,18%
LBNL Continued Improvement (CI) with CCS	2,50%	1,16%	-0,14%	-0,74%	-0,74%	-0,50%	-0,53%	-0,83%	-4,33%	-4,06%	-3,62%	-2,68%	7,05%	5,44%	4,18%	2,95%	0,51%	0,28%	-0,17%	-0,18%
LBNL Low Carbon (LC)	1,71%	0,26%	-0,89%	-1,84%	-0,86%	-0,62%	-1,00%	-1,91%	-4,97%	-4,81%	-3,88%	-2,68%	7,03%	5,41%	4,16%	2,93%	0,51%	0,28%	-0,17%	-0,17%
Tyndall S3	2,41%	-4,85%	-4,98%	-4,30%	-0,32%	-4,04%	-4,98%	-4,30%	-2,19%	-5,46%	-5,00%	-4,02%	4,55%	4,38%	5,13%	4,15%	0,37%	0,27%	-0,14%	-0,14%
Tyndall S4	2,41%	0,57%	-6,59%	-4,91%	-0,32%	-0,60%	-6,21%	-4,52%	-2,09%	-3,47%	-3,46%	-3,98%	4,44%	4,36%	3,22%	3,72%	0,37%	0,28%	-0,14%	-0,14%
UNDP Emissions Abatement (EA)	1,89%	0,71%	-1,07%	-3,56%	-0,75%	-1,06%	-2,20%	-4,36%	-3,81%	-3,60%	-3,25%	-2,58%	5,80%	4,90%	4,25%	3,64%	0,65%	0,47%	0,13%	-0,26%
UNDP Emissions Control (EC)	1,89%	0,71%	0,45%	0,32%	-0,75%	-1,06%	-0,75%	-0,81%	-3,81%	-3,60%	-3,22%	-2,31%	5,80%	4,90%	4,28%	3,71%	0,65%	0,47%	0,13%	-0,26%
UNDP Reference	4,14%	2,00%	0,96%	0,57%	-0,17%	-0,12%	-0,21%	-0,15%	-2,21%	-3,29%	-3,25%	-2,72%	5,87%	4,93%	4,29%	3,71%	0,65%	0,48%	0,13%	-0,26%

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